IN PHASE MOTOR BUS TRANSFER

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Abstract

To increase the robustness of the electrical power supply to an industrial facility, two independent power supplies are typically routed to the facility. A power supply typically consists of a power source and a power line used to transmit the power from the source to the facility. Each power supply terminates in an independent power distribution node know as a bus. If for some reason one of the two power supplies become unavailable either due to a fault on the power line or unavailability of the source, it is possible to parallel the two buses together and keep the facility fully operational.

Induction motors comprise the bulk of the load on the buses, requiring that before the two buses are connected together the voltages of the buses be in synchronism. The process by which the two buses are connected to one another is known in the electrical power industry as an "in-phase motor bus transfer." In this dissertation the requirements for a successful in-phase motor bus transfer are examined and a new method which does not require extensive studies or testing is proposed. The method's robustness is tested under extreme power system conditions by first subjecting the motor bus to various external fault conditions. Once the motor bus is isolated the ability of the new method to synchronously and successfully transfer the isolated bus to an alternative power source is tested under a variety of different operating conditions.

This dissertation shows that the new proposed method successfully performs an in-phase motor bus transfer and synchronously connects the motor bus to the alternative power source, without first having to conduct any advanced system studies or tests. The new method requires the user to have very little knowledge of the power system or the motor loads on the individual buses.

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Chapter I: Introduction

1.1 Introduction

Most critical industrial facilities such as manufacturing plants or mines are supplied from two independent electrical power supplies. Where an electrical power supply consists of a power source and a power line (feeder), to deliver the electrical power from the source to the factory (load). The two independent supplies typically terminate in two independent power distribution nodes known as buses. The dual supply ensures complete redundancy in the event of one of the power supplies becoming unavailable for any reason, such as a fault on one of the power lines. Under normal system operating conditions the two buses are not connected to one another to ensure that a disturbance in one power supply does not result in a disturbance in the other power supply. For example, if the two power supplies are connected together and a fault occurs on one of the power lines, the fault impacts both power supplies. Whereas, if the systems are separated, the fault is localized to only one of the power supplies. However, the option to connect the two buses together in case of emergency via a circuit breaker known as a bus coupler is avaiable. This option is exercised in order to keep critical processes connected to the bus that lost it power supply functioning.

Connecting these two buses together after a disturbance on one of the power supplies is not a simple or trivial exercise. Typically, before one of the buses is connected to the other bus (or alternative power supply), the bus is isolated for a brief period of time so as to assist in clearing the fault on the power line. In most cases AC induction motors are connected to these buses and once these motor's are isolated from the primary power supply some of these motors become induction generators and generate power for the remainder of the loads on the isolated bus. The magnitude and frequency of the voltage generated by these induction motors that now act as generators is different than that of the healthy bus, and as such the isolated bus cannot be connected to the healthy bus (or alternate power source) at any arbitrary instance in time. If the isolated bus is connected to the healthy bus or the alternative bus at any arbitrary instant in time, large transient airgap torques in the motors may result that can destroy not only the motors but also the shafts of the loads driven by these motors. So, the practice in industry has been to try and connect (transfer) the isolated bus to the healthy bus (alternative power supply) at the instant in time when the two voltages are perfectly in-phase (synchronism) with each other, hence the term “In-phase Motor Bus Transfer.” To realize a successful in phase motor bus transfer at present requires some detailed studies of the bus and its associated loads and testing of the motor bus to be transferred. One of the objectives of this dissertation is to understand all the factors that influence a successful in phase motor bus transfer. Thereafter, an algorithm (method) that does not require any detailed knowledge of the motor bus or any in depth studies or testing is developed. Finally a motor bus transfer scheme is modelled in a real time digital simulator (RTDS™), this model is used to validate the performance of the new proposed in-phase motor bus transfer algorithm under different operating conditions of the motor bus.

Chapter I, Introduction, reviews the literature with regards to motor bus transfer. Then since the AC induction motor is at the heart of the motor bus transfer, a detailed analysis of the three phase AC induction motor is given in Chapter II, Analytical Analysis of a Three-Phase Induction Motor. This analysis is required to understand what factors determine the transient airgap torque developed by an induction motor during a motor bus transfer. The analysis of the induction motor during the transient period is done in the “qd0” domain.

Chapter III, Motor Bus Transfer, discusses the present practices and requirements of a motor bus transfer scheme. The chapter highlights the short comings of some of the methods that employ frequency tracking and proposes two new solutions that are frequency invariant, these methods are then modelled in a Real Time Digital simulator (RTDS®) to test and verify their validity. The implementation of the proposed new methods in the RTDS® is discussed in detail in Chapter IV, Power System and Algorithm Implementation in a Real Time Digital Simulator (RTDS™).

Chapter V, Performance of Method 1, Motor Bus Transfer Logic, discusses the results obtained by using one of the new proposed in phase bus transfer algorithms. Chapter V, also discusses the different factors that determine the success of an in-phase motor bus transfer and shows that the new proposed methods does not require elaborate system studies or testing to ensure a successful in-phase motor bus transfer. Chapter V concludes with a simple method to determine whether a successful in-phase motor bus transfer is possible in a specific industrial plant.

Chapter VI, Conclusion and Future Work, discusses what has been achieved in this dissertation, and discusses possible in-phase motor bus transfers future work.

1.2 Literature Review

Following is a review of motor bus transfer literature; the review focuses on what has been done to date and also verifies that this is a worthwhile topic to pursue for a PhD dissertation. The literature review also serves to help gain an understanding of why motor bus transfer schemes have been implemented in the power industry. The literature is reviewed in ascending chorological order; begining with the first paper that was presented in 1940.

Brief comments and or summary of each of the more relevant papers is given in the following section. Some papers are just mentioned (referenced) but no description or summary is given about them, the reason for this is that the contents have been discussed previously.

Some of the papers in the review are not directly related to the topic of motor bus transfer, but relate to transient torques generated in the airgap of motors (synchronous motors in particular) due to a fault condition on the power system or when the faulted line is switched back into service. These papers were reviewed to obtain a better understanding of the phenomena of transient torques generated in the air gap of a motor after a transient condition occurred on the power system. The transient airgap torque generated in a synchronous motor following a disturbance on a power is similar in nature to that of an induction motor when it is transferred to an alternative power source after a disturbance on the power system.

1.) A.M. Wahl, L.A. Kilgore, "Transients Starting Torques in Induction Motors", presented at the AIEE summer convention, Swampscott, Mass, June 24-28, 1940.

This is one of the first papers to mention transient torque of an electrical motor during starting. Even though this paper does not mention or discuss anything about fast motor bus transfers, it lays the foundations for the behavior of induction motor when a voltage is suddenly applied to a motor. The paper mentions that when a voltage is suddenly applied to a motor a fundamental frequency torque several times (2–3 times) the pullout torque is developed by the motor during the first few power system cycles. The paper also investigates the torque developed by a motor if the motor contactor does not close all three poles simultaneously and mention is made that the torque developed under these conditions maybe higher (up to 40%), than the torque developed when all three poles are closed simultaneously. The paper mentions that some motors are started in a star delta arrangement (wye/delta), this was done to reduce the starting current drawn by a motor, and under this condition the transient torque could be greater than the initial starting transient torque. If we consider this last statement, this phenomena is very similar to a fast motor bus transfer in that once the motor is close to its rated speed the star connected motor contactor is de-energized, and before the delta connected motor contactor is energized the motor is disconnected from the power supply. During this disconnection period the motor voltage is decaying and the angular difference between the source and motor is increasing. Considering that motor contactors of this era may have taken up to 100 milliseconds to close, one can easily envision how starting a motor in star delta is very similar to a fast motor bus transfer. This is a very good fundamentals paper with regards to transient torques developed by a motor.

2.) R.C. Moore, " Residual Voltage in Induction Motors Influences Load Transfer Time", Allis-Chalmers Electrical Review, Third Quarter, 1955

This paper discusses the fundamentals of an induction motor once it is disconnected from its main supply source. It discusses the concept of residual voltage and how this voltage (V) is related to the residual flux (λ) in the motor and the speed of the rotor (ω), $V \propto \lambda, \omega$. The paper mentions that the decay of the residual voltage in the motor is dependent on the magnetizing inductance, the rotor inductance and the rotor resistance. This paper discuss how the machine can be designed such that the time constant (X/R) can be reduced so that a residual transfer can occur as rapidly as possible. This concept reflects the thinking of the time whereby a transfer only occurred when the residual voltage was low enough so as not to create a large inrush current or torque once the motor is reconnected to a healthy supply.

3.) D.G. Lewis, W.D. Marsh, "Transfer of Steam Electric Station Auxiliary Buses", AIEE Transactions, June 1955.

This paper is primarily concerned with how to keep the boiler of a steam power station operational during emergency conditions. The paper mentions three modes of transfer, namely: permanent parallel operation of a bus, no intentional delay of a bus transfer where a close signal is issued at the same time as the trip signal is issued, and a delayed transfer where a close is only issued when the main breaker opens. The paper echos the philosophy of the time where a delayed transfer only occurs when the motors residual voltage reaches a value of less than 25% of nominal. The paper presents a very good mathematical analysis of residual voltage and frequency when the motor is islanded. The paper also discusses the torque developed in a motor when the motor is connected to an auxiliary bus. The paper addresses the issue of multiple motors on a bus and mentions, if the motors all have the same electrical and mechanical properties, each motor can be considered as not being connected to a common bus and that the bus voltage will decay at the rate as determined by the motors open circuit X/R ratio (time constant). However, if the motors are dissimilar, after a elapse of about 3 cycles of the bus being isolated from the source, the bus voltage shift behind the voltage (rotor flux) of the high inertia motors and therefore these motors supply energy to the low inertia motors. The frequency on the bus being the average of the motor speeds of all the motors on the bus.

This paper high lights a few important issues:

- The frequency measured on the bus is not representative of a specific motor's frequency

- The voltage magnitude on the bus is not representative of the residual voltage of a specific motor
- The bus voltage angle is not representative of the residual voltage angle (Rotor flux angle) of an individual motor.

4.) G.F. Walsh, "The Effects of Reclosing on Industrial Plants" Volume XXIII-Proceedings of the American Power Conference, 1961, pp.768-778.

This paper discusses the effects of reclosing the supply to an industrial plant on the industrial plant electrical equipment. The issue of the current drawn from the supply, as well as the torque developed by the induction motors once the industrial plant is reconnected to the supply is also discussed. The paper states that when an automatic reclose is initiated the transient current produced should not be higher than the short circuit current of the transformer, since this is what the transformer bracing is designed for. In addition to the previous requirement, the current should not be greater than the current for which the motor is braced at, and corresponds to the rated voltage divided by the locked rotor inductance of the motor. This paper is also the first to mention that the peak shaft torque should not exceed 6 times the rated torque of the motor (6 times the rated torque corresponds to the torque produced by a phase-to-phase fault at the terminals of the machine). Also mentioned in the paper is that when an in-phase transfer occurs, the peak electrical torque is developed when the angular difference between the motor voltage and the voltage on the bus is a 120°. The paper also states that studies have determined that if the residual voltage is below 25% of nominal, no stress will be placed on the motor or associated electrical equipment such as the supply transformers. Not only is the issue of reclosing of induction motors addressed in this paper, but also the effect of reclosing on synchronous motors. The paper concludes by discussing solutions of how to prevent utility reclosing practices from damaging industrial equipment, motors in particular.

5.) C.C. Young, J. Dunki-Jacobs, "The Concept of In-Phase Transfer Applied to Industrial Systems Serving Essential Service Motors," AIEE Transactions, January 1961.

Young and Dunki-Jacobs were the first to suggest the concept of an in-phase transfer, the suggestion was driven by the change in the steam plant generation industry, from having steam turbines drive large loads, such as boiler feed pumps to having induction motors drive these loads. These larger motors had larger time constants and as such longer time was required for the residual voltage to drop below the 25% nominal voltage before a transfer of the load was allowed. This longer wait time raised the concern of more severe voltage dips and longer recovery times and the possibility of stalling some of the motors. The paper discusses the in-phase transfer principle and characterizes the motor residual voltage for a single motor and multiple interconnected motors. The paper states that for a single motor the residual voltage is a function of the electrical energy stored in the magnetic circuit of the motor (residual flux) and the mechanical energy stored in the rotational parts of the motor and load. For multiple interconnected motors if the motors and their loads are identical then the motors will decelerate at identical rates. With the motors decaying at identical rates, no interchange of stored electrical or mechanical energy occurs, which is similar to the condition of each motor being independently open circuited. If motors and their loads are not identical the motors with inertia's higher than the average inertia will decelerate more slowly and if the rotor flux of the motors with the higher inertia decays more slowly, these motors will supply the energy to the other motors and loads on the bus. When compared to the open circuit condition the "higher inertia" motors will decelerate faster as compared to the "low inertia" motors that will decelerate slower. The result of this is that the interconnected motors will tend to remain in synchronism.

Young and Dunki-Jacobs also list as set of requirements for a successful “in-phase transfer” and these are:

- Motor starters or circuit breaker used as starters have to remain closed (in service).
- The frequency and residual bus voltage with respect to time must be known.
- The motor and load characteristics allow the reacceleration of all essential motors after the reapplication of voltage.
- A fast breaker utilizing stored mechanical energy for reclosing will be required (typically a spring charged mechanism).
- A relay capable of sensing the relative phase angle relationship between two voltage sources is needed, which can be set to operate at a particular phase angle.

The paper mentions that when the angular difference between the two sources is 60° the peak transient torque can be as high as 12 times rated torque. These transient torques produce both foundation stresses and stresses in the shaft. The paper is one of the first to mention that in order to prevent these transient shaft torques from damaging the shaft and coupling, it is to ensure that the peak shaft torque never exceeds six times the rated torque. Incidentally induction motors are designed to withstand a phase-to-phase fault at the terminals of the machine which produces a torque of approximately six times rated torque. The paper further mentions that wound induction motors and synchronous motors require special consideration. Analysis of the induction motor under different system conditions is also done in this paper.

6.) S.S. Kalsi, D.D. Stephen, B. Adkins, "Calculation of system – Fault Currents Due to Induction Motors," Proceeding of IEE, Vol.118, No.1, January 1971.

This paper deals with the calculation of fault current contribution of a large induction motor, so that the current rating of the circuit breaker (switchgear) can be determined. The authors state that the short circuit current of an induction motor can be adequately represented by two exponentially decaying functions, determined by four parameters namely; the transient and subtransient reactance's and the associated time constants. The authors use the two axis theory as developed by Park in 1929 that is used for synchronous motor calculations. The authors use this method because the theory of short circuits in an induction motor closely follows that of a synchronous motor. The paper makes one important statement in that it states (and proves) that the terminal voltage of the machine decreases by an amount equal to the voltage drop across the subtransient reactance of the motor when the supply to the motor is disconnected. This statement answers a very fundamental question namely, "*What is the motor voltage across the terminal of the motor when the motor is disconnected from its power supply?*" This paper is a very good tutorial paper in that it derives all of the equations from first principles!

7.) S.N. Talukdar, H.E. Sinnot, "Calculating the Transformer Inrush currents that Result from The Transfer of Power Plant Auxiliary Buses," Paper C72098-7, IEEE 1972 Summer Meeting.

In this paper Talukdar and Sinnot propose a method to calculate the transformer inrush current when they transfer auxiliary load from one source to the other. The case that they consider is the one in which the two sources are first paralleled and then the primary breaker is opened. The authors propose a relative simple method by which the inrush current in the auxiliary transformer can be calculated when the two sources are paralleled.

The authors incorrectly state that the current drawn during the first cycle of reclosing is going to be the largest and therefore only the 1st cycle needs to be considered. Consider the following scenario in which the two systems that are going to be connected together are at two slightly different frequencies (59.8 Hz and 60.0 Hz respectively). Even if the two systems are connected together when the angular difference between the two systems is zero, then depending on the inertia of the two systems with respect to one another the system will move towards the same frequency. However, until the two systems come into synchronism with one another, the two systems will be out of step with one another and the maximum current will occur when the two voltages are 180 degrees out of phase with one another!

At the time this paper was written no machine (motor) models were available in EMTP™. Today this scenario can be modeled using the alternative transients program (ATP™) or EMTP ™ or any similar transients modeling program and give the current several cycles after the auxiliary bus has been transferred.

8.) S.S. Kalsi, "Switching transients in large deep bar squirrel cage induction motors," presented at the IEEE PES winter meeting, New York, N.Y., January 28 – February 2, 1973.

In this paper Kalsi calculates the electrical torque and associated current during different short circuit and starting conditions. During these conditions the motor draws or delivers large amounts of current which in turn subjects the motor and driven equipment to abnormally large forces (torques). The values of these forces needs to be determined accurately so that the motor shaft end windings support and coupling of the driven machinery can be designed correctly. Kalsi addresses the following short circuit conditions:

- Direct short circuit: a short circuit is applied directly to the terminals of the motor while the motor is still connected to the supply.
- Indirect short circuit: the motor is first disconnected from the supply and a short circuit is applied directly across the terminals of the motor a few cycles later.
- Motor is initially at standstill.
- Motor is initially running without trapped flux in the rotor (approximately equivalent than a residual voltage bus transfer.)
- Motor initially running with trapped flux in the rotor (equivalent to and in phase fast motor bus transfer.)

Under all these different conditions the torque developed by the motor can be divided into three prominent components namely; a unidirectional torque that decays with a time constant, a symmetrical torque that oscillates at the rotor frequency and decays with a transient time constant and a symmetrical torque that oscillates at the rotor frequency that decays with a subtransient time constant. The currents drawn or delivered by the motor can similarly be broken up into the same three categories. This paper is a very good tutorial paper in that it derives all the analytical equations from first principles.

9.) R.H. McFadden, "Re-Energizing Large Motors after Brief Interruptions—Problems and Solutions," Pulp and Paper Industrial Technical Conference, IEEE, PAPCON 77, pp 84–94.

This paper addresses the problem from the point of view of the pulp and paper industry. The paper begins by describing how a motor bus can be disconnected and suddenly reconnected to a power source; one of the main reasons is due to automatic reclosing of the transmission line feeding the motor bus so as to maintain maximum serviceability to the customer. The other reason, since the bus supplies critical load, is that bus is equipped with an automatic transfer scheme. In either case the bus gets disconnected from the source and then some arbitrary time later the bus gets reconnected to a source. McFadden goes on to explain how this sequence can be detrimental to not only the motors connected to the bus, but also the loads that are connected to the motor, since the torque developed during the reclose can be much greater than the designed torque of the load shaft.

The general concept of the problem of reconnecting motor loads to a power source is addressed by the author. He states that during the open time interval the magnitude of the motor voltage changes very little and that when the motor voltage and system voltage are 180 degrees out of phase the magnitude difference between the two sources is very close to 2 per unit. Should the motor bus be reconnected at this time, the motors would develop a torque twice the normal start up torque of the motors.

The author uses simplified mathematical models to determine the voltage at the terminals of the motors during the open interval time. The simplified model is also used to calculate the transient torque developed by the motor when the motor is reconnected to the bus.

The most interesting statement made by the author is that should the line supplying the motor bus experience a fault on it, the motors will contribute to the fault current and as a result of this the motor voltage would collapse to such an extent that during a reclose the motor residual voltage could be ignored. *This statement is only true if the fault is a three phase fault, close in to the motor bus, and lasting for a considerable amount of time. Considering that roughly 85% of all line faults are single line to ground faults this statement does not hold true and one of the aspects of this dissertation is to investigate how different fault types and their duration affect the motors residual voltage.*

McFadden is one of the first to consider the impact of reconnecting the motor bus to the source on synchronous motors. McFadden states that the reconnection of a synchronous motor can be described by the superposition of two effects. The first is due to the motor action of the damper windings and the second by the synchronous machine action of the main rotor. McFadden states that the magnitude of the two effects is approximately the same, but they are characterized by two different time constants. The motor action has a time constant equal to that of the subtransient time constant T_d" and the synchronous machine effect by the transient time constant T_d'.

The effects of having multiple motors on the bus are summarized as follows;

- After the bus is isolated, the motors with the highest inertia act as induction generators. These machines supply the accelerating power to the lower inertia motors and bring all the motors on the bus more or less into synchronism.

- The bus voltage under this condition decreases more rapidly than in the case of having a single isolated motor. This rapid decrease is due to the losses caused by the currents flowing between the motors
- The field fluxes in the motors decay approximately at the same rate. The motors with the slower decaying field flux supply the faster decaying field flux motors with reactive power (VARS).
- After the bus is reconnected to the power source, individual motors behave independently from one another.

McFadden discuss the types of damage sustained by motors due to out of phase reclosing, these are:

- Loosening of the winding bracing due to the large magnetic forces. This results in failure of the winding insulation
- Loosening of the rotor bars of the induction motor, resulting in vibration and fatigue failure.
- Failure of the motors rotor shaft due to fatigue.

One of the most interesting aspects of McFadden's paper are his criteria for a safe reconnection of the motor bus to the power source, these are:

- Avoid reclosing when the magnitude difference between the residual voltage (motor voltage) and the power system is greater than 1.25 to 1.35 p.u. of the motors rated voltage. *(this is the first time this criteria is specifically called out)*

- If the residual voltage is less than 0.33 p.u., then the motor bus can be reconnected to the system at any instant in time.
- No reclosing should occur 0.25 to 0.4 seconds after the motor bus has been disconnected from the power source.
- A high speed bus transfer can occur if the residual voltage angle lags the system voltage by more than 80°.

McFadden then goes on and discusses different methods to prevent out-of-phase reclosing for motor busses. He concludes the paper by discussing other switching transients that can create dangerous torques or transient currents, one of these being the switching of shunt capacitor banks.

10.) ***P.C. Krause, W.C. Hollopeter, D.M. Triezenberg, P.A. Rusche, "Shaft Torques During out-of-phase synchronization" IEEE Transactions on Power Apparatus and Systems, vol. PAS-96, no.4, July/August 1977.***

This paper was written as a consequence of two shaft failures of two different gas turbines at Consumers Energy. The authors performed computer simulations to determine the torques created in the turbo generators when an out-of-phase synchronization event occurred. Even though this dissertation only concentrates on induction motors, the literature review includes the effect of out-of-phase synchronization of both induction and synchronous motors to get a broader understanding of the phenomena. In their simulation the authors performed out-of-phase synchronization of a synchronous motor from 0° to 120° in 20° degree increments for machine voltages both leading and lagging the system voltage. The computer study showed three important results:

- During incorrect synchronization, mal-synchronization, the turbo generator shaft can be subjected to large instantaneous torques which can cause shaft failure but at the same time the short circuit capacity (current) of the motor is not exceeded. These large instantaneous torques means that the motor can sustain shaft damage without sustaining any winding damage. The motor is designed to sustain stator currents and instantaneous shaft torques resulting from a three phase fault at the terminals of the motor. However, an out-of-step synchronization can result in an instantaneous shaft torques 2–3 times the design torque of the motor without exceeding the short circuit capability of the motor!
- The maximum instantaneous shaft torque is developed when the motor is synchronized 120° out-of-phase.
- If the motor voltage is leading the system voltage, the instantaneous torque developed by the motor is 2 – 4 times greater than when the motor is lagging the system voltage!

The authors go on to state that since mal-synchronization has profound effects on the shaft of the synchronous motor, serious consideration should be given to selecting and operating synchronization equipment. Also, reclosing should not occur if the motor voltage leads that of the power system.

11.) J.D. Gill, "Transfer of motor loads between out-of-phase sources" IEEE Transactions on Industry Applications, Vol.IA-15, no.4, July/August 1979.

Gill approaches this paper form the "reliability of supply" point of view and includes the automatic transfer scheme as part of the emergency system. His intention is to determine a set of criteria for a fast in-phase motor bus transfer from either the normal power source to an emergency power source (such as a backup diesel generator) or from the emergency power source to the normal power source. The fast motor bus transfer criteria have to meet the following conditions;

- The motors must not sustain any electrical or mechanical damage.
- The instantaneous torque developed during the transfer must not damage shafts of either the motor or the load.
- The instantaneous current drawn during the transfer must not result in the overcurrent or overload protection operating and thereby isolating the bus.

Gill noted that if the load on the bus consisted not only of motors, but also contained lighting, heating and other miscellaneous loads, the inrush current will be reduced and the subsequent torque developed will not create a problem for either the motors or their connected loads. He also noted that if the motors on the bus were smaller than 50 hp (40 kW), the transients caused by and out-of-phase reclose would be fairly insignificant.

Gill ran a series of test cases using a 111 hp motor and came to the following conclusions;

- If the angle difference between the motor bus voltage and the source voltage is less than 30° when the motor bus is transferred, the resulting inrush current would be less than half of the motors normal starting (energization) current.

- If the angle difference between the motor bus voltage and the source voltage is between 30° and 60° when the motor bus is transferred, then the resulting inrush current is between half and the normal motor energization current.

- If the angle difference between the motor voltage and the source voltage is between 60° and 90° when the motor bus is transferred, then the resulting inrush current is going to be greater than normal energization current of the motor.

- When the angle difference between the motor voltage and the source voltage is greater than 90°, the instantaneous overcurrent protection operated and isolated the motor bus. Gill observed an inrush current 50% greater than the normal energization (start up) current of the motor.

Gill concluded that for a successful motor bus transfer with the motors on the bus greater than 50 hp the voltage magnitude difference between the source and motor should not be greater than the nominal voltage of the motor. Therefore, the maximum angle difference between the motor bus and the source should be less than 60°.

12.) C.V. Watters, "A simplified Procedure for Determining the Auxiliary Bus Voltage and Phase Angle during Bus Transfer," IEEE Transaction on Power Apparatus and Systems, Vol PAS-100, No.6, June 1981.

In this paper C.V. Watters presents a method whereby the voltage and angle of the auxiliary bus with relation to the reserve bus can be computed for the first ½ second after the auxiliary bus has been isolated from the main bus. In this method the average inertia/power ratio of the motors connected to the auxiliary bus are calculated. All motors with an inertia/power ratio greater than the average inertia/power ratio are placed in one category and motors with an inertia/power ratio less than the average inertia/power ratio in another category. In the category where the motors have the higher than average inertia/power ratio the motors will act as generators and provide active and reactive power to the remaining loads on the bus. Typically all fan motors such as forced air draft fan (FDF) and induced air draft fan (IDF) motors fall in this category. The motors in the category with the lower than average inertia/power ratio will act as motors and draw active and reactive power from the bus. Typically all pump motors such as boiler feed pump (BFP) and cooling water pumps etc. fall in this category.

The method develops an equivalent generator and motor model. For the generator model an open circuit time constant is determined and for the pump motor a speed torque curve is determined. The models are verified by a stability study in that the active and reactive power generated by the "generators" has to be matched by the active and reactive power absorbed by the motor loads. He compares his simulation results to a study conducted by an electric utility in 1967. There is a reasonable correlation between his simulation and the study. *What is interesting to note that in 1980 when the paper was written, the closing time of a large tie breaker was in the order of 10-*

14 cycles (170–234 milliseconds). This paper was written to advocate the use of fast motor bus transfer within power plants.

13.) ***I.M. Canay, H.J. Rohrer, K.E. Schnirel, "Effects of electrical disturbances, grid recovery voltage and generator inertia on maximization of mechanical torques in large turbo generator sets" IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No.4 July/August 1980.***

In this paper Canay investigates what impact different electrical disturbances have on large multistage (multi-mass) turbo generators (synchronous motors). In the paper the authors state that in general turbo generators are designed to handle short circuits at the machine terminals, but that often a second contingency such as an evolving fault, or a high speed reclose on a power line can cause an oscillation in the generator shaft that goes beyond the design limits of shafts. The paper emphasizes that it is not possible to predict the most unfavourable stresses that a generator shaft can be subjected to, but that these condictions need to be simulated by using different fault clearing and reclosing times. The paper does recommend that faults on the power system close to generator terminals should be cleared as rapidly and possibly, and for three phase faults close to the generator terminal, auto reclosing of the powerlines to be inhibited.

14.) ***R.H. Daugherty, "Analysis of transient electrical torques and shaft torques in induction motors as a result of power supply disturbances" IEEE transactions on power apparatus and systems, Vol. PAS-101, no.8, August 1982.***

This is one of the best papers in this area because it addresses not only the effects on the motor due a fast transfer, but also the effect on the motor driven load (equipment). The paper derives models for both the motor and the load. The motor is represented by means of the conventional three phase model and the load is represented by a mass-torsional spring model. The two models are interconnected thru the motors electrical air gap torque, the speed and position of the rotor. This paper is an excellent tutorial paper on this subject because it derives both the electrical and mechanical models from first principles. The paper mentions the importance of the residual flux in the motor and the effect this flux has on the inrush current and hence the transient torque generated when the motor is reconnected to an alternate supply (power source). The transient electrical torque developed when the motor is reconnected is dependent on the speed of the rotor and the trapped flux when the motor was disconnected. Since the mass-torsional spring model is described by a set of linear equations, the laws of superposition hold. Therefore, any change in the electrical torque can simply be added to the existing torque of the shaft. The result of electrical and mechanical torque being that the two torques could be either in-phase or out-of-phase resulting in either a larger or smaller total transient torque. Therefore, the total transient shaft torque is not only dependent on the speed of the rotor and the trapped flux (electrical torque), but also the transient torque present on the shaft (mechanical torque) at the instant the motor is reconnected to the auxiliary supply. Therefore, the magnitude of the electrical torque and the shaft torque response cannot be determined from the phasor difference of the voltages alone. This paper is one of the first to challenge the industrial standard (ANSI Standard C50.41) that in-phase reclosing should occur when the resultant vectorial volts per hertz between the motor residual voltage and the alternate source should not exceed 1.33 V/Hz. The mass-torsional spring model provides a torsional resonance frequency (ω_n) of the shaft system and this enables the user to check if the air gap electromagnetic torque contains and frequency components near the torsional resonance frequency.

15.) ***I.M. Canay, "A Novel Approach to the Torsional Interaction and Electrical Damping of Synchronous Machines, Part I: Theory" IEEE transactions on power apparatus and systems, vol. PAS-101, no.10, October 1982.***

Essentially this paper has nothing to do with fast motor bus transfer, but Canay discusses the issue of torsional interaction between the electrical and mechanical system in a turbo generator caused by series capacitors in transmission lines. However, this interaction between the electrical and mechanical systems of a turbo generator is very similar to the interaction between the electrical (induction motor) and the mechanical system (motor driven loads) when a fast motor bus transfer occurs.

16.) ***I.M. Canay, "A Novel Approach to the Torsional Interaction and Electrical Damping of Synchronous Machines, Part II: Application to an arbitrary network" IEEE transactions on power apparatus and systems, vol. PAS-101, no.10, October 1982.***

Similar comments as for paper number 15 "*A Novel Approach to the Tosional interaction and Electrical Damping of Synchronous Machines, Part 1: Theory.*"

17.) ***R.L. Nailen, "Avoiding Switching Transient Damage in Motor Circuits", Consulting –Specifying Engineer, March 1987, pp 86–88.***

This paper mentions some instances where industrial motors and the connected loads were damaged due to reclosing occurring on the utility network. Mention is also made that the shunt capacitors connected to the industrial bus can further exacerbate the problem of reclosing. Shunt capacitor banks reduce the decay time of the voltage on the bus therefore it will take longer for the motor voltage to decay. This delay in the motor voltage decay can lead to greater occurrences of motor damage due to reclosing occurring on the utility network. The paper does mention one interesting fact that the torque that is produced during the reclose is effectively the “airgap” torque and not necessarily the torque experienced by the rotor or its associated load.

18.) John S.C Htsui, “Non-simultaneous Reclosing Air-Gap Transient Torque of Induction Motor: Part II, Sample Studies and Discussions of Reclosing on ANSI C50.41”, IEEE Transactions on Power Apparatus and Systems, Winter Meeting1986, 214-1.

In this paper Htsui, investigates the torque developed when the three poles of a motor are not reclosed simultaneously. He recloses the first two circuit breaker poles simultaneously and a time later corresponding (which corresponds to an angular difference) he closes the third circuit breaker pole. In this paper he wishes to determine the optimal angle to reclose the third circuit breaker pole so as to develop the least amount of airgap torque in the motor. For this study he uses a 1250/2500 hp 12/10 pole motor and proceeds to determine the criteria for the third pole by using 4 test cases.

In the first case he tests for the criteria when there is no residual voltage present on the motor (this is done by having a delay time before initiating reclose, 9 seconds after the motor was disconnected from the power supply). He, however, makes no mention of the speed (slip) of the motor when this test is conducted and in the ensuing discussion at the end of the paper Daugherty points out this fact.

In the second case he has the motor speed decrease to half (i.e., slip = 0.5 p.u.) and a dead time of 9 seconds, meaning that the residual voltage in this case has also decayed to a value close to zero.

In the third test he has the motor slip decrease so that the slip is equal to 0.278 and the dead time is 2 seconds. The residual flux depends on the open circuit time constant of the motor, however, from the data obtained it indicates that there was no residual voltage on the motor.

In the fourth test case the motor slip decrease to 0.016 p.u. and this occurs after 100 milliseconds and since this time is much shorter than the open circuit time constant of the motor there is still sufficient residual voltage on the motor, when the motor is reconnected to the power source.

Htsui came to the following conclusion after his experiments;

- The reclosing airgap torque consists of three components; namely a steady state torque, a non-oscillatory decaying torque and an oscillatory torque.

- When the residual flux has decayed (i.e., there is no residual voltage on the motor) the reclosing phase position of the system voltage when the first two poles are energized and phase position of the system voltage when the third pole is closed affects the magnitude of peak transient torque developed by the motor. The maximum magnitude transient torque is developed when the system voltage has a phase angle of zero degrees (zero instantaneous voltage) and the third pole is closed 90° later (i.e., the voltage has a phase angle of 90°). The minimum magnitude transient torque occurs when system voltage has a phase angle of 90° (maximum instantaneous voltage) and the third pole is closed 90° later (the voltage has a phase angle of 180°).

- When the residual flux has decayed and the motor is running at half its nominal speed (slip = 0.5) then there is no significant difference between when the first two circuit breaker poles are energized and when the third circuit breaker pole is energized.
- When there is residual flux present, carefull analysis of when to energize the first two circuit breaker poles two poles and when to close the third pole has to be done, so as not to develop an airgap torque that can be dangerous to the motor or the load shafts.
- A significant comment is that Htsui states that the 1.33 V/Hz criteria given by the ANSI standard does not have any real relevance here and that one needs to calculate the resultant airgap transient torque developed using a computer model developed by him in an earlier paper namely; "*Magnitudes, Amplitudes and Frequencies of Induction-Motor Air Gap transient Torque Through Simultaneous Reclosing with or Without Capacitors*"

Hstui develop a computer model to calculate the transient torque developed by a motor for the different reclosing condition he discussed in the paper and claims good correlation between the model and actual test data.

This dissertation does not consider non-simultaneous reclosing and this paper was just reviewed to gain a better understanding of this topic as a whole.

19.) K.E. Yeager, "Bus Transfer of Multiple Induction Motor Loads in a 400 Megawatt Fossil Power Plant", IEEE Transaction on Energy Conversion, Vol.3, No. 3, September 1988.

This paper is a report on the comparison between a computer simulation and an actual field test of a bus transfer for a multiple motor bus of a 400MW fossil fired power plant. This report mentions that during the transfer time or “dead time” some motors act as generators to the bus and that this role may change during the dead time. The paper relies on the work done by Daugherty and Htsui. The field tests validate to a degree that the computer model used for this simulation is valid. Mention is also made that obtaining sufficient motor and load data does not warrant a more sophisticated model. The paper also mentions that the ANSI/NEMA criteria of that time are not sufficient to limit excessive torque on the motor or load shafts.

20.) R.H. Daugherty, “Bus transfer of AC Induction Motors: A perspective”, IEEE Transactions on industry applications, vol.26 no.5, September/October 1990.

This paper mentions two rules of thumb with regards to the residual voltage of an induction machine when it is disconnected from the power source.

The first rule of thumb states that, when the motor is disconnected from the primary source the open circuit voltage (terminal voltage) suddenly changes to be equal to the voltage across the magnetizing branch (in both magnitude and phase). This sudden change in voltage requires that the current through the magnetizing branch remains unchanged before the interruption and after the interruption. The problem with this theory or rule is that the current through the rotor would need to change from the current before the interruption (load current) to the magnetizing current (after the interruption). This change in current would mean the motor has a sudden change in torque.

The second rule of thumb assumes that the current in all three stator phases are suddenly interrupted and become zero. With this rule of thumb the rotor current before the interruption and after the interruption must remain the same. This sudden decrease in stator current implies that the “load” or rotor current then flows through the magnetizing reactance and the open circuit voltage would now be proportional to the pre interruption rotor current. If the motor was fully loaded prior to the interruption this could result in a very large open circuit voltage.

Using the equations derived in his previous paper Daugherty proves that the first rule of thumb has more credibility than the second. However, he does caution that one needs to understand what the basis is behind it. He states that there is no clear way to estimate the voltage magnitude and phase angle immediately after the breaker opens.

21.) T.A. Higgins, W.L. Snider, P.L. Young, H.J. Holley, “Report on Bus Transfer Part I – Assessment and Application,” IEEE Transactions on Energy Conversion, Vol.5, No.3, September 1990, pg. 462–469.

This paper is the first of three papers (reports) on fast motor bus transfer and is applicable to steam powered generating plants. The first paper presents the application philosophy and a means by which to evaluate bus transfer performance. For this report a typical station layout for a generator without a generator breaker is used. The generator is connected to the grid via the generator step up transformer (GSU). The station service transformer (SST) is used for generator start up and shut down. For the case of startup once the unit is on line the station service load is transferred to the unit auxiliary transformer (UAT). If the unit is taken off-line this action is performed in reverse.

The policy until the early 1970 was, “no load, dead bus transfer” in these applications. Changes in unit design and the availability of better transfer device prompted a re-evaluation of the previously employed method. The paper begins by giving an overview of the available schemes at the time (1990), namely the residual voltage, the in-phase and, fast bus transfer. The paper mentions and shows examples of how the residual voltage is affected by both the inertia and the per unit load of motor. The motivations for a bus transfer are mentioned and discussed both for a nuclear and fossil fuel power plant. In nuclear power plants maintaining forced reactor cooling during shutdown is of critical importance. For fossil fuel power plants it is important to keep both the induction draft (I.D) and forced air draft (F.D) fans in service in order to prevent explosion or implosion of balanced draft boilers. One of the criteria for a successful bus transfer is the prevention of excessive duty/wear on system components. One of these systems components being the station service transformer (SST). During an out-of-phase bus transfer the SST could be exposed to large inrush currents that could dramatically decrease the life expectancy of the SST. A further requirement being that the processes must remain operational, that means that if the bus transfer is successful, the new source must be capable of restoring the voltage level on the bus to within normal operating levels. Stated differently, the new source must be capable of providing the required reactive power to the bus so as to re-accelerate the motors to their normal operating speeds.

22.) T.A. Higgins, W.L. Snider, P.L. Young, H.J. Holley, "Report on Bus Transfer Part II – Computer Modeling For Bus Transfer Studies," IEEE Transactions on Energy Conversion, Vol.5, No.3, September 1990, pg. 470–476.

This is the second of the three papers in which a bus transfer in a steam generating station is analyzed; this paper addresses the issue of correctly modeling the loads of the bus to be transferred. It appears from the paper that single phase modeling is applied. The paper further discusses how to correctly model these loads. The induction motors for this study were modeled based on the work of Kalsi, Stephen and Adkins.

23.) T.A. Higgins, W.L. Snider, P.L. Young, H.J. Holley, "Report on Bus Transfer Part III – Full Scale Testing and Evaluation," IEEE Transactions on Energy Conversion, Vol.5, No.3, September 1990, pg. 477–484.

This is the third paper in the series and is a report on the full scale testing and evaluation carried out by Southern Electric Systems (SES) on three different fossil and nuclear generating facilities.

The first series of tests were carried out on an 890 MW fossil fired unit. The auxiliary systems are powered by two 6.9 kV buses and two 4.16 kV buses. The 6.9 kV buses primarily supply high inertia motors of 1500 Hp and above. The 4.16 kV buses supply low inertia motors of 200 Hp and 1500 Hp. The results showed that the 6.9 kV buses could utilize supervised fast transfer schemes with a residual voltage scheme as a backup scheme. (This result is to be expected since these motors are high inertia motors, therefore they decelerate slowly, maintaining both voltage magnitude and phase angle). The 4.16 kV bus on the other hand was not suited for a fast transfer scheme due to the rapid deceleration of the voltage magnitude and angle. The 4.16 kV bus was, therefore, better suited for a residual voltage transfer scheme. The actual test results and the simulated results were within close tolerance of each other and as such the simulation models did not require adjustment.

The second series of tests were carried out on a 790 MW fossil fired unit. The auxiliary plant design is essentially the same as the 890 MW fossil fired unit except that this unit has four 4.16 kV buses. The loads on these units are somewhat equally distributed, but the loads include a

6000 hp adjustable speed drive (ASD) for the ID fan motors and a 7000 hp single speed FD fan motor. The implementation and testing of a transfer scheme occurred in conjunction with the boiler being converted to a balanced draft boiler operation. The conversion resulted in the number of 4.16 kV buses being expanded from two to four. The older buses (A and B) were equipped with solenoid activated circuit breakers and had relatively slow closing times (12–21 cycles) at the same time the loads on these buses had low inertia and as a result these buses were selected for a residual voltage transfer scheme. The existing FD fans were transferred to the newer buses (C and D). These buses were equipped with faster stored energy circuit breakers. The ASD ID fans were added to the newer buses. Even though the studies suggested that a supervised fast in-phase transfer scheme was possible, due to the uncertainties associated with the ASD, a decision was made to for a residual voltage transfer scheme for the ID fans.

The third series of tests was carried out on a 1215 MW nuclear unit. The auxiliary plant design consists of two 13.8 kV buses and two 4.16 kV buses connected to two unit auxiliary transformers (UAT). The 13.8 kV buses supply pump loads (typically of low inertia). Pump loads would normally result in a rapid deceleration of the rotor and as such result in a rapid decrease of the motor residual voltage and phase angle. However, in this case the reactor coolant pumps are equipped with high inertia flywheels which preserve both the residual voltage magnitude and angle. This use of flywheels made the 13.8 kV buses suitable for supervised fast bus transfer schemes. The 4.16 kV buses supplied low inertia loads and as such a residual voltage transfer scheme was selected.

The bus transfer scheme implementation and testing not only proved useful in validating the schemes, they were also used to verify and obtain more accurate computer models.

24.) R.W. Patterson, "Utility Reclosing and Industrial Motors" Pulp and Paper Industry Technical Conference, 2009, PPIC 2009.

This paper discusses the affects large motor loads have on the high speed reclosing of tapped transmission lines and also what effects high speed reclosing has on large motors. Most faults on transmission lines are temporary in nature and by simply isolating the faulted transmission line from the power system for tens of cycles (typically 10 -20 cycles) the fault will be cleared. The time that the faulted transmission line is disconnected/isolated from the power system is known as the dead time. The dead time is so selected that the hot ionized air has sufficient time to dissipate and be replaced by cooler un-ionized air. However, if the transmission line is tapped by a significant motor load, the dead time before attempting to reenergize the line has to be significantly increased because of the residual voltage of the motors.

This paper discusses an issue experienced by the Tennessee Valley Authority (TVA) during a high speed non-supervised reclose of one of their tapped 161 kV lines. The line could not be successfully reclosed because the residual voltage from the large motor load fed the fault while the line was isolated; therefore when the line was reenergized the fault was reestablished. At the same time because the reclose was unsupervised the voltage applied to the line was out of phase with the motor voltage this resulted in a large inrush current into the motors which developed high torque in the machine shaft and in the rotor coils of the motors. The paper then goes on how to properly coordinate reclosing when tapped motor loads are encountered. The paper gives minimum dead times for tapped motor loads on transmission lines.

25.) M.V.V.S. Yalla, "Design of a High-Speed Motor Bus Transfer System" Industrial and Commercial Power systems Technical Conference, May 2009.

This paper proposes a new algorithm for calculating the voltage magnitude and phase angle of the residual voltage of the motor bus after the bus has been disconnected. The problem with using a traditional Discrete Fourier Transfer (DFT) algorithm is that it requires a fixed number of samples per cycle (SPC) typically 16 or 32. When the motor bus is disconnected from its primary source, the frequency of the motor bus can decay very rapidly and tracking the frequency of the system and adjusting the DFT may prove challenging. This new algorithm proposes calculating the voltage magnitude and phase angle separately. The voltage magnitude is calculated using the RMS method and the phase angle is calculated using the DFT method. However, for both cases the frequency of the motor bus has to be known. So what this method proposes is that of instead of adjusting the sampling time (Δt) between samples to keep the number of samples per cycle constant, it keeps the sampling time between samples constant (i.e., Δt is fixed) and the number of samples per cycle is increased. From the paper it appears that the numbers of samples per cycle are increased consecutively, but the paper does not address the issue of what factors determine when the numbers of samples are incremented (It is possible that this is done while the scheme is being commissioned). The paper shows cases where this algorithm was successfully applied but to validate the success of the method, the author should have also showed the inrush current into the motor bus when the motor bus was transferred onto the auxiliary bus.

1.3 Summary

Fast motor bus transfer schemes were first envisioned in power generating plants in order to keep the boiler feed pump and boiler alive during emergency conditions. The initial bus transfers were done once residual voltage of the motors had dropped below 25% of the nominal voltage so as to not cause any adverse effects on the motor and there connected rotating loads. In the late 1960's, the boiler feed pumps, which used to be driven by steam turbines were being replaced by electrical induction motors. Boiler feed pump electric motors have a long open circuit time constant meaning that it would take several second before the motors residual voltage dropped below 25% of its nominal voltage. This slow decay in the BFP motor voltage in turn created another problem in that by the time that the open circuit voltage on the BFP motor dropped below 25% of it nominal voltage all other motors connected to the same bus would have either been disconnected from the auxiliary bus by their under-voltage protection relays or would have stalled. This then led to the era of the fast and in-phase motor bus transfer. However at this time the closing time of the available circuit breakers was tens of cycles and a reliable fast and in-phase motor bus transfer could not be realized using these breakers. Therefore, at the same time as the interest in fast motor bus transfer schemes was being explored onboard energy storage circuit breakers were being developed. These circuit breakers stored the opening and closing energy in springs and offered consistent closing times of a few cycles (3–4 cycles). An industrial standard was developed that stated for a fast and in-phase motor bus transfer to occur that the residual voltage between the motor bus and the emergency supply bus had to be less than 1.33 V/Hz. This standard was chosen so that no fast transfer would create a torque greater than 1.78 per unit. However, in the early 80's engineers proved that there is a torsional interaction between the electrical and mechanical systems of a motor and its driven load. Even if the proposed standard was followed, if the electromagnetic air gap torque contains frequency that are near or coincided with torsional resonance frequency of the power system, large transient torques can be generated during a fast or in-phase transfer.

It can also be stated that the majority and most influential papers on motor bus transfer where written between 1940 and 1990, in the last 24 years not much has developed with regards to motor bus transfer schemes.

Chapter II: Analytical Analysis of a Three-Phase Induction Motor

2.1 Introduction

This chapter endeavors to explain what happens when a three phase induction motor is disconnected from its power source and then reconnected to that power source some time later. This dissertation will examine and explain what factors determine the voltage across the terminals of the induction motor immediately after the motor is disconnected from the power source. Next the dissertation examines what determines the rate of decay of the current in the motor (rotor current) and the rotor frequency and how these two factors relate to the voltage across the terminals of the motor while the motor is disconnected from the power source. After this, the chapter discusses what factors influence the current drawn by the motor and the subsequent torque developed by the motor once the motor is reconnected to the primary power source.

Most importantly this chapter will illustrate that to analyze the motor during transient conditions the traditional motor model (Steinmetz model) cannot be used, and the motor has to be analyzed in the "dq0" reference frame. The chapter will end with a numerical example in which a three phase induction motor is disconnected from its primary power source and after some arbitrary time is reconnected to that power source. The example illustrates one of the limitations of using a non-iterative method to calculate the currents drawn, the electromechanical torque developed, and the power delivered by the motor after the motor is reconnected to the power source.

2.2 Voltage across the terminals of the machine immediately after the machine is disconnected.

One of the pertinent questions asked by many engineers involved in fast motor bus transfer is "*What is the voltage at the motor terminals immediately after the motor has been disconnected (or isolated) from the source bus?*" Daugherty in his paper discusses the two schools of thought [1].

One school of thought is that once the motor is disconnected from the power source the voltage across the terminals of the motor is equal to the back emf of the motor. Examining Fig. 2.1(a) it can be seen that the back emf of the motor (V_{back_emf}) is equal to the voltage across the magnetizing impedance (X_m) of the motor. The voltage across X_m, is equal to the voltage at the terminal of the motor (V_{Term}) less the voltage drop across the stator impedance ($R_S + jX_S$). The voltage drop across the stator impedance is not constant, therefor the back emf is not constant. The back emf is inversely proportional to the load of the motor i.e. the higher the load of the motor the lower the back emf. The only caveat with this theory is that the current in the rotor would suddenly change from the load current (I_{Rotor}) to the magnetizing current (I_{Mag}), Fig. 2.1(b). This means that the torque produced by the rotor would have to suddenly decrease. The merit to this idea is that the flux in the machine does not change instantaneously. The voltage across the magnetizing branch before the motor is disconnected (time = t_0^-) is the same as the voltage across the magnetizing branch just after the motor is disconnected (time = t_0^+). This further implies that the flux in the machine does not change instantaneously ($\lambda(t_0^-) = \lambda(t_0^+)$), which is what we know to be true.

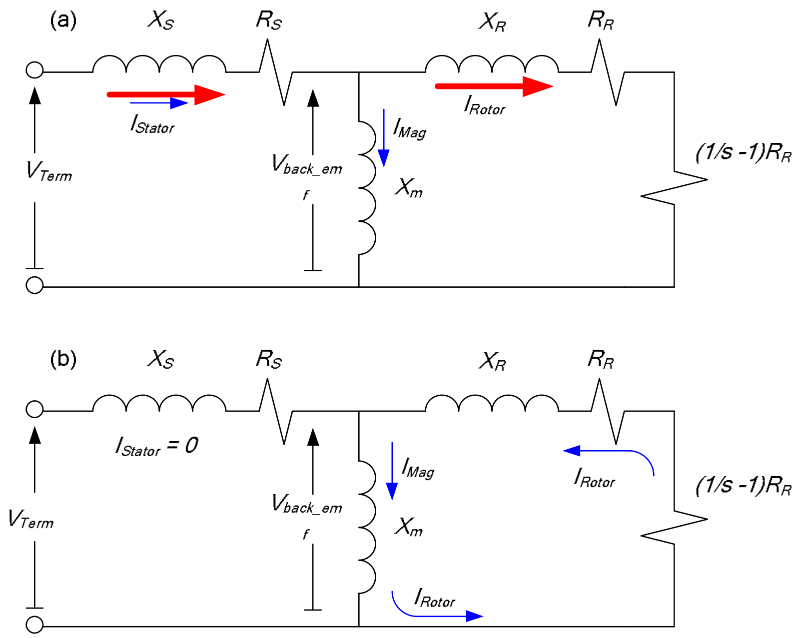


Fig. 2.1: Current distribution in an induction motor under normal operating conditions, (b) current distribution in an induction motor after the motor has been disconnected from the voltage source and the conservation of flux is observed.

The second school of thought is that when the motor is disconnected from the source the rotor current circulates through the magnetizing branch as shown in Fig. 2.2.

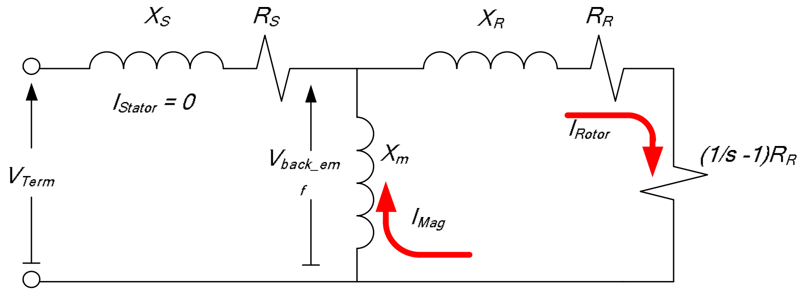


Fig. 2.2: Current distribution in an induction motor if the conservation of output torque is observed.

This means that the torque produced (output) by the motor does not change instantaneously. However, what this now implies is that the flux in the magnetizing branch has to change instantly, observe:

$$\lambda_M\,(t_0{}^-) = L_M \cdot I_{Mag}$$

$$\lambda_M\,(t_0{}^+) = L_M \cdot I_{Rotor}$$

And

$$I_{Rotor} \gg I_{Mag}$$

Therefore

$$\lambda_M(t_0{}^+) \gg \lambda_M(t_0{}^-)$$

Since the magnetizing branch flux is directly proportional to the voltage across the magnetizing branch as shown by equation (2.1).

$$V_M = \omega \cdot \lambda_M \tag{2.1}$$

Therefore when the flux in the magnetizing branch changes instantaneously the voltage across the magnetizing branch has to change instantaneously. Even though this school of thought preserves the torque of the motor, it requires the flux in the magnetizing branch of the motor to change instantaneously. The flux in the magnetizing branch cannot change instantaneously since the time constant (Equation 2.2) of the circuit is determined by the inductance (L_R) and resistance (R_R) of the rotor circuit and the inductance of the magnetizing branch (L_M).

$$\tau = \frac{(L_R + L_M)}{R_R} \tag{2.2}$$

To determine which of the above two schools of thoughts has the greater credibility a motor equivalent circuit as shown in Fig. 2.3 is used. This circuit contains not only the magnetizing inductance (L_M) but also the resistance (R_M) which represents the ferromagnetic core losses.

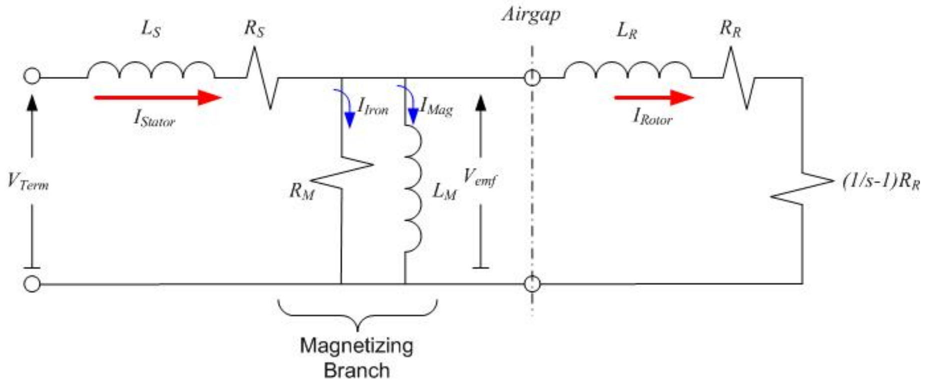


Fig. 2.3: Equivalent circuit of an induction motor under steady state conditions, the iron loss circuit is included in the magnetizing branch.

Fig. 2.4 is the vector diagram for the circuit shown in Fig. 2.3 when the slip (s) is not equal to zero (i.e., the motor is delivering torque to a load).

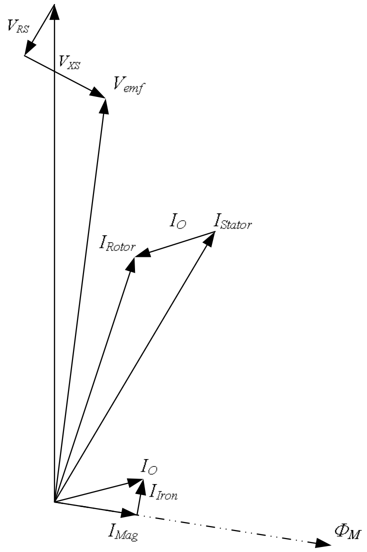


Fig. 2.4: Vector Diagram of an induction motor under steady state load conditions. Observe that the rotor current is in the same direction as the stator current.

From Fig. 2.3 the following observations can be made, the current in the stator (I_{Stator}) is equal to the sum of the currents in the magnetizing branch (I_{Iron} , I_{Mag}) plus the current in the rotor (I_{Rotor}), (Equation 2.3):

$$I_{Stator} = I_{Iron} + I_{Mag} + I_{Rotor} \qquad (2.3)$$

A question that can be asked is, "*If the motor is suddenly disconnected from its power source i.e., the circuit breaker feeding the motor is opened, does the current in the stator go to zero immediately?*" To answer this question, consider the stator and rotor windings of a motor as two individual windings that produce their own leakage flux (Φ_S, Φ_R respectively) and linked together via a mutual flux (Φ_M) as shown in Fig. 2.5. The ferromagnetic core between the two winding provides a low reluctance path between the two windings resulting in an effective mutual flux between the two windings.

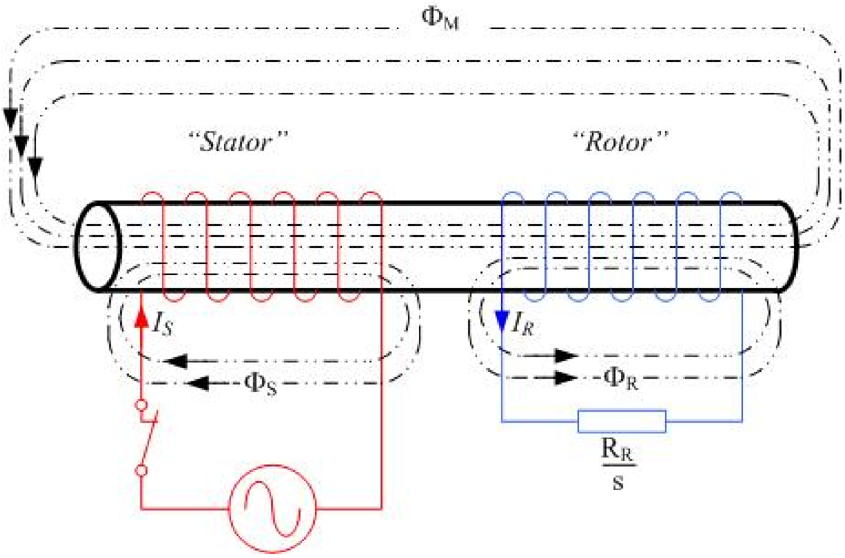


Fig. 2.5: A simple two winding equivalent circuit diagram representation of an induction motor showing the stator and rotor currents and the respective leakage and mutual flux created as a result of currents flow in these windings.

When the "stator" winding is connected to the power source, current (I_S) will flow in the stator winding. The current in the stator winding will setup both a leakage flux in the stator (this leakage flux gives rise to the stator leakage inductance represented in Fig. 2.3) and a mutual flux (this flux gives rise to the mutual inductance shown in Fig. 2.3). This mutual flux will setup a voltage drop across the rotor winding proportional to number of windings and the slip of the rotor. The current draw by the rotor (I_R) is dependent on the resistance of the rotor. This rotor current in turn gives rise to a rotor leakage flux (which in turn then produces the rotor leakage inductance shown in Fig. 2.3).

When the stator winding is disconnected from the power source, Fig. 2.6, the current in the stator winding cannot go to zero instantaneously; because the leakage inductance of the stator winding will prevent a sudden change in current.

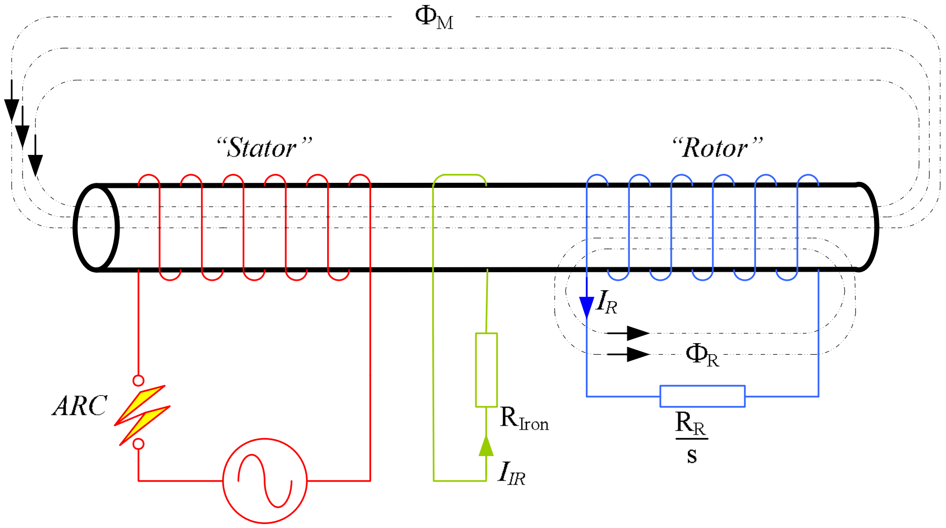


Fig. 2.6: Flux distribution in an induction motor when the stator circuit is disconnected from the voltage source, the energy stored in the stator leakage flux is dissipated in an electric arc formed when the circuit breaker contacts separate.

As the circuit breaker contacts begin to separate the current in the stator winding is changing at a very rapid rate (*di/dt is large*), this rapid change in current results in a large voltage being developed across the contacts of the circuit breaker $\left(V = L_s \cdot \frac{di}{dt}\right)$. As a result of the large voltage being developed across the contacts of the circuit breaker, an arc is established across the circuit breaker contacts and the energy stored in the stator leakage inductance is dissipated in the form of heat in the arc. To maintain the mutual and rotor leakage flux in the magnetic circuit a large current is momentarily injected in to a third winding as shown in Fig. 2.6. This third winding models the eddy current losses in the circuit. This circuit has a very low inductance since it couples a small amount of flux lines in the ferromagnetic core see Fig. 2.7.

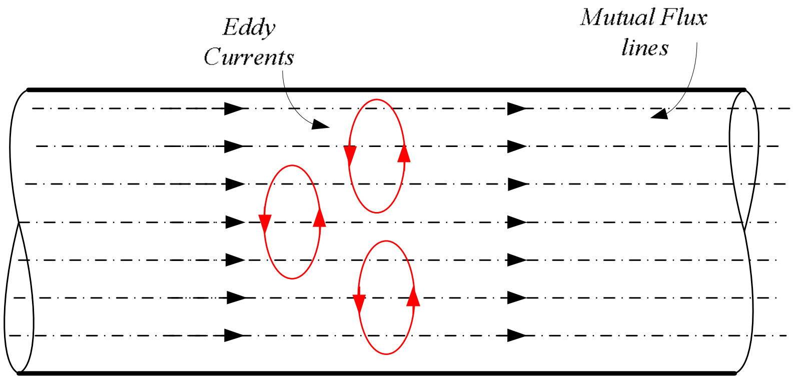


Fig. 2.7: Eddy currents shown in a magnetic circuit, note that these current only couple a fraction of the flux lines therefore this “third winding” has a very short time constant.

If we now try and reconcile the Steinmetz equivalent circuit (Fig. 2.3) with the magnetic circuit of the motor (Fig. 2.6) it can be seen that the current in the rotor and the magnetizing branch are now forced through the ferromagnetic core loss circuit (R_M) representing increased eddy current and hysteresis losses, as shown in Fig. 2.8.

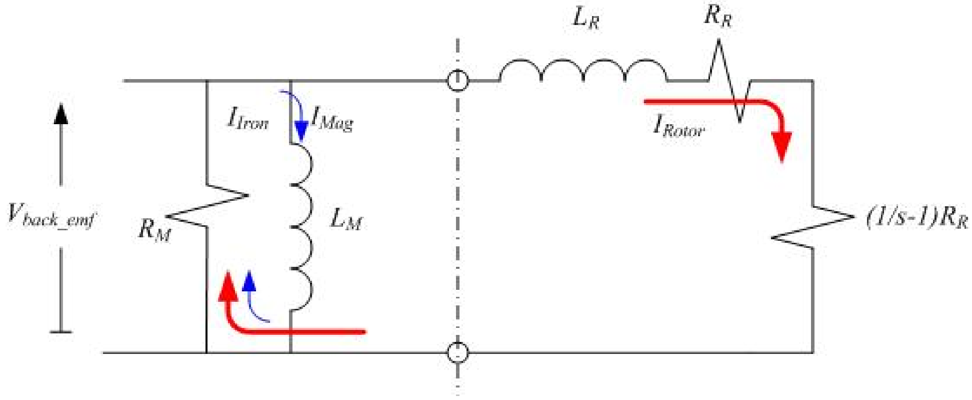


Fig. 2.8: The instant the motor is disconnected from the voltage source the rotor current is "forced" through the ferromagnetic core loss circuit for a time period determined by the inductance and resistance of the ferromagnetic loss circuit (R_M).

A question that can be asked at this time is, "*Why does the voltage drop across the magnetizing branch (*$V_{back\ emf}$*) not increase when both the magnetizing current and the rotor current are forced through the iron core loss circuit?*" To answer this question examine the ferromagnetic core circuit more closely. The ferromagnetic losses can be divided into two categories namely the hysteresis losses, these are as a result of material cycling through its hysteresis loop (Fig. 2.9a), and the eddy currents losses, due to the induction of currents circulating within the ferromagnetic material (Fig. 2.9b).

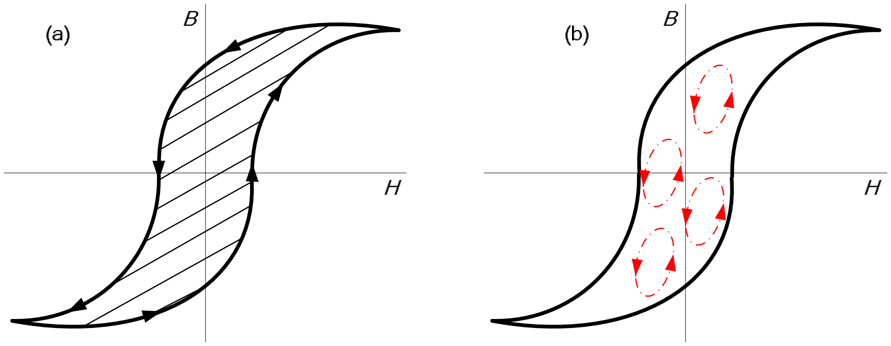


Fig. 2.9: The ferromagnetic losses are divided into categories, (a) the hysteresis losses (b) eddy currents.

For a sinusoidal variation in the flux density, the specific losses (watts/kg) on a pure theoretical basis can be expressed as follows [*2*], [3], [4], and [5]:

$$p_{hysteresis} = k_h \cdot f \cdot {B_{max}}^x \tag{2.5}$$

$$p_{Eddy\_current} = k_e \cdot f^2 \cdot d \cdot \frac{B^2}{\rho} \tag{2.6}$$

Where:

k_h is dependent on the molecular structure of the material

x lies between 0.8 to 2.3

ρ (electrical resistivity)

d (thickness of the lamination)

f (frequency)

B (flux density)

B_m (maximum flux density)

From equations (2.5) and (2.6) the respective resistance for each of the two types of losses can be calculated as follows, using the resistive component of the magnetizing current (I_{Iron}).

$$R_{Hysterisis} = \frac{P_{Hysterisis}}{{I_{Iron}}^2} \tag{2.7}$$

$$R_{Eddy\_current} = \frac{P_{Eddy\_current}}{{I_{Iron}}^2} \tag{2.8}$$

What is interesting about equations (2.5) and (2.6) is that they are both dependent on the flux density in the ferromagnetic material and the speed of rotation of the rotor (f). Examining this problem from the point of view of the energy density of the electromagnetic field (E_{fld}). The energy density before the power source is disconnected (at t_0^-) and that immediately after the power source is disconnected (at t_0^+) are the same. The energy stored in the magnetic field can be determined from the flux density (B) and the magnetic field intensity (H) as follows [2], [3], [4], and [5];

$$E_{fld} = \frac{1}{2}BH \tag{2.9}$$

But the flux density of the field is related to the magnetic field intensity via the permeability (μ) of the ferromagnetic material of the core.

$$B = \mu H \tag{2.10}$$

Assuming that the permeability of the ferromagnetic material remains constant during this time period, the energy density of the field (E_{fld}) can be expressed as a sole function of the flux density;

$$E_{fld} = \frac{B^2}{2 \cdot \mu} \tag{2.11}$$

This is similar to the kinetic energy of a mass (m -kg) travelling at a velocity of (v -m/s), when the force applied to the mass is suddenly removed the kinetic energy $\left(E_{Kinetic} = \frac{1}{2}mv^2\right)$ stored in the mass before the force is removed and immediately after the force is removed are the same.

Equation 2.11 states that the energy density of the magnetic field is directly proportional to the flux density (B) and since the energy density at t_0^- and t_0^+ is the same, the flux density has to follows suit during this time period. Therefore the hysteresis and eddy current losses during this time period also remain constant. This therefore implies that the fictitious resistances (R_m, Fig. 2.8) representing the hysteresis and eddy current losses have to decrease dramatically, when the current through the ferromagnetic loss circuit increases dramatically. This brings another point of interest forward in that the Steinmetz model for an induction motor is really only applicable under steady state conditions, and does not apply during transient state conditions. This then answers why the voltage across the magnetizing branch does not increase when both the magnetizing and rotor current are forced through the iron core loss circuit.

As was mentioned the “third winding” in Fig. 2.6 has a very small inductance and therefore a very small time constant and a few milliseconds after the motor is disconnected from the source the current through the iron core loss circuit goes to almost zero (the iron losses in the rotor go to zero since the current in the rotor is effectively dc). Therefore the “third winding” used to account for the *magnetomotive force* balance in Fig. 2.6 becomes no longer necessary and can be omitted from the circuit. This implies that Fig. 2.6 can now be redrawn as shown in Fig. 2.10.

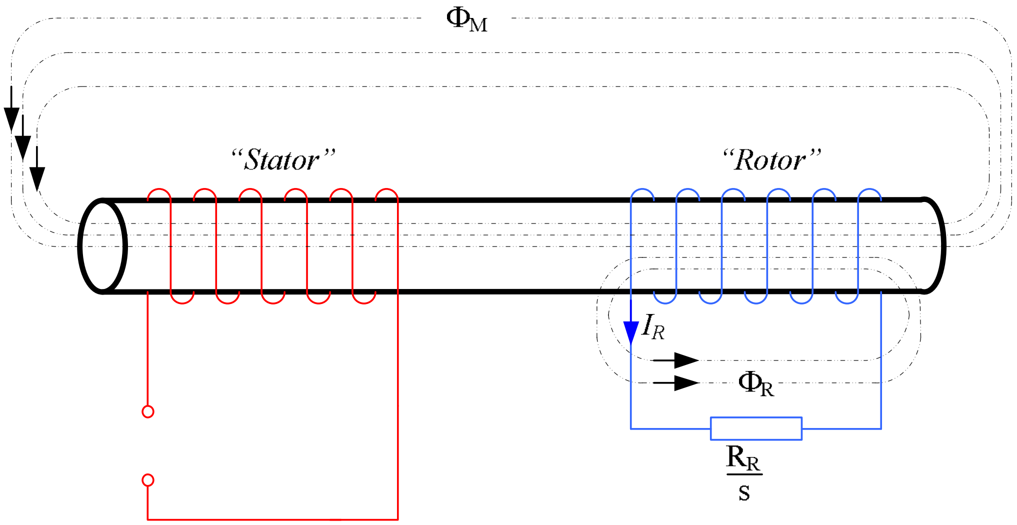


Fig. 2.10: Sketch of the remaining fluxes in the motor once the motor has been disconnected and the leakage flux in the stator winding has been dissipated.

From the above discussion it can be concluded that the voltage drop that appears across the terminals of the motor just after the motor is disconnected is equal to the voltage that was across the magnetizing impedance (X_m) prior to the motor being disconnected.

2.3 Voltage and Current during open interval period

2.3.1 The "dq0" Reference Frame

Since this dissertation deals with the motor during the transient period, the behavior of the motor during the transient period will be done using the "dq0" reference frame. In the "dq0" reference frame a three phase induction motor can be fully described by the following set of six equations [6], [7], [8], and [9]:

$$v_{ds} = (r_s + pL_s) \cdot i_{ds} - \omega L_s \cdot i_{qs} + pL_m \cdot i_{dr} - \omega L_m \cdot i_{qr} \tag{2.12}$$

$$v_{qs} = \omega L_s \cdot i_{ds} + (r_s + pL_s) \cdot i_{qs} + \omega L_m \cdot i_{dr} + pL_m \cdot i_{qr} \tag{2.13}$$

$$v_{0s} = (r_s + pL_{ls}) \cdot i_{0s} \tag{2.14}$$

$$v_{dr} = pL_m \cdot i_{ds} - (\omega - \omega_r)L_m \cdot i_{qs} + (r_r + pL_r) \cdot i_{dr} - (\omega - \omega_r)L_r \cdot i_{qr} \tag{2.15}$$

$$v_{qr} = (\omega - \omega_r)L_m \cdot i_{ds} - pL_m \cdot i_{qs} + (\omega - \omega_r)L \cdot i_{dr} - (\omega - \omega_r)L_r \cdot i_{qr} \tag{2.16}$$

$$v_{0r} = \ (r_r \ + pL_{lr}) \cdot i_{0r} \tag{2.17}$$

Where: $p = \frac{d}{dt}$

$$L_s = L_{ls} + \ L_m \ and \ L_r = L_{lr} + \ L_m$$

In most cases the motors are connected in delta or ungrounded wye (star) so that no neutral (ground) current can flow in either case. Therefore in both instances, assuming no external $v_{0,}$ the neutral axis voltages v_{0s} and v_{0r} are zero, the induction motor is now fully described by equations (2.12), (2.13), (2.15), and (2.16), also

$$v_{qds} = v_{qs} - \ j \cdot v_{ds} \tag{2.18}$$

$$v_{qdr} = v_{qr} - \ j \cdot v_{dr} \tag{2.19}$$

Similar equations to (2.18) and (2.19) can be used to describe the motor currents i_{qds} and i_{qdr}. Applying equation (2.18) to equation (2.12) and (2.13) and equation (2.19) to equation (2.15) and (2.16) the following two equations are now obtained;

$$v_{qds} = \ \{r_s + \ L_s(p + j\omega)\} \cdot i_{qds} + L_m(p + j\omega) \cdot i_{qdr} \tag{2.20}$$

$$v_{qdr} = \ \{L_m(p + j(\omega - \omega_r))\} \cdot i_{qds} + \{r_r + L_r(p + j(\omega - \omega_r))\} \cdot i_{qdr} \tag{2.21}$$

Equations (2.20) and (2.21) will be used throughout this chapter to describe the induction motor; the complex vector equivalent circuit for an induction motor is then as shown in Fig. 2.11.

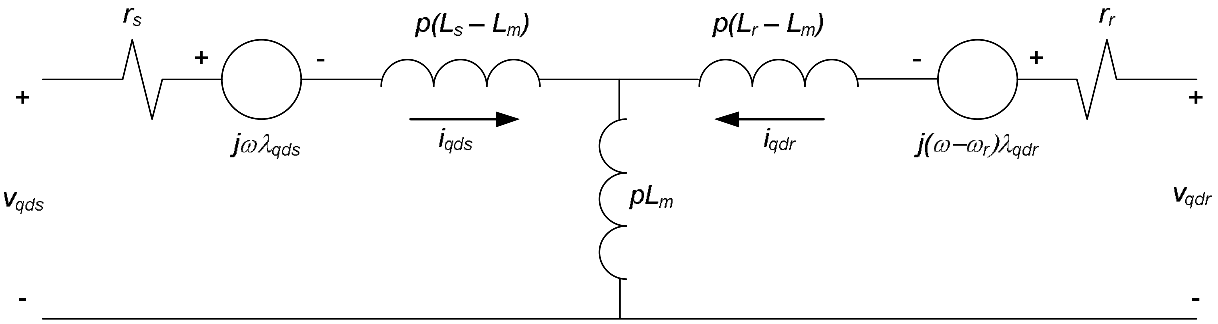


Fig. 2.11: The complex vector equivalent circuit diagram of an induction motor.

Where:

$$\lambda_{qds} = L_s \cdot i_{qds} + L_m \cdot i_{qdr}$$

$$\lambda_{qdr} = L_m \cdot i_{qds} + L_r \cdot i_{qdr}$$

Another operational form of the induction motor with a squirrel cage rotor (zero voltage developed/ applied across the rotor) can be obtained by multiplying equation (2.21) with the (p + jω)/ {p + j (ω - ω_r)} operator and setting $v_{qdr} = 0$ to obtain:

$$0 = L_m(p + j\omega)\cdot i_{qds} + \left[\frac{r_{r}(p+j\omega)}{p+j(\omega-\omega_r)} + L_r(p + j\omega)\right] \cdot i_{qdr} \tag{2.22}$$

Using equations (2.20) and (2.22) an alternative complex vector equivalent circuit for a squirrel cage induction motor can be derived as shown in Fig. 2.12.

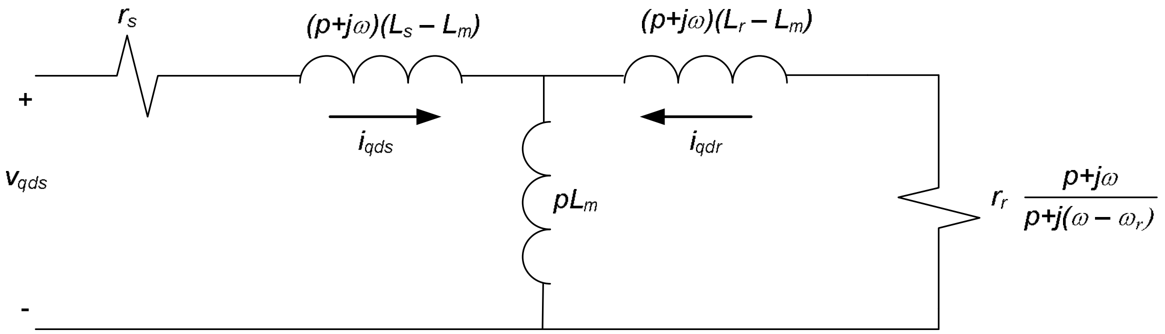


Fig. 2.12: The complex vector diagram of a squirrel change induction motor ($V_{qdr} = 0$)

Using equation (2.20) and (2.21) the terminal current and voltage at the instant that the motor is disconnected from the voltage source can now be examined.

2.3.2 The Complex Vector Operational Impedances

In any arbitrary rotating reference the complex vector equations for a squirrel cage induction motor, where the applied rotor voltage ($v_{qdr} = 0$) are given by equations (2.23) and (2.24).

$$v_{qds} = \{r_s + L_s(p + j\omega)\} \cdot i_{qds} + L_m(p + j\omega) \cdot i_{qdr} \tag{2.23}$$

$$0 = \{L_m(p + j(\omega - \omega_r))\} \cdot i_{qds} + \{r_r + L_r(p + j(\omega - \omega_r))\} \cdot i_{qdr} \tag{2.24}$$

Equations (2.23) and (2.24) are also known as the stator and rotor differential equations respectively. For ease of use, the complex operational impedance are abbreviate as follows;

$$Z_{ss} = r_s + L_s(p + j\omega)$$

$$Z_{sr} = L_m(p + j\omega)$$

$$Z_{rs} = L_m(p + j(\omega - \omega_r))$$

$$Z_{rr} = r_r + L_r(p + j(\omega - \omega_r))$$

Therefore the complex vector equations for an induction motor (equations 2.23 and 2.24) can be re-written as;

$$v_{qds} = Z_{ss} \cdot i_{qds} + Z_{sr} \cdot i_{qdr} \tag{2.25}$$

$$0 = Z_{rs} \cdot i_{qds} + Z_{rr} \cdot i_{qdr} \tag{2.26}$$

Examining the complex operational impedances, it can be seen that these always contain the derivative operator p (d/dt), however the frequency dependent terms are dependent upon the selected reference system. In the stator reference frame (ω = 0), the complex impedance are expressed as follows;

$$Z^s{}_{ss} = r_s + L_s p$$

$$Z^s{}_{sr} = L_m p$$

$$Z^s{}_{rs} = L_m (p - j\omega_r)$$

$$Z^s{}_{rr} = r_r + L_r (p - j\omega_r)$$

In the stator reference frame the stator impedances (Z_{ss}, Z_{sr}) are real, the rotor impedances (Z_{rs}, Z_{rr}) are complex and dependent on the rotor speed (ω_r). In the rotor reference frame ($\omega = \omega_r$) the impedances are expressed as follows;

$$Z^r{}_{ss} = r_s + L_s (p + j\omega_r)$$

$$Z^r{}_{sr} = L_m (p + j\omega_r)$$

$$Z^r{}_{rs} = L_m p$$

$$Z^{r}{}_{rr} = r_r + L_r p$$

In the rotor reference frame the stator impedances are now complex and once again dependent on the rotor speed (ω_r), however this time the rotor impedances are real. Finally in the synchronous reference ($\omega = \omega_e$), the impedances are expressed as follows;

$$Z^{e}{}_{ss} = r_s + L_s(p + j\omega_e)$$

$$Z^{e}{}_{sr} = L_m(p + j\omega_e)$$

$$Z^{e}{}_{rs} = L_m\big(p + j(\omega_e - \omega_r)\big)$$

$$Z^{e}{}_{rr} = r_r + L_r\big(p + j(\omega_e - \omega_r)\big)$$

In the synchronous reference frame all impedances are complex and are dependent on both the synchronous frequency (ω_e) and the rotor frequency (ω_r).

2.3.3 The Open Interval voltages and currents

The rotor fluxes (λ_{qdr}) the instant before the motor is disconnected (t_0^-) and the instant after the motor is disconnected (t_0^+) have to be the same. Using this information the current in the rotor circuit just after the motor has been disconnected can be calculated using equation (2.27).

$$i_{qdr}(t_0^+) = \frac{\lambda_{qdr}(t_0^-)}{L_r} \tag{2.27}$$

Equation (2.27) indicates that rotor flux just before the motor is disconnected needs to be determined so that the current in the rotor circuit just after the motor is disconnected can be determined. To determine what the rotor flux is just prior to the motor being disconnected use is made of the conventional Steinmetz model. Using the Steinmetz model the stator current (i_{qds}) and rotor currents (i_{qdr}) just prior to the motor being disconnected are calculated. Once the stator and rotor currents have been calculated, the rotor fluxes (λ_{qdr}) just prior to the motor being disconnected is calculated using the following equations;

$$\lambda_{qdr} = L_r \cdot i_{qdr} + L_m \cdot i_{qds} \tag{2.28}$$

To calculate the rotor current a Thévenin equivalent circuit looking back from the rotor resistance (r_r/s) is created as shown in Fig. 2.13.

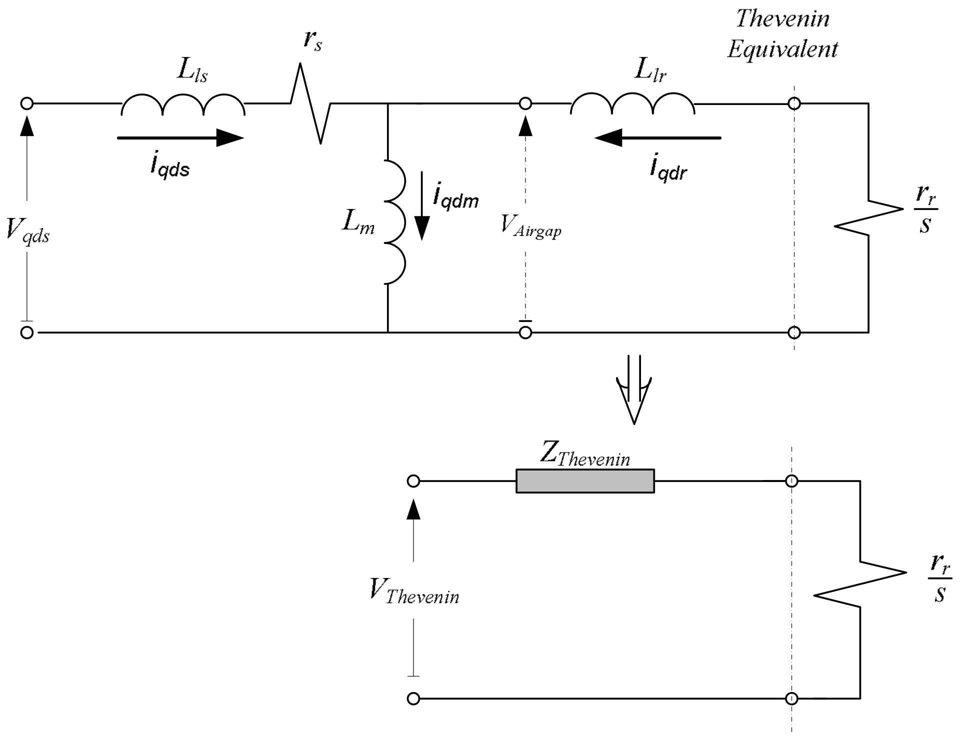


Fig. 2.13: Thévenin equivalent circuit of an induction motor used to calculate the rotor current under steady state load conditions.

Using the Thévenin equivalent circuit shown in Fig.2.13 the rotor current is calculated as follows;

$$\mathrm{i_{qdr}} = \frac{-\mathrm{V_{Thevenin}}}{\mathrm{Z_{Thevenin}}+\frac{\mathrm{r_r}}{\mathrm{s}}} \tag{2.29}$$

Once the rotor current (i_{qdr}) have been calculated the air gap voltage is calculated,

$$v_{airgap} = -\left(\frac{r_r}{s} + j\omega_e L_{lr}\right) \cdot i_{qdr} \tag{2.30}$$

From which the magnetizing current (i_{qdm}) is calculated;

$$i_{qdm} = \frac{v_{airgap}}{j\omega_e L_m} \tag{2.31}$$

Once the rotor current and magnetizing current has been calculated the stator current is calculated.

$$i_{qds} = i_{qdm} - i_{qdr} \tag{2.32}$$

Having calculated i_{qdr} and i_{qds} the rotor flux linkage (λ_{qdr}) before the motor is disconnected (at time t_0^-) from the source as per equation (2.28) can be calculated. Knowing the rotor flux linkage at time t_0^-, the initial rotor current (i_{qdr}) at time t_0^+ can be calculated using equation (2.27). With the motor disconnected from the power source, the stator current ($\mathrm{i_{qds}}$) is equal to zero and the motor equivalent circuit basically consist of the rotor RL circuit as is shown in Fig. 2.14.

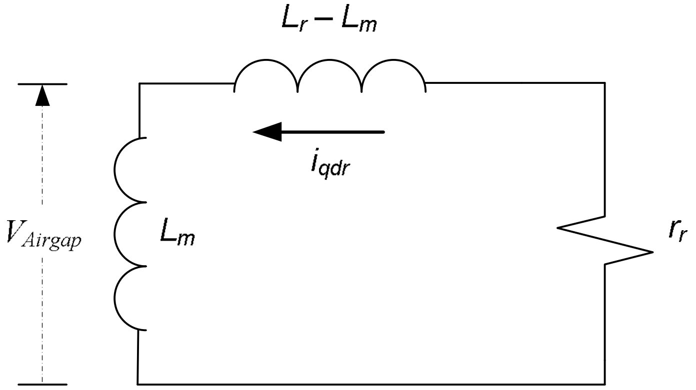


Fig. 2.14: Equivalent circuit of an induction motor, in the rotor reference frame, for the case when the motor has been disconnected from the voltage source.

Making use of Fig. 2.14 and using the rotor reference frame, the instantaneous rotor current ($i_{qdr}(t)$) at any instance in time during the open interval period can be calculated as follows;

$$i_{qdr}(t) = i_{qdr}(t_0^+) \cdot e^{-\frac{t}{\tau_r}} \tag{2.33}$$

Where:

$$\tau_r = \frac{L_r}{r_r} \tag{2.34}$$

An interesting observation is that when the motor is disconnected from the power source the rotor current (i_{qdr}), when viewed from the rotor reference frame ($\omega = \omega_r$), is basically a "DC" current, very similar to the rotor current in a synchronous motor! Using equation (2.19) the rotor current can be decomposed into the direct axis (i_{dr_r}) current component and quadrature axis (i_{qr_r}) currents component.

$$i_{dr\_r} = Im(i_{qdr})$$

$$i_{qr\_r} = Re(i_{qdr})$$

Knowing the rotor current at any instance in time, the stator voltage (v_{qds}) at any instant in time during the open interval period can be calculated using equation (2.23). Equation (2.23) is repeated here for convenience.

$$v_{qds} = \{r_s + L_s(p + j\omega)\} \cdot i_{qds} + L_m(p + j\omega) \cdot i_{qdr}$$

However, during the open interval period the stator current is zero and therefore equation (2.23) reduces to

$$v_{qds} = L_m(p + j\omega) \cdot i_{qdr} \tag{2.35}$$

Substituting i_{qdr} in to equation (2.35) and differentiating, equation (2.36) is obtained;

$$v_{qds}(t) = L_m \left(j\omega - \frac{1}{\omega_e \cdot \tau_r}\right) \cdot i_{qdr}\,(t_0^+) \cdot e^{\frac{t}{\tau_r}} \tag{2.36}$$

Equation (2.36) assumes that the speed (frequency) of the rotor remains constant, stated differently the rotor and load have an infinite moment of inertia (J). However this is not the case and if the motor is supplying a load torque (T_{load}) before the motor was disconnected the motor will still be supplying the same load torque once the motor is disconnected. With the motor disconnected from the power supply and the mechanical load still attached to the motor the rotor will begin to decelerate. The deceleration of the rotor and the connected load is determined as follows [1], [10];

$$\alpha = \frac{-T_{load}}{J_{motor} + J_{load}} \tag{2.37}$$

If the load torque is independent of speed or changes very little for small change in speed, which is typical during an open interval of a few cycles, then the deceleration can be assumed to be constant and the stator voltage can be computed as follows,

$$v_{qds\_tl}(t) = v_{qds}(t) \cdot e^{\alpha t}$$

Or

$$v_{qds\_tl}(t) = L_m \left(j\omega - \frac{1}{\omega_e \cdot \tau_r}\right) \cdot i_{qdr}\left(t_0^+\right) \cdot e^{\left(\frac{1}{\tau_r} + \alpha\right)t} \tag{2.38}$$

So the rotor current (i_{qdr}) and motor stator voltage (v_{qds}) during the open interval period can be computed using equations (2.33) and (2.38) respectively.

2.4 Initial Current and torque after the Reclose

The equations for the transient rotor and stator currents in the general reference frame are as follows [6], [11]:

$$i_{qds}(t) = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + I_{ss} e^{j\omega t} \tag{2.39}$$

$$i_{qdr}(t) = C_3 e^{\lambda_1 t} + C_4 e^{\lambda_2 t} + I_{sr} e^{j\omega t} \tag{2.40}$$

The 1st two terms of equation (2.39) and (2.40) are the transient terms and the third terms of these equations are the steady state terms. The solution to the transient equations involves the simultaneous solution of the motors stator and rotor differential equations (Equation 2.22 and 2.23). The typical approach to solve equations (2.39) and (2.40) is to solve for the eigenvalues (λ_1 and λ_2) first, and then solve for the unknown coefficients (C_1,…C_4,) using the initial conditions.

2.4.1 Steady State (constant speed) Eigenvalues

The steady state part of the solution can be obtained using the steady state equivalent model (Steinmetz model) [6]. Putting the induction motor equations into matrix form equation (2.41) is obtained.

$$\begin{bmatrix} v_{qds} \\ v_{qdr} \end{bmatrix} = \begin{bmatrix} Z_{ss} & Z_{sr} \\ Z_{rs} & Z_{rr} \end{bmatrix} \cdot \begin{bmatrix} i_{qds} \\ i_{qdr} \end{bmatrix} \tag{2.41}$$

From equation (2.41) the characteristic equation is obtained by setting the driving voltage (sources) to zero and by letting the impedance matrix equal "***A***". Substituting the current matrix by any arbitrary complex exponential solution "i" the eigenvalues (λ_1 and λ_2) for the impedance matrix "A" are obtained as follows [12];

$$Ai - \lambda i = 0 \tag{2.42}$$

Which is equivalent to;

$$(A - \lambda I)i = 0 \tag{2.43}$$

Where *I* is the identity matrix, to obtain a non-trivial solution for equation (2.43) (i.e., where "i≠ 0")

$$det(A - \lambda I) = 0 \tag{2.44}$$

Substituting the impedance matrix back into equation (2.44) ,equation (2.45) is obtained.

$$det\left(\begin{bmatrix} Z_{ss} & Z_{sr} \\ Z_{rs} & Z_{rr} \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\right) = 0$$

$$det\begin{bmatrix} Z_{ss}-\lambda & Z_{sr} \\ Z_{rs} & Z_{rr}-\lambda \end{bmatrix}=0$$

$$(Z_{ss}-\lambda)(Z_{rr}-\lambda)-Z_{rs}\cdot Z_{sr}=0 \tag{2.45}$$

Solving equation (2.45) the eigenvalues (λ_1 and λ_2) are obtained;

$$\lambda_1 = -\frac{1}{2}\left(\frac{1}{\tau'_r}+\frac{1}{\tau'_s}\right)+j\left(\frac{\omega_r}{2}-\omega\right)-\frac{1}{2}\sqrt{\left(\frac{1}{\tau'_r}+\frac{1}{\tau'_s}\right)-\frac{4\sigma}{\tau'_r\cdot\tau'_s}+j2\omega_r\left(\frac{1}{\tau'_s}-\frac{1}{\tau'_r}\right)} \tag{2.46}$$

$$\lambda_2 = -\frac{1}{2}\left(\frac{1}{\tau'_r}+\frac{1}{\tau'_s}\right)+j\left(\frac{\omega_r}{2}-\omega\right)+\frac{1}{2}\sqrt{\left(\frac{1}{\tau'_r}+\frac{1}{\tau'_s}\right)-\frac{4\sigma}{\tau'_r\cdot\tau'_s}+j2\omega_r\left(\frac{1}{\tau'_s}-\frac{1}{\tau'_r}\right)} \tag{2.47}$$

Where:

$$\sigma = 1-\frac{{L_m}^2}{L_r\cdot L_s}$$

$$\tau'_s = \sigma\tau_s$$

$$\tau'_r = \sigma\tau_r$$

$$\tau_r = \frac{L_r}{r_r}$$

$$\tau_s = \frac{L_s}{r_s}$$

(Appendix A contains the detailed derivation of λ_1 and λ_2)

2.4.2 Transient State Coefficient determination

Having obtained the eigenvalues of the motor, the transient state unknown coefficients can be obtained if the initial conditions are known. Considering the stator transient current equation (2.39) the unknown coefficients C_1 and C_2 have to be determined. The eigenvalues, λ_1 and λ_2 having being determined for the rotor speed prior to the condition. Using the initial currents and the derivatives of the initial currents, C_1 and C_2 can be determined using equation (2.39);

$$i_{qds}(t) = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + I_{ss} e^{j\omega t}$$

Determining the initial current by setting t = 0 equation (2.39) becomes;

$$i_{qds}(0) = C_1 + C_2 + I_{ss} \tag{2.48}$$

And the derivative of the initial current is,

$$pi_{qds}(0) = \lambda_1 C_1 + \lambda_2 C_2 + j\omega_e I_{ss} \tag{2.49}$$

Solving equations (2.48) and (2.49) simultaneously the equations for C_1 and C_2 are determined as follow;

$$C_1 = \frac{\lambda_2 \cdot i_{qds}(0) - pi_{qds}(0) + (j\omega_e - \lambda_2) \cdot I_{ss}}{\lambda_2 - \lambda_1} \tag{2.50}$$

$$C_2 = \frac{pi_{qds}(0) - \lambda_1 i_{qds}(0) + (\lambda_1 - j\omega_e) \cdot I_{ss}}{\lambda_2 - \lambda_1} \tag{2.51}$$

Using equation (2.40) and repeating a similar procedure for the rotor transient currents as for the stator transient's currents, the equations for C_3 and C_4 are derived.

$$C_3 = \frac{\lambda_2 \cdot i_{qdr}(0) - pi_{qdr}(0) + (j\omega_e - \lambda_2) \cdot I_{sr}}{\lambda_2 - \lambda_1} \tag{2.52}$$

$$C_4 = \frac{pi_{qdr}(0) - \lambda_1 i_{qdr}(0) + (\lambda_1 - j\omega_e)\cdot I_{sr}}{\lambda_2 - \lambda_1} \qquad (2.53)$$

Examining equations (2.49, 2.50, 2.51, and 2.52) it can be seen that these are dependent on the initial currents ($i_{qds}(0), i_{qdr}(0)$) and the derivatives of the initial currents ($pi_{qds}(0), pi_{qdr}(0)$). To obtain these quantities use is made of the motor differential equations (2.22) and (2.23) using the initial condition for the particular case. Since the case of interest is the is the one in which the motor gets reconnected to the power source, after being disconnected from the power source for a brief period of time, this will define the initial condition used in the motor differential equations (2.23) and (2.24). Using the rotor reference frame ($\omega = \omega r$) these equations become,

$$V_s = r_s i_{qds} + L_s(p + j\omega_r)i_{qds} + L_m(p + j\omega_r)i_{qdr} \qquad (2.54)$$

$$0 = L_m pi_{qds} + r_r i_{qdr} + L_r pi_{qdr} \qquad (2.55)$$

Where:

V_s is the source voltage connected to the motor stator.

Extracting the derivative terms and rearranging the equations;

$$\begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} pi_{qds} \\ pi_{qdr} \end{bmatrix} = \begin{bmatrix} -(r_s + j\omega_r L_s) & -j\omega_r L_r \\ 0 & r_r \end{bmatrix} \begin{bmatrix} i_{qds} \\ i_{qdr} \end{bmatrix} + \begin{bmatrix} V_s \\ 0 \end{bmatrix}$$

Letting $L = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix}$ and $Z = \begin{bmatrix} -(r_s + j\omega_r L_s) & -j\omega_r L_r \\ 0 & r_r \end{bmatrix}$

The equation is obtained in the form of the current derivative terms,

$$\begin{bmatrix} pi_{qds} \\ pi_{qdr} \end{bmatrix} = L^{-1}Z \begin{bmatrix} i_{qds} \\ i_{qdr} \end{bmatrix} + L^{-1} \begin{bmatrix} V_s \\ 0 \end{bmatrix} \tag{2.56}$$

Solving equation (2.56) the derivative of the currents are as follows;

$$pi_{qds} = \frac{-L_r(r_s+j\omega_r L_s)}{\sigma L_r L_s} i_{qds} + \frac{(-j\omega_r L_m L_r + r_r L_r L_m)}{\sigma L_r L_s} i_{qdr} + \frac{L_r V_s}{\sigma L_r L_s} \tag{2.57}$$

$$pi_{qdr} = \frac{L_m(r_s+j\omega_r L_s)}{\sigma L_r L_s} i_{qds} + \frac{(j\omega_r L_m{}^2 + r_r L_s)}{\sigma L_r L_s} i_{qdr} - \frac{L_m V_s}{\sigma L_r L_s} \tag{2.58}$$

Using the initial conditions, the stator current (i_{qds}) is obtained. The initial value of the stator current is zero, there was no current flowing in the stator during the open interval period, therefore equations (2.57) and (2.58) reduce to:

$$pi_{qds} = \frac{(-j\omega_r L_m L_r + r_r L_r L_m)}{\sigma L_r L_s} i_{qdr} + \frac{L_r V_s}{\sigma L_r L_s} \tag{2.59}$$

$$pi_{qdr} = \frac{(j\omega_r L_m{}^2 + r_r L_s)}{\sigma L_r L_s} i_{qdr} - \frac{L_m V_s}{\sigma L_r L_s} \tag{2.60}$$

(Appendix B contains the detailed derivation of C_1… C_4 and Appendix C contains the detailed derivation of pi_{qds} and pi_{qdr})

Having obtained all the unknowns for the stator and rotor transient currents, the stator and rotor currents after the motor is reconnection to the power source can be calculated. With the stator and rotor currents calculated the motor torque can also be calculated using the following equation.

$$T_{em} = L_m Im\left(i_{qds} \cdot i_{qdr}{}^{*}\right) \tag{2.61}$$

Where:

$i_{qdr}{}^{*}$ is the conjugate of the rotor current

2.5 Numerical Example

Following is a numerical example, showing how to go about calculating the voltage and currents in an induction motor prior to the the motor being disconnected, then while the motor is isolated, then and after the motor is reconnected to a power source. The example also calculates the torque developed by the motor after being reconnect to the power source. A mathematical software package, MATHCAD™ [13], will be used to perform the calcualtions.

2.5.1 Machine Parameters in per unit (p.u)

$r_s = 0.008$ $L_{ls} = 0.125$ $L_m = 3.0$ $L_{lr} = 0.125$ $r_r = 0.01$

$p = 2$ (number of poles) $f_{nom} = 60\text{Hz}$

$L_S = L_{ls} + L_m$ $L_r = L_{lr} + L_m$

$= 3.125$ $= 3.125$

The Steinmetz Equivalent circuit of the motor under steady state conditions is shown as in Fig. 2.15.

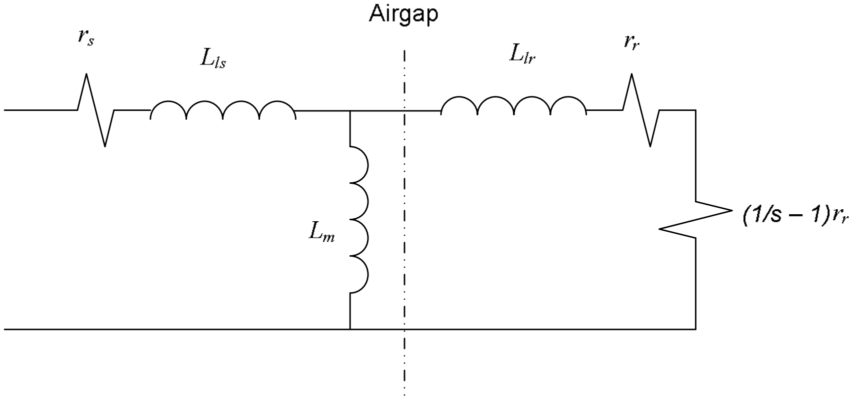


Fig. 2.15: Steinmetz equivalent motor circuit under steady state operating conditions.

2.5.2 Base quantities in "abc" domain

Given

S_{base} = 1000 Hp (746 kVA) V_{base} = 960 V *(line to line voltage)*

Calculate the base current (I_{base}) and the base impedance (Z_{base})

$$I_{base} = \frac{S_{base}}{\sqrt{3}\,V_{base}} \qquad Z_{base} = \frac{{V_{base}}^2}{S_{base}}$$

$I_{base} = 448.67\text{A}$ $Z_{base} = 1.235\Omega$

Calculate the base electrical angular frequency *(ω_{e_base})* and the base inductance (*L_{base}*)

$$\omega_{e\_base} = 2\pi f_{nom} \qquad L_{base} = \frac{Z_{base}}{\omega_{e\_base}}$$

ω_{e_base} =377 rad/sec $L_{base} = 3.277\text{mH}$

Calculate the base mechanical angular frequency *(ω_{m_base})* and the base torque (*T_{ba}*)

$$\omega_{m\_base} = \frac{\omega_{e\_base}}{\frac{p}{2}} \qquad T_{base} = \frac{S_{base}}{\omega_{m\_base}}$$

ω_{m_base} =377 rad/sec T_{base} =1979 Nm

Calculate the base flux linkage (λ_{base})

$\lambda_{base} = L_{base}\, I_{base}$

λ_{base} = 1.47 Wb

2.5.3 Base Quantities in "qd0" domain

Calculating the base voltage (V_{qd_base}) and the base voltage (I_{qd_base})

$$V_{qd\_base} = \frac{\sqrt{2}V_{base}}{\sqrt{3}} \qquad I_{qd\_base} = \sqrt{2}I_{qd\_base}$$

V_{qd_base} = 783.84 V I_{qd_base} = 634.52 A

Calculating the base flux linkage (λ_{qd_base})

$$\lambda_{qd\_base} = L_{base}I_{qd\_base}$$

Or

$$\lambda_{qd\_base} = \sqrt{2}\,\lambda_{base}$$

λqd_base = 2.079 Wb

Calculating the stator (τ_s) and rotor (τ_r) open circuit time constants

$$\tau_s = \frac{L_s}{\omega_{e\_base}\, r_s} \qquad \tau_r = \frac{L_r}{\omega_{e\_base}\, r_r}$$

τ_s = 1.036 sec τ_r = 0.829 sec

Calculating the time constant ratio (α)

$$\alpha = \frac{\tau_r}{\tau_s}$$

$\alpha = 0.8$

Calculating the coupling coefficient ratio (σ)

$$\sigma = 1 - \frac{L_m^2}{L_r L_s}$$

$\sigma = 0.078$

Calculating the stator (τ_s') and rotor (τ_r') short circuit time constants

$$\tau_s' = \sigma\tau_s \qquad \tau_r' = \sigma\tau_r$$

$\tau_s' = 0.081$ sec $\qquad$ $\tau_r' = 0.065$ sec

2.5.4 Determining the Steady state operating parameters of the motor

Following are the rated operating voltage and frequency of the motor and the rated torque supplied by the motor to a load during steady state.

$V_{qds} = 1.0$ pu $\qquad$ $\omega_e = 1.0$ p.u $\quad$ $T_{em} = 1.0$ pu

$\omega_s = \omega_e$ (we set the synchronous angular frequency equal to the electrical angular frequency)

Calculating the steady state motor parameters (in per unit).

$X_{ls} = \omega_e L_{ls}$ $\qquad$ $X_{lr} = \omega_e L_{lr0}$ $\quad$ $X_m = \omega_e L_m$

$X_{ls} = 0.125$ $X_{ls} = 0.125$ $X_{ls} = 0.125$

$X_s = X_{ls} + X_m$ $X_r = X_{ls} + X_m$

$X_s = 3.125$ $X_r = 3.125$

Next the slip of the machine needs to be calculated, this is done by deriving the Thévenin equivalent circuit looking from the rotor resistance (r_r/s) back toward the stator terminal as shown in Fig. 2.16.

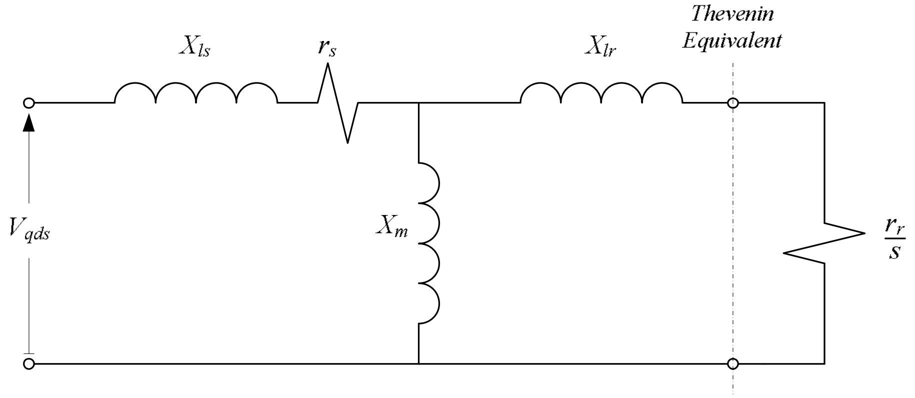


Fig. 2.16: Equivalent circuit of an Induction motor under steady state operating conditions, this model is used to derive the Thévenin Equivalent circuit of an induction motor when viewed from the rotor "terminals" of the motor.

$$V_{THV} = V_{qds} \frac{jX_m}{r_s + j(X_{ls} + X_m)}$$

$V_{THV} = 0.96 \angle 0.147°$

$$Z_{THV} = \frac{(r_s + jX_{ls})jX_m}{r_s + j(X_{ls} + X_m)} + jX_{lr}$$

$Z_{THV} = 0.0074 + j0.245$

$R_{THV} = 0.0074$ $X_{THV} = 0.245$

Using the Thévenin voltage (V_{THV}) and impedance (Z_{THV}) the equivalent Steinmetz motor circuit under steady state conditions is redrawn as shown in Fig. 2.17.

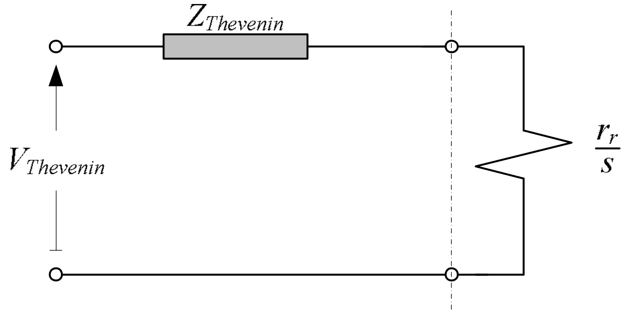


Fig. 2.17: Thévenin equivalent circuit of an induction motor when viewed from the rotor terminals of the induction motor.

Using the Thévenin equivalent circuit and the torque delivered by the machine the steady state slip of the motor is calculated.

$$T_{SS} = \frac{I_r^2 r_r}{s\omega_s}$$

In the above equation, the rotor current (I_r) is replaced by the ratio of the Thévenin voltage and the total impedance of the circuit, namely the sum of the rotor resistance divided by the slip plus the Thévenin impedance. Therefore replacing the rotor current by the ratio of the Thévenin voltage divided by the total impedance, the torque equation can be rewritten as;

$$T_{SS} = \frac{|V_{THV}|^2}{\left[\left(\frac{r_r}{s}+R_{THV}\right)^2+X_{THV}^2\right]}\frac{r_r}{s\omega_s}$$

Since the steady state torque (T_{SS}) is know

$T_{SS} = T_{em} = 1.0$

The slip (s) of the motor under steady state conditions can now be solved by substituting the value of torque (1.0) into the steady state torque equation as follows:

$$1.0 = \frac{|V_{THV}|^2}{\left[\left(\frac{r_r}{s} + R_{THV}\right)^2 + X_{THV}{}^2\right]} \frac{r_r}{s\omega_s}$$

Solving for slip (s);

s = 0.01198

Knowing the slip (s) the rotor speed/angular frequency ω_r, can now be calculated/determined

$$\omega_r = (1 - s)\omega_s$$

$\omega_r = 0.988$

Calculating the stator (I_{qds}) and rotor (I_{qdr}) currents and the corresponding stator (λ_{qds}), rotor (λ_{qdr}) and mutual (λ_{qdm}) flux linkages.

Rotor current

$$I_{qdr} = \frac{-V_{THV}}{\frac{r_r}{s} + Z_{TH}}$$

$I_{qdr} = 1.094 \angle 163.93°$

Voltage across the air gap

$$V_{AG} = -I_{qdr}\left(\frac{r_r}{s} + jX_{lr}\right)$$

$V_{AG} = 0.924 \angle -7.56°$

Magnetizing branch current

$$I_{qdm} = \frac{V_{AG}}{jX_m}$$

$I_{qdm} = 0.308 \angle -97.56°$

Stator current

$$I_{qds} = I_{qdm} - I_{qdr}$$

$I_{qds} = 1.18 \angle -31.03°$

Motor mutual flux linkage

$$\lambda_{qdm} = L_m I_{qdm}$$

$\lambda_{qdm} = 0.924 \angle -97.56°$

Total Stator flux linkage

$$\lambda_{qds} = \lambda_{qdm} + L_{ls} I_{qds}$$

$\lambda_{qds} = 0.992 \angle -89.72°$

Total Rotor flux linkage

$$\lambda_{qdr} = \lambda_{qdm} + L_{lr} I_{qdr}$$

$\lambda_{qdr} = 0.914 \angle -106.07°$

2.5.5 Initial open circuit rotor current

$$\tau = \frac{2\pi}{(\omega_e - \omega_r)\omega_{e\_base}}$$

$\tau = 1.39$ sec

In synchronous reference frame

$$I^s_{qdr\_1} = \frac{\lambda_{qdr}}{L_r}$$

$I^s_{qdr\_1} = 0.292\angle -106.07°$

In rotor reference frame

$$I^r_{qdr\_1} = I^s_{qdr\_1} e^{j(\omega_e - \omega_r)\omega_{e\_base}\tau}$$

$I^r_{qdr\_1} = 0.292\angle -106.07°$

2.5.6 Rotor current while the motor is disconnected from power source

To calculate the rotor current while the motor is disconnected from the power source use will be made of the initial open circuit rotor current ($I^r_{qdr\_1}$) calculated in section 2.5.5. Then using the rotor open time constant (τ_r) the rotor current during the time period while the motor is disconnected from the power source will be calculated as follows.

$$I^r_{qdr}(t) = I^r_{qdr\_1} e^{\frac{-t}{\tau_r}}$$

Fig. 2.18 and Fig. 2.19 are the plots of the magnitude and angle respectively of the rotor current ($I^r_{qdr}(t)$) during the time that motor is disconnected from the power source for this example the "open time interval" is 300 milliseconds (18 power system cycles at 60 Hz).

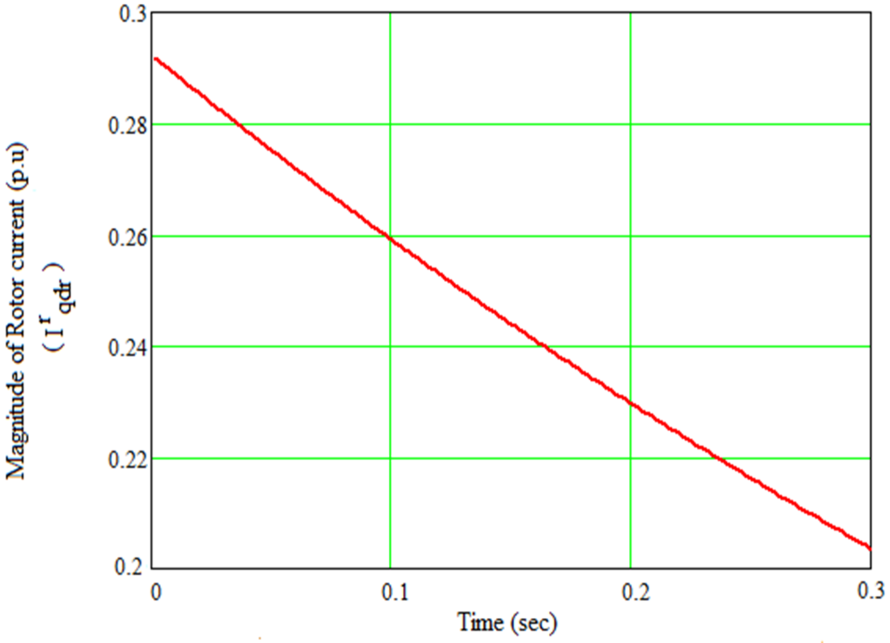


Fig. 2.18: Plot of the magnitude of the rotor current during the period that the motor is disconnected from the power source.

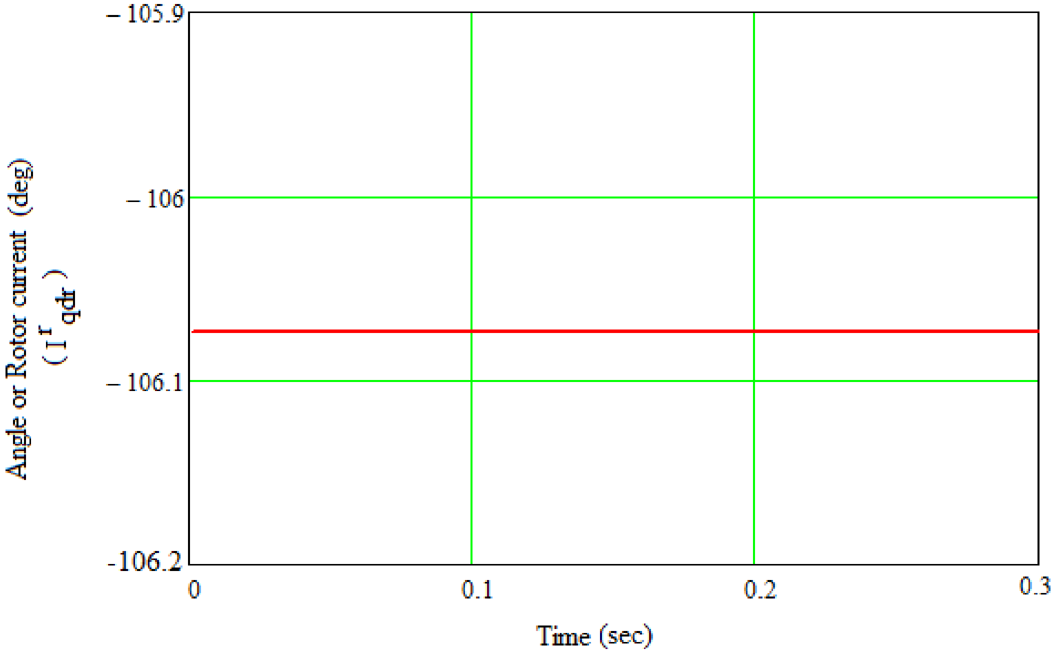


Fig. 2.19: Plot of the angle of the rotor current during the period that the motor is disconnected from the power source.

From Fig. 2.18 it can be seen that the rotor current after the motor has been disconnected from the power source decreases, this is due to the effect of the rotor resistance i.e it dissipates energy, if there rotor had no resistance the rotor current magnitude would remain constant. The rate at which the rotor current decrease is determined by the open circuit time constant (τ_r) of the rotor and therefore aplot of the rotor curremnt after the motor is disconnected from the power source , similar to that of Fig. 2.18 can be used to determine the open circuit time constant of the rotor. Since of the rotor refernce frame is used, the angle of the rotor current remains constant as is clearly illustrated by the Fig. 2.19.

2.5.7 Stator voltage while the motor is disconnected from power source

In the rotor reference frame

$$V_{qds}^{r}\,(t) = L_m \left(j\omega_r - \frac{1}{\omega_{e_{base}} \tau_r} \right)$$

Fig. 2.20 and Fig. 2.21 are plots of the magnitude and angle, respectively of the stator voltage ($V^r_{qds}(t)$) in the rotor reference frame for the time interval while the motor is disconnected from the power source. Since no current flows through the stator winding the voltage across the stator terminals is identical to the voltage across the motor magnetizing branch and is directly proportional to the rotor current.

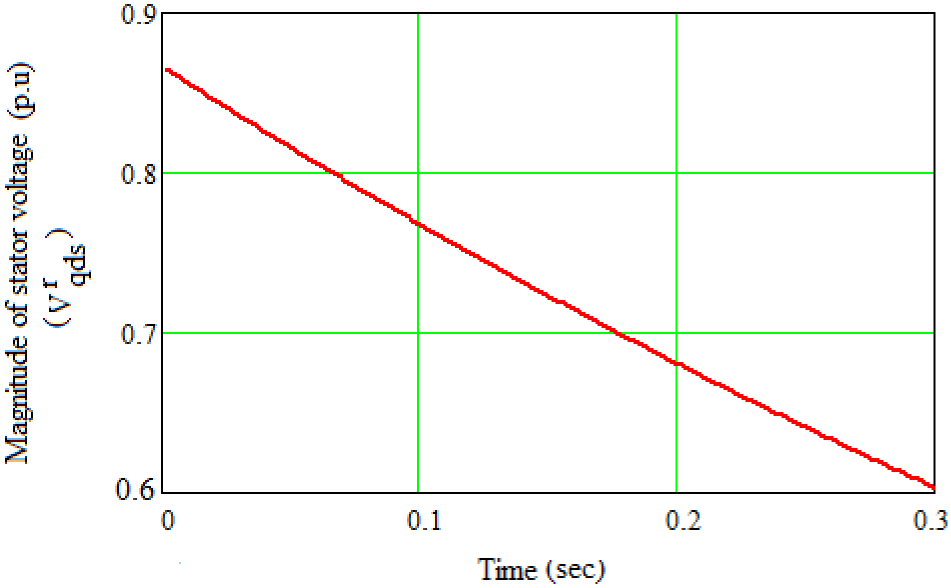


Fig. 2.20: Plot of the motor stator voltage magnitude during the period that the motor is disconnected from the power source.

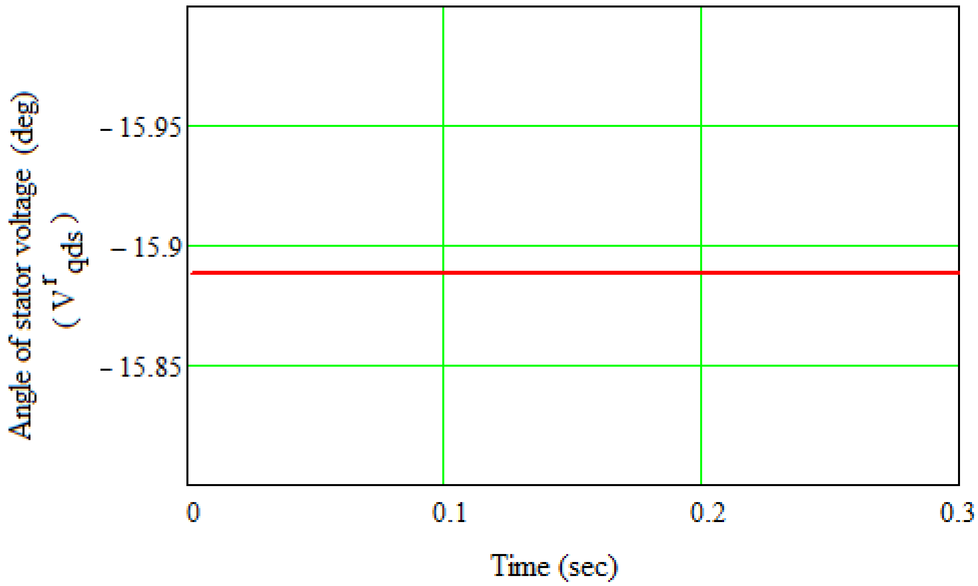


Fig. 2.21: Plot of the motor stator voltage angle during the period that the motor is disconnected from the power source.

In the stator reference frame ω = 0, and ω_r will be assumed to constant (this assumption will be discussed later) therefor stator voltage is expressed as follows;

$$V^s_{qds}(t) = V^r_{qds}e^{j\omega_r\omega_{e\_base}t}$$

In the stator reference frame the motor stator voltage is now a time varying voltage phasor and in order to plot the stator voltage the real part (*Re*) of the stator voltage in the stator reference frame needs to be obtained. Taking the real part of the stator voltage in the "*qd0*" domain the "A-phase" voltage in the "abc" domain is obtained as follows;

$$V_{a\_s}(t) = Re\left(V^s_{qds}(t)\right)$$

Fig. 2.22 is a plot of the real component of the stator voltage ($V^s_{qds}(t)$) in the stator reference frame.

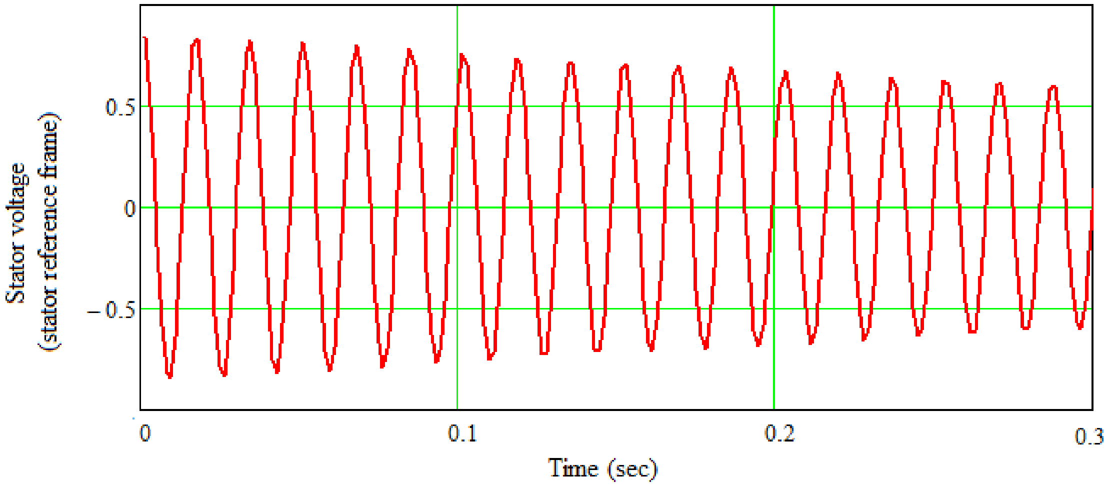


Fig. 2.22: Plot of the stator voltage in the synchronous reference frame, this is the voltage of the "A-phase" voltage in "abc" reference frame.

Comparing the voltage of the power system versus that of the voltage at the stator terminals of the motor it can be seen from Fig. 2.23 that the voltage at the terminals of the motor decays both in magnitude and frequency.

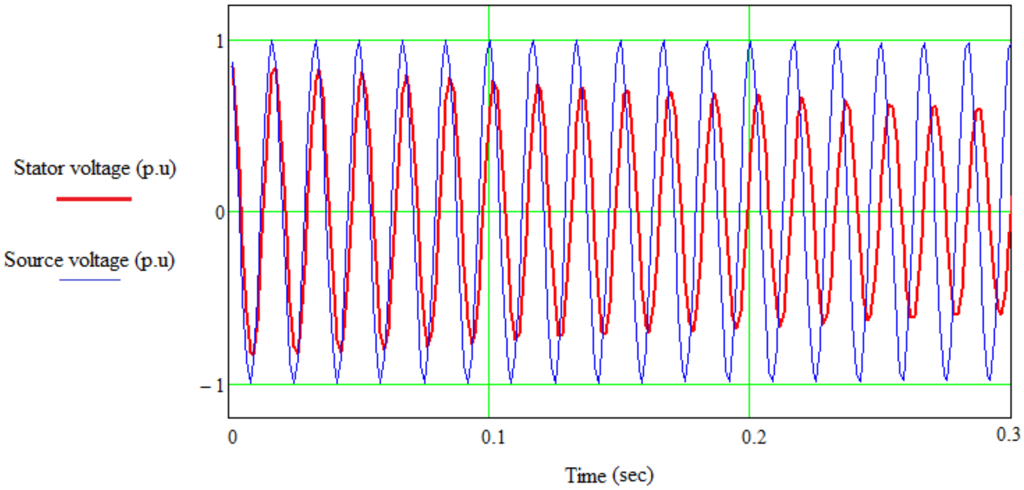


Fig. 2.23: Plot of the motor stator terminal voltage against the voltage of the power source.

Plotting the voltage difference between the motor stator terminals and the power system, as shown in Fig. 2.24, it can be seen that as the open time interval increase the difference between the two voltage sources increases.

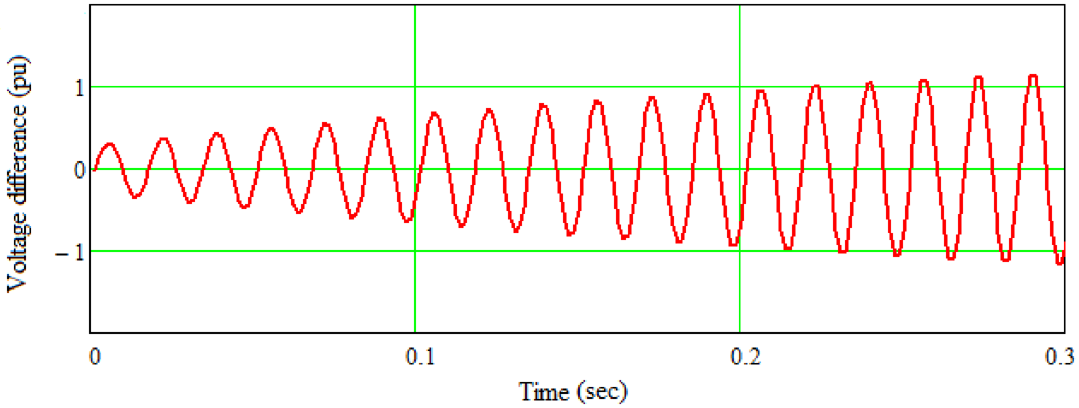


Fig. 2.24: Plot of the voltage difference between the motor stator terminal voltage and the voltage of the power source.

The maximum theoretical difference between these two sources is 2 pu, in practice the value is less than 2 p.u since the motor stator voltage will be less than 1 p.u when the motor is disconnected from the power source (the maximum difference is when the two voltages are 180° out-of-phase with one another). As time increases the voltage difference between the voltage at motor terminals and the voltage of the power source will initially increase as shown in Fig. 2.25, and as the motor terminal voltage decays the voltage difference will begin to decrease until it reaches a voltage difference of 1 pu at which time the voltage at the terminal of the machine is zero if the open period is longer. The magnitude of voltage difference between the two voltage sources is calculated as follows;

$$|V_{diff}(t)| = \sqrt{\frac{\left(V_{diff}(t)\right)^2 + \left(V_{diff}(t-\Delta t)\right)^2 - 2V_{diff}(t)V_{diff}(t-\Delta t)\cos(\omega_{e\_base}\Delta t)}{\sin\left(V_{diff}(t-\Delta t)\right)}} \qquad (2.62)$$

Where:

Δt = the time difference between two consecutive voltage samples in seconds

(The equation for calculating the magnitude difference between two consecutive voltage samples is derived in Appendix D.)

Fig. 2.25 is a plot of the voltage magnitude difference between the motor stator terminal and the power source for the time period of the open interval, in this case 300 milliseconds.

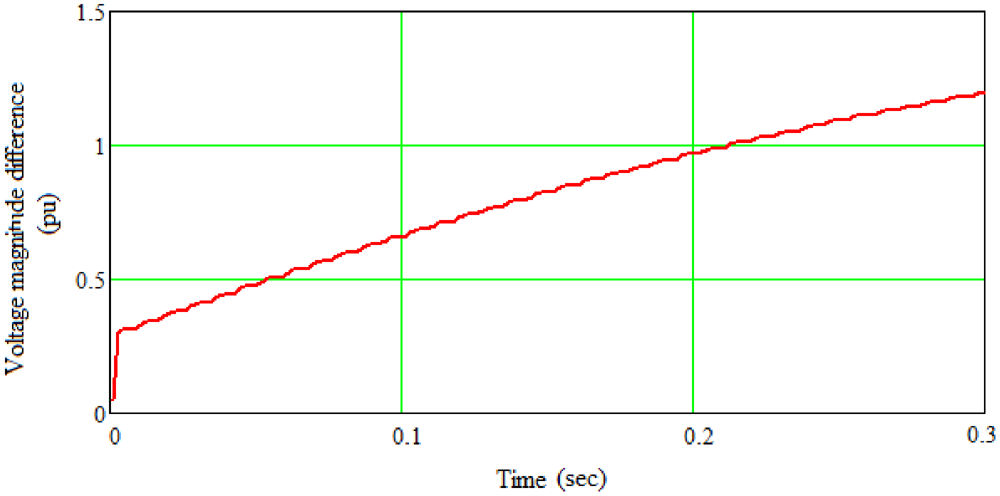


Fig. 2.25: Plot of the voltage magnitude difference between the motor stator terminals and the power source over the 300millisceond open time interval period.

Fig. 2.26 is a plot of the voltage magnitude difference between the motor stator terminal and the power source for a time period of 900 milliseconds. In Fig. 2.26 the voltage difference between the two voltage source at first increases and then as the flux in the motor begins to decay, the voltage at the motor stator terminals decays, resulting in a smaller stator terminal voltage which result in a lower voltage difference between the two voltage sources.

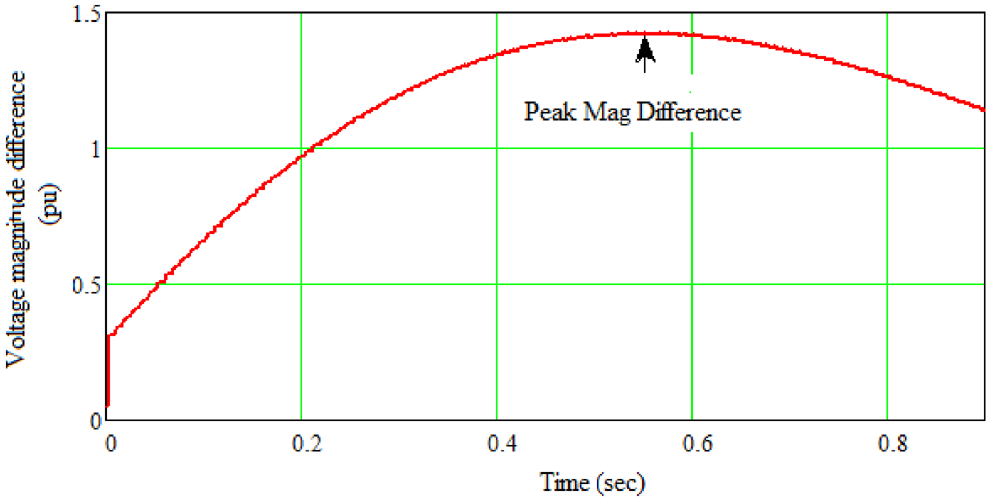


Fig. 2.26: Plot of the voltage magnitude difference between the motor stator terminals and the power source over a 900 millisecond open interval time period.

2.5.8 Initial rotor current and rotor current derivatives after the motor is reconnected to the power source

The initial rotor current (t_0^+) when the motor gets reconnected to the power source is going to be the equal to the rotor current the instant just before (t_0^-) the motor gets connected to the power source. The reason why the current in the rotor does not change has been discussed already, and is due to the fact that the flux in the rotor cannot change instantaneously. Therefore the initial current in the rotor is calculated as follows for t_n = 300ms;

$$I^s_{qdr\_rc} = I^r_{qdr}(t_n)e^{j\omega_r \omega_{e\_base} t_n}$$

$$I^s_{qdr\_rc} = 0.203\angle{-171.84°}$$

The motor stator terminal voltage at the instant the motor gets connected to the power system is going to be equal to the voltage of the power source at the instant that the motor gets connected to the power source. Note the voltage at the terminals of the machines can change instantaneously

$$V_{qdr\_rc}^{s} = V_{qds}(t_n)e^{j\omega_r \omega_{e\_base} t_n}$$

$V^s_{qds\_rc} = 1.00\angle 12°$

The derivative of the rotor current is obtained as follows;

$$pI_{qdr\_rc}^{s} = \frac{\omega_{e\_base}\left[-L_m V_{qds\_rc}^{s} + \left(j\omega_r L_m{}^2 - L_s r_r\right) I_{qdr\_rc}^{s}\right]}{\sigma L_s L_r}$$

$pI^s_{qdr}\_rc = 1477\angle\text{-}168°$ pu/sec

2.5.9 Initial stator current and stator current derivative after the motor is reconnected to the power source

The stator current during the time period that the motor was disconnected from the power source was zero (no current flowed in the stator windings), therefore the stator current at the instant that the motor is reconnected to the power source will be zero (again the flux in the stator winding cannot change instantaneously).

$I^s_{qdrs\_rc} = 0.00$

The derivative of the stator current is obtained as follows;

$$pI_{qds\_rc}^{s} = \frac{\omega_{e\_base}\left[L_r V_{qds\_rc}^{s} + (L_m r_r - j\omega_r L_m L_r) I_{qdr\_rc}^{s}\right]}{\sigma L_s L_r}$$

$pI^s_{qdr}\_rc = 1536\angle 11°$ pu/sec

2.5 10 Transients following the reconnection of the motor to the power source

Eigenvalues

Using the rotor reference frame (ω_{rf} =0),

$\omega_{r\_m} = \omega_r \omega_{e\_base}$

ω_{r_m} = 372.47 rad/sec

$$k_1 = \frac{-1}{2\sigma\tau_r}(1+\alpha) + j\left(\frac{\omega_{r\_m}}{2} - \omega_{rf}\right)$$

k_1 = (-13.849 + j186.238) rad/sec

$$k_2 = \frac{1}{2\sigma\tau_r}\sqrt{(1+\alpha)^2 - 4\sigma\alpha - \left(\omega_{r\_m}\sigma\tau_r\right)^2 + j(\alpha-1)\omega_{r\_m}\sigma\tau_r}$$

k_2 = (1.543 + j185.769) rad/sec

$$\lambda_1 = k_1 + k_2$$

λ_1= (-12.306 + j0.469) rad/sec

$$\lambda_2 = k_1 - k_2$$

λ2= (-15.391 + j372.006) rad/sec

Constants

$$C_1 = \frac{-pI^{s}_{qds\_rc} + \left(j\omega_e\omega_{e\_base} - \lambda_2\right)I_{qds}}{\lambda_2 - \lambda_1}$$

C_1 = -0.838 + j4

$$C_2 = \frac{pI^s_{qds\_rc} + (\lambda_1 - j\omega_e\omega_{e\_base})I_{qds}}{\lambda_2 - \lambda_1}$$

C_2 = -0.173 – j3.392

$$C_3 = \frac{\lambda_2 I^s_{qdr\_rc} - pI^s_{qdr\_rc} + (j\omega_e\omega_{e\_base} - \lambda_2)I_{qdr}}{\lambda_2 - \lambda_1}$$

C_3 = 0.592 – j3.884

$$C_4 = \frac{pI^s_{qds\_rc} - \lambda_1 I^s_{qds\_rc} + (\lambda_1 - j\omega_e\omega_{e\_base})I_{qdr}}{\lambda_2 - \lambda_1}$$

C_4 = 0. 259 + j3.552

Currents

Using the eigenvalues (λ_1,λ_2) and the constants (C_1,C_2,C_3,C_4) the stator (I_{qds}) and rotor (I_{qdr})curr ents that flow in the motor when the motor is reconnected to the power source can be calculated as follows;.

$$I_{qds}(t) = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + I_{qds} e^{j\omega_e\omega_{e\_base}t}$$

$$I_{qdr}(t) = C_3 e^{\lambda_1 t} + C_4 e^{\lambda_2 t} + I_{qdr} e^{j\omega_e\omega_{e\_base}t}$$

Fig. 2.27 and Fig. 2.28 are plots of the real and imaginary components of the stator and rotor current for 500 milliseconds after the motor was reconnected to the power source

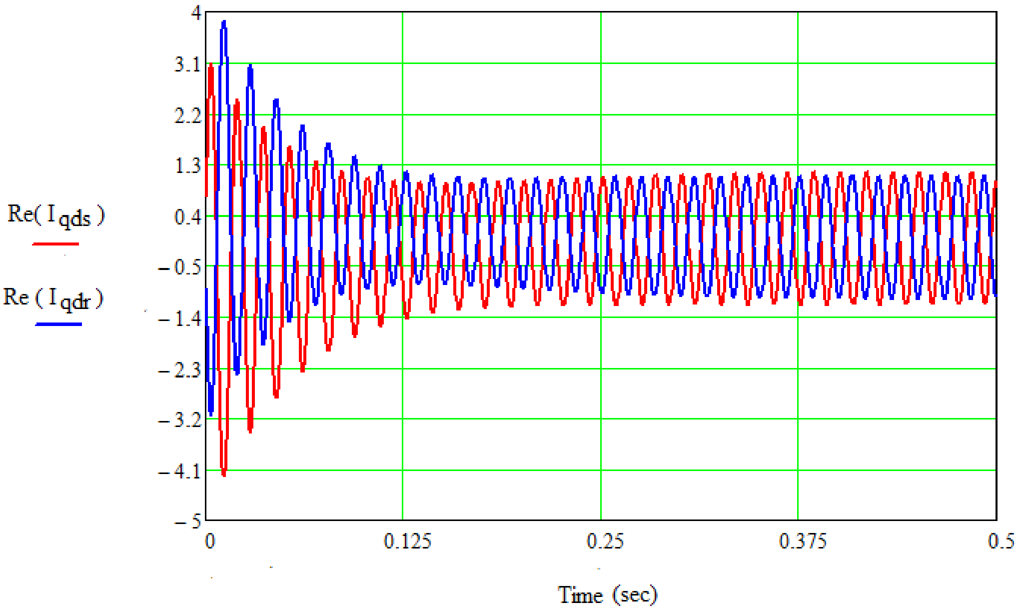


Fig. 2.27: Plot of the real component of the stator current (I_{qds}) and the real component of the rotor current (I_{qdr}) for 500 milliseconds after the motor has been reconnected to the power source.

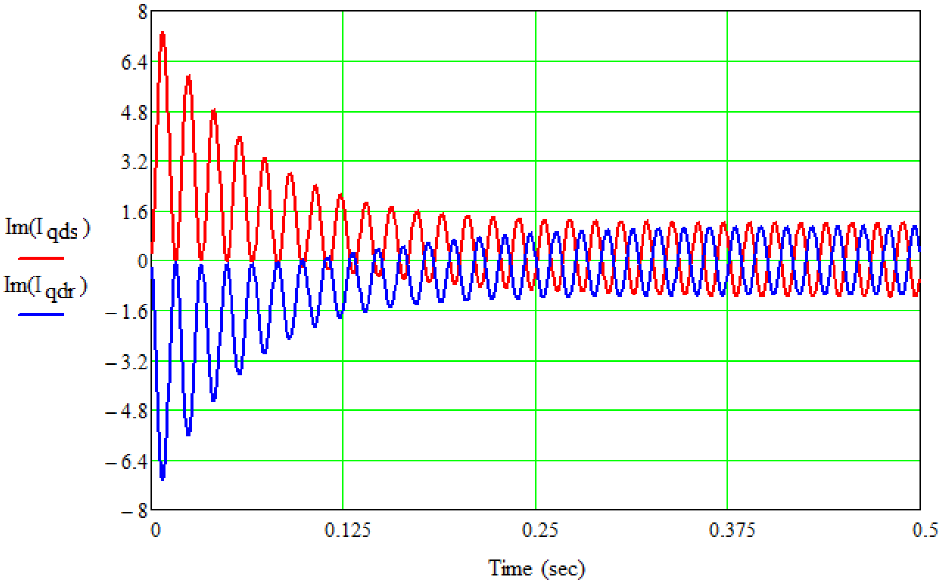


Fig. 2.28: Plot of the imaginary component of the stator current (Iqds) and imaginary component of the rotor current (Iqdr) for 500 milliseconds after the motor has been reconnected to the power source.

Torque

Once the stator and rotor currents have been calculated, the electromechanical torque (T_{em}) developed by motor can be calculated using the following equation;

$$T_{em}(t) = L_m\left(I_{qds}(t)I_{qdr}(t)^*\right)$$

Fig. 2.29 is a plot of the electromechanical torque developed.

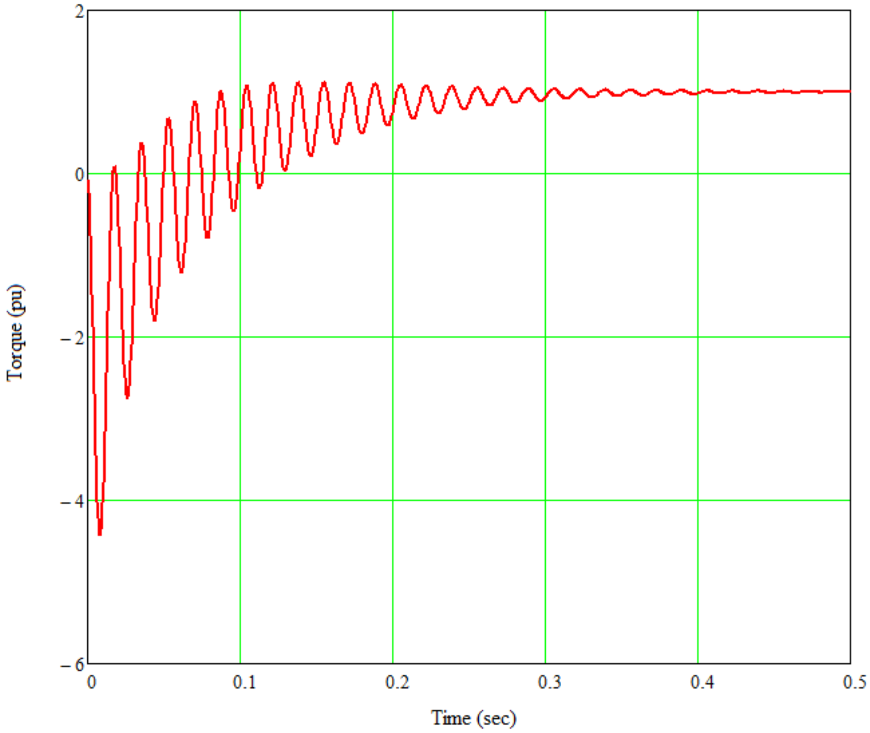


Fig. 2.29: Plot of electromechanical torque developed by the motor 500 milliseconds after the motor was reconnected to the power source.

Power

At the same time as calculating the electro mechanical torque (T_{em}) developed by the motor the power (P_{em}) delivered by the motor across the air gap can be calculated as follows;

$$P_{em}(t) = -Re\left[jL_m\left(I_{qds}(t) + I_{qdr}(t)\right)I_{qdr}(t)^*\right]$$

Fig. 2.30 is a plot of the power delivered over the 500 millisecond time period after the motor was reconnected to the power source.

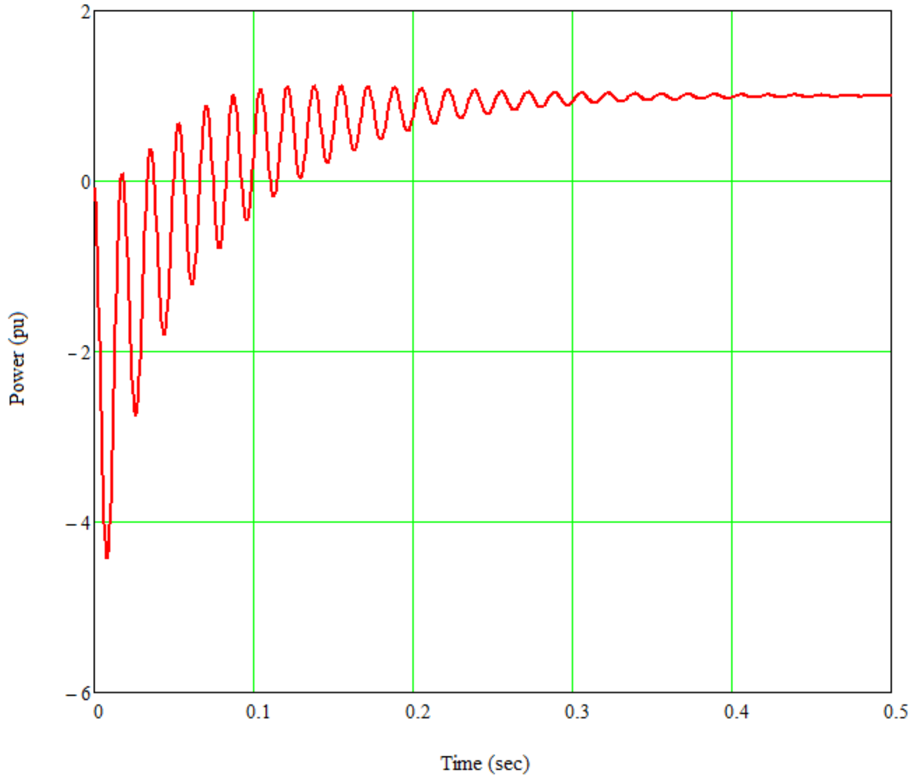


Fig. 2.30: Plot of power developed by the motor across the air gap for a time period of 500 milliseconds after the motor was reconnected to the power source.

Comments on Results

Comparing the plots of the electromechanical torque (T_{em}) developed by the motor to the power delivered (P_{em}) by the motor across the air gap it can be seen that these two graphs (plots) are identical. Stated differently, in general the ratio of the power delivered to the motor and electromechanical torque developed is the rotor angular velocity (ω_r), in this case the ratio of these two values is equal to 1 p.u. The reason for this is that the eigenvalues (λ_1,λ_2) where calculated assuming a constant rotor velocity, which for this case is not completely correct as shown in Fig. 2.23, since the rotor velocity decreases. To simulate this behavior correctly an iterative solution that calculates the eigenvalues, the constants and torque after each iteration is required. This is best done by using a simulation tool such as the RTDS®. This is what is done in Chapter IV.

The mathematical method presented in this chapter for analyzing the behaiour of an induction motor during the different phases of a motor bus transfer are good for determining the values of the motor voltage and current prior to the open interval period, and at the instant that the motor is disconnected from the power supply and during the open interval interval. However to calculate the motor currents and subsequent torque developed by the motor at the instant the motor is reconnected to the alternative power source requires that the eigenvalues of the motor be calculated. In order to calculate the eigenvalues a specific motor speed needs to be selected and in doing so the speed of the rotor during the open interval period is assumed to be constant, i.e the motor has infinite inertia. However we know this is not the case and that the motor slows down during the interval periods as shown by equation (2.37), therefore the eigenvalues that are calculate correspond to only specific value of rotor speed. This means that the motor currents and subsequent calculated torque are not correct. However if the open interval period is short and the inertia high enough the error in calculating the motor current when the motor is connected to the alternative source will be small and the results obtained by this method give a good indicvation of the torque developed by the motor when connected to the alternative power source.

Chapter III: Motor Bus Transfer

3.1 Overview

In Chapter II, the dissertation examined and mathematically analyzed the effect of a single induction motor being disconnected from a primary power source and then being reconnected to that power source some arbitrary time later. This chapter will examine the effect when a bus with multiple induction motors and dynamic loads connected to it (as is typically the case in industry) is disconnected from its primary power source and a short time later is connected (transferred) to an alternative power source. The reason for the bus being disconnected from its primary source is typically to aid in clearing a fault condition on the transmission (or distribution) line feeding the bus. Once the bus has been disconnected from its primary source, the bus is typically connected to the alternative power source as rapidly as possible so as to allow the industrial process to remain operational. A sketch showing a typical bus configuration of a substation feeding an industrial complex is shown in Fig.3.1.

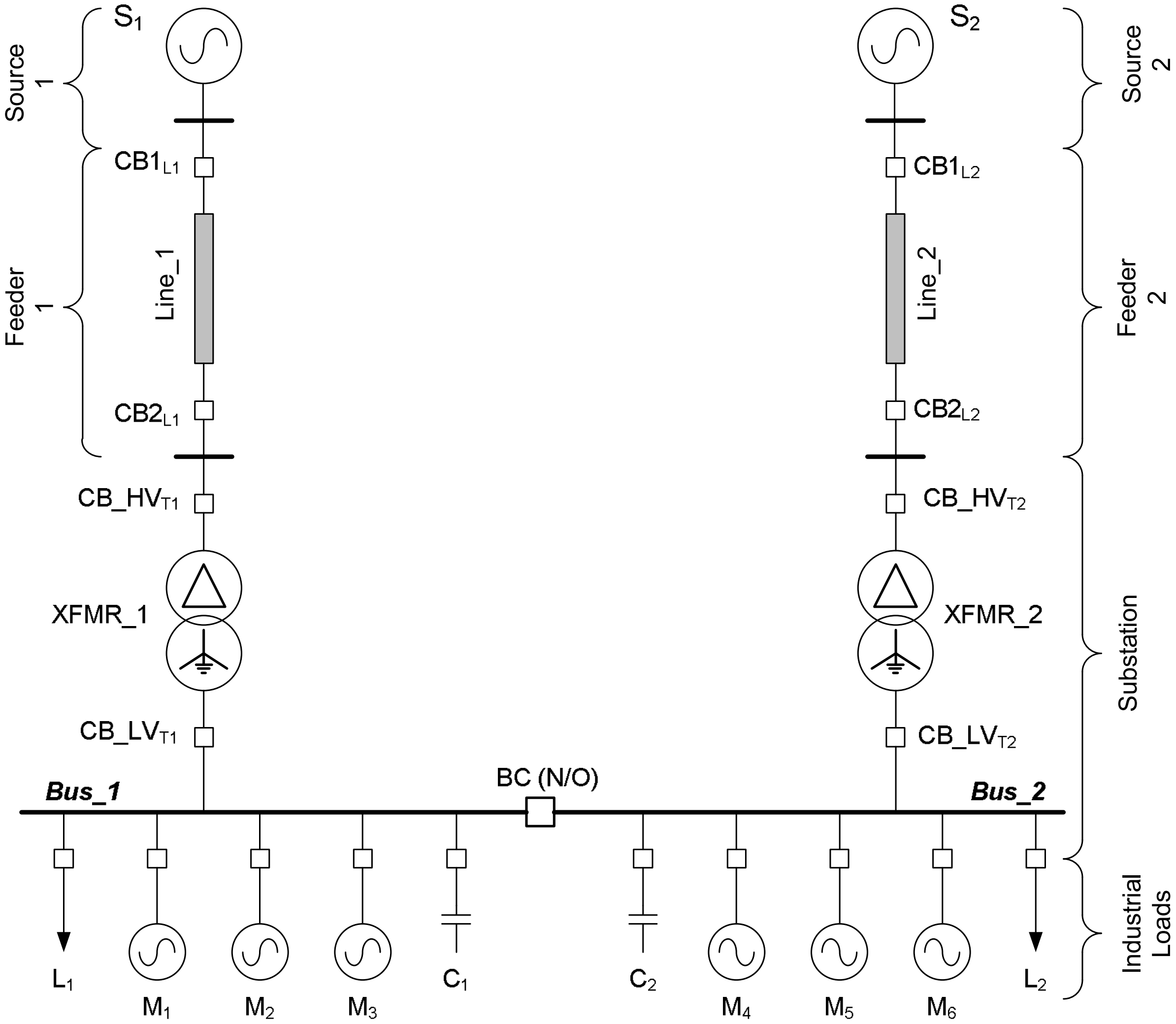


Fig. 3.1: Typical bus configuration of an industrial substation showing two individual buses feed from two independent sources capable of being connected together via a bus coupler (BC).

From Fig. 3.1 it can be seen that the substation consists of two independent busses being fed from two independent power sources with the bus coupler (BC) normally open (N/O). The reasons for this redundancy are;

- A fault on one of the feeders will only impact one of the buses (the system is usually operated with the bus coupler open).

- If one of the feeders supplying one of the buses experiences a permanent failure the industrial complex can be supplied from a single source by simply closing the bus coupler breaker, thereby connecting the two buses together.

- The substation is operated with the bus coupler (BC) in a normal open position in order to reduce the fault current magnitude. Operating the substation in this manner allows for the use of circuit breakers with lower interrupting capacity, which reduces the price and maintenance requirements of the circuit breakers in the substation.

Assume that feeder 1 in Fig.3.1 develops a single phase to ground fault, to clear this fault circuit breakers at both terminals of the feeder ($CB1_{L1}$ and $CB2_{L1}$) need to be opened. Once $CB1_{L1}$ is open, Bus 1 is isolated from the primary source. However if $CB2_{L2}$ is not opened the fault is being feed from the back emf of the induction motors connected to Bus 1. Therefore, $CB2_{L1}$ needs to be opened before Bus_1 can be connected to the alternative power source (S_2). Otherwise the unfaulted bus will be connected to the fault, depressing the voltage on the unfaulted bus and possibly leading to a shutdown of the entire plant if the voltage depression due to the feeder fault is severe. A sketch showing the fault current contributions from different elements of the power system is shown in Fig.3.2.

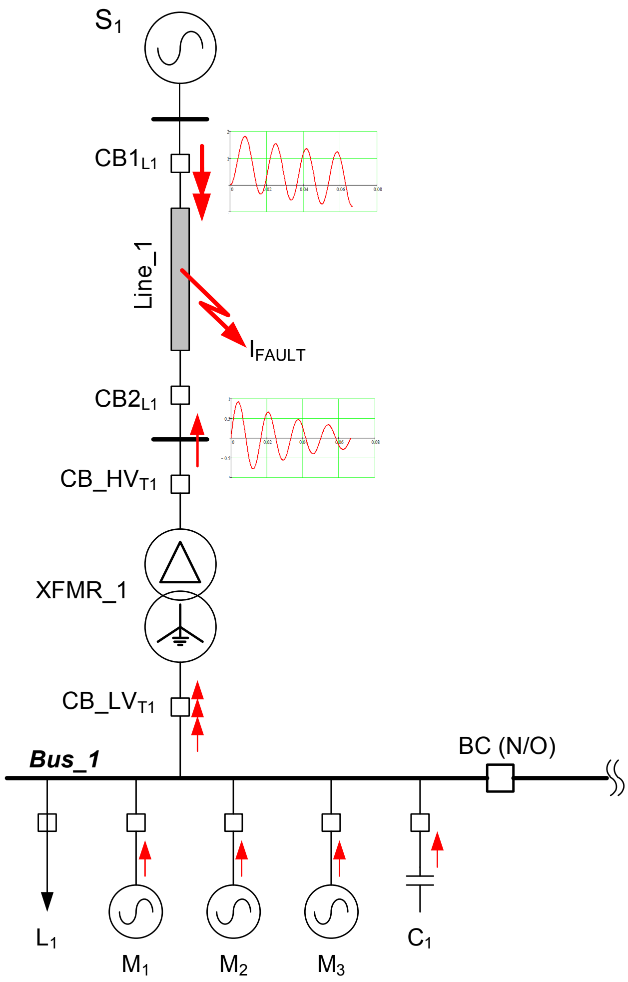


Fig. 3.2: Sketch of the fault current contribution from both the source (S_1) and the motor bus (*Bus_1*), note that the motors and the shunt capacitor bank will contribute currents towards the fault.

In Chapter II, it is shown that when a motor is disconnected from its primary power source the voltage at the terminal of the motor does not decrease to zero immediately. Rather, the voltage at the terminals of the motor equals the voltage across the magnetizing branch of the motor prior to motor being disconnected. The frequency of the voltage correspond to the frequency (speed) of the rotor prior to the motor being disconnected. Different than in the Chapter II, before the bus is isolated from the power system, the motors on the bus supply fault current to the fault, as shown in Fig. 3.2. The magnitude of the fault current contributed by each individual motor is dependent on the magnitude of the voltage across the motors magnetizing branch and the impedance between the fault and the motors magnetizing branch. Once the substation bus is isolated from the power system and the fault, the voltage on the substation bus will be lower than if the bus was simply disconnected from the power system. This lower voltage on the substation bus is the reason why it is important to reconnect the bus to the auxiliary (alternative) power source as soon as possible in order to save the process. Should the voltage on the substation bus decay below a certain threshold, undervoltage protection will automatically take motors and processes off line. However it is not possible to simply connected the isolated substation bus to the alternative source at any instant in time, since there will be a difference in the voltage magnitude, frequency and phase angle between the isolated substation bus and the alternative power source.

In this chapter the following issues will be addressed and/ or discussed;

- Requirements for a motor bus transfer [14], [15], [16], [17], [18], and [19];
- Challenges of present methods to ensure a successful motor bus transfer;
- Propose and explain a new method for doing motor bus transfer.

3.2 Motor Bus Transfer Requirements

In this section the present common methods of accomplishing a motor bus transfer in the power industry are discussed.

The IEEE guide for Motor Bus Transfer [19], defines two types of transfer methods, namely:

- The Closed Transition Transfer or Hot Parallel Transfer, here the bus being transferred is connected to the alternative (auxiliary) power source before being disconnected from its primary power source. The bus under transfer is never isolated from any power source.
- The Open Transition Transfer, the bus is disconnected from its primary power source first before the bus is transferred to the alternative (auxiliary) power source. This means the bus under transfer is isolated from any power source for a specific period of time.

This dissertation will exclusively concentrate on the Open Transition Transfer, since this is the method that is most commonly used in industry today. The open transition transfer is classified into three basic methods, namely:

- The fast transfer;
- The in-phase transfer;
- The residual voltage transfer.

A good method to illustrate the three transfer methods is to us a graphical illustration that depicts the decay in both the voltage magnitude and angle after the motor bus has been disconnected from its primary power source. The three zones that correspond to the three open transition transfer methods found in typical literature [19], are shown in Fig.3.3.

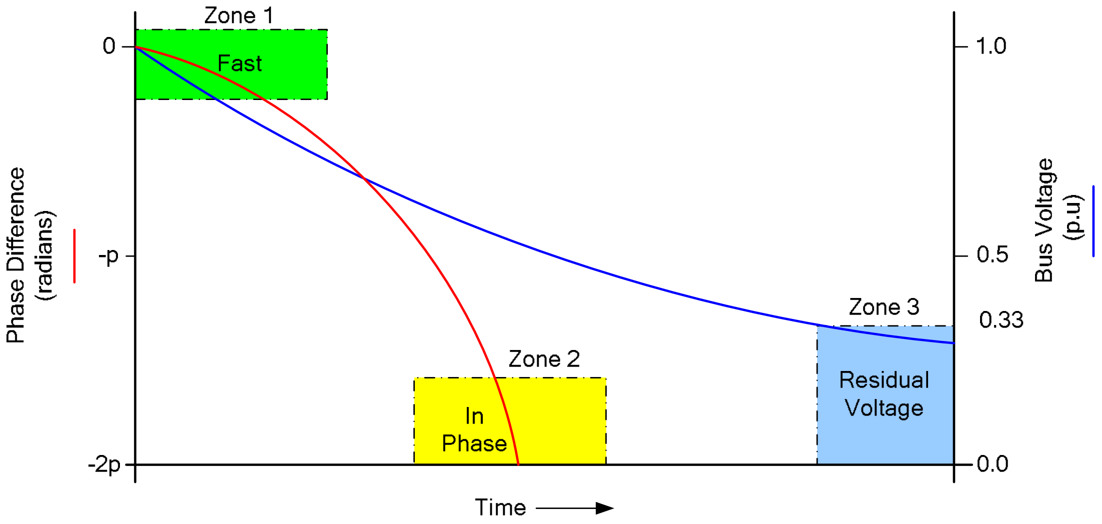


Fig. 3.3: Sketch showing the three zones during which a motor bus transfer can occur, namely the fast transfer, the in-zone transfer and the residual voltage transfer.

However, an alternative and maybe more intuitive method to illustrate or graphically represent the three transfer methods is shown in Fig. 3.4. The following assumptions were made for the in phase transfer development:

- The ratio of the per unit (p.u) voltage with respect to the p.u frequency of the alternate source remains constant and is usually 1 (this is a valid assumption since the alternative source will be operating at its nominal voltage and frequency).

- The ratio of the per unit voltage with respect to the per unit frequency of the isolated bus will remain constant and will usually be 1 (this assume that the voltage and frequency decay at the same rate , the rate of voltage decay is dependent on the reactive power being drawn by the equipment on the bus and the decay of frequency of the isolated bus is dependent on the power being absorbed by the bus, the inertia of the motors and their associated loads. The higher the inertia of the loads the slower the rate of frequency decay for a given power requirement on the bus.

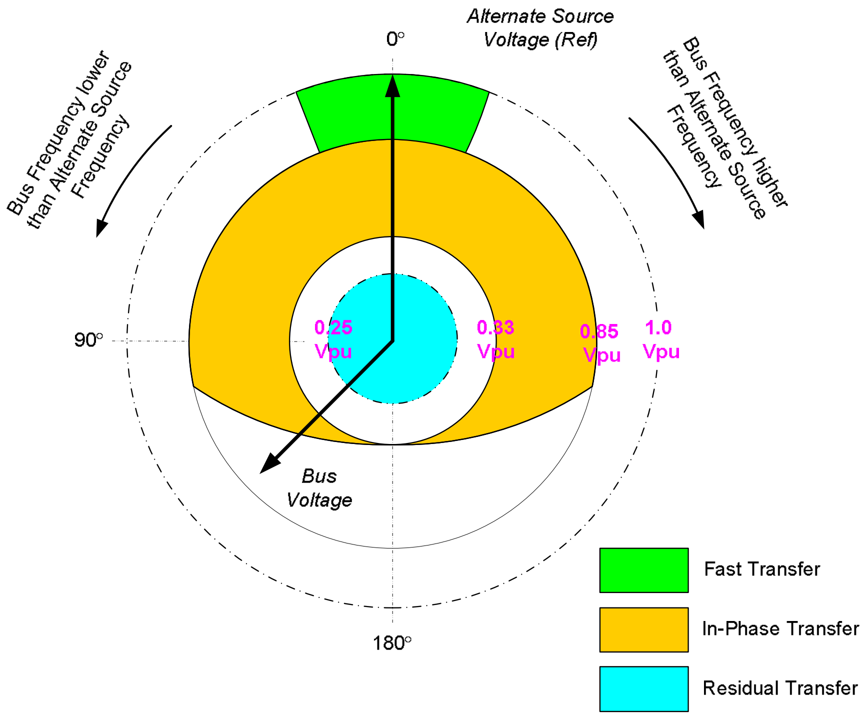


Fig. 3.4: An alternative view of how to illustrate the three modes of bus transfer, in this sketch the voltage magnitude and angle are shown in relation to each other.

3.2.1 The Fast Transfer

In this mode the isolated bus is connected to the alternate (auxiliary) supply if the voltage magnitude and phase angle difference is within the limits as specified by zone 1. Typically to facilitate a fast transfer use is made of a high speed circuit breakers with a closing time of 1 cycle (16.67 ms) or less. Typical industrial circuit breakers (which make use of vacuum bottles) have a closing time of approximate 3 – 4 cycles (50 – 66 milliseconds) [20]. This method, in addition to high speed breakers, also requires the use of high speed synchronizing supervision instrumentation. This mode of transfer does not typically occur after the line feeding the bus experience a power system fault, since the fault will lower the voltage on the motor bus below the minimum required bus voltage for a fast transfer.

3.2.2 The In-Phase Transfer

For an in-phase transfer the voltage magnitude on the motor bus has to be greater than 0.33V p.u. and the voltage angle difference between the motor bus and the alternate source has to result in a volts-per- hertz difference of less than 1.33 p.u. V/Hz between the bus and the alternative source [19]. Fig. 3.5 show how the angle between the alternative source volts-per-hertz and the motor bus volts-per-hertz is calculated, equation (3.1) shows the actual calculation used to calculate the maximum allowed closing angle in order to meet the IEEE recommendation of 1.33 V/Hz.

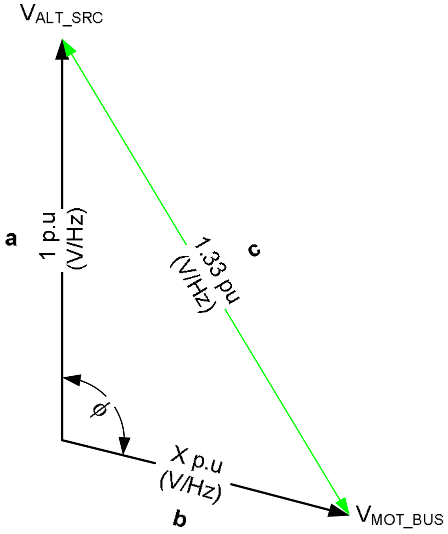


Fig. 3.5: A vector diagram of the relationship between the alternating source and motor bus volts-per-hertz from this the maximum allowable transfer angle is calculated. Note typically the alternative source (V_{ALT_SRC}) voltage is taken as the reference and the motor bus voltage (V_{MOT_BUS}) rotates with respect to alternative source voltage.

$$\phi = acos\left(\frac{c^2-(a^2+b^2)}{-2ab}\right) \tag{3.1}$$

From Fig. 3.5 and equation (3.1) it can be seen that in order to continuously and accurately calculate the maximum allowable closing angle for an in-phase transfer, the voltage and frequency of both the alternating source and the motor bus have to be continuously calculated/measured. The motor bus is ideally connected (transferred) to the alternative source when the angular difference between the volts-per-hertz of the alternative source and the motor bus is zero. In order to accurately predict when the volts-per-hertz angle between the alternative source and motor bus are going to coincide with one another, the voltage magnitude, angle and frequency of the alternative source and motor bus needs to be measured/calculated. In addition to this, the slip frequency of the motor bus voltage with relationship to the alternative source has to be calculated. Knowing the slip frequency and the actual closing time of the circuit breaker, the instant in time when to issue the close command to the transfer circuit breaker (bus coupler) can be calculated.

If the motor bus volts-per-hertz magnitude is between the volts-per-hertz limits shown in Fig. 3.4, the slip frequency between the alternative source and the motor bus is calculated by calculating the rate of change of the angle difference between the volts-per-hertz of the two systems, the equation for calculating the slip frequency is shown in equation (3.2).

$$\Delta f = \frac{\Delta(\theta_{Alternative\_source} - \theta_{Bus})}{\Delta t} \tag{3.2}$$

Knowing the slip frequency (Δf) between the two systems and the closing time of the circuit breaker, the exact moment in time when to issue the closing pulse/signal to the circuit breaker can be determined. Following is an example illustrating how to determine the moment when to issue the closing pulse/signal to the transfer circuit breaker.

Example:

Slip frequency = -1.5 Hz/sec (the bus frequency is slower than the alternate source frequency, which is typically the case)

Breaker closing time = 50 milliseconds [typical for a 33kV SF_6 circuit breaker]

Calculating the angle by which the bus voltage has to lag the alternate power source voltage.

$$V_{ANG_{BUS}} = \ slip\ frequency\left(\frac{Hz}{sec}\right) \cdot 360\left(\frac{\mathrm{deg}}{\mathrm{Hz}}\right) \cdot breaker\ closing\ time(sec)$$

$$V_{ANG_{BUS}} = \ -1.5 \cdot 360 \cdot 0.05$$

$$V_{ANG_{BUS}} = -27^0$$

Therefore when the bus volts-per-hertz lags the alternative source volts-per-hertz by 27° the close pulse should be sent to the circuit breaker.

Fig. 3.6 illustrate the moment in time (angle) when the close pulse to the circuit breaker is issued so that the circuit breaker poles close when the voltage of the motor bus is perfectly in-phase with the voltage of the alternate power source.

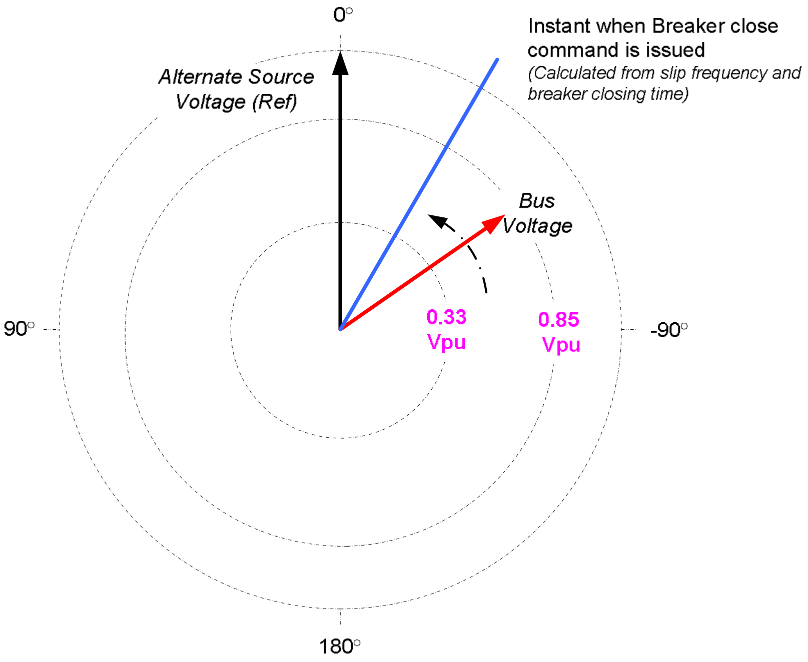


Fig. 3.6: A sketch showing when a relay should issue a close command to the bus-coupler taking the breaker closing time into account so as to accomplish an in-phase transfer with zero angular difference between the motor bus voltage and the alternative power source voltage.

Calculating the voltage magnitude, angle and the slip frequency and of the bus voltage is no easy task, especially when the frequency of the voltage is changing constantly (this will be explained later in this chapter).

3.2.3 The Residual Voltage Transfer

For a residual transfer to occur the voltage of the motor bus has to be below the residual voltage limit (typically 0.25V p.u.). A residual transfer is unsupervised by the phase angle or slip frequency as it is not possible to exceed the 1.33 V/Hz limit set by the in phase transfer due to the voltage decay. Two factors have to be taken into account for a residual voltage transfer to be successful;

- The under voltage protection time out trip of the motor,

- The stall point of the motors if the frequency is too low.

Therefore the residual transfer has to be coordinated with the under voltage time of the motors on the bus and the inertia of the motors and the load on the bus during the time that the motor bus is isolated from all power sources to be able to act before the motors trip or stall. Since the frequency of the motors is determined by the inertia of the motors on the bus and the load (MW) on the bus, if the residual transfer cannot occur successfully due to the rapid deceleration of the motors on the bus (this will occur when the load on the bus exceeds the inertia of the motors) it may become necessary to drop load (load shed) to enable a successful residual voltage transfer.

3.3 Challenges to Present Motor Bus Transfer Methods

To understand the challenges present motor bus transfer methods/schemes face it is necessary to examine how a motor transfer is accomplished at present. To do this a motor bus transfer algorithm that is implemented in a modern digital protective device will be analyzed. The analysis will begin with how the data is acquired, processed, filtered and converted into magnitude and angles. Fig. 3.7 is a simple sketch of a data acquisition for a modern digital relay.

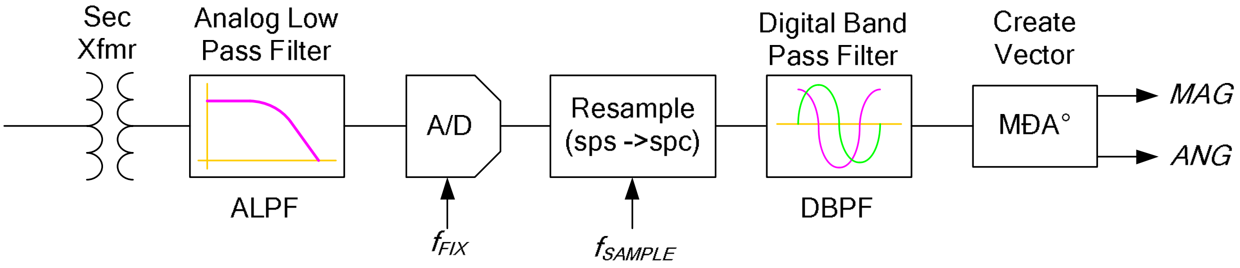


Fig.3.7: Simple sketch of a frequency tracked data acquisition system for a modern digital protective device.

A detailed description of each element in the data acquisition chain is give in [21]. What is not discussed in [21] is frequency tracking and sampling frequency (f_{SAMPLE}) or *resampling frequency*. The resampling frequency is the frequency at which the data is resampled. Data is typically obtained at a fixed rate i.e., 2000 samples per second. However before that data can be used by a protection relay the data has to be passed through a digital band pass filter (DBPF) in order to extra the frequency of interest and eliminate all other harmonic frequencies. The digital bandpass filter is design to have a fixed number of taps or samples per cycle (typically 16 or 32). The resampling frequency is determined by multiplying the number of taps of the DBPF (samples per cycle, SPC, of the DBPF) with the actual frequency of the power system. To ensure the correct number of integer samples per cycle the relay needs to accurately calculate the system frequency so as to accurately compute the re-sampling frequency. Calculating the frequency of the power system can be done in two ways namely;

- By determining the time between two consecutive positive or negative zero crossing and inverting this time to obtain the frequency of the power system or
- By determining the rate of change of angle of the system voltage angle ($f = d\phi/dt$).

Of these two methods the time between two consecutive positive and two consecutive negative zero crossing is the preferred method used to determine the frequency of the power system. Fig. 3.8 illustrates how the time between two positive and two negative going zero crossings is determined.

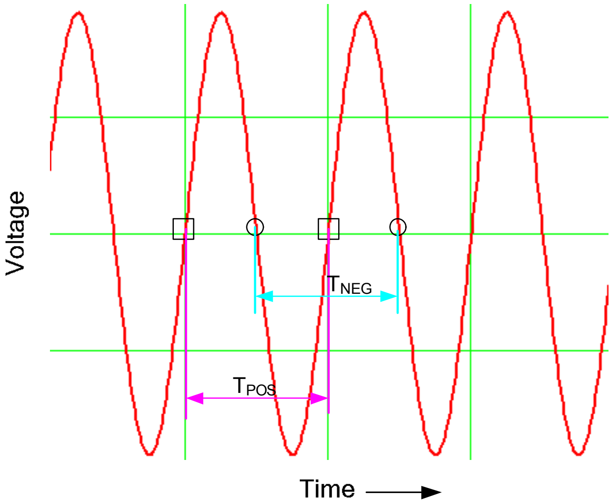


Fig.3.8: Sketch showing how the time between to positive going and two negative going zero crossing is determined, using this time the frequency of the power system is determined.

Once the time between two consecutive positive going or negative going zero crossings has been obtained the frequency of the signal is obtained. Equation (3.3) show how the frequency of the power system is calculated using the time difference of two positive going zero crossings;

$$Freq_{NEW} = \frac{1}{T_{POS}} \tag{3.3}$$

The power system frequency can be calculated similarly using the time difference between two a negative going zero crossing. If this method is used a new power system frequency is obtained every ½ a power system cycle. This new frequency ($Freq_{NEW}$) cannot be used without checking its validity to calculate f_{SAMPLE}. Knowing that the frequency of a power system cannot change drastically between one frequency measurement to the next (the inertia of the rotating machines in the power system will prevent this), one of the checks that is done is to check if the rate of change of frequency (df/dt) between the latest (present) frequency measurement ($Freq_{NEW\_k}$) and previous frequency measurement ($Freq_{NEW\_k-1}$) falls within a predefined limit. The predefined limit on the rate of change of frequency is there to ensure that the frequency calculation is not corrupted by an erroneous frequency as can happen if there is a high frequency component present in the signal. The presence of a high frequency component, as shown in Fig.3.9 or a glitch in the A/D converter will corrupt the power system frequency calculation. Therefore to prevent the frequency tracking algorithm from using this corrupted frequency measurement the *df/dt* limit criteria is used. The new calculated frequency will exceed the predefined *df/dt* limit and therefore not be used by the frequency tracking algorithm.

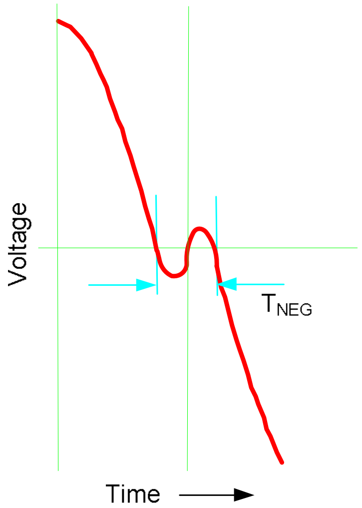


Fig. 3.9 Sketch showing how a high frequency signal can result in the relay incorrectly calculating the time between two successive negative going zero crossings. A severe voltage harmonic distortion will also manifest itself in this shape.

If the new frequency ($Freq_{NEW\_k}$) falls within the predefined limits as set by the rate of change criteria, the new frequency will be used in calculating the newest re-sampling frequency. However the re-sampling frequency is not simply a product of the predefined number of samples per cycle and the newest calculated power system frequency. If this would be the case, the output of the digital band pass filters (DBPF) would be very erratic. The reason for this is as follows, the DBPF is typical a finite impulse response filter (FIR) usually with a one cycle window. This means data in this window is typically one cycle old and was acquired by re-sampling the sample per second (sps) data at one frequency. If data is input into the FIR that was re-sampled at a different frequency the data in the FIR is no longer coherent and the output of the FIR filter is no longer going to be coherent. For this reason a change in the power system frequency does not result in an instantaneous change in the re-sampling frequency (f_{SAMPLE}) of the relay. A simple sketch of a typical protective relays frequency tracking algorithm is shown in Fig.3.10.

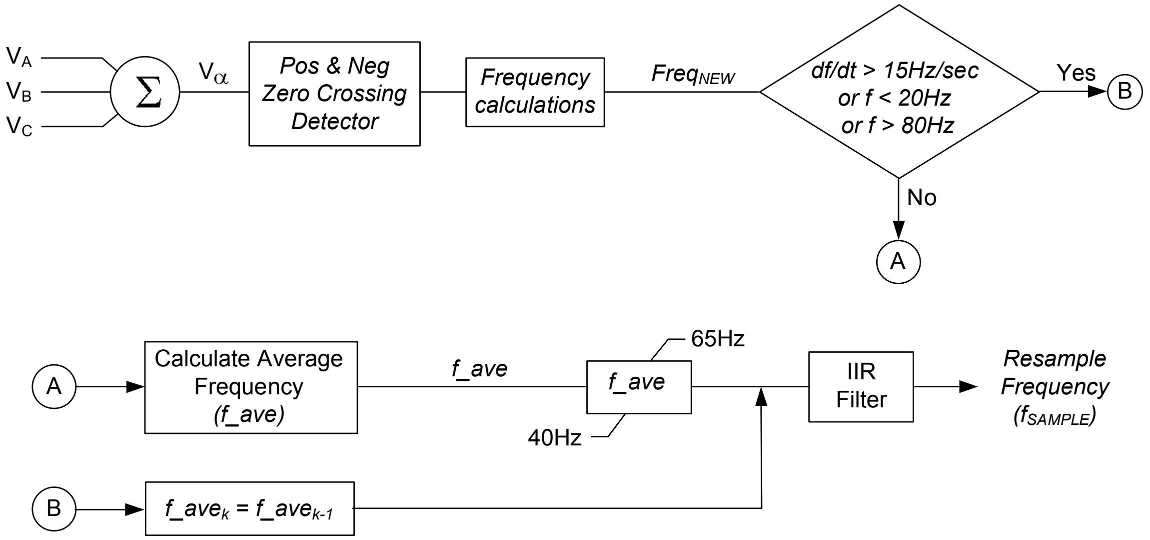


Fig. 3.10: Simple sketch of a frequency tracking algorithm used in a numerical protection relay.

The simple sketch of the frequency tracking algorithm in Fig. 3.10 shows that the newly calculated frequency ($Freq_{NEW}$) is passed through an averager first (this simply averages the frequency over the last two cycles). The output of the averager (*f_ave*) is then input into an infinite impulse response (IIR) filter. The output of the IIR filter is known as the “relay frequency,” this is the frequency that is used by the data acquisition algorithm to calculate the re-sampling frequency (As mentioned early the re-sampler is simply the predefined samples-per-cycles multiplied by the relay frequency). The IIR filter results in the “relay frequency” slewing to the new power system frequency. The rate at which a relay slews to the power system frequency is a design criteria chosen with care by relay designers after taking many factors into consideration. The typical response of the “relay frequency” (used to calculate the re-sampling frequency) to a change in the power system frequency is shown in Fig.3.11.

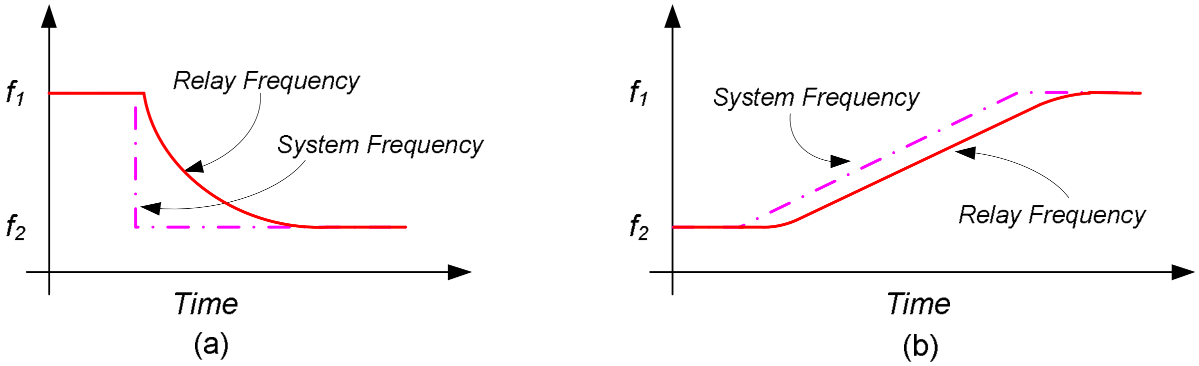


Fig. 3.11: The response of the a frequency tracking algorithm for a step change in the system frequency (a), response of the frequency tracking algorithm for a gradual excursion is the power system frequency (b).

The lag of the relays frequency with respect to that of the actual power system frequency, when there is a frequency excursion on the power system is shown in Fig.3.11. To see what effect this has on the relay, assume that the power system frequency experiences an incremental frequency increase in frequency (due to the loss of a large load), similarly as shown in Fig. 3.11 (b).

In protective relaying the magnitude and angle of the voltage and current must accurately reflect that of the power system. From the simple data acquisition sketch shown in Fig. 3.7 it can be seen that once the data has been re-sampled the re-sampled data is input into the DBPF to extract (isolate) the frequency of interest (typically the nominal power system frequency) and once this is done a phasor quantity is created from which the magnitude and angle of a particular quantity (voltage or current) is calculated. It is the effect of the difference between the relay and power system frequency on the calculation of the voltage or current magnitude and angle that are of concern here.

Assume that the power system losses a significant load and as a result of this the power system frequency increase from 60 to 64 Hz at a rate of 7.5 Hz per second as show in Fig. 3.12.

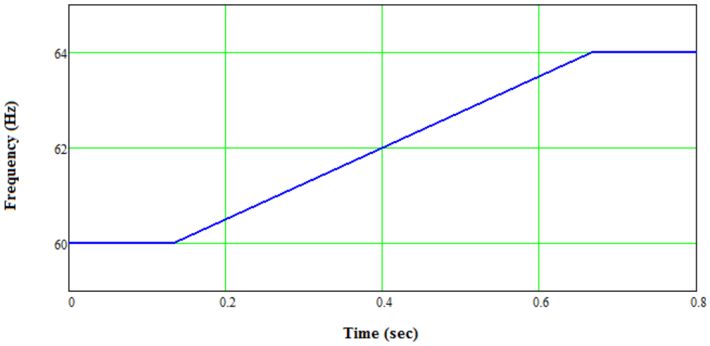


Fig. 3.12: Frequency response of the power system after a the loss of a major load, the frequency increases from 60–64 Hz in 533 milliseconds (ramp rate of 7.5 Hz/second)

The relay will correctly measure the change in the power system frequency and input this into the frequency tracking algorithm but as mentioned early the “relay frequency” is not going to change instantaneously. The relay frequency is going to slew to the new frequency at a rate governed by the frequency averaging algorithm and the IIR filter of the frequency tracking algorithm. The lag between the relay frequency and the measured (power system) frequency for a specific frequency algorithm design is shown in Fig. 3.13. The particular frequency tracking algorithm shown in Fig. 3.13 has a averaging and IIR filter, the averaging filter in design uses the average value of the last 4 frequency measurements and the IIR filter is a $1/8^{th}$, $7/8^{th}$ filter, that means the filter uses $1/8^{th}$ of the newest frequency value and $7/8^{th}$ of the previous calculated frequency value.

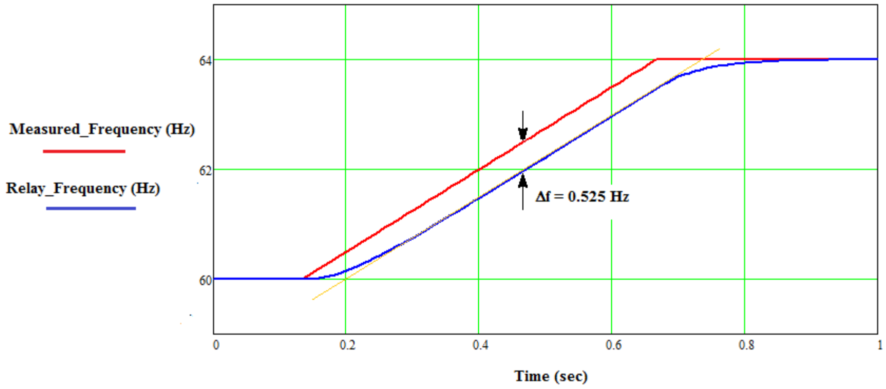


Fig. 3.13 Response of the relay frequency tracking algorithm (blue trace) compared to the frequency of the power system (red trace), during a loss of load on the power system.

The lag between relay frequency and the measured (system) frequency is approximately 0.525 Hz during the frequency excursion on the power system, this is shown in Fig. 3.13. The effect of this lag in frequency on the voltage magnitude and angle calculations is shown in Fig. 3.14 and Fig. 3.15 respectively.

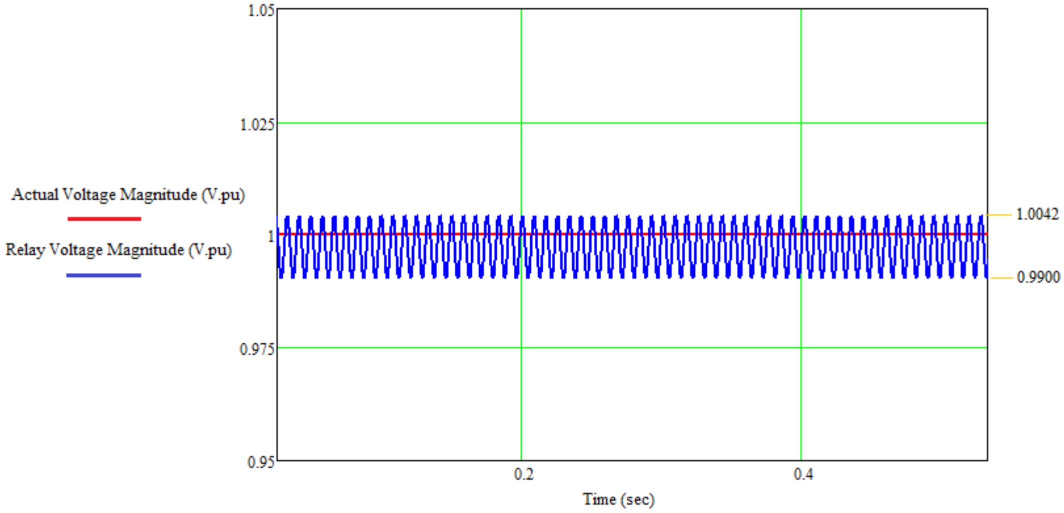


Fig. 3.14: Effect on the voltage magnitude as calculated by the relay while the frequency of power system and the frequency of the relay are not in synchronism.

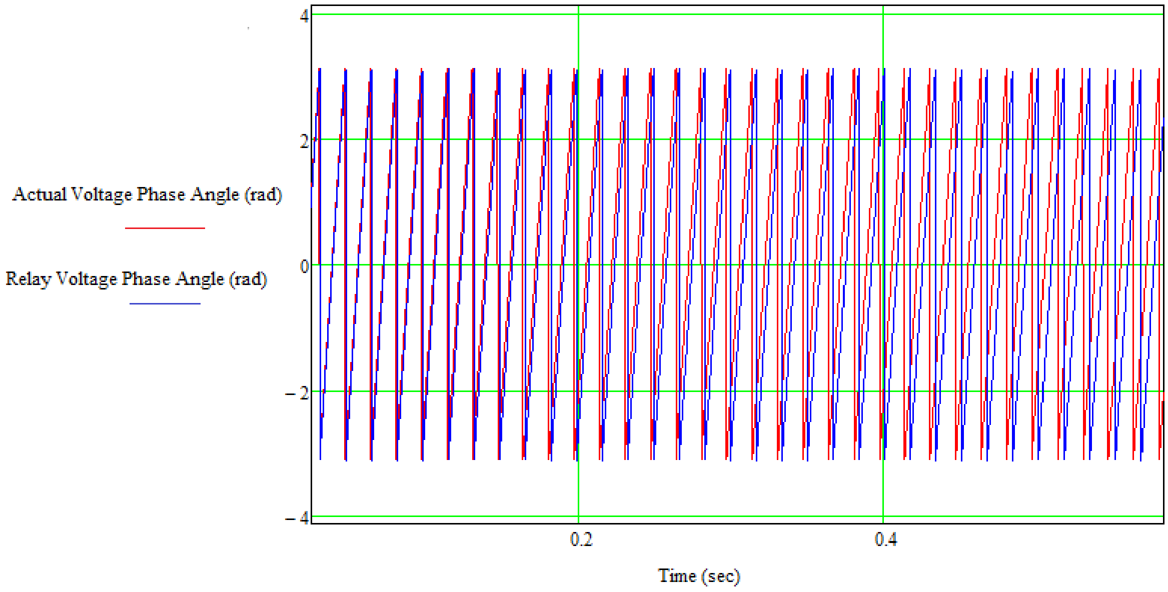


Fig. 3.15: Effect of the power system frequency and relay frequency not being in synchronism on the calculation of the voltage phase angle.

Examining Fig. 3.14 is can be seen that the voltage magnitude calculated by the relay fluctuates between 1.0042 V per unit (p.u.) and 0.9900 V p.u. Averaging the voltage magnitude over one power system cycle, a voltage magnitude in the order of 0.995 V p.u. is obtained. A voltage magnitude of 0.995 p.u equates to an error of 0.5%, which, one can argue under the circumstances is acceptable. However, observing the voltage phase angle as calculated by the relay in Fig. 3.15 it can be seen that initial there is very little difference between the phase angle calculated by the relay and that of the actual power system but as time goes on this angular difference increases significantly. A plot of the voltage angular difference between the powers system voltage angle and the voltage angle calculated by the relay over a time period of 0.5 seconds is shown in Fig. 3.16.

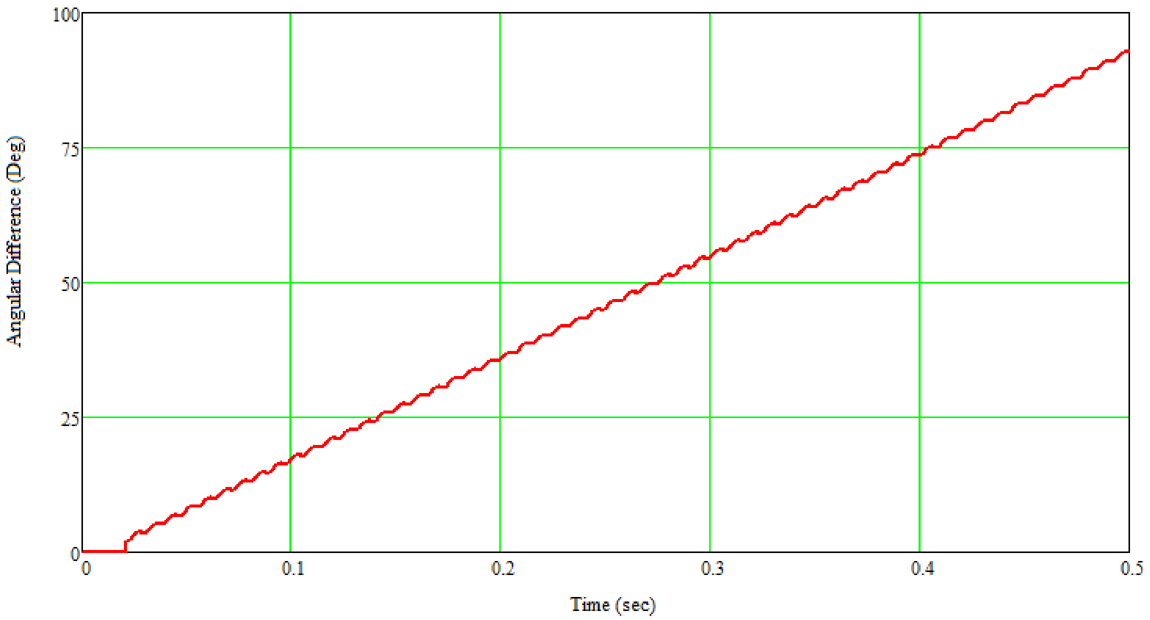


Fig. 3.16: Plot of the voltage angular difference between that of power system and that calculated by the relay.

The voltage angular difference plot of Fig. 3.16 shows that the longer the relay frequency lags behind the power system frequency the greater the angular difference between the voltage phase angle of the power system and the voltage phase angle calculated by the relay. For the example where the system experiences a frequency excursion of 7.5 Hz per second it can be seen from Fig. 3.16 that after a ½ second the angular difference between the power system voltage phase angle and the voltage phase angle calculated by the relay is approximately 90 degrees. As the relay frequency catches up to the power system frequency this anglular difference will reduce until, when the relay frequency and power system frequency match each other again after the excursion the angulare difference and magnitude error will tend to zero.

The question that can be asked at this stage is, "*What does all the discussion above have to do with the motor bus transfer?*" To answer this question consider the equivalent circuit of an induction motor as shown in Fig. 3.17 and ask what happens to the frequency of motor terminal voltage, when the motor gets disconnected from its primary power source.

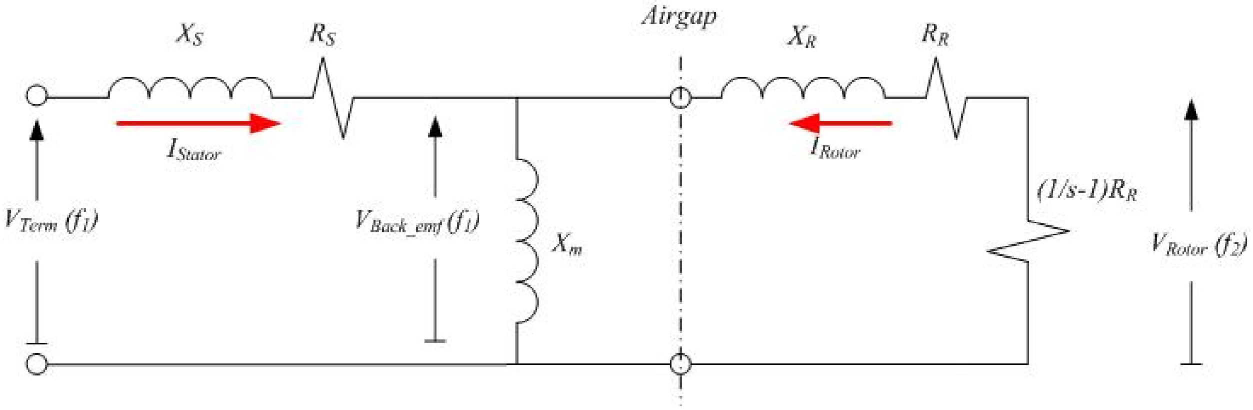


Fig. 3.17: Sketch of equivalent circuit of a squirrel cage induction motor.

When the motor is connected to the primary power source, the frequency at the terminals of the machine (f_1) is equal to that of the power system supplying the motor. Similarly the frequency of the voltage across the magnetizing branch (back emf) is going to be equal to the system frequency. However, for current to flow in the rotor of an induction motor, to enable the motor to do useful work and output power/torque, there must be a difference in frequency between the rotor circuit and the stator circuit. The difference between the frequency of the stator circuit (f_1) and frequency of the rotor (f_{rotor}) is termed "slip frequency" ($f_2 = f_1 - f_{rotor}$) and the larger the value of the slip frequency (f_2) the greater the magnitude of current in the rotor, the more torque is delivered by the motor. Therefore the frequency of the voltage across the rotor circuit and the current in the rotor are equal to the slip frequency (f_2).

When the motor gets disconnected from the primary power source (isolated), the voltage magnitude at the terminals of the motor decreases from the pre disconnect magnitude (V_{Term}) to the magnitude of the voltage across the excitation branch (V_{Back_emf}). The frequency of the voltage at the terminal of the motor is going to decrease from the system frequency (f_1) to that of the rotor frequency (f_{rotor}). Then what happens to the rotor frequency? To answer this question the dynamics of the system to which the motor is connected at that moment in time needs to be examined.

The frequency of the motor (speed of the rotor) after the motor has been disconnected from the primary power source is dependent on the mechanical torque (T_{MECH}) delivered by the load to the rotor of the motor, the electrical torque (power) delivered by the motor (T_{ELEC}) and the moment of inertia (J_{LOAD}) of the motor load plus that of the rotor of the motor (J_{ROTOR}). The relationship between the torque delivered by the motor, the inertia of rotor (J_{ROTOR}) and the inertia of the mechanical load (J_{MECH}) is sketched in Fig. 3.18.

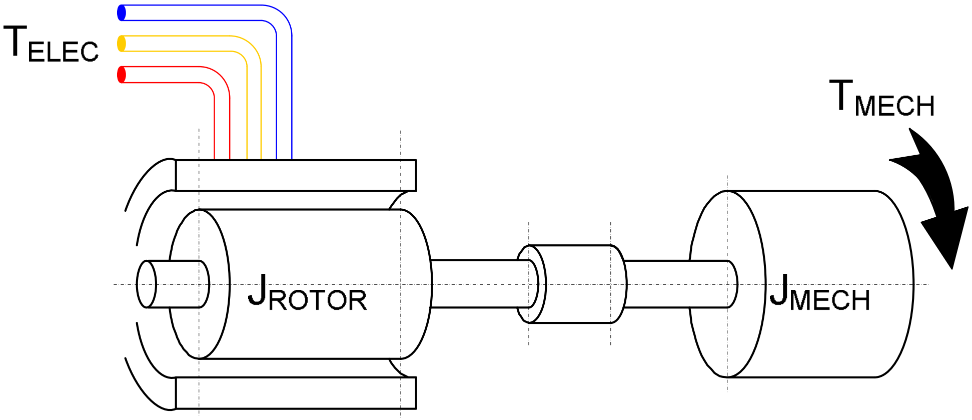


Fig. 3.18: Sketch showing how mechanical torque is converted to electrical torque (power) during the time that the motor bus is isolated from any power source.

The deceleration torque (T_{DECEL}) of the motor can be expressed as follows; [22], [23]

$$T_{DECEL} = T_{MECH} - T_{ELEC} \tag{3.4}$$

Where:

T_{DECEL}, T_{MECH}, and T_{ELEC} are in Newton meters (Nm)

The deceleration due to the unbalance (difference) between the mechanical and electrical torques is used to determine the equation of motion, equation (3.5).

$$J_{TOTAL}\frac{d\omega_m}{dt} = T_{DECEL} \tag{3.5}$$

Where:

$J_{TOTAL} = J_{LOAD} + J_{ROTOR}$ ($kg \cdot m^2$)

ω_m is the angular velocity of the rotor in mechanical radians per second (rad/sec)

Using the rated angular velocity of the rotor (ω_{m_0}) in mechanical radian per second, the inertia constant (H) can be defined as follows

$$H = \frac{1}{2} \cdot \frac{J{\omega_{m\_0}}^2}{VA_{BASE}} \tag{3.6}$$

Using equation (3.6) the moment of inertia (J) can be expressed in terms of the inertia constant (H) as follows:

$$J = \frac{2H \cdot VA_{BASE}}{{\omega_{m\_0}}^2} \tag{3.7}$$

Substituting equation (3.7) into equation (3.5) equation (3.8) is obtained.

$$T_{DECEL} = \frac{2H \cdot VA_{BASE}}{{\omega_{m\_0}}^2} \cdot \frac{d\omega_m}{dt} \tag{3.8}$$

Base torque (T_{BASE}) can be expressed as shown in equation (3.9).

$$T_{BASE} = \frac{VA_{BASE}}{\omega_{m\_0}} \tag{3.9}$$

Dividing equation (3.9) by T_{BASE} on the left and right hand side, equation (3.10) is obtained.

$$T_{DECEL\ (pu)} = \frac{2H}{\omega_{m\_0}} \cdot \frac{d\omega_m}{dt} \tag{3.10}$$

Furthermore the per unit rotor angular velocity ($\omega_{r(pu)}$) in electrical radians per second can be express as follows;

$$\omega_{r(pu)} = \frac{\omega_m}{p} \cdot \frac{p}{\omega_{m\_0}}$$

$$\omega_{r(pu)} = \frac{\omega_m}{\omega_{m\_0}} \tag{3.11}$$

Where:

p is the number of machine pole pairs

Therefore the equation of motion in the "per unit" system can be expressed as follows;

$$2H \cdot \frac{d\omega_r}{dt} = T_{DECEL} \tag{3.12}$$

Rearranging equation (3.12) the rate of change or the rotor angular velocity is obtained.

$$\frac{d\omega_r}{dt} = \frac{T_{DECEL}}{2H} \tag{3.13}$$

The rate of change of the rotor angular velocity in turn relates to the rate of change of the frequency at the terminals of the machine, since mechanical energy from the load is being converted into electrical energy. Mechanical energy is being taken out of the system and therefore the system is going to slow down (ω_r is going to decrease). Equation (3.13) shows that the larger the difference between the mechanical and electrical torque is, the more rapidly the rotor angular velocity is going to decelerate. At the same time the larger the moment of inertia of the load and the rotor the slower the rotor angular velocity is going to decelerate. Using this information and the initial slip frequency of the motor a plot of the motor frequency once the motor has been disconnected from the primary power supply can be generated as shown in Fig.3.19.

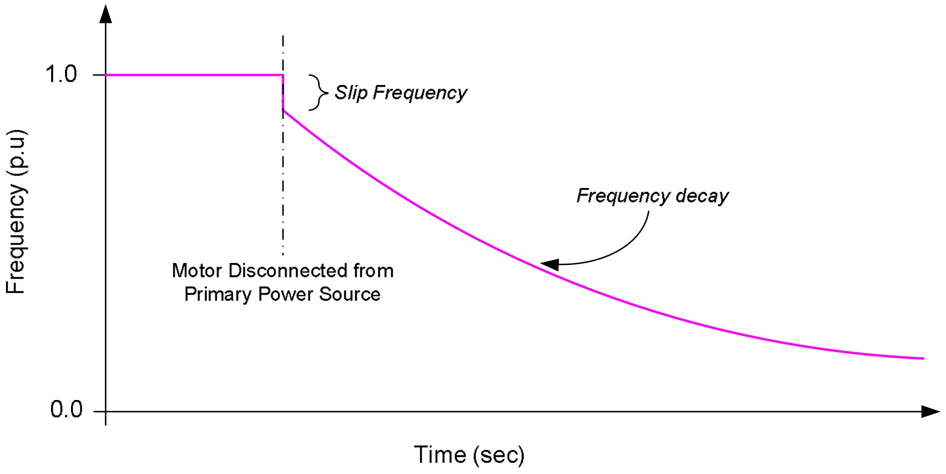


Fig. 3.19: Plot of the motor terminal frequency once the motor has been disconnected from the primary power source.

Comparing Fig. 3.19 to the frequency on a power system when a sudden loss of generation occurs, and to the response of the relay frequency for a sudden loss of load (Fig. 3.13) it can seen that in both cases the relay frequency will lag behind that of the power system. This lag in frequency will result in the relay not accurately calculating the power system voltage magnitude and phase angle. The effects of the relay frequency not accurately reflecting the power system frequency during a frequency excursion on a power system are shown in Fig. 3.14, Fig. 3.15 and Fig. 3.16. However, the effect on the voltage phase angle is more pronounced over time than are the effect on the voltage magnitude when the relay frequency and that of the power system do not match. During the time period when the motor is isolated from any power source, electrical power for the bus is derived from the rotating inertia of the load connected to the rotor of the motor. The frequency of the motor is decreasing, because the motor is converting mechanical energy into electrical energy. Since the relay frequency lags behind the actual motor frequency, the relay is not accurately going to calculate the magnitude and phase angle of the voltage at the terminals of the motor which negatively impacts in-phase motor bus transfer calculations.

3.4 Transient Equivalent Circuit of an Induction Motor

To determine whether an inaccuracy of the voltage magnitude or voltage phase angle has a greater impact on the motor and its associated load during a motor bus transfer, analysis of response during a motor bus transfer has to be done. To do this an accurate equivalent circuit model of an induction motor during transient conditions has to be obtained. Following is a derivation of a transient equivalent circuit of an induction motor.

3.4.1 Constant Rotor Flux Linkage (Transient Equivalent circuit)

In this dissertation the behavior of the machine for a short period of time after the motor is disconnected from the power source is of interest. A conceptual model can be obtained by using the flux linkage equations of an induction motor which are; [6], [11]

$$v_{qds} = r_s \cdot i_{qds} + (p + jw) \cdot \lambda_{qds} \tag{3.14}$$

$$v_{qdr} = 0 = r_r \cdot i_{qdr} + [p + (\omega - \omega_r)] \cdot \lambda_{qdr} \tag{3.15}$$

In this case the damping of the machine is ignored (which is equivalent to ignoring the resistance of the motor), this results in simple eigenvalues. Therefore ignoring the voltage drop across the rotor resistance (i.e., $r_r = 0$), equation (3.15) can be re written as;

$$0 = [p + (\omega - \omega_r)] \cdot \lambda_{qdr} \tag{3.16}$$

Using the rotor reference frame ($\omega_r = 0$), equation (3.16) reduces to;

$$0 = p{\lambda^r}_{qdr} \tag{3.17}$$

Equation (3.17) has two solutions, one of these being a trivial one and won’t be considered herein and occurs if;

$$\lambda^r_{qdr} = 0, \tag{3.18}$$

The other solution is the one of interest namely when;

$$\lambda^r_{qdr} = \text{constant}, \tag{3.19}$$

This implies that

$$\lambda^r_{qdr} = \lambda^r_{qdr\_0} \tag{3.20}$$

Equation (3.20) states that the flux in the rotor is equal to the flux in the rotor at the instant the transient was initiated for a short time after the transient occurred. In the general reference frame moving at a speed of ω, the rotor flux linkage can be expressed as;

$$\lambda^r_{qdr} = \lambda^r_{qdr\_0} \cdot e^{-j(\omega-\omega_r)t} \tag{3.21}$$

From the flux linkage (λ) equations the following equations can be derived;

$$\lambda_{qds} = L_S \cdot i_{qds} + L_M \cdot i_{qdr} \qquad (3.22)$$

$$\lambda_{qdr} = L_M \cdot i_{qds} + L_R \cdot i_{qdr} \qquad (3.23)$$

Rewriting equation (3.23) in terms of i_{qdr};

$$i_{qdr} = \frac{\lambda_{qdr} - L_M \cdot i_{qds}}{L_r} \qquad (3.24)$$

Substituting equation (3.24) into equation (3.22) obtains;

$$\lambda_{qds} = L_S \cdot i_{qds} + L_M \frac{(\lambda_{qdr} - L_M \cdot i_{qds})}{L_R} \qquad (3.25)$$

$$= \left(L_S - \frac{L_M^2}{L_R}\right) \cdot i_{qds} + \frac{L_M}{L_R} \cdot \lambda_{qdr}$$

$$= L_S\left(1 - \frac{L_M^2}{L_S \cdot L_R}\right) \cdot i_{qds} + \frac{L_M}{L_R} \cdot \lambda_{qdr}$$

$$= \sigma L_S \cdot i_{qds} + \frac{L_M}{L_R} \cdot \lambda_{qdr}$$

$$= L_S{}' \cdot i_{qds} + \frac{L_M}{L_R} \cdot \lambda_{qdr} \qquad (3.26)$$

Where:

$$\sigma = 1 - \frac{L_M^2}{L_S \cdot L_R}$$

$$L_S{}' = \sigma L_S$$

Substituting equation (3.26) into equation (3.14) the motor stator voltage can be expressed as;

$$v_{qds} = [r_S + (p + j\omega) \cdot L_S'] \cdot i_{qds} + (p + j\omega) \cdot \tfrac{L_M}{L_R} \cdot \lambda_{qdr\_0}^{r} \cdot e^{-j(\omega-\omega_r)t} \tag{3.27}$$

Expanding the 2nd half of equation (3.27);

$$=> \ (p + j\omega) \cdot \frac{L_M}{L_R} \cdot \lambda_{qdr\_0}^{r} \cdot e^{-j(\omega-\omega_r)t}$$

$$=> \ \left(-j(\omega - \omega_r) \cdot \frac{L_M}{L_R} \cdot \lambda_{qdr\_0}^{r} + j\omega \cdot \frac{L_M}{L_R} \cdot \lambda_{qdr\_0}^{r}\right) \cdot e^{-j(\omega-\omega_r)t}$$

$$=> \ j\omega_r \cdot \frac{L_M}{L_R} \cdot \lambda_{qdr\_0}^{r} \cdot e^{-j(\omega-\omega_r)t}$$

Defining E_{qd}' as the voltage behind the transient reactance,

$$E_{qd}' = \ j\omega_r \cdot \tfrac{L_M}{L_R} \cdot \lambda_{qdr\_0}^{r} \tag{3.28}$$

Using the definition of E_{qd}' from equation (3.28) the equation for v_{dqs} is defined as;

$$v_{qds} = [r_S + (p + j\omega) \cdot L_S'] \cdot i_{qds} + E_{qd}' \cdot e^{-j(\omega-\omega_r)t} \tag{3.29}$$

Using equation (3.29) the transient equivalent circuit for an induction motor in the general reference frame can be constructed as shown in Fig. 3.20.

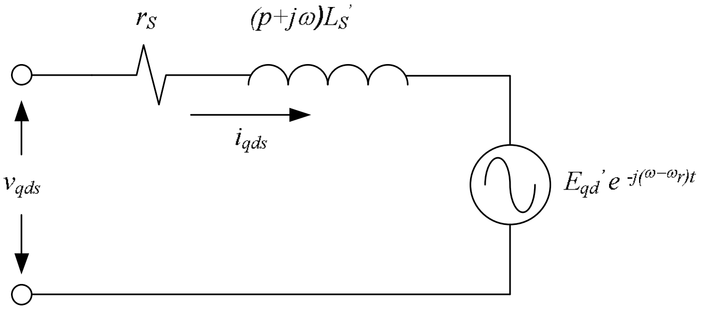


Fig. 3.20: The transient equivalent circuit for an induction motor in the general reference frame.

3.4.2 Determing the voltage behind the transient reactance

The most common circuit for representing the transient equivalent of an induction motor is in the stator reference frame (i.e., ω = 0), rewriting equation (3.29) for the stator voltage (v_{qds}) in the stator reference frame equation (3.30) is obtained.

$$v_{qds}^{s} = [r_S + p \cdot L_S'] \cdot i_{qds}^{s} + E_{qd}' \cdot e^{j\omega_r t} \tag{3.30}$$

Similarly as for equation (3.29), equation (3.30) can be used to derive the transient equivalent circuit for an induction motor in the stator reference frame as shown in Fig. 3.21.

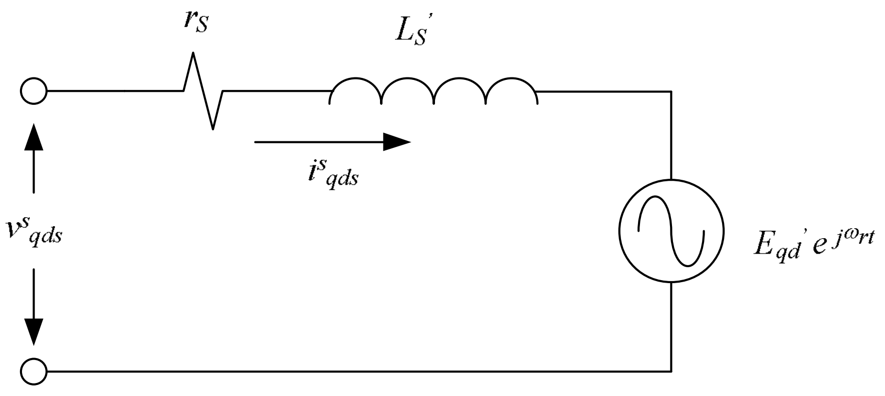


Fig. 3.21: Transient equivalent circuit for an induction motor in the stator reference frame, (ω = 0).

From Fig. 3.21, the voltage behind the transient, E_{qd}', can be defined as a balanced sinusoidal voltage, where the frequency of this voltage is determined by the frequency of rotation of the rotor (ω_r) with respect to the stator voltage (v^s_{qds}). The voltage E_{qd}' is proportional to the rotor flux linkage (λ^s_{qdr}) which is present at the instant the transient is initiated (for motor bus transfers studies, this is when the motor is disconnected from its primary power source). This is also assuming the machine is in steady state just prior to the initiation of the transient, the steady state rotor flux just prior to the transient can be used to determine E_{qd}'. Assuming that there was no fault prior to the motor being disconnected from its primary power source. Using the stator reference frame the induction motor in steady state can be depicted as shown in Fig. 3.22.

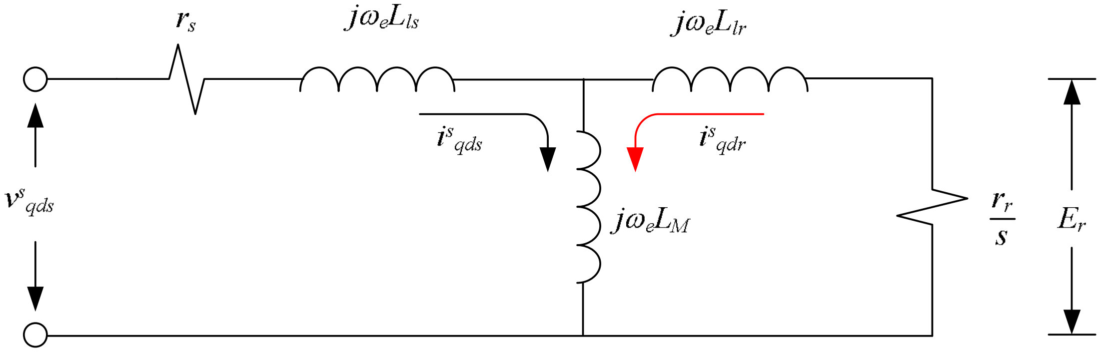


Fig. 3.22: Equivalent circuit of an induction motor in steady state using the stator reference frame, this circuit will be used to evaluate the value of E_{qd}' prior to the transient.

Using the equivalent circuit of an induction motor as shown in Fig. 3.22, the voltage drop across the rotor resistor (r_r/s) can be expressed by equation (3.31).

$$E_r = j\omega_e \cdot L_M\left(i^s_{qds} + i^s_{qdr}\right) + j\omega_e \cdot L_{lr} \cdot i^s_{qdr} \tag{3.31}$$

Where:

$j\omega_e \cdot L_M \cdot (i^s_{qds} + i^s_{qdr})$ is the volt drop across the magnetizing impedance (L_M)

$j\omega_e \cdot L_{lr} \cdot i^s_{qds}$ is the volt drop across the rotor leakage impedance (L_{lr})

Rearranging some of the terms of equation (3.32) the voltage across the rotor resistance can be expressed as

$$E_r = j\omega_e \cdot L_M \cdot i^s_{qds} + j\omega_e \cdot (L_M + L_{lr}) \cdot i^s_{qdr} \tag{3.32}$$

But the total rotor inductance (L_R) is equal to the sum of the mutual inductance (L_M) plus the rotor leakage inductance (L_{lr}). Substituting the sum of these two inductances into equation (3.32), the voltage drop across the rotor resistance is expressed as;

$$E_r = j\omega_e \cdot \left(L_M \cdot i^s_{qds} + L_R \cdot i^s_{qdr}\right) \tag{3.33}$$

But

$\lambda^s_{qdr} = \left(L_M \cdot i^s_{qds} + L_R \cdot i^s_{qdr}\right)$, the rotor flux linkage

Therefore

$$E_r = j\omega_e \cdot \lambda^s_{qdr} \tag{3.34}$$

Equation (3.34) states that at the instant the transient is initiated the flux linkage in the rotor, λ^s_{qdr} (in the stator reference frame), becomes the trapped flux linkage in the rotor, $\lambda^r_{qdr\_0}$ (in the rotor reference frame). Using this information an equation for the voltage behind the transient reactance equation (3.28) can be obtained.

$$E_{qd}' = j\omega_r \cdot \frac{L_M}{L_R} \cdot \lambda^s_{qdr} \tag{3.35}$$

Rewtiting equation (3.34) in terms of the rotor flux linkage.

$$\lambda_{qdr}^{s} = \frac{E_r}{j\omega_e} \tag{3.36}$$

Substituting equation (3.36) into equation (3.35) the equation for the voltage behind the transient reactance (3.36) in terms of the voltage across the rotor resistance can be expressed as;

$$E_{qd}{}' = \frac{j\omega_r \cdot L_M}{j\omega_e \cdot L_R} \cdot E_{r0}$$

$$= \frac{\omega_r \cdot L_M}{\omega_e \cdot L_R} \cdot E_{r0} \tag{3.37}$$

Where:

E_{r0} is the voltage across the rotor resistance at the instant that the switching transient occurs equation (3.37) can be expressed in terms of the slip (s) of the machine, slip being defined as;

$$s = \frac{\omega_e - \omega_r}{\omega_e}$$

$$s = 1 - \frac{\omega_e}{\omega_r} \tag{3.38}$$

Rearranging terms in equation (3.38)

$$\frac{\omega_e}{\omega_r} = 1 - s \tag{3.39}$$

Substituting equation (3.39) into equation (3.37) the voltage behind the transient impedance ($E_{qd}{}'$) in terms of the voltage across the rotor resistance and the slip of the motor, equation (3.40) is obtained.

$$E_{qd}{}' = \frac{L_M}{L_R} \cdot (1 - s) \cdot E_{r0} \tag{3.40}$$

With the transient equivalent circuit for an induction motor and the voltage behind transient reactance; the factors that influence the active and reactive power drawn by a motor when it is connected to an alternative power source can now determined.

3.5 Factor Governing the Active and Reactive Power Drawn During the Motor Bus Transfer

The factors that influence the active and reactive power drawn by a motor when the motor bus is connected to an alternative power source will now be analyzed. A simple circuit sketch of a motor being connected to an alternating power source is shown in Fig3.23.

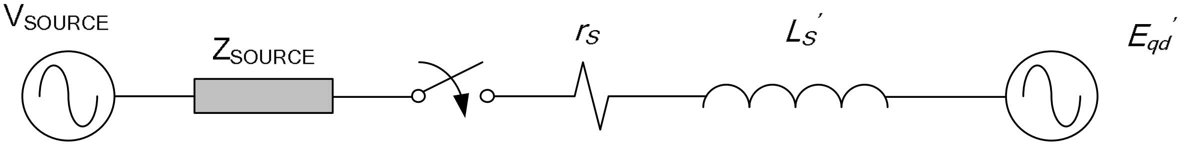


Fig. 3.23: Sketch of the equivalent circuit of the alternative power source and the motor before the motor is connected to the alternative (source impedance of alternative source included).

Assuming that the impedance of the source (Z_{SOURCE}) is much lower than the impedance of the motor (that the source is very strong) the circuit in Fig.3.23 can be further simplified to that shown in Fig.3.24.

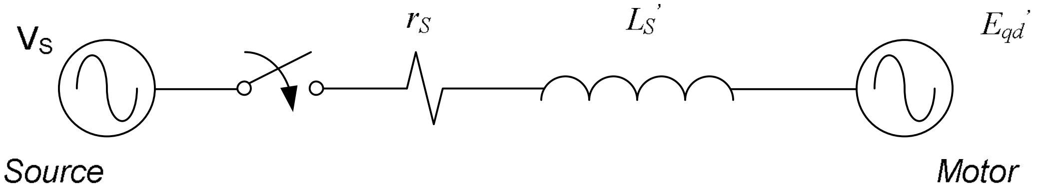


Fig. 3.24: Sketch of the equivalent circuit of the alternative power source and the motor before the motor is connected to the alternative (source impedance of alternative source excluded)

With the aid of Fig. 3.24, an equation (3.41) can be derived to calculate the current drawn by the motor when the motor is connected to the alternative power source.

$$V_S = r_S \cdot i + L_S{}' \cdot \frac{di}{dt} + E_{qd}{}' \tag{3.41}$$

Letting $V_S = V \cdot \sin(\omega t)$ and $E_{qd}{}' = E \cdot \sin(\omega_r t + \phi)$ substitute these equation into equation (3.41) and rearrange terms equation (3.42) is obtained.

$$Vsin(\omega t) - Esin(\omega_r t \; + \phi) \; = r_S \cdot i + L_S{}' \cdot \frac{di}{dt} \tag{3.42}$$

Converting equation (3.42) into the "s-domain" by taking the Laplace transform on both sides of equation (3.42), the following equation is obtained [24];

$$\frac{V \cdot \omega}{(s^2+\omega^2)} - E\left(\frac{\omega_r \cos\phi}{(s^2+\omega_r{}^2)} + \frac{s \sin\phi}{(s^2+\omega_r{}^2)}\right) = r_S \cdot i(s) + L_S{}' \cdot si(s) + L_S{}' I(0) \tag{3.43}$$

Let

$$\alpha = \frac{r_S}{L_S{}'} \tag{3.44}$$

Substituting equation (3.44) into equation (3.43) and rearranging terms so the equation is in terms of *i(s)*;

$$i(s) = \frac{V \cdot \omega}{L_S{}'(s+\alpha)(s^2+\omega^2)} - \frac{E\omega_r \cos\phi}{L_S{}'(s+\alpha)(s^2+\omega_r{}^2)} - \frac{E\omega_r \, s \sin\phi}{L_S{}'(s+\alpha)(s^2+\omega_r{}^2)} + \frac{I(0)}{(s+\alpha)} \tag{3.45}$$

Converting equation (3.45) back into the time domain by taking the inverse Laplace transform the equation for the current (*i(t)*) at any instant in time when the motor is connected to the alternative power source can be calculated using equation (3.46).

$$i(t) = \frac{V\omega}{L_S'(\alpha^2+\omega^2)}\left(e^{-\alpha t} - \cos\omega t + \frac{\alpha}{\omega}\sin\omega t\right)$$

$$- \frac{E\omega_r\cos\phi}{L_S'(\alpha^2+\omega_r^2)}\left(e^{-\alpha t} - \cos\omega_r t + \frac{\alpha}{\omega_r}\sin\omega_r t\right)$$

$$- \frac{E\omega_r\sin\phi}{L_S'(\alpha^2+\omega_r^2)}(-\alpha e^{-\alpha t} + \omega_r\sin\omega_r t + \alpha\cos\omega_r t) + I(0)e^{-\alpha t} \tag{3.46}$$

Equation 3.46 is the exact solution of the current drawn by the motor the instant that the motor is connected to the alternative power source. Multiplying equation (3.46) with the alternative power source voltage, Vsin(ωt), determines the active and reactive power supplied by the alternative power source to the motor. However, to get a more intuitive feel of what factors determine the active and reactive power drawn by the motor when it is transferred a simple model of a motor connected to power source can be used as shown in Fig. 3.25.

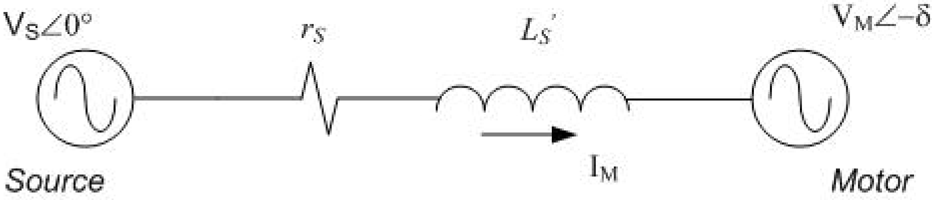


Fig. 3.25 Sketch of the alternative source connected to the motor, only considering the motor stator impedances.

With the aid of Fig. 3.25 the apparent power (S) drawn by the motor can be calculated using equation (3.47) [25];

$$S = V_S \cdot I_M^* \tag{3.47}$$

The current, I_M, drawn by the motor can be calculated by dividing the voltage difference between the source voltage and the motor voltage by the stator impedance.

$$I_M = \frac{V_S\angle\, 0° - V_M\angle{-\delta°}}{r_S + jX_S{}'} \tag{3.48}$$

Where $X_S{}' = \omega L_S{}'$

Expressing the voltages ($V_S\angle 0°$and $V_M\angle{-\delta°}$) in their rectangular format and multiplying by the right hand side numerator and denominator of equation (3.48) by the complex conjugate of the denominator term the motor current, I_M , is solved;

$$I_M = \frac{(r_s V_S - r_S V_m \cos\delta + X_s{}' V_m \sin\delta) + j(-X_S{}' V_S + r_S V_M \sin\delta + X_S{}' V_M \cos\delta)}{r_S{}^2 + X_S{}'^2} \tag{3.49}$$

And taking the complex conjugate;

$$I_M{}^* = \frac{(r_s V_S - r_S V_m \cos\delta + X_s{}' V_m \sin\delta) - j(-X_S{}' V_S + r_S V_M \sin\delta + X_S{}' V_M \cos\delta)}{r_S{}^2 + X_S{}'^2} \tag{3.50}$$

Substituting equation (3.50) into equation (3.47) and taking the real part of equation (3.47) the active power drawn by the motor is obtained.

$$P = Re(S)$$

$$P = \frac{r_S V_S{}^2 - r_S V_m V_S + X_S{}' V_m V_S \sin\delta}{r_S{}^2 + X_S{}'^2} \tag{3.51}$$

Taking the imaginary part of equation (3.47) the reactive power, supplied by the alternative power source to the motor is obtained.

$$Q = Im(S)$$

$$Q = \frac{-X_S V_S{}^2 + r_S V_m V_S + X_S{}' V_m V_S \cos\delta}{r_S{}^2 + X_S{}'^2} \tag{3.52}$$

Typically the stator leakage impedance, $L_S{}'$, of an induction motor is much larger than the stator resistance, r_s, therefore the stator resistance in equations (3.51) and (3.52) can be neglected and equations (3.51) and (3.52) can be further reduced to their simplist approximate forms.

$$P = \frac{V_m V_S \sin\delta}{X_S{}'} \tag{3.53}$$

$$Q = \frac{V_m V_S \cos\delta - V_S{}^2}{X_S{}'} \tag{3.54}$$

Equation (3.53) indicates that the active power (P) drawn from the alternative power source is dependent on the magnitude of the two voltages and the angle between them. However, the magnitudes of the voltages changes relatively slowly when compared to the change in angle between the two voltages. This means that the power drawn by the motor from the alternative power source is predominantly determined by the angular difference between the two voltages at the instant that the motor get connected to the alternative power source. The active power and torque developed by an induction motor are related to each other via the angular velocity (ω_r) as shown by equation (3.55). The torque developed by the motor at the instant of reclosing is primarily determined by the angular difference (δ) between the voltage of the alternative source and the voltage at the terminals of the motor.

$$\frac{d\delta}{dt} = \omega_r = \frac{P_{em}}{T_{em}} \tag{3.55}$$

Therefore for the motor to develop the smallest amount of transient torque, the motor should be connected to the alternative power source at the instant when the angular difference between the motor voltages and the alternative source voltage is as close to zero as is practically possible. From the review in Chapter 3, if the voltage phase angle is computed from a frequency tracked signal, there will be a difference between the actual voltage phase angle and the computed voltage phase angle. If this erroneous computed voltage phase angle is used to transfer the motor bus to an alternative source a correct in-phase bus motor bus transfer is highly unlikely.

This means that using a frequency tracked voltage to calculate the voltage phase angle of a voltage that is changing in frequency (as is the case with an induction motor isolated from a power source and is spinning down) is not a good idea and should not be used when an in-phase motor bus transfer is desired.

3.6 New Methods proposed for Motor Bus Transfer

Using frequency tracked signals to calculate the phase angle between an isolated motor bus and an alternative power source is not the best method to determine the phase angle and slip frequency between the two voltage sources. *What method should then be used to calculate the angular difference and slip frequency between two voltage sources?* The answer seems simple enough, use a quantity that is independent of the frequency of the power system and the motor bus!

3.6.1 The stationary “dq0” reference frame (Clarke components).

One method that can be used to calculate the voltage magnitude and angle of both the motor bus and alternative power source is using the “dq0” stationary reference frame, alternatively known as the Clarke components. The “dq0” components can be obtained by from the instantaneous voltage or current samples as [6], [18],

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = k \begin{bmatrix} \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ -\sin(\omega t) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.56}$$

Where:

$$k = \sqrt{\frac{2}{3}} \; or \; \frac{2}{3}$$

Using the stationary reference frame, $\omega = 0$, and selecting k = 2/3, equation (3.56) now reduces to equation (3.57).

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.57}$$

Using equation (3.57) an expression for V_d and V_q are obtained.

$$V_d^0 = V_\alpha = \frac{2}{3}\left(V_a - \frac{V_b}{2} - \frac{V_c}{2}\right) \tag{3.58}$$

$$V_q^0 = V_\beta = \frac{1}{\sqrt{3}}(V_b - V_c) \tag{3.59}$$

The transfer of the motor bus to the alternative power source is a balanced phenomenon and most motor connections are either delta or in wye (star) without a neutral connection. As a result, the sum of the three voltages sum to zero and as a result of this $V_0 = 0$. (*The result of the three voltages summing to zero also results in other three phase variables such as the stator phase currents, stator flux linkages and rotor currents also summing to zero [6].*)

So a transformation from the “abc” domain to the “dq” domain via equations (3.58) and (3.59) is equivalent to a transformation from a three phase domain to a two phase domain when the three phase quantities in the “abc” domain summate to zero, as is the case with most induction motors. Implementing equation (3.58) and (3.59) graphically as shown in Fig. 3.26 it can be seen that the d and q components (or alpha and beta components) are orthogonal to each other.

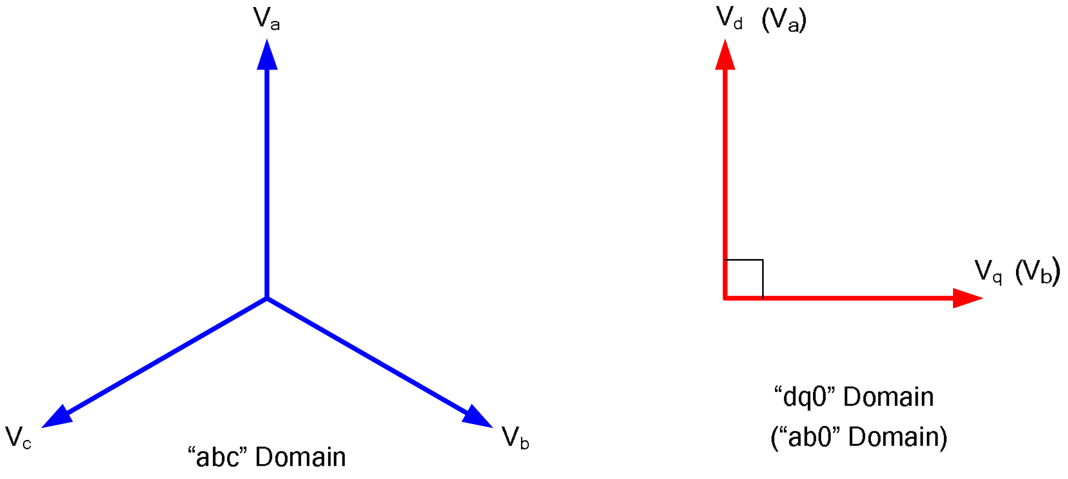


Fig. 3.26 A phasor representation of a three phase voltage in the “abc” domain (a) and in the “dq0” domain (b).

Using equations (3.58) and (3.59) and the fact that these two quantities are orthogonal to one another a phasor quantity ($V_{\alpha\beta}$) can be created as follows:

$$V_{\alpha\beta} = V_\alpha + jV_\beta \tag{3.60}$$

The magnitude and angle of the phasor quantity can be calculated using simple geometry and trigonometry;

$$V_{\alpha\beta\_MAG} = \sqrt{{V_\alpha}^2 + {V_\beta}^2} \tag{3.61}$$

$$V_{\alpha\beta\_ANG} = \text{atan}\left(\frac{V_\beta}{V_\alpha}\right) \tag{3.62}$$

Equations (3.60), (3.61), and (3.62) indicate that there is no longer any dependence on frequency when calculating the magnitude and angle of a voltage or current quantity. A further advantage of this method is that the magnitude and angle of a quantity can be calculated using the instantaneous samples of voltage and current irrespective of the system frequency.

3.6.2 Using Frequency Independent Voltage and Angle Calculations to determine the Optimum Closing Angle.

This dissertation discusses two methods to determine the best angle (moment in time) at which to connect the motor bus to the alternative power source. Both methods will make use of equations that are independent of the frequency of the residual motor bus voltage and the frequency of the alternative power source. Method 1 transforms the voltage from the "abc" domain into the "dq0" domain using the stationary reference frame. This is synonymous to transforming the voltages from the "abc" domain to the "dq0" domain. Once both the voltages are in the "dq0" domain the phasors for the motor bus and the alternative source voltages using the "dq" components are computed. Then the magnitude and angle difference between these two components is calculated. Using the rate of change of the motor bus voltage angle, the moment in time when the two voltages will be in phase is determined.

In method 2 the voltages are transformed from the "abc" domain into the "dq0" domain but for this method only the "d" component is used. In this method the coincidence between the motor bus and alternative source voltage is computed. Using the rate of change of the coincidence between the two voltages the moment in time when the two voltages will be in-phase is determined.

3.7 Method 1: Calculating the slip angle between the two voltages

The first proposed method calculates the magnitude and angle of both the voltage on the motor bus and the alternative power source. Using the angles of the voltages, the angular difference between the two voltages is calculated. From the angular difference, the relative slip (slip frequency) between the two voltages source is calculated. Knowing the breaker closing time and the slip frequency between the two voltages, the exact angle (moment in time) is calculated for when to send the close signal to the circuit breaker to initiate closing. Issuing the breaker closing signal before the two voltages are in perfect synchronism allows the two voltages to be in near synchronism (the angular difference between the two voltages being zero) when the breaker poles close, i.e. when electrical contact is made. Before any manipulation of the voltage and current signals can be performed the signals need to be conditioned. A simple sketch of the data acquisition path used by method 1 is shown in Fig. 3.27.

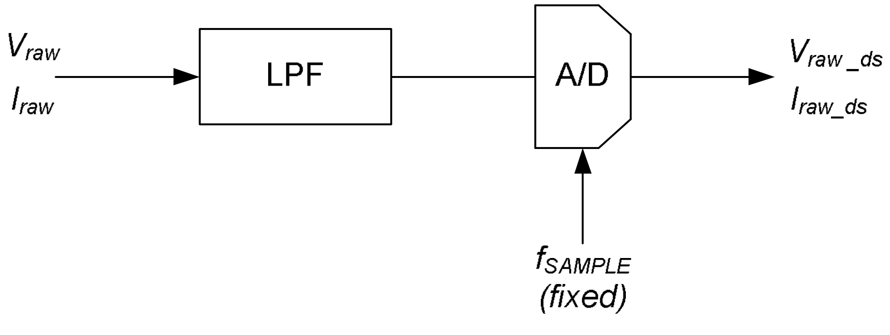


Fig. 3.27: Sketch of a simple data acquisition system.

The simple data acquisition sketch shown in Fig.3.27 illustrates that the raw voltage and current signals (V_{raw}, I_{raw}) are conditioned by passing them through a low pass filter (LPF). The purpose of the low pass filter is twofold:

- Prevent aliasing;
- Remove any high frequency components and noise [21].

After the analog signals have been conditioned by the LPF, the signals are input into the analog to digital converter (A/D) where the signal will be sampled at a fixed frequency and the voltages and currents are converted from analog signals to digital signals. The specifics of the LPF and the sampling frequency (f_{SAMPLE}) of the A/D will be discussed in the Chapter IV.

Once the input signals have been conditioned and digitized, the alpha and beta quantities for each input signal (i.e., voltage or current) is calculated using equations (3.58) and (3.59). From the alpha and beta quantities the magnitude and angle of the respective signals are calculated using equations (3.60) and (3.61). In this way a single signal is obtained that represents the three phase voltages on the motor bus and the alternative power source. Similarly a single current represents the current being generated or consumed by a motor on the motor bus. Since the voltage that is measured at the motor bus is the voltage at the terminal of the motor(s) and not the voltage behind the transient reactance of the motor (which is approximately equal to the voltage across the magnetizing branch of the motor since $L_M >> L_{lr}$), the voltage behind the transient reactance of the motor still needs to be calculated. By calculating the voltage behind the transient reactance of the motor and synchronizing the closing of the motor bus onto the alternative power source, when the angle between the alternative voltage source and the voltage behind the transient reactance of the motor is at a minimum (ideally zero), the motor will draw the lowest possible current and develop the lowest possible transient torque. Using the voltage at the motor bus (which is equivalent to the voltage at the terminal of the motor) and the current of the motor and the motor parameters the voltage behind the transient reactance is calculated using equation (3.63).

$$E_{\alpha\beta\_mot} = V_{\alpha\beta\_bus} + R_S I_{\alpha\beta\_mot} + L_S{}' \frac{dI_{\alpha\beta\_mot}}{dt} \tag{3.63}$$

Where:

$V_{\alpha\beta\_bus}$ is the derived $V_{\alpha\beta}$ voltage from the measured bus voltage;

$I_{\alpha\beta\_mot}$ is the derived $I_{\alpha\beta}$ motor current from measured motor current;

R_S is the stator resistance in per unit.

$L_S{}'$ is the stator transient inductance in per unit.

Generally there is more than one motor on the motor bus, and the motor or motors that will act as the generator(s) is generally the motor(s) with the highest inertia [26]. Since the motor with the highest inertia is going to be the dominant motor responsible for generating power during the period of isolation, synchronization of the motor bus with the alternative power source will be between the voltage behind the transient of the motor with the highest inertia and the alternative power source.

In theory each motor could be synchronized independently onto the bus. However this is not practical at this moment in time since this would require that the current of each motor connected to the bus would need to be monitored. Furthermore, each motor would need to be isolated from the bus and then synchronized independently. The other downside of this approach would be that motor(s) with low inertia would probably stall since they will not have enough energy (inertia) to keep themselves rotating.

Using the motor with the highest inertia to synchronize against means that only the parameters of this motor need to be known so as to enable the calculation of the voltage behind the transient reactance. A sketch of a typical motor bus is shown in Fig.3.28, the available measurements are shown in black and the measurements that need to be calculated are shown in blue.

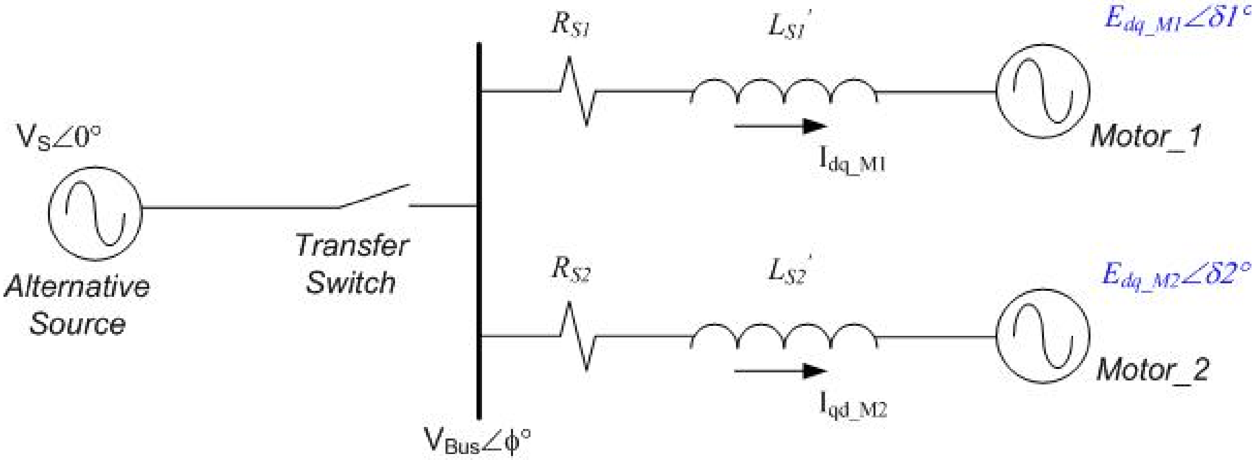


Fig. 3.28: Sketch of a simple motor bus with two motors attached to the bus.

A plot of the voltage at the motor bus (terminal of the motor) and the voltages behind the transient reactance for the two motors shown in Fig. 3.29. The difference in phase between, the voltage at the motor bus, the voltage behind the transient for the motor that acts as a generator and the voltage behind the transient for the motor that remains a motor are shown in Fig.3.29. Also shown in Fig.3.29 is that the voltage behind the transient for the motor that acts as the generator leads the other two voltages as would be expected.

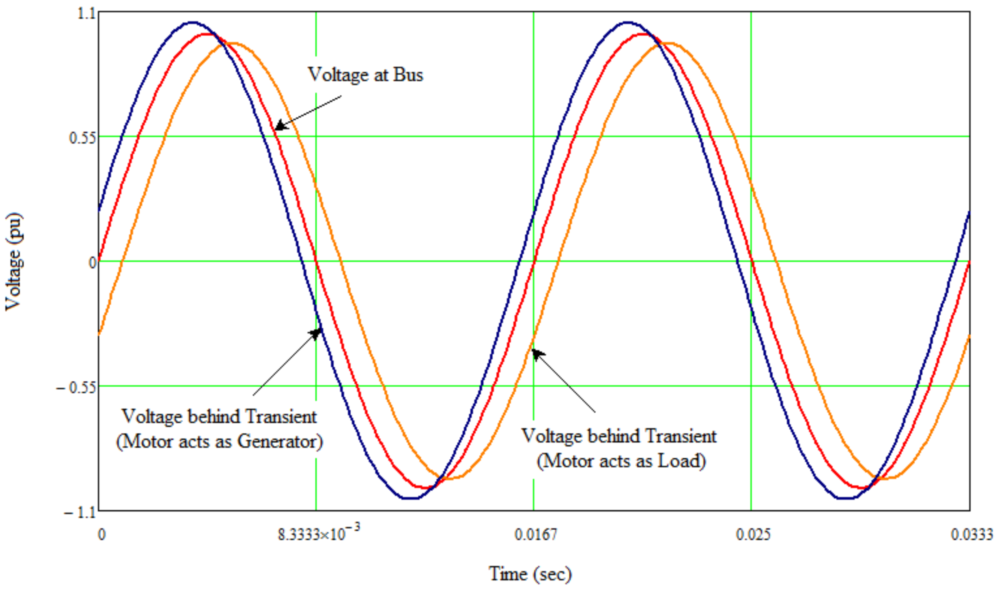


Fig. 3.29: An oscillographic plot showing the angular relationship between the voltage at the motor bus (motor terminals) and the voltage behind the transient reactance of the motor for the case where the motor acts as an induction generator and for the case when the motor acts as a load.

Once the voltage behind the transient reactance of the motor with the highest inertia has been calculated, the relative angle between this voltage and the voltage of the alternative source can be calculated. The rate of change of the relative angle between the two voltages allows the relative slip between these two quantities to be calculated. With the relative slip and the angle of the voltage behind the transient reactance of the motor calculated, the moment in time when to issue the close signal to the circuit breaker is calculated. Since a circuit breaker cannot close it contacts (poles) instantaneously, the close signal is given before the two systems come into perfect synchronism. This way when the circuit breaker contacts do close the two system will be in perfect synchronism. Typically a circuit breaker has a minimum and a maximum closing time in this case use the maximum closing time. Krause et al. [27] indicate that closing the circuit breaker such that the motor voltage lags the voltage of the alternative source, results in a lower transient airgap torque generated in the motor than if the motor voltage where to lead the voltage of the alternative power source. A sketch of the logic used to calculate the instantaneous voltage magnitude and angle of the alternative power source and the voltage behind the transient is shown in Fig.3.30 [28], [29], and [30]. (*Details on how to calculate the derivative of the current will be given in Chapter IV*)

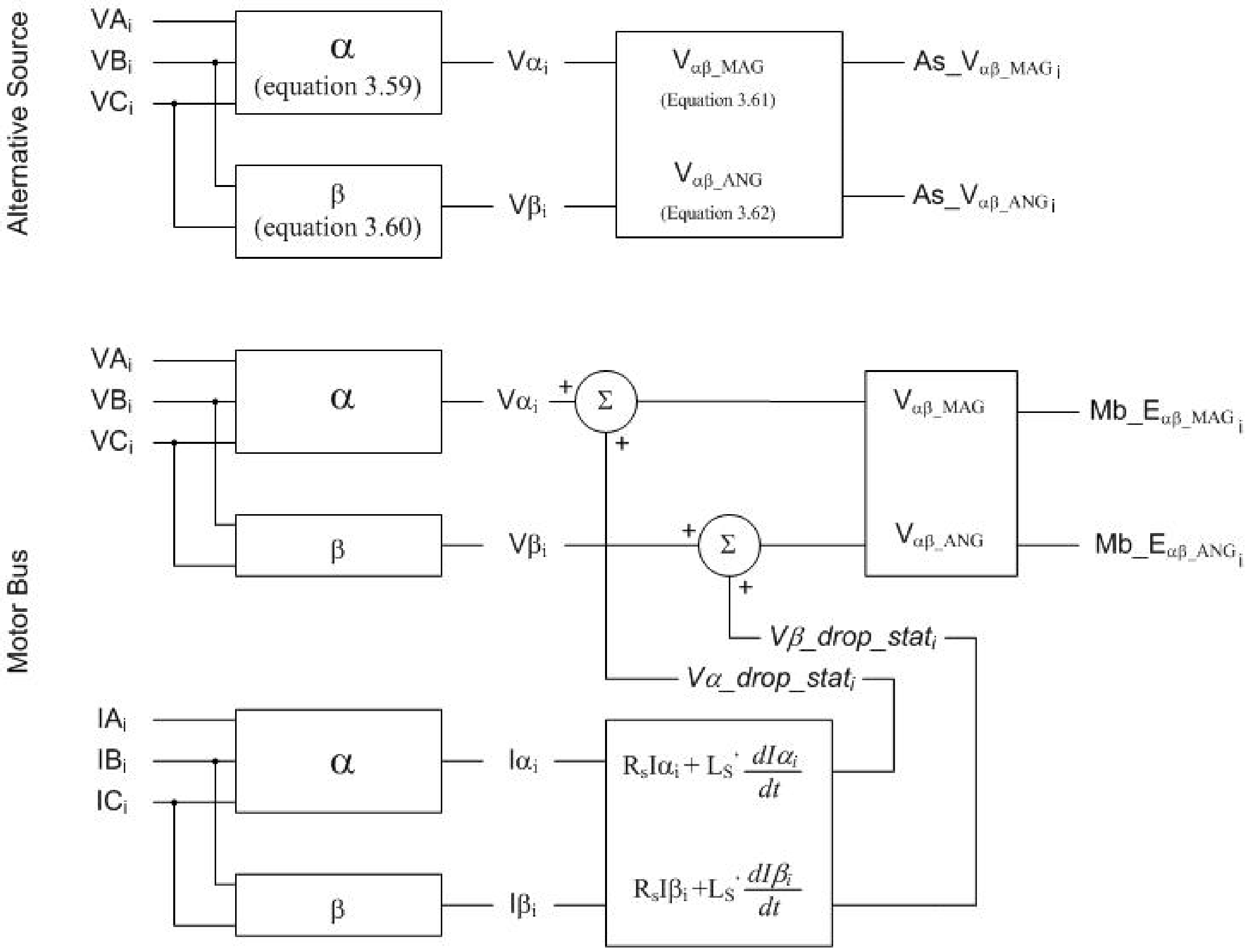


Fig. 3.30: Simple sketch illustrating how the instantaneous magnitude and angle of both the alternative power source and the voltage behind the transient reactance are obtained.

A sketch showing the logic of how to calculate the slip frequency and the time when to issue the breaker closing signal, taking the breaker closing time into account is shown in Fig.3.31.

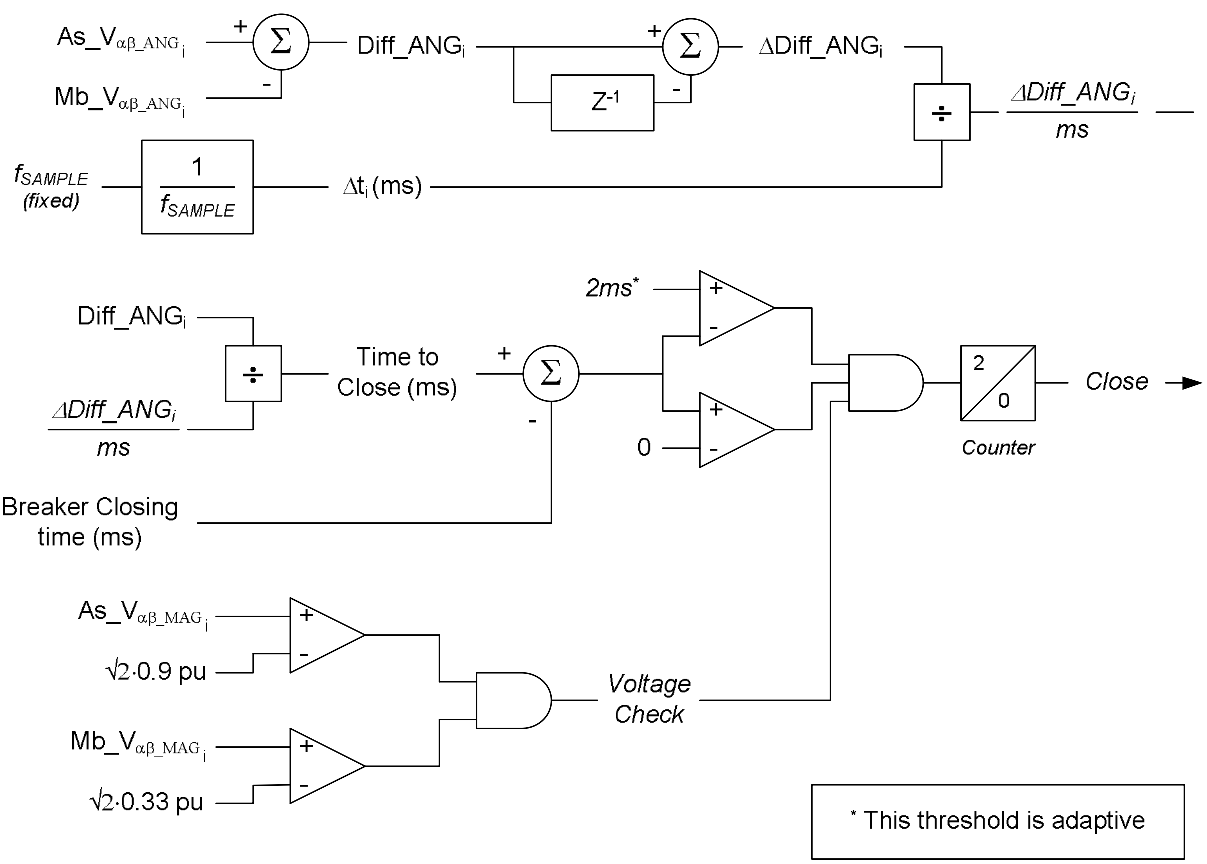


Fig. 3.31: Simple sketch showing how the slip frequency, the angular rate of change and closing pulse to the circuit breaker is calculated

As can be seen from Fig. 3.31 the logic issues a "Close" command to the circuit breaker if the difference between the time to close and the breaker closing time is between 0 and an "adaptable" upper threshold limit. The upper threshold limit is determined by the slip rate of the system, the higher the slip rate the further the window opens (until an upper threshold is reached). The lower the slip rate, the more the window will close until a minimum threshold limit is reached. The goal of this logic is to close the breaker (with the breaker closing time consider) between -5° and 0 ° of top dead center using the alternative voltage source as the reference. The adaptive threshold value is determined using equation (3.64).

$$T_{\text{Threshold}} = \frac{\Delta \text{Diff\_ANG}_{\text{i}}/\text{ms}\cdot(\text{number of security counts}+1)\cdot\text{processing rate (ms)}}{5°} \qquad (3.64)$$

For example, assume that the system has a slip rate of 10Hz per second (3.6° per millisecond), and that the number of security counts is 2, and the processing rate is 1 kHz (1 millisecond), then the threshold is;

$$T_{\text{Threshold}}(\text{ms}) = \text{ceil}\left[\frac{3.6\cdot(2+1)\cdot 1}{5}\right]$$

$$= \text{ceil}\left[\frac{3.6\cdot(2+1)\cdot 1}{5}\right]$$

$$= 3 \text{ ms}$$

The threshold will have an upper limit of 10 milliseconds and a lower limit threshold of 1 millisecond (or the processing rate of the device in milliseconds) which ever value is larger. A further enhancement that can be made to the adaptive timer is to use a weighted average over the last three processing intervals. If the processing rate of the algorithm is faster than the deceleration of the motor, then a simple averaging of the last three threshold times maybe sufficient since the incremental change per processing interval will be negligible. If the processing rate of the algorithm is not faster than the deceleration of the motor then the last calculated value should be used without any averaging.

In addition to the angle supervision, the logic is supervised by the magnitude of both the motor bus and the alternative source. A motor bus transfer will only be allowed if the alternative source voltage is healthy (i.e., if the voltage magnitude of the alternative source is above 90% of the nominal voltage) and if the voltage magnitude of the voltage behind the transient is greater than 33% of the nominal voltage of the bus.

The method is implemented so that it follows the recommendations of Krause et al [27]. The method is designed to close the circuit breaker when the motor bus voltage lags the alternative source voltage, this will result in a lower transient airgap torque.

This method offers the following benefits:

- It is immune to frequency changes on the motor bus and alternative voltage source;
- It does not require any elaborate system studies;
- It requires minimal settings (the breaker closing time and the parameters of the motor with the highest inertia).

The drawbacks of this method are as follows:

- It requires the user to enter in the closing time of the transfer breaker;
- It requires one set of current inputs (if you want to sync the alternative source with the voltage behind the transient reactance of the motor),
- It requires the user to enter in the motor parameters for the motor with highest inertia (this is the same motor from which the current inputs are required).

However the method will work even if no motor data or current information is available from the motor. In this case the method will then simply synchronize the motor bus voltage with the alternative voltage source. So in essence this method has only one drawback and that is that the circuit breaker closing time must be known and this is readily obtainable from the circuit breaker data sheet supplied by the circuit breaker manufacturer [20].

3.8 Method 2, calculating the coincidence between the two voltages

The second method presented in this dissertation will not be discussed in too much detail but will be discussed in greater detail in a paper that will follow up this dissertation. The second method uses the coincidence of the two voltage wave forms to transfer the motor bus to the alternative power supply. When the two wave forms are perfectly aligned, as shown in Fig. 3.32, there is no angular difference between the two voltages (the two voltages are perfectly in synchronism) and it is an ideal time to connect the motor bus to the alternative power source.

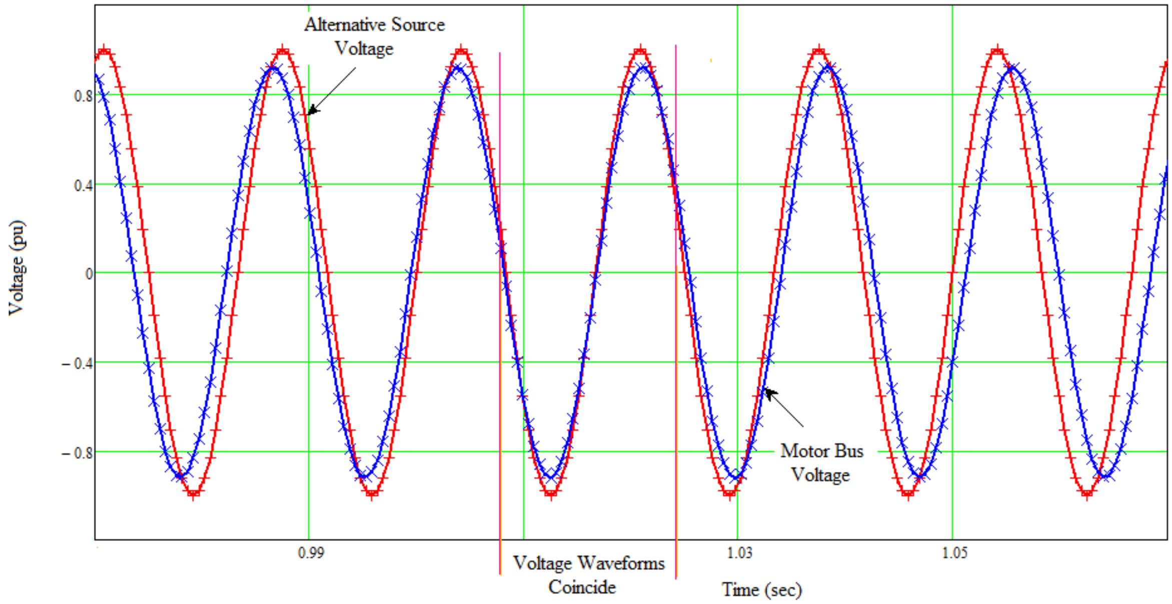


Fig. 3.32: A basic illustration on the operating principle of the wave form coincidence method.

As in method 1, before any manipulation of the data occurs the data is conditioned by passing it through a LPF and digitized by means of an A/D converter that samples the analog data at a fixed rate as shown in Fig. 3.25. Once the data has been conditioned then the alpha quantities (V_α) of both the alternative source voltage and the motor bus voltage are calculated using equation (3.58). Note this method does not require the calculation of the beta voltage quantity

(V_β). Similarly as in method 1, the voltage drop across the motor transient reactance is calculated. The calculated voltage drop is then added to the voltage at the terminals of the motor (voltage at the motor bus) to obtain the voltage behind the transient reactance of the motor. Once the voltage behind the transient reactance of the machine has been calculated the logic enables the check for the coincidence between the two wave forms. The coincidence check can be done in a number of ways, one method is to count how long the two signals are coincident with one another and once the number of counts cross a pre-determined threshold the close command to the transfer breaker is issued. As is the case in method 1 this method also compensates for the breaker closing time so as to enable the circuit breaker contacts to close when the two voltages are perfectly in-phase with one another thereby minimizing the transient airgap torque developed by the motor on the bus.

Chapter IV: Power System and Algorithm Implementation in Real Time Digital Simulator (RTDS™)

4.1 Overview

In this Chapter the proposed solution (method 1) will be implemented in a Real Time Digital Simulator (RTDS®) [31]. Not only will the power system be modelled in the simulator but also the logic (algorithm) of the proposed bus transfer method. With both the power system and logic of the proposed method modelled in the simulator, the power system will be subjected to numerous fault conditions in Chapter 5. The reason for simulating a fault on the power system is that not only will the power source contribute to the fault current but also the motors connected to the motor bus, and this is one of the main reasons why a bus transfer occurs in industry. The result of the motor bus contributing to the fault current is a reduction in the internal voltage of the motors. Therefore when the motor bus is isolated, in order to clear the system fault, the magnitude of the voltage on the motor bus will be lower than if the motor bus was simply disconnected from the power system under normal system conditions. Additionally, the frequency of the voltage on the motor bus will be lower than the normal slip frequency of the motors, since the motors will also deliver real power to the power system during the fault condition (this power is dissipated by the resistive components of the power system). Once the motor bus is isolated the in-phase bus transfer algorithm will be enabled so as to connect the isolated motor bus to the alternative source when the voltages of the two systems are nearly perfectly in-phase with one another. After the motor bus is connected to the alternative source the actual angular difference between the two system voltages when the two systems are connected is determined. As explained in Chapter III, the closing signal to the bus coupler is given before the two voltages are in perfect phase (synchronism) with each other so that when the contacts of the bus coupler make (50 – 66 milliseconds after the close signal is sent) the two voltages are predicted to be perfectly in-phase with each other. Additionally the transient torque developed by the motors following the transfer will also be calculated. This information will then be used to evaluate the performance of the proposed method.

To verify the performance of the proposed method a model of a simple industrial substation consisting of two independent motor buses, as shown in Fig. 4.1, will be modeled in the RTDS. The two motor buses are fed from two independent sources (S_1 and S_2). This configuration is used so that if one source is out of service, the two buses can be feed (powered) from the other independent source by simply connecting the two buses together via the bus coupler (BC). The system is normally operated with the bus coupler in the open (N/O) position. The reason for operating the substation with the bus coupler in the open position is for following two reasons;

- Reduce the fault current on the bus, which means the circuit breakers can have lower fault ratings (cheaper circuit breakers);
- A fault on one bus or system will not impact the other system.

A fault is thrown on the feeder supplying Bus 2 (Line_1), the fault is cleared after a predefined time and Bus 2 is isolated. Once Bus 2 is isolated the motor bus transfer logic is enabled and will then attempt to connect Bus 2 to Bus 1 via the BC. A transfer is considered successful if the following criteria are met;

- The motor bus is connected to the alternative power source when the two voltages are in synchronism with one another (the angular difference should not be more than 30 degrees ≈ 1.5 millisecond at 60Hz);

- No voltage collapse after the motor bus transfer occurs (Abide by the ITI curves);
- No overload of the alternative power source under steady state operating conditions i.e., the transformer or alternate source must not supply more than 1.p.u current after the transient conditions have expired;
- The airgap instantaneous torque does not exceed 6 p.u. (shaft criteria, the motor bus transfer must not result in a shaft shearing, a three phase fault on the power system results in a motor developing a transient torque of 6 p.u.).

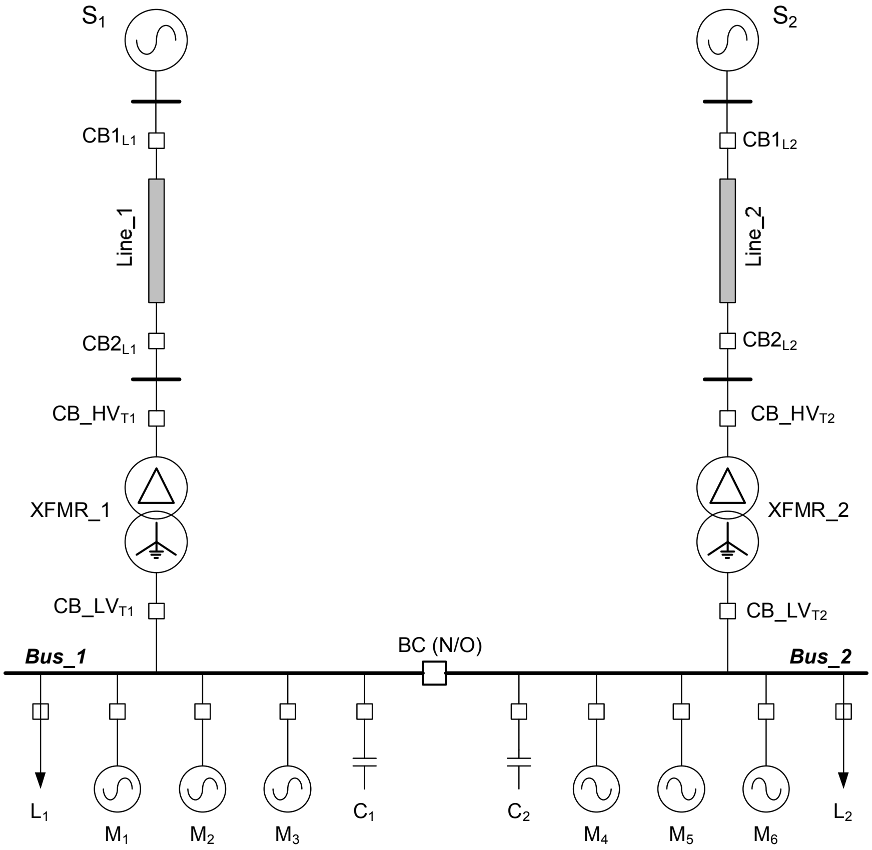


Fig. 4.1: Sketch of a simple industrial substation consisting of two independent busses and a bus coupler (BC).

4.2 Model Power System Overview

As mentioned in the previous section, the RTDS model will consist of two independent motor busses (Bus 1 and Bus 2) being feed from two independent 34.5 kV sources via two transmission lines. Each of the transmission lines terminates in a 20MVA 34.5/2.3 kV transformer. The transformers have an impedance of 10% (Z= 10%) and are of the YDAB vector group type. As can be deduced from the transformer secondary voltage, the motor busses are operated at a nominal line-to-line voltage of 2.3 kV.

Each motor bus has three induction motors connected to it, a variable dynamic load (which represents a collection of smaller induction motors plus some passive loads) and a shunt capacitor bank for power factor correction. The motors are a mix of 500 Hp (≈375kW) and 1000 Hp (≈750 kW) induction motors. The motors will drive loads with inertia constants (H) ranging between 0.527 – 1.15 s. One of the 1000 Hp motors on bus 2 (the motor bus) will drive a load with an inertia constant of 1.15 s. This motor will act as the induction generator during the period that the motor bus is isolated. The variable dynamic load on the bus is adjusted between 0.1 – 5.0 MW and 0.1 – 0.5 MVARS. The dynamic loads are configured such that they behave as constant loads i.e., they consume constant MW's and MVAR's if the voltage is above 70% of the rated bus voltage (i.e., $V_{LN} > 0.93$ kV). If the voltage drops below the 70% of the nominal bus voltage these loads become constant impedance loads. When the loads become constant impedance loads the current draw by the loads is now dependent on the voltage of the system, therefore as the system voltage decreases so does the current drawn by the loads. The shunt capacitor bank is in fact a three stage capacitor bank that can provide the following reactive power to each bus, 40, 80, and 120kVAR the shunt capacitor banks will be at a given level for each test case. It is also possible to switch out (take out of service) the shunt capacitor banks. Some of the test cases will be done with the shunt capacitor bank out of service

Data for the 1000 Hp (≈750 kW) induction motors as entered into RTDS® (*per unit values are on the motor base*)

Electrical Data:

V_{LN} rated = 1.328 kV (2.3 kV line-to-line)

I rated = 188 A

f_{nom} = 60 Hz

R_S (R_a) = 0.003 p.u. (stator resistance)

X_{LS} (X_a) = 0.07 p.u. (stator leakage impedance)

X_{MD0} = 2.00 p.u. (unsaturated magnetizing impedance)

Number of rotor cages = 1 (single bar rotor machine)

R_R = 0.003 p.u. (rotor resistance)

X_{LR} = 0.07 p.u. (rotor leakage impedance)

σ = 0.066 p.u (coupling coefficient - calculated)

$L_{S'}$ = 0.138 p.u (transient reactance – calculated)

Z_{BASE} = 7.064 Ω (base impedance ohms)

Mechanical Data:

$H = 0.527 – 1.15$ s (inertia constant of motor plus load, these are the minimum and maximum values of H)

$D = 0.00$ p.u. (frictional damping)

Data for the 500 Hp (375 kW) induction motors (*per unit values are on the motor base*)

Electrical Data:

V_{LN} rated = 1.328 kV (2.3 kV line-to-line)

I rated = 94 A

$f_{nom} = 60$ Hz

R_s (R_a) = 0.018 p.u. (stator resistance)

X_{ls} (X_a) = 0.085 p.u. (stator leakage impedance)

$X_{MD0} = 3.807$ p.u. (unsaturated magnetizing impedance)

Number of rotor cages = 1 (single bar rotor machine)

$R_r = 0.0035$ p.u. (rotor resistance)

$X_{lr} = 0.085$ p.u. (rotor leakage impedance)

$\sigma = 0.043$ p.u (coupling coefficient - calculated)

$L_{S'} = 0.168$ p.u (transient reactance – calculated)

Z_{BASE} = 7.064 Ω (base impedance ohms)

Mechanical Data:

H = 0.527 – 0.75 s (inertia constant of motor plus load, these are the minimum and maximum values of H)

D = 0.00 p.u. (frictional damping)

All motors in the simulation are initiated in the torque mode with an initial slip of 1 p.u. (the rotor is at standstill).

The loads (torque) of the motor are either directly proportional to the speed of the motor (i.e., similar to a generator) or proportional to the square of the speed of the motor (such as a fan or pump load). The loading of the motors range between 40 - 60% which is typical for machines in industry. The power system model will be processed with a time step of 50 microseconds (or processing rate of 20 kHz).

4.3 Motor Bus Transfer model overview

As was shown in [21], it is possible to model not only the power system in the RTDS® but also the control algorithms and the protection algorithms. This dissertation is not so much concerned about the difference in processing rate between the power system logic and the control logic. This dissertation is more concerned about the validity of the motor bus in phase transfer logic as compared to the implementation of the logic. Therefore the control logic presented in this dissertation will be processed at the same rate as the power system logic, (A different model is available where the control logic is processed with a time step of 500 microseconds or processing rate of 2 kHz with similar results but does not form part of this dissertation).

As was mentioned in Chapter III, before any of the data from the power system model can be consumed by the control algorithm the data needs to be conditioned by means of a LPF. For the in phase transfer the fundamental frequency component (50 or 60 Hz) of the power system is of primary interest and the cut off frequency of the LPF is selected such that the fundamental frequency is passed through the filter without it attenuation and any higher order harmonic frequencies (5nd and 6th etc.) are attenuated. Therefore, a cut off frequency (f_C) of 150 Hz was selected. Because of its magnitude response, a 2nd order Butterworth filter was selected as the LPF in this instance. If the algorithm were to be implemented in a particular piece of hardware the LPF filter could be implemented using discrete hardware components or it can also be implemented in firmware using the following equation [32];

$$y_k = A_1 y_{k-1} + A_2 y_{k-2} + B_0 x_k + B_1 x_{k-1} + B_2 x_{k-2} \tag{4.1}$$

Where: A_1, A_2, B_0, B_1, and B_2 are a function of the cut off frequency and the folding frequency (half the processing frequency). In this case the LPF is implemented in the rTDS using equation (4.1).

For the case where the device has a processing rate of 2 kHz the coefficients for the Butterworth filter with a cut-off frequency of 150 Hz are;

$A_1 = -1.34896$

$A_2 = 0.513982$

$B_2 = 0.041254$

$B_1 = 0.082507$

$B_0 = 0.041254$

A plot of the frequency response using the coeffecicents above is shown in Fig. 4.2, from the graph it can see that the -3dB point is at ≈ 950 rad/sec (150Hz).

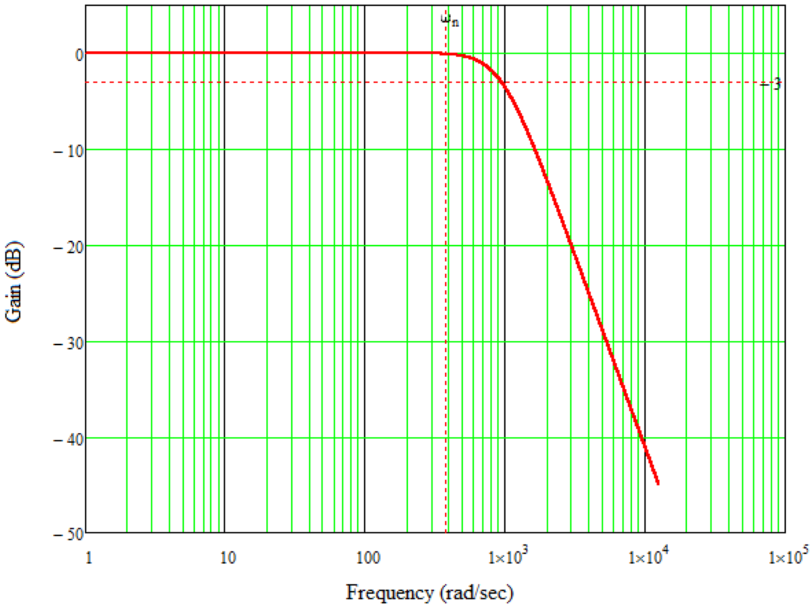
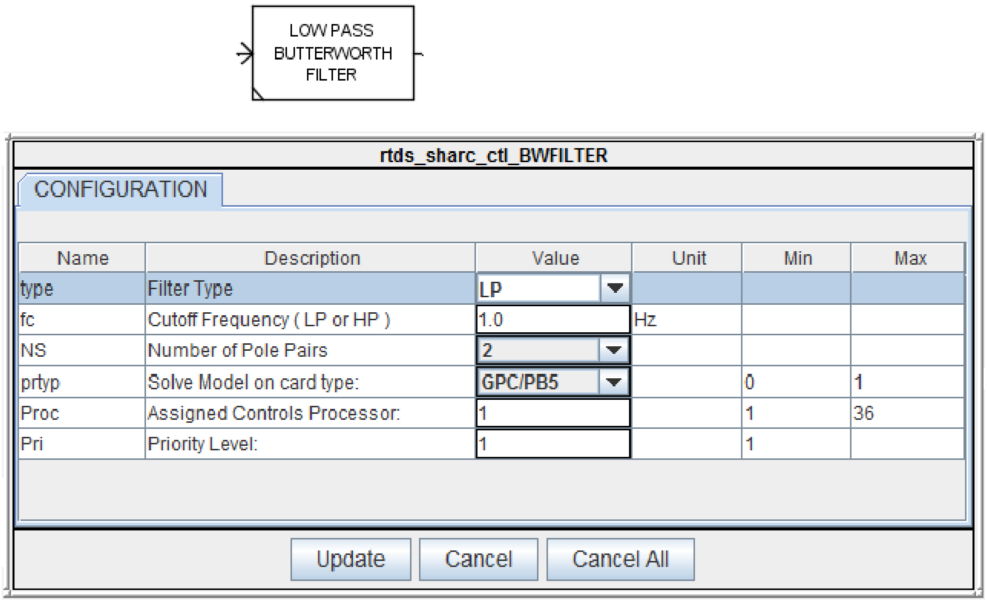


Fig. 4.2: Frequency response of a 2nd order Butterworth filter with a cut off frequency of 150 Hz.

In the RTDS®, the Butterworth filter block shown in Fig. 4.3 can be used. The user simply enters the order of the Butterworth filter and the cut-off frequency and, the coefficients of the filter are calculated by the RTDS® software.



Name	Description	Value	Unit	Min	Max
type	Filter Type	LP			
fc	Cutoff Frequency (LP or HP)	1.0	Hz		
NS	Number of Pole Pairs	2			
prtyp	Solve Model on card type:	GPC/PB5		0	1
Proc	Assigned Controls Processor:	1		1	36
Pri	Priority Level:	1		1	

Fig. 4.3: Simple implementation of a High pass or Low pass filter in the RTDS® and the parameters a user is required to enter.

Once the data has been conditioned the alpha and beta quantities for the voltages on Bus 1 and Bus 2 are calculated. For all test cases Bus 1 is going to serve as the alternative power source and Bus 2 is going to be the motor bus, which is going to be transferred to the alternative power source (Bus 1). The alpha and beta current quantities for the motor with the highest inertia are also calculated. Using the alpha and beta voltages from the alternative source, the instantaneous phasor ($V_{\alpha\beta}$) is computed. The alpha and beta voltages and the $V_{\alpha\beta}$ phasor are computed in the RTDS ® using the logic as shown in Fig. 4.4.

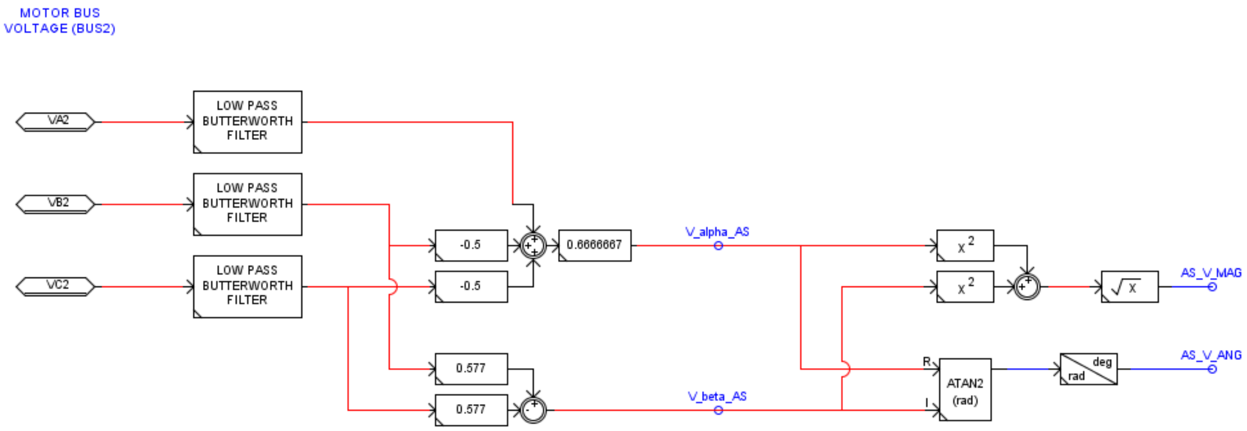


Fig. 4.4: V_{ALPHA} and V_{BETA} computation in RTDS®, for the alternative power source also shown is the computation of the $V_{\alpha\beta}$ phasor.

As mentioned earlier, the voltage behind the transient reactance of the motor with the highest inertia for the motor bus needs to be calculated. Fig. 4.5 illustrates how the alpha and beta voltages for the motor bus are calculated and how the alpha and beta currents for motor 1 (the motor with the largest moment of inertia) are computed. Once the alpha and beta currents for motor 1 have been calculated the voltage drop across the transient reactance and the stator resistance is calculated. Once the voltage drop across the transient reactance has been calculated the voltage behind the transient reactance of motor 1 (the motor with the largest inertia) can be calculated. The implementation of equation (3.63) in the RTDS® is shown in Fig 4.5.

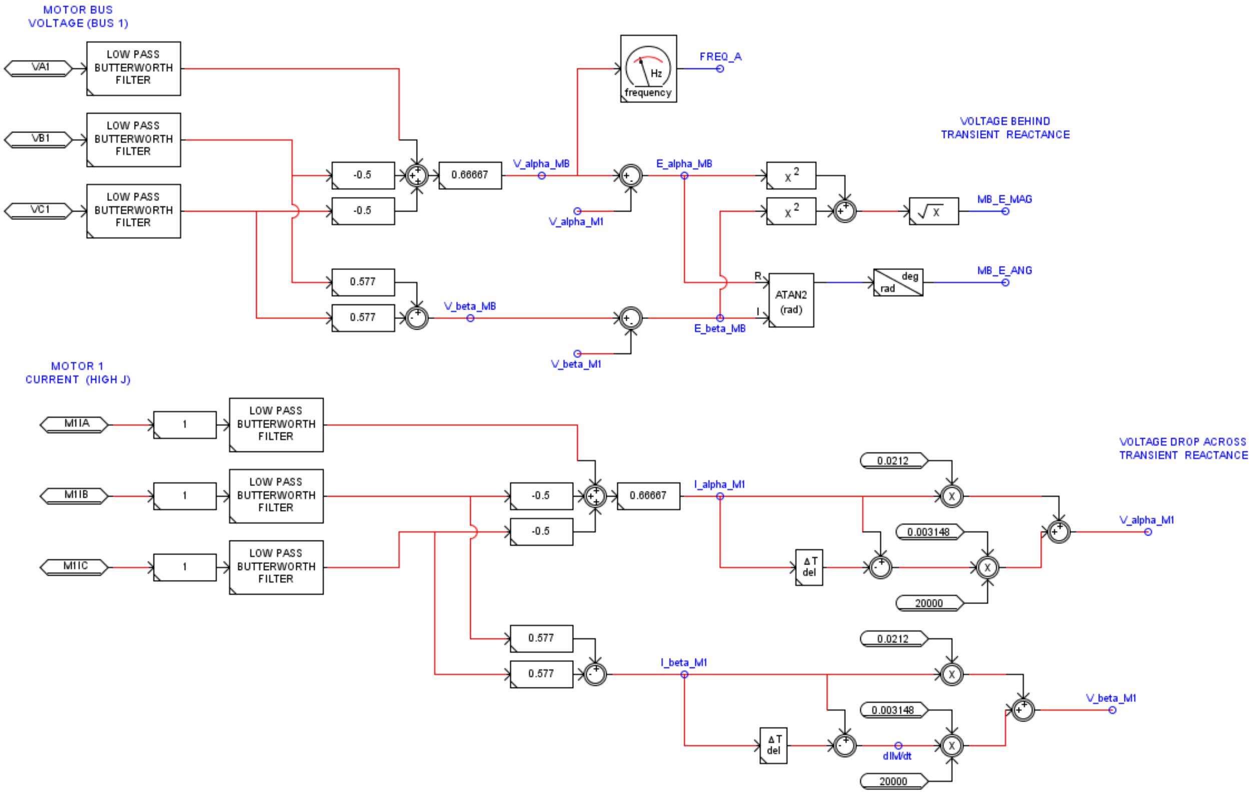


Fig. 4.5: V_{ALPHA} and V_{BETA} computation in RTDS for the Motor Bus that is going to be transferred, the logic also includes the calculation for the voltage drop across the motor transient reactance So that the voltage behind the transient reactance can be determined. Also shown is the computation of the $V_{\alpha\beta}$ phasor for the voltage behind the transient reactance.

With the alpha and beta quantities for the alternative power source and the voltage behind the transient reactance calculated, the instantaneous phasors (magnitude and angle) are calculated for the alternative power source and the voltage behind the transient reactance of motor 1. The magnitude and angle calculation for these two quantities are implemented in the RTDS® as shown in Fig.4.4 and Fig.4.5 respectively.

Using the two angle quantities (AS_V_ANG and MB_E_ANG) the difference between the two angular quantities is calculated. However, the calculated angles have a range from -180° to 180°, therefore it is possible for the difference between the two angles to “wrap” i.e., compute a value that is greater than 180° (or less than -180°). For example if AS_V_ANG = 175° and MB_E_ANG = -175° the actual difference between the two voltages is only 10° in reality (voltage AS_V leading voltage MB_E). However, the computed difference (AS_V_ANG-MB_E_ANG) would be 350° and therefore the angle needs to be unwrapped. The logic that calculates the difference between the two voltage angles and "unwraps" the result is shown in Fig. 4.6.

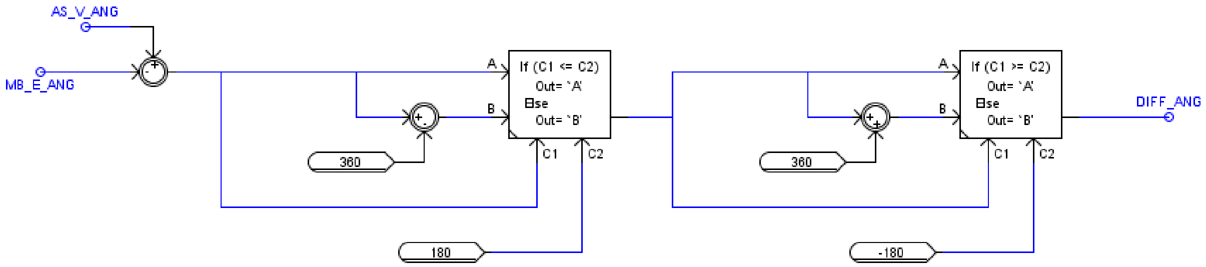


Fig. 4.6: Logic in the RTDS® used to calculate angular difference between the two voltages and unwrap the resulting angular difference.

The difference between two consecutive angular quantities (D_DIFF_ANG), see Fig.4.7, is used to calculate the slip frequency (DEL_ANG_MS) between the two voltages; this calculation is done in the following manner. The present value of the angular difference (DIF_ANG_k) is subtracted from the angular difference a processing interval earlier (DIF_ANG_{k-1}) and divided by the time difference (Δt) between the two consecutive values. In order to obtain an "aged value" of the angular difference the previously calculated value of the angular difference is stored in a buffer. Once the slip frequency has been calculated it is possible to calculate at which moment in time the two voltages will be in perfect synchronism by dividing the angular difference between the two voltages (DIFF_ANG) by the slip frequency. The method to calculate the slip frequency and the time when the two voltages will in perfect synchronism in the RTDS® is shown in Fig.4.7.

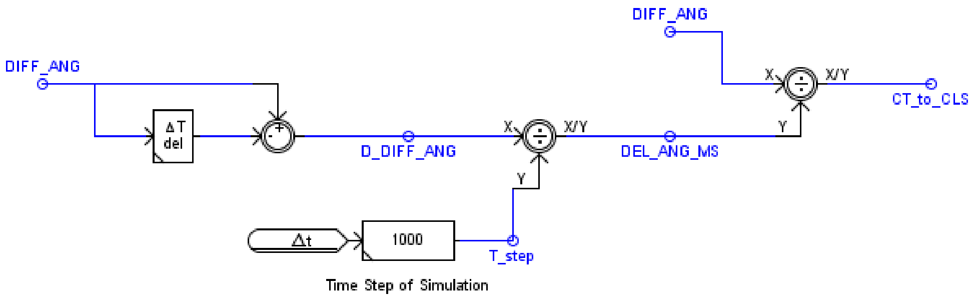


Fig. 4.7: Calculating the slip Frequency and time when the two voltages will be in perfect synchronism in RTDS®.

Since no circuit breaker can close instantaneously the logic needs to compensate for the circuit breaker closing time. With the motor frequency (rotor speed) decreasing, the slip frequency between the motor bus and the alternative source will be negative as a result of this, the time to close is negative. Therefore the circuit breaker closing time needs to be added to the decreasing slip value. In this manner the close signal to the circuit breaker is given before two voltages are in perfect sync with each other, this ensures that when the breaker contacts close the two voltages are in perfect synchronism with one another. A diagram showing how the circuit breaker closing time compensation is done in the RTDS® is shown in Fig. 4.8.

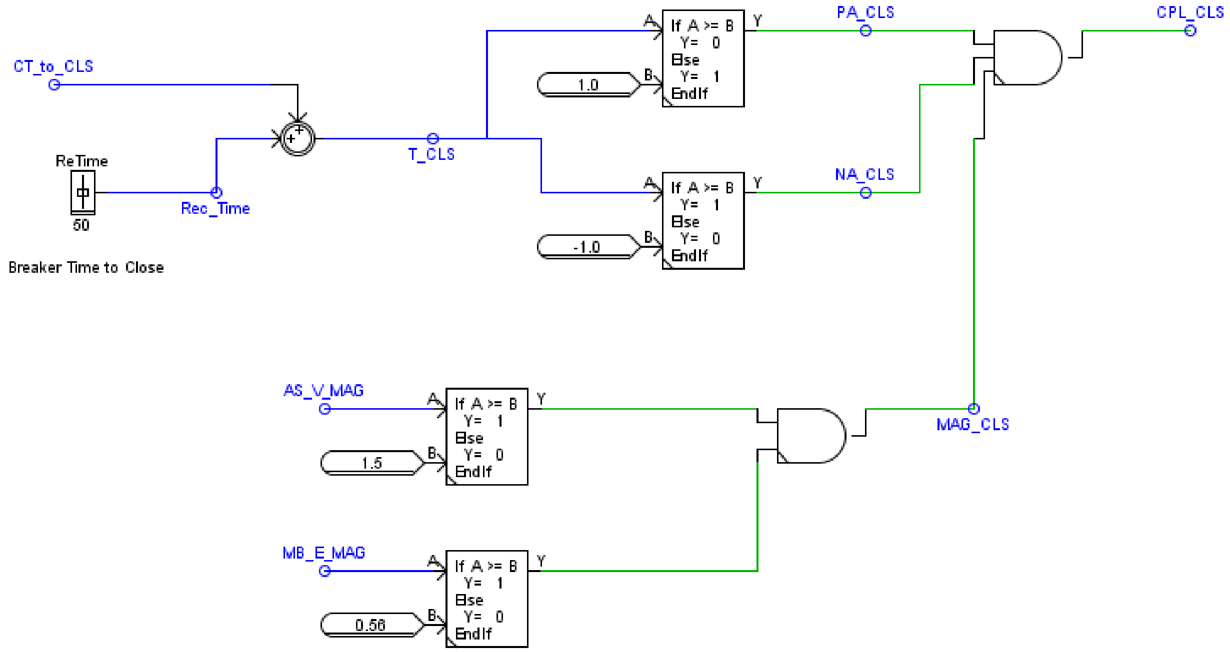


Fig. 4.8: Calculating the moment in time when to issue the close pulse to the circuit breaker so as to ensure that when the circuit breaker closes the two voltages are in perfect synchronism.

As stated earlier a circuit breaker cannot close it contacts instantaneously and since the breaker module within RTDS does not have a close delay setting, this logic has to be realized externally. In addition to this, since one of the parameters that can be change while running the simulations without recompiling the whole case (RTDS model) is the breaker closing time, the breaker closing time will be implemented using a slider that can be adjusted in the run time mode. Implementation of the circuit breaker delayed closing logic in the RTDS® is shown in Fig.4.9.

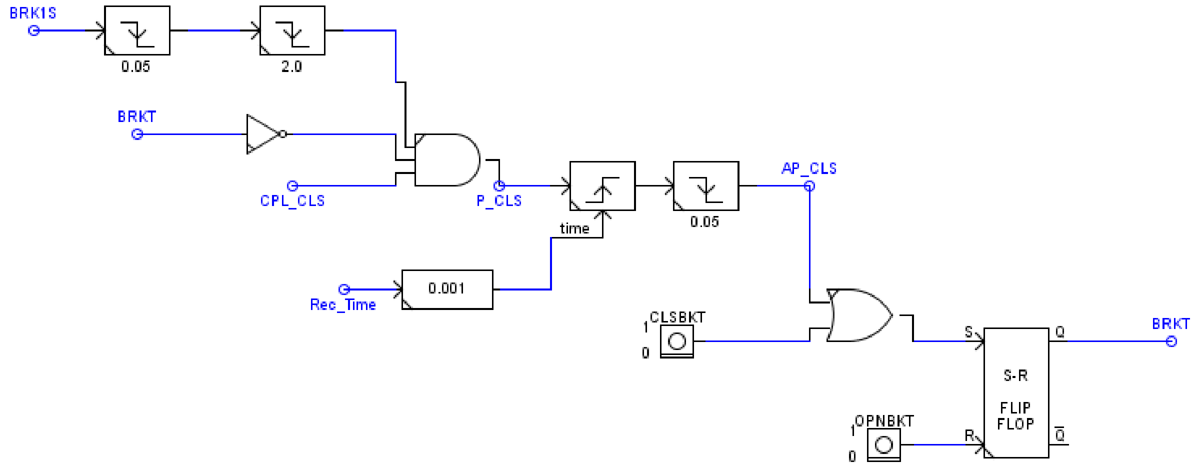


Fig. 4.9: The delayed closing logic and other closing supervision conditions for the bus coupler breaker. The bus coupler breaker is the breaker that connects the isolated motor bus to the alternative power source.

4.4 Summary

This chapter discussed how the power system and the control algorithm for the in phase motor bus transfer is implemented in the RTDS®. The Chapter describes the power system configuration and the implementation of the in phase motor transfer logic in detail. A detailed explanation of the in phase motor transfer logic is given.

Chapter V: Performance of the Method 1, Motor Bus Transfer Logic.

5.1 Introduction

This chapter details the performance of one of the new proposed in-phase motor bus transfer methods, namely method 1. The primary plant model consist of two motor buses as shown in Fig.4.1. A fault is applied to line 2, to clear the fault the two terminals of line 2 need to be disconnected, namely source 2 (S_2) and motor bus 2 (Bus 2). By disconnecting Bus 2 from the line Bus 2 becomes isolated from it power supply. Once Bus 2 is isolated from the power line, the in-phase motor bus transfer algorithm is enabled and transfers Bus 2 to the alternative power supply, namely Bus 1. Once the in-phase transfer has been completed the performance of the in-phase motor bus transfer is recorded. This chapter provides detailed comments on the performance of the new proposed in-phase motor bus transfer algorithm know as method 1.

Using the primary plant model and the in-phase motor bus transfer logic implemented in the RTDS®, the performance of the algorithm is evaluated against the following criteria as stated in Chapter III;

- The motor bus is connected to the alternative power source when the two system voltages are in phase with one another.
- No voltage collapse on the alternative power source occurs after the motor bus transfer and the voltage remains within the Information Technology Industry Council (ITI) specification (formerly known as the Computer Business Equipment Manufacturers Association (CBEMA) curve [33].)

- The alternative power source is not overloaded once the system reaches steady state, stated differently the transformer or alternative source do not supply more than 1.0 p.u. rated current.

- The airgap instantaneous torque does not exceed 6.0 p.u. (Shaft criteria: the motor bus transfer must not result in the shearing of the motor or load shaft.)

The ITI/CBEMA curve as of the year 2000 is shown in Fig. 5.1.

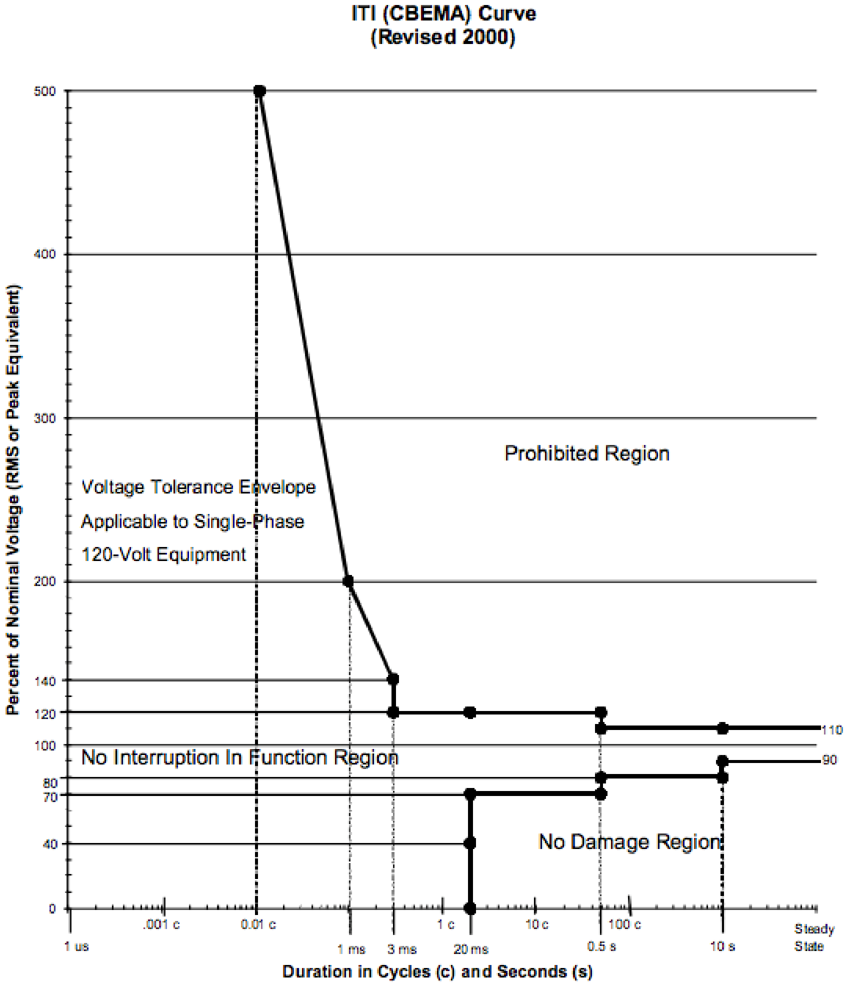


Fig. 5.1: The Information Technology Industry (ITI/CBEMA) curve that specifies the voltage magnitude limits within which an electric utility must operate [33].

The success of a motor bus transfer after a fault condition on the power system supplying the motor bus depends on many different factors. This dissertation will only concentrate on the following power system operating conditions, the reason for selecting these specific conditions is explained following the conditions.

- Fault type (single line to ground fault (SLG) and three phase fault (3ϕ))

  SLG faults are the most common types of power systems fault on a power system. They constitute approximately 80% of all faults on the power system with overhead lines. SLG faults may also produce the highest phase fault current and the largest single phase voltage depression. Three phase faults are the most severe faults on the power system and result in the largest reduction of all three phase voltages on the motor bus. They also result in the lowest voltage behind the transient reactance of the motor once the fault is cleared.

- Fault duration (33 ms and 67 ms)

  The longer the duration of a fault on a power system the more severe the consequence of the fault. Typical medium voltage circuit breakers have an opening time between 2 – 4 cycles. In this dissertation both ends of the operating spectrum will be examined. Should a fault last longer than approximately 6 cycles on a power system, a breaker failure condition will be declared and the motor bus transfer logic will be inhibited. With regards to the motor bus, the longer the duration of the fault the lower the residual voltage on the motor and the lower the chances of a successful in phase motor bus transfer.

- Source strength (*SIR*: 0.5, 2.5 and 5.0)

  The stronger the source the greater the contribution of fault current from the source to the fault. In addition, the stronger the source the lower the voltage drop across the system once the isolated motor is connected to the alternative source. The lower voltage drop results in a quicker acceleration of the motor on the isolated source. The weaker the source the greater the fault current contribution from the motor bus, resulting in a lower residual voltage on the motor bus once the fault is cleared. A strong source is one that has a SIR ≤ 0.5 *and a weak source is one that has a SIR* ≥ 5.0 *for this dissertation.*

- Inertia of the motor and load (*H*: 0.527s, 0.725s and 1.15s)

  The inertia of the load determines how much energy the mechanical load or the motor, from energy stored in the rotor, can transfer to the motor bus once the motor bus is isolated. The greater the inertia of the motor the greater the stored energy the motor has. Therefore, the motors with the greatest inertias will act as the generators during the time period that the motor bus is isolated.

- Load on the motor bus (0.25 p.u., 0.5 p.u and 0.75 p.u.):

  The load on the motor bus will determine how quickly the rotational energy stored by the motors and the loads is dissipated. The greater the loads the more rapidly both the motor bus voltage and frequency will decrease once the motor bus is isolated.

Therefore, the more heavily loaded the motor bus the lower the possibility of a successful in phase motor bus transfer.

- Breaker closing time (16.67 ms, 33 ms, 50 ms and 67 ms)

  The faster the breaker closing time the greater the possibility of the two voltages being in phase with one another when the breaker contacts close. The slower the breaker the greater the possibilities that the voltages will not be perfectly in-phase with one another, especially if the motor bus is more heavily loaded.

- Shunt Capacitor Bank (In/Out of service).

  Shunt capacitor banks provide voltage support. During the motor bus isolation period the shunt capacitor will retard the reduction of the voltage on the motor bus by providing reactive power support. The result of the shunt capacitor bank being connected to the motor bus during the isolation period is that the voltage will decay at a slower rate than if the shunt capacitor bank was not connected. Therefore, by the shunt capacitor bank being connected the chances of a successful motor bus transfer are increased.

One of the unique features of this dissertation is that it investigates the success of a motor bus transfer after the motor bus was involved in a power system fault. None of the reviewed literature in Chapter I addressed this particular scenario previously.

The results for each combination of the different operating conditions discussed above are in Appendix E. The results record the following data:

- The peak torque developed by the motor during the fault (*see Fig. 5.2 for details*),
- The peak reclosing torque (three points will be recorded for this see Fig. 5.2 for details),
- Frequency and voltage on the motor bus at the instant it is transferred *(see Fig. 5.3 for details),*
- Steady state voltage after the transfer, and
- Verification that the ITI (CBEMA) criteria was not violated.

To determine the performance of the in-phase motor bus transfer logic developed in this dissertation, a fault is thrown on the power system. The fault is cleared and the motor bus is isolated from all power sources. Once the motor bus is isolated, the in-phase motor bus transfer logic is enabled to transfer the isolated motor bus to the alternative power source. Should the in-phase motor bus logic successfully connect the isolated motor bus to the alternative power source the performance of the logic is evaluated. The performance of the logic is done by recording the transient torque developed by the motor before the fault, during the fault, and immediately after the motor bus has been transferred. An example plot of the motor torques (Motors 1, 2 and 3) before the fault, during the fault, and when the motor bus is connected to the alternative power source is given in Fig.5.2. The maximum torques developed by the motor during these conditions is also shown in Fig.5.2. In addition to monitoring the motor torques, the frequency on the motor bus is monitored as well as the voltage on the alternative voltage source. The voltage on the alternative bus is monitored to ensure that the alternative source does not collapse following the motor bus transfer. A sample plot of the motor bus voltage, the alternative bus voltage and the frequency of the motor bus for the same conditions as shown Fig 5.2 are shown in Fig.5.3.

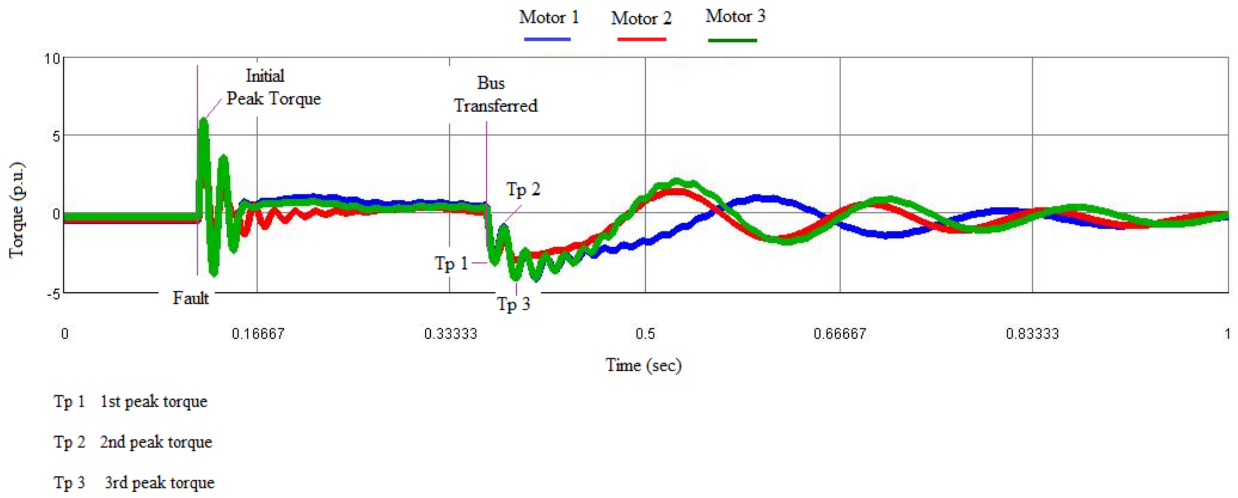


Fig. 5.2: Plot of the motor torques before the fault, during the fault, while the motor bus (Bus 2) is isolated and when the motor bus gets transferred to the alternative source (Bus 1).

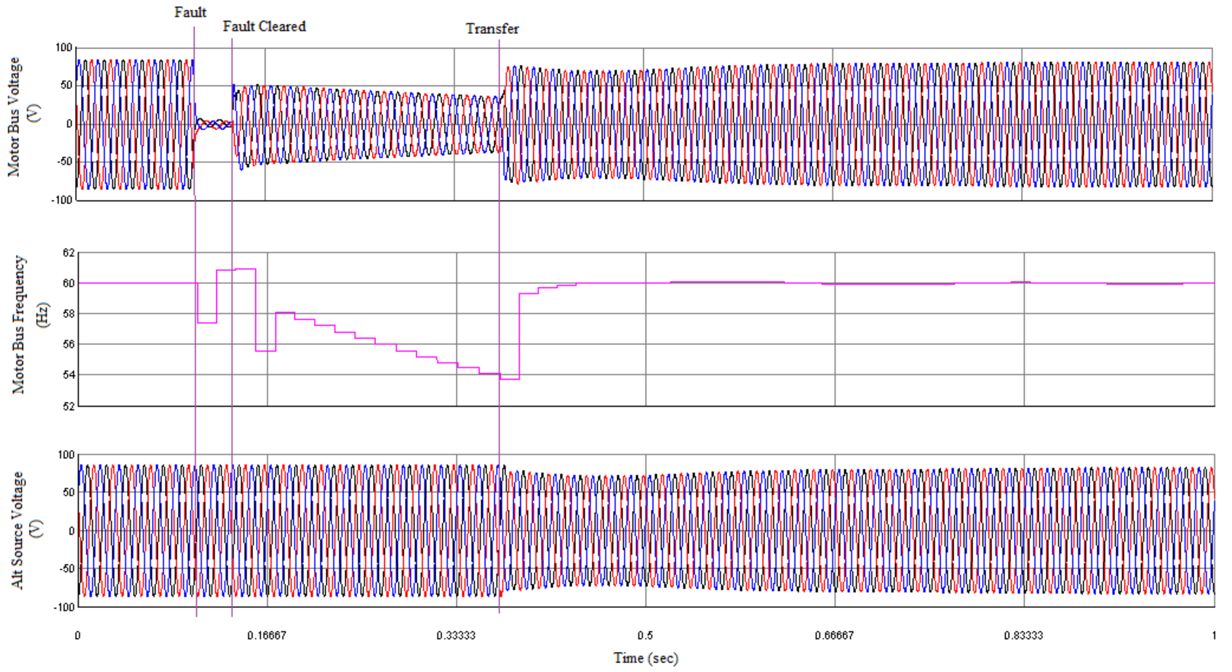


Fig. 5.3: Plot of the voltages on the motor and the alternative source bus. Also shown is the frequency on the motor bus.

5.2 Result Analysis and Observations

The results are analyzed independently for the single line to ground faults (SLG) and the three phase faults (3ϕ), the observations are done along the same lines. From these two distinct fault types the overall observations and analysis will be made while discussing all of the cases in detail.

5.2.1 Single Line to Ground Fault Observations and Analysis

With respect to single line to ground faults the following observations can be made. The higher the SIR value (i.e., the weaker the source becomes), the greater the torque developed by the motors during the fault. For an SIR equal to 0.5, the torque developed by the motors as a result of the faults was approximately 2.25 p.u. of the motors rated torque. For an SIR equal to 5.0, the torque developed by the motors during the fault more than doubled to a value of 5.1 p.u. of rated torque. The reason for this increase in torque will be explained with the aid of Fig. 5.4 [34], [35]. The stronger the source (the lower source impedance) the larger fault current contributed by the source (I_{SOURCE}), and this results in a larger volt drop (V_{FAULT}) across the fault resistance (R_F). This larger voltage drop results in a smaller voltage difference between the motor bus and the fault point, resulting in a smaller current contribution (I_{M_B}) from the motor bus. Due to the smaller motor currents the torque developed by the motors during the fault condition is smaller (torque is proportional to current).

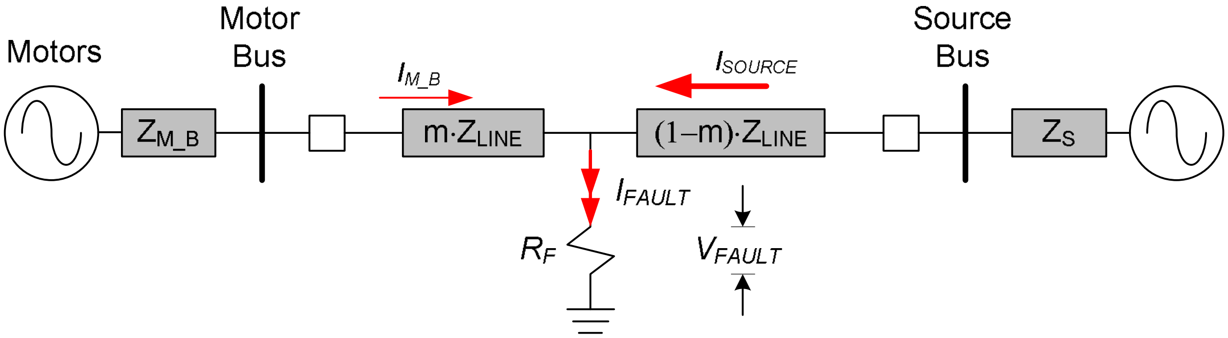


Fig. 5.4: Sketch of the equivalent circuit of the motor bus and the source for a fault on the line supplying the motor bus.

Therefore, as the impedance of the source increases (i.e., SIR increases), the fault current contribution from the source bus decreases, causing the voltage drop across the fault resistance to decrease. This decrease in the voltage drop across the fault resistance results in a larger voltage difference between the motor bus and the fault point, which results in a larger current contribution from the motors. This larger fault current contribution from the motors connected to the motor bus is responsible for the larger torque developed by the motors during the fault.

The strength of the source also has other effects on the motor bus. For example, when the source is strong, the voltage drop on the motor bus during the fault is not as high as when the source is weak. The result of the lower voltage drop is that when the motor bus is disconnected from the fault and isolated from any power source, the voltage on the motor bus recovers to a higher voltage level than if the source was weaker. The impact of having a higher voltage when the motor bus is isolated from the fault has an effect of the motors when the motor bus is transferred to the alternative power source. To understand the impact of this effect we need to consider the motor bus under different loading scenarios.

5.2.1.1 Lightly Loaded Motor Bus

When the motor bus is lightly loaded (i.e., load ≤ 25%) and the source is strong (SIR = 0.5), the voltage on the motor bus during the fault is not as depressed, as is the case when the source is weak. This lower depression of the voltage on the motor bus during the fault results in the voltage on the motor bus recovering to a higher voltage magnitude after the fault is cleared. Note that the unfaulted phases do not experience any voltage depression during fault (the power system is solidly grounded). Therefore, once the fault is cleared the voltages (fluxes) on the unfaulted phase help restore the flux on the faulted phase. The fluxes on the unfaulted phases resulting in the fluxes on all three phase to be be balanced. Since no fault is present in the motor, the sum of the phase fluxes have to sum to zero. The voltages of all three phases are therefore equal and balanced. Because of the higher voltage on the motors (greater voltage behind the transient reactance) during the isolated period, the motors supply greater energy to the loads on the bus, compared to the case when the voltage on the bus is lower. The higher motor voltage results in the voltage and speed (frequency) of the motor being reduced to a greater extent than if the voltage on the bus was lower (*more energy is transferred from the rotating loads to the electrical loads on the bus*). However, it is interesting to note that at the time of the transfer the voltage on the motor bus had deceased to approximately 55% of the nominal voltage, compared to the frequency on the bus (motor speed) only decreasing by about 17.4%.

However, as the source impedance increases (and the SIR increases), the voltage on the motor bus during the fault condition decreases and as a result when the motor bus is isolated the voltage on the motor bus is lower. This lower voltage on the motor bus results in the motors supplying less power to the electrical loads on the bus during the period when the motor bus is isolated.

Due to the low voltage on the bus before the bus is isolated, the voltage on motor bus at the time of transfer will be low (50% of the nominal voltage value). However, the frequency on the motor bus is higher (83.8% of nominal frequency value) for this condition.

5.2.1.2 Heavily loaded Motor Bus

When the motor bus is heavily loaded (i.e., load $\geq 75\%$) and the source is strong (SIR ≤ 0.5), then the voltage drop on the motor bus during a fault condition is similar to that as for the lightly loaded. In both cases the voltage drop on the motor bus is lower than if the source was weak. However, during the isolation period the motors supply greater amounts of energy to the loads on the bus as compared to when the bus is lightly loaded. This greater amount of energy supplied by the motor to the bus results in the voltage and frequency of the motor bus decaying more rapidly than for the case when the motor bus was lightly loaded. The lower voltage on the motor bus during the isolation period results in a lower torque being developed by the motors immediately after the transfer. This lower torque developed by the motors when the motor bus voltage is low may at first sound counter intuitive but one needs to remember that the torque developed by the motors (T_{em}) is dependent on the flux linkage of the magnetizing branch (λ_{qdm}), the current in the rotor (i_{qdr}) and the angle between these two quantities. Using equation (2.61) we can develop this relationship.

$$T_{em} = L_m Im\left(i_{qds} \cdot i_{qdr}{}^{*}\right) \qquad (5.1)$$

But we know that the flux linkage in the magnetizing branch can be expressed as

$$\lambda_{qdm} = \mathrm{L}_m\left(i_{qds} + i_{qdr}\right) \qquad (5.2)$$

Substitute equation [5.2] into equation [5.1] the final torque equation in terms of flux linkage, equation (5.3), is obtained. (Note that ($i_{qdr} \cdot i_{qdr}{}^{*}$) is real and disappears out of the equation)

$$T_{em} = Im\left(\lambda_{qdm} \cdot i_{qdr}{}^{*}\right) \qquad (5.3)$$

Equation [5.3] confirms that the flux linkage of the magnetizing branch of the motors impacts the torque developed by the motor. The rotor current also influence the torque developed by the motor but the flux linkage of the magnetizing branch changes much slower. The magnetizing branch of a motor has an inductance approximately 30 times greater than that of the stator or rotor leakage inductance of a motor. Therefore the residual flux linkage of the motor has a greater impact on the transient torque developed by the motor than the rotor current in the motor. The above is confirmed by the results from case 13 and case 49. For case 13 the SIR is 0.5 and the torque developed by Motor 1 after the transfer is -4.0 p.u, with the voltage and frequency on the motor bus just before the transfer being 51.05 Hz and 0.466 kV respectively. For case 49 the SIR is 5.0 and the torque developed by Motor 1 after the transfer is -2.68 p.u. with the voltage and frequency on the motor bus being 51.75 Hz and 0.37 kV respectively.

The heavily loaded bus conditions increases the affect the closing time of the transfer breaker has on the torque developed by the motors immediately after the transfer. The algorithm described in Chapter III uses present and past values of the bus voltage to predict the time (taking into account the breaker closing time) when the voltage behind the transient of the motor and alternative source will be in perfect synchronism. However, due to the nature of the motor loads the frequency does not decrease perfectly linearly but follows more of a parabolic trajectory, as shown in Fig. 5.5.

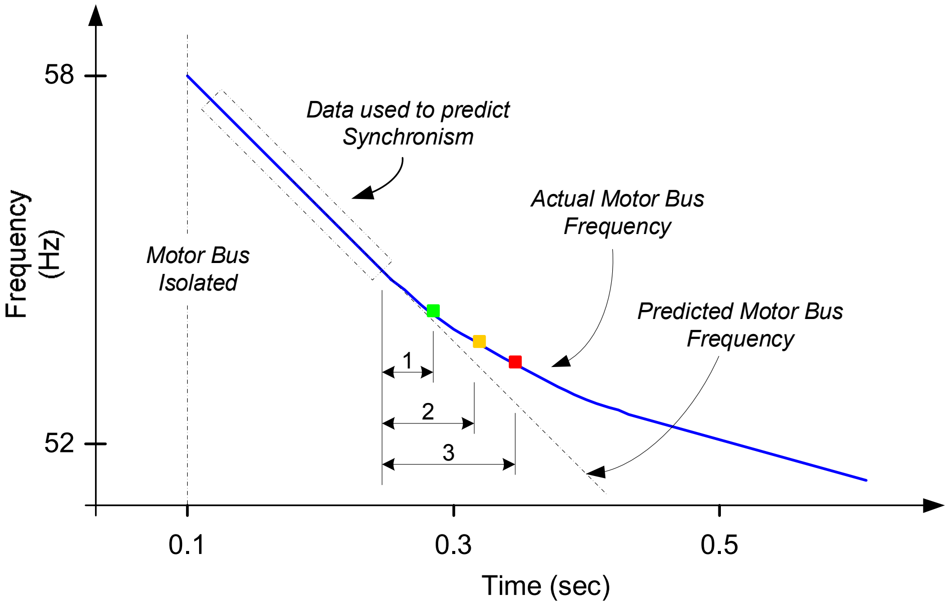


Fig. 5.5: Sketch showing the decay of the motor bus frequency when the motor bus is heavily loaded. The sketch shows the difference between the actual bus frequency and the predicted bus frequency and the effect the transfer breaker closing times have on error in the closing angle.

The result of the non-linear decrease in frequency is that the time predicted by the algorithm using historical data results in the transfer occurring when the two systems are not in perfect synchronism. If the breaker has a fast closing time (< 2 cycles) then the effect is not as pronounced as if the breaker has slow closing time (> 3 cycles). The impact of the three chosen breaker closing times are shown in Fig.5.5. When the breaker has a fast closing mechanism, the predicted closing frequency and actual frequency have a very small error (shown with a green box on Fig. 5.5) and the two systems are connected to each other when the voltages are nearly perfectly in synchronism. As the breaker mechanism becomes slower the error between the predicted frequency and actual frequency becomes larger and the systems are connected together when the voltages are not in perfect synchronism (shown with a red box in Fig. 5.5). As can be expected when the two systems are connected to each other when the two voltages are not in perfect synchronism, the torque developed by the motors immediately after the transfer will be higher than if the two voltages were in perfect synchronism. The closing algorithm can be adjusted to compensate for this behavior but this would require the user to do extensive testing, which is not desired. Using the algorithm as proposed in Chapter III the worst case transfer occurred when the bus was heavily loaded and the transfer breaker had a closing time of 67 milliseconds (4 cycles at 60 Hz). Even under this condition the angular error at the time of closing was approximately 35° (1.8 milliseconds when the bus had a frequency of 52 Hz). The relationship between the motor bus voltage and the alternative power source just prior (2 milliseconds) to the breaker contacts closing for the three different breaker closing times shown in Fig. 5.5 are illustrated in Fig.5.6. The motors in these cases are connected to a heavily loaded bus which worsens the condition.

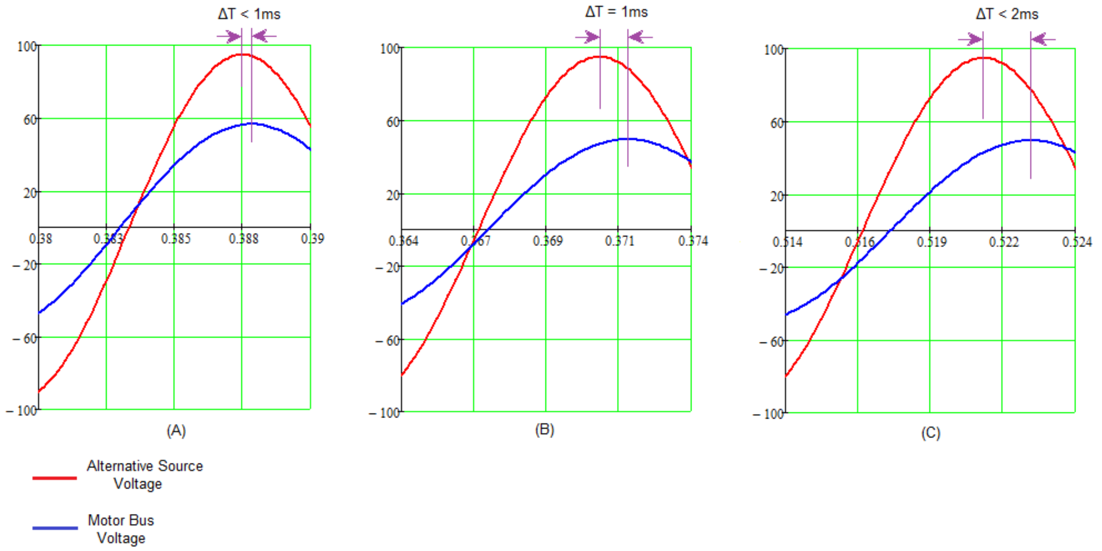


Fig. 5.6: Voltage plot showing how the closing times of the transfer breaker influence the synchronization angles between the alternative source voltage and the bus voltage. When the breaker has a closing time of 2 cycles (33 ms), the difference between the two voltage angles is significantly less than 1ms (< 19°) (A), if the breaker has a closing time of 3 cycles (50 ms) then the angular difference is approximately 1 ms or ≈ 19° (B), and if the breaker has a closing time of 4 cycles (67 ms), then the angular difference is approximately 2 ms or ≈38 ° (C) .

The advantage of using a transfer breaker capable of closing within a short time delay is clearly illustrated in Fig.5.6. The benefit is that the two systems will be coupled together when the voltages of the two systems are in near perfect synchronism with each other, resulting in the motors developing a lower torque immediately after the motor bus is transferred to the alternative voltage source.

The fault duration of the SLG fault was varied from 2 cycles (33ms) to 4 cycles (67 ms). The duration of the fault only resulted in the faulted phase's voltage being lower at the time that the fault was cleared. This resulted in the voltage on the motor bus being slightly lower (approximately 2%) when the motor bus was isolated. Remember the unfaulted phases are not impacted by the fault. This change did not have any negative impact on the ability of the bus to be transferred to the alternative power source. So it can be said that the duration of the SLG fault does not negatively impact the ability of the motor bus to have a successful transfer.

5.2.2 Three Phase Fault Observation and Analysis

When the feeder supplying the motor bus is subject to a three phase fault (3ϕ), the maximum air gap torque developed by the motors is independent of the SIR of the power system. The reason for this is that a three phase fault normally has very little fault resistance (R_F) when compared to a SLG fault. A sequence diagram for a three phase fault on this power system as shown in Fig.5.7 helps to clarify this point [34], [35].

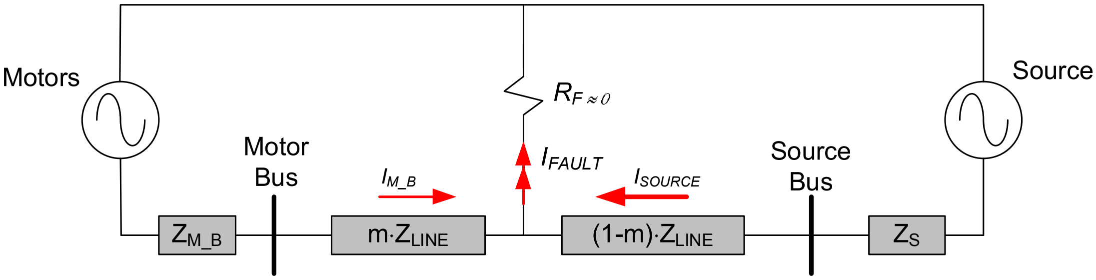


Fig. 5.7: Sequence diagram for a three phase fault on the power line supplying the motor bus.

Analysis of Fig. 5.7 shows that the fault current contributed by the motor bus (I_{M_B}) is only dependent on the impedance between the motors and the fault point, since the voltage at the fault point is approximately zero. The reason for this is that the fault resistance (R_F) is approximately zero, resulting in an insignificant voltage drop across the fault resistance irrespective of the fault current contributed by the Source (I_{SOURCE}). Therefore the fault current contribution from the motor bus is independent of the strength of the source.

The load on the motor bus has a small effect on the maximum airgap torque developed by the motors during a three phase fault. The reason for this is that at higher load levels the voltage drop across the transmission line and the power transformer is greater. Therefore the voltage at the motor bus is lower resulting, in the motors developing a lower maximum airgap torque during a three phase fault. However the difference is insignificant, under light loading condition the maximum torque developed by the motors is 6.0 p.u as compared to 5.65 p.u. when the, motor bus is heavily loaded.

The most significant difference between a three phase fault and a single line-to-ground (SLG) fault is the duration of the fault coupled with the loading of the bus. Unlike a SLG fault, a three phase fault involves all three phases and as such the voltages on all three phases collapse during the fault and there are no unfaulted phases to support the faulted phases. The longer the fault duration, the more the flux in the magnetizing branch of each motor decreases, since each motor will supply reactive power (VARS) to the fault. Once the fault is cleared the remaining flux in the magnetizing branches of the motors will determine the voltage on the motor bus. The frequency of the motors does not change significantly while the fault is present as compared to the voltage since very little active power (watts) is dissipated during a three phase fault condition. The resistance in the power lines result in some power losses but these are insignificant. Once the fault is cleared the magnitude of the voltage on the bus is determined by the residual flux in the motor magnetizing branches and the frequency of voltage is very close to the rotor frequency prior to the fault. The loading on the bus will determine how rapidly the power supplied by the motors is dissipated.

As a result factors that determine a successful motor bus transfer following a three phase system fault are the duration of the fault and the loading of the motor bus. Each of these scenario and there effects on a successful bus transfer are discussed separately in the following sections.

5.2.2.1 Fast Fault Clearing and Lightly Loaded Bus

If the motor bus is isolated from the fault very rapidly (within 2 cycles), the reactive power supplied by the motors to the fault is limited and as such when the bus is isolated, the remaining magnetizing flux will be higher than if the bus were connected to the fault for a longer period of time. The higher flux value will result in a higher residual voltage on the motor bus when the bus is isolated. If the bus is lightly loaded, the power transfer between the mechanical loads and the electrical loads on the bus will be low. Therefore the active and reactive power demanded by the motors is low. This low demand in active and reactive power results in the voltage magnitude and frequency of the motors decaying slowly. This slow decay in the motor bus voltage and frequency results in a greater possibility for a successful motor bus transfer. If a shunt capacitor bank is connected to the bus at the time of the fault, the shunt capacitor bank will aid in supplying reactive power to the loads. The reactive power support from the shunt capacitor bank results in the motors having to supply less of the reactive power therefore reducing the decrease in the motor flux. Having a higher voltage magnitude on the bus further assisting a successful motor bus transfer.

The addition of the capacitor bank on the motor bus, results in a higher voltage magnitude on the motor bus when the fault is cleared and the bus is isolated. This higher motor bus voltage results in a higher residual flux linkage (λ_{qdm}) in the motors connected to the motor bus than if the capacitor bank was not connected to the motor bus, and can result in higher transient airgap torques being developed by the motors when they are transferred to the alternative power source. The motors develop higher transient torques when the bus transfer breaker (bus coupler) is slow to close. The result of the slow close is that the buses are connected to one another when the voltage are not perfectly synchronized (the reason for this has been discussed in the SLG section). The rotor current (i_{qdr}) drawn by the motors under the non-synchronized situation is going to be greater than if the voltages where perfectly synchronized resulting in a greater transient airgap torque being developed (since the flux on the magnetizing branch is the same) by the motors following the transfer, Fig. 5.8 will aid in this explanation.

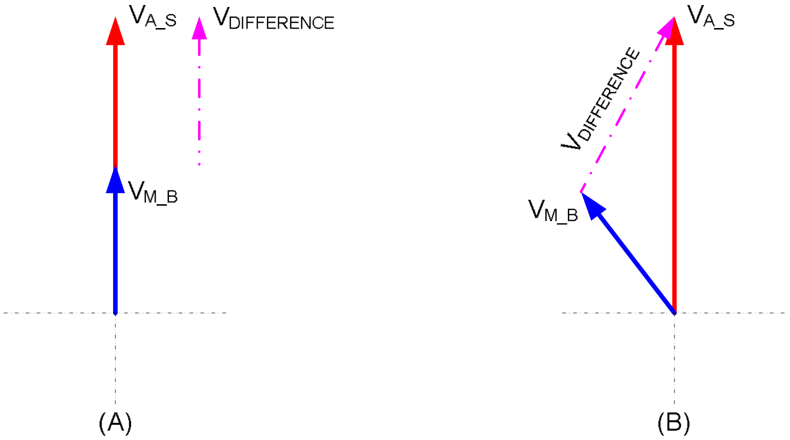


Fig. 5.8: Phasor diagrams showing the relative position of the motor bus voltage (V_{M_B}) phasor and the alternative power source voltage (V_{A_S}) phasor for when the two buses are connected , for a perfectly in phase (synchronized) transfer (A) and when the voltage are out of phase with each other (B).

From Fig. 5.8 it can be seen that when the two voltages are in perfect phase with each other at the time the two buses are connected to each other, the resulting voltage difference is smaller than if the voltages are not in phase with each other. When the two bus voltages are not in perfect synchronism with one another a higher rotor current is drawn than if the two voltages are in perfect synchronism with one another. The higher rotor current results in a higher transient airgap torque being developed by the motors. Therefore, the scheme performs better if both the power line circuit breaker (used to isolate the motor bus from the fault) and the bus coupler (used to connect the two buses to each other) have fast acting mechanisms (operating times of 2 cycles or less).

5.2.2.2 Fast Fault Clearing and Heavily Loaded Bus

In this case the residual voltage on the motors when the motor bus is isolated from the fault is the same as in the lightly loaded bus. The difference now is that the motor bus is heavily loaded and this higher loading results in more current being drawn from the motors during the period that the motor bus is isolated. The higher current results in the flux and frequency in the motors decaying rapidly, the magnetizing branch of the motors provides the reactive power and the active power is supplied by the load and motor rotor inertia. If a shunt capacitor bank is connected to the bus at the time of the fault it helps retain voltage by providing reactive power support during the fault, and to the loads after the bus is isolated. Because the motor bus was isolated rapidly, the residual voltage on the motor bus was high enough to enable a successful bus transfer. In this specific case the minimum value of the motor frequency before being transferred was 51 Hz (a decay of 18% from the nominal value) and the minimum voltage on the bus was 0.39 kV (a decay of 70%). Note, that the voltage to qualify for an in-phase voltage was set to 0.44 kV, (33% of the nominal bus line-to-neutral voltage), but the logic does not use the voltage on the motor bus to qualify an in-phase motor bus transfer but the voltage across the magnetizing branch of the motor, which is greater than 0.44 kV. With these conditions the motor bus transferred successfully. Another important point of interest is that the transient airgap torque developed by the motors after the transfer was lower than in the previous case, this is due to the lower magnetizing flux linkage. However, the inrush current drawn by the motors was higher than in the previous case, this is expected since the bus voltage was lower than in the previous scenario. The voltage drop on the alternative bus immediately after the transfer was higher in this case than in the previous case but the voltage on the auxiliary bus recovered to remain within the ITI Curve limits.

5.2.2.3 Slow Fault Clearing and Lightly Loaded Bus

If the motor bus is isolated from the fault after about 4 cycles (slow clearing), the motors will be supplying a large amount of reactive power to the fault, which results in a large reduction of the flux in the motors. Therefore when the fault is isolated, the flux will be low (approximately 40% of nominal) resulting in a low voltage on the isolated bus. With the motor bus voltage below 70% of the nominal voltage, the dynamic loads change from being constant power loads to being constant impedance loads, meaning that the current drawn from the motors is now proportional to the voltage on the bus. Therefore the lower the voltage, the lower the reactive and active power drawn from the motors on the bus, which manifests itself is a slower decay of the voltage magnitude and frequency. In this instant having the capacitor bank connected to the motor bus helps support the voltage during the isolation period (since the capacitor bank supplies VARS to the loads during the isolation period) and contributes to the success of the bus transfer. In this scenario once again the voltage reduces by a greater percentage than the frequency. The voltage reduction before the bus is transferred is in the region of 70% compared to a frequency reduction of between 16 -19% (depending on the inertia of the motor and loads at the time of the transfer.) The impact of the inertia constant (H) during a bus transfer operation will be addressed separately. It is interesting to note that due to the large reduction in the magnetizing branch flux (which reduces the flux linkage), the transient airgap torque developed by the motors after the bus is transferred is relatively low in the region of 1.8 - 2.25 p.u. A further interesting point to note is that even though the current practice states that if the bus voltage is below 0.33 p.u. reclosing can be done using the a residual voltage criteria. The residual voltage criteria allows the motor bus to be transferred at any instant when the voltage is below 0.33 p.u. However, if an in-phase transfer occurs, which is still possible since the voltage on the bus is high enough to accurately measure the voltage phase angle, the transient torque developed by the motor following the in-phase transfer will be lower than for the random residual voltage transfer, resulting in longer life for the motor shafts and couplings.

5.2.2.4 Slow Fault Clearing and Heavily Loaded Bus

If the fault is slow to clear as mentioned in the section above, the flux in the motor's magnetizing branch is severely reduced to approximately 40% of the nominal value. This means that when the bus is isolated the voltage is already severely depressed. Add to a severely depressed voltage a heavily loaded bus and the motor bus voltage will collapse further, to the point that when the two voltages come into synchronism with one another, the voltage on the motor bus is so low that an in-phase motor bus transfer as defined by the standard [15] is no longer possible. However what is interesting to note is that the frequency at this time is only reduced to approximately 80% of it nominal value. If the motor bus is transferred at this point it is no longer an in-phase transfer but a residual voltage transfer. However, if the motors are still rotating, the current drawn by the motors if transferred to the alternative power source would be lower than if the motors where at standstill. As mentioned previously, even when the voltage is below 0.33 V p.u., an in-phase motor bus transfer still provides benefits in that it result in a lower transient airgap torque being developed by the motors after they are transferred to the alternative power source.

5.2.3 Impact of the inertia constant (H) of the motors and Loads

The inertia constant of the motors and the loads has a direct influence on the frequency of the voltage on the motor bus after the bus is isolated. The higher the moment of inertia (J) and thereby the inertia constant (H), the slower the decay of the frequency on the motor bus. Conversely, the lower the moment of inertia the higher the decay of the frequency on the motor bus. This phenomena can readily be explained, the higher the moment of inertia the more energy is stored in the form of rotational energy. Therefore when the bus is isolated there is more stored energy available for the loads on the motor bus. Therefore for the same electrical bus load, when the bus is isolated, the energy demands of the bus don't change, but because there is more rotational energy available the decrease in the frequency of the motor bus is lower. Therefore the higher the inertia constant the lower the decay rate of the frequency during the isolation period of the bus. Note the stored rotational energy does not influence the decay rate of flux in the motors nor does the frequency of the bus impact the transient torque developed by the motors immediately after the bus transfer.

5.2.4 The Effect of the V/Hz Ratio

The IEEE C50.41 standard [15] states that if the p.u. volts per hertz ratio is less than 1.33 p.u. then the maximum transient torque developed by the motor would be less than 1.77 p.u. From all test cases run, the per unit volts per hertz was below 1.33 p.u. However the transient torque developed by the motor after the transfer was complete was considerably higher than 1.77 p.u. in some cases even if the two voltages where in perfect synchronism when the two buses were connected to each other. In his papers [1], [10] Daugherty confirms this finding, and the reason for the error in the IEEE standard is that they state that if the V/Hz p.u. ratio is 1.33. The motor current at this instant would not exceed 1.33 p.u., which when using the relationship that the electrical torque developed by the motor is proportional to the square of the current (5.4), would result in a torque no greater than 1.77 p.u.

$$T_{EM} = k \cdot I^2 \tag{5.4}$$

The error in this reasoning is that the IEEE guide is using the Steinmetz model (the steady state model) to predict the torque developed by the motor during a transient condition. As was shown by equation (5.3), the transient torque developed by the motor after the transfer is dependent not only on the current drawn by the motor but more importantly by the residual voltage across the motor magnetizing branch. The impact of residual voltage of the motor is borne out by the results of the 386 test cases in this dissertation. Furthermore from the data obtained from the tests, the frequency of the motor bus voltage has no significant effect on the transient torque developed by the motor. The only effect that the frequency of the rotor has on the transient torque developed by the motor after the transfer is that the time period between the 1st peak torque and the 3rd peak torque in Fig. 5.2 is equal to 1/ frequency of the rotor at the time of the transfer.

One of the conclusions of this dissertation is that the 1.33 V/Hz p.u. ratio does not determine the magnitude of the transient torque developed by the motor after the transfer.

5.3 Summary

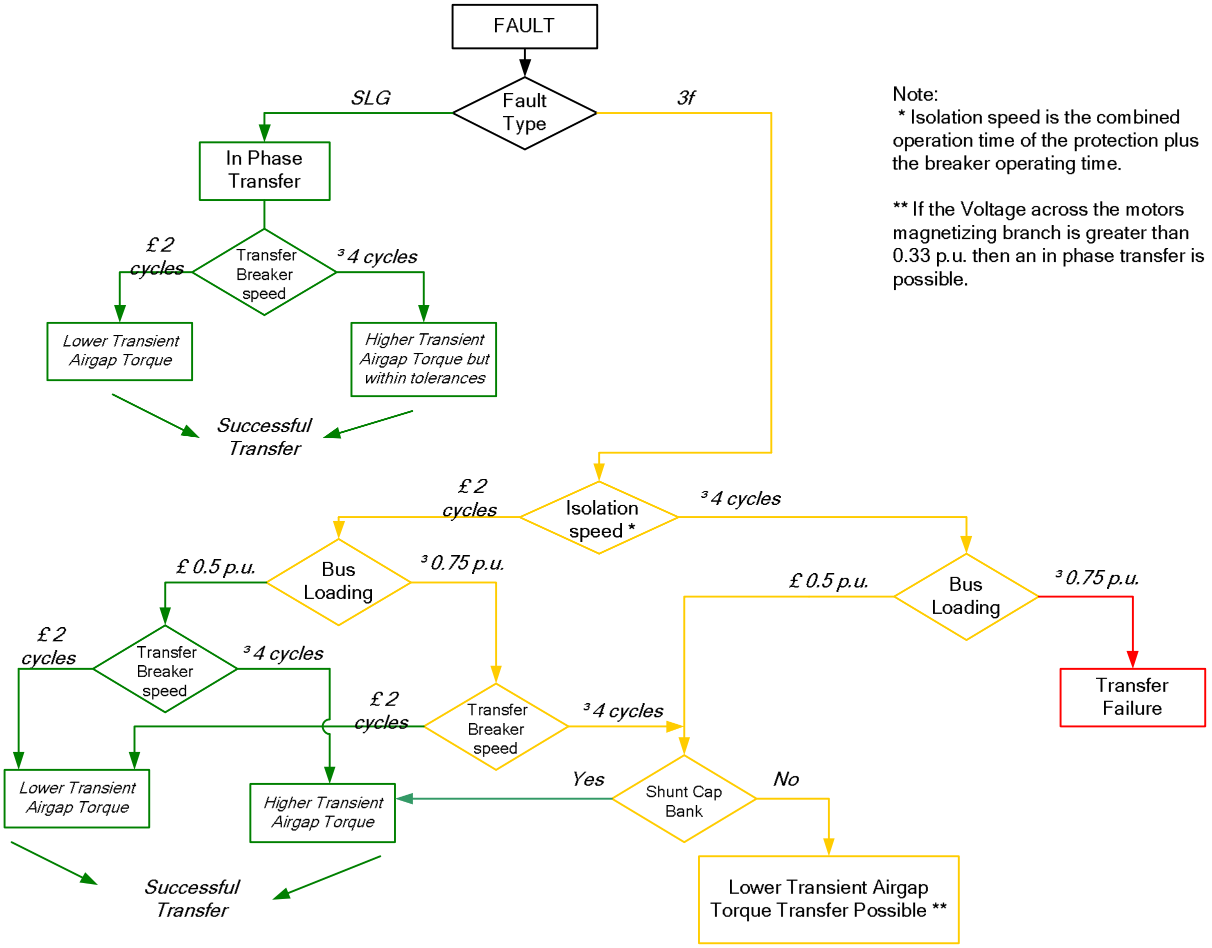
In summary, if a single phase line-to-ground fault occurs prior to the bus being isolated there is a 100% chance of a successful in phase motor bus transfer, irrespective of any of the factors that have been mentioned. However, to ensure that the motors on the bus develop the lowest possible transient airgap torque following the transfer of the motor bus, it is recommend that a bus coupler that has a fast operating mechanism is used. A fast operating mechanism will ensure that the transfer occurs when the two voltages have the lowest possible voltage phase angle between each other when the two buses are connected together.

If the system experiences a three phase fault prior to the bus being isolated then, the following factors play a very decisive role in determining whether the bus can be successfully transferred:

- The operating speed of the line protection and the breaker opening time (the fault clearing time)
- The load on the motor bus at the time of the fault
- Whether the shunt capacitor bank (used for power factor correction) is connected to the bus

Similarly to the single line-to-ground fault, to ensure the development of the least possible transient torque following the motor bus transfer it would be advisable to use a bus coupler breaker that has a fast operating breaker mechanism.

In summary to ensure a successful in-phase motor bus transfer with the lowest possible transient torque development following the transfer the use of high speed line and bus coupler breakers is recommended. Fig. 5.9 is a flow chart that can be used to determine beforehand whether a specific industrial loads such as an industrial facility or mine will experience a successful in-phase motor bus transfer.



Note:
* Isolation speed is the combined operation time of the protection plus the breaker operating time.

** If the Voltage across the motors magnetizing branch is greater than 0.33 p.u. then an in phase transfer is possible.

Fig. 5.9: A simple flow diagram that can be used beforehand to determine whether a specific industrial installation will be suitable for an in-phase motor bus transfer scheme.

The flow diagram in Fig.5.9 can be summarized as follows:

- If a single line to ground fault precedes the isolation of the motor bus, the chances of the motor bus successfully performing an in-phase motor bus transfer are very high. Neither the duration of the single to ground fault, nor the loading of the bus are going to negatively impact the success rate of the in-phase motor bus transfer. The closing time of the transfer breaker plays a role in the transient torque developed by the motors following the in-phase motor bus transfer. If the transfer breaker closes in 2 cycles or less the transient torque developed by the motors is less than 6 p.u., irrespective of the loading of the bus. If the bus is heavily loaded and the transfer breaker closes in 4 cycles or more, then the transient torque developed by the motors can be greater than 6.p.u., in this case the transfer will not be perfectly in-phase. Therefore, the color green is used in the flow diagram for the single line to ground fault scenario, since the chance of a successful in-phase motor bus transfer are high.

- If a three phase fault precedes the isolation of the motor bus then a number of factors impact the chances of a successful in-phase motor bus transfer. The most important of these factors being the time taken to isolate the motor bus from the fault. The longer it takes to isolate motor bus, the lower the chances of a successful in-phase motor bus transfer.
    - If the motor bus is isolated from a three phase fault in less than 2 cycles then the motor bus stand a very good chance of performing a successful in-phase motor bus transfer. The loading of the bus and the operating speed of the transfer breaker are going to impact the transient torque developed by the motors following the in-phase motor bus transfer. The lighter the loading of the bus and the faster the operating speed of the transfer breaker the lower the transient developed by the motor. That is why the color green is used to illustrate the path for the case when the bus is isolated in 2 cycles or less and the loading of the bus is light, since the chances for an in-phase bus transfer a high. When the motor bus is heavily loaded and the transfer breaker has an operating time of 4 cycle or more then there is a possibility that an in-phase motor bus may not occur and for this reason the path is drawn in yellow.

- When the motor bus is isolated from a three phase fault in 4 cycle or more, then the chances of a successful in-phase motor bus transfer are dependent on the loading of the motor bus, if the motor bus is loaded at less than 50% of rated capacity then there is a possibility of a successful in-phase transfer, but if the bus is loaded more than 75% of rated capacity then there is very little chance of an in-phase motor bus transfer, therefore the color red is used to indicate this path.

In summary a green line/path in Fig.5.9 indicates that an in-phase motor bus transfer is high likely. A yellow line/path indicates that here is a good chance of a successful in-phase motor bus transfer and a red line/path indicates a very low chance of a successful in-phase motor bus transfer.

Chapter VI: Conclusion and Future Work

6.1 Summary

The work begins with a comprehensive literature review on what has been done in industry with regards to motor bus transfer in general. The literature review spans a period of roughly 70 years beginning in the 1940's to the present day. Following the literature review, Chapter 2, provides a detailed analysis of a three phase induction motor. A transient model of the induction motor is developed to gain a better understanding of the behavior of an induction motor during bus transfer. Chapter II, concludes with a numerical example of a single motor being transferred to an alternative source. Chapter III, gives an overview of what is presently done in industry with regards to motor bus transfer and discusses some of the short coming of these methods and proposes two new methods of performing an in-phase motor bus transfer. The new methods are independent of frequency, one of the weaknesses of the present day methods. One of these methods is explained and discussed in detail, namely the method that uses both the calculated alpha and beta voltage components, this method is reffered to as method 1. Chapter IV, discusses the implementation of method 1 in a real time digital simulator. Chapter V, discusses the perfomance of the of the in-phase motor bus transfer algorithm contained in Appendix E, for different system operating criteria. From the results obtained in Appendix E it can be seen that the new proposed algorithm works very well, requiring no system studies and very little knowledge about the power system. The goal at the onset of this work was to develop and in-phase motor bus transfer method that would require very little system studies and very little knowledge of the power system and this goal was met.

6.2 Conclusion

Industrial and mining facilities require motor bus transfer schemes to keep critical processes going in the event of one of the supply sources becoming unavailable for a number of reasons. To date before a motor bus transfer scheme is taken into service (commissioned) multiple studies and tests need to be undertaken to ensure a successful bus transfer without damaging any of the motors or there connected loads. However, it is not always possible to foresee, simulate or test all possible scenarios that can occur prior or during a motor bus transfer. This dissertation presents a method whereby a motor bus transfer can be taken into service without requiring any studies or tests. The only information required is; the closing time of the bus coupler breaker (transfer breaker), name plate data from the motor with the highest inertia, and the current measurement from this motor during the isolation period (this current measurement is usually available from the motor protection CT's). The proposed method calculates the instant when the closing signal to the bus coupler breaker is sent, taking the closing time of the breaker mechanism into consideration. In doing so the contacts of the bus coupler breaker close at the instant when the voltages behind the transient impedance of the motor and the alternative power source are in perfect synchronism (in-phase) with each other. Having the circuit breaker contacts close when the two voltages are in perfect synchronism with each other results in the lowest possible transient airgap torque being developed by the motors following the transfer of the motor bus.

6.3 Future Work

The use of large synchronous motors is becoming prevalent in many manufacturing and mining industries to drive large pump and fan loads. This dissertation did not consider synchronous motors so the next logical step would be to include synchronous motors into this environment. Synchronous motors are not as robust as inductions motors. Synchronous motors cannot handle as high of a transient airgap torque as an equivalent size induction motor can. However, the transfer algorithm (method 1) proposed in this dissertation can also be applied if synchronous motors are connected to the motor bus by selecting tighter voltage margins. How to determine these tighter voltage margins can be a definite topic of research especially if a correlate with the construction of the synchronous machine can be made.

Going hand in hand with investigating how to successfully transfer synchronous motors would be to study and investigate the effect of using a static transfer switch [28], [29] instead of mechanically operated circuit breakers. Static switches can transfer the isolated motor bus to the alternative power source in a few hundreds of a microseconds as compared to a few tens of milliseconds required by a mechanical operated transfer breaker.

In addition to monitoring the voltage and current of a motor, the rotor angle measurement could also be used to determine angle of the voltage behind the transient reactance. This dissertation showed that in general the motor bus voltage decayed at a faster rate than the frequency (rotor speed). It becomes difficult to accurately calculate the angle of a voltage that has a small magnitude. Therefore, research to determine at which magnitude of motor voltage to complement the calculated voltage angle on the motor bus using the measured motor angle, could lead to a lower airgap transient torque being developed by the motor.

At present a motor transfer is only regarded as an in-phase transfer if the voltage on the motor bus is greater than 33% of the nominal voltage. This dissertation showed that a successful in phase motor bus transfer can still be executed at a voltage well below this voltage value, since even at a voltage well below 0.33 p.u. an airgap torque of 2-3 times the rated per unit torque is possible if the angular difference between the two voltages is large enough. Further work needs to be done so as to determine when a true residual transfer can occur, so that the angular difference between the two systems results in no significant airgap torque being developed. Furthermore, even when the voltage has totally decayed the chances are good that the motors will still be rotating and transferring the motors to alternative source will still be more viable than having to restart the entire bus when the motors are at standstill. Motors, with rotors that are still rotating, will draw a lower starting current and result in lower voltage dips on the power system than if the motors where at a complete standstill. A subject to research could be to determine at what value of frequency does it becomes non-viable to transfer the motor bus.

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Appendices

Appendix A: Determining the Steady State (constant speed) Eigenvalues Equations:

The characteristic equation for the motor is

$$Z_{ss}Z_{rr} - Z_{sr}Z_{rs} = 0$$

Substitution gives us,

$$[r_s + L_s(p + j\omega)]\left[r_r + L_{sr}\left(p + j(\omega - \omega_r)\right)\right] - [L_m(p + j\omega)]\left[L_m\left(p + j(\omega - \omega_r)\right)\right] = 0$$

Replacing ***p*** by λ and multiplying;

$$\big[r_r r_s + \lambda r_r L_s + j r_r \omega L_s + \lambda r_s L_r + \lambda^2 L_r L_s + j\omega L_s \lambda L_r + j r_s \omega L_r + j\omega L_s \lambda L_r - \omega^2 L_r L_s - j r_s \omega_r L_r - j\omega_r L_r \lambda L_s + \omega\omega_r L_r L_s\big] - \big[\lambda^2 {L_m}^2 + j\omega\lambda {L_m}^2 + j\omega\lambda {L_m}^2 - \omega^2 {L_m}^2 - j\omega_r \lambda {L_m}^2 + \omega\omega_r {L_m}^2\big] = 0$$

Gathering like terms;

λ^2

$\lambda^2 L_r L_s - \lambda^2 {L_m}^2$

$\lambda^2\left(L_r L_s - {L_m}^2\right)$

$\lambda^2 \sigma L_r L_m$ Since $\sigma = 1 - \frac{L_m}{L_r L_s}$

λ

$$\lambda r_r L_s + \lambda r_s L_r + j\lambda\omega L_s L_r + j\lambda\omega L_s L_r - j\lambda\omega_r L_s L_r - j\lambda\omega {L_m}^2 - j\lambda\omega {L_m}^2 + j\lambda\omega_r {L_m}^2$$

$$\lambda r_r L_s + \lambda r_s L_r + j2\lambda\omega L_s L_r - j\lambda\omega_r L_s L_r - j2\lambda\omega {L_m}^2 + j\lambda\omega_r {L_m}^2$$

$$\lambda r_r L_s + \lambda r_s L_r + j2\lambda\omega\left(L_s L_r - {L_m}^2\right) - j\lambda\omega_r\left(L_s L_r - {L_m}^2\right)$$

$$\lambda r_r L_s + \lambda r_s L_r + j2\lambda\omega\sigma L_s L_r - j\lambda\omega_r\sigma L_s L_r$$

$$\lambda\left(r_r L_s + r_s L_r + j\sigma L_s L_r\,(2\omega - \omega_r)\right)$$

λ^0

$$r_s r_r + jr_r\omega L_s + jr_s\omega L_r - \omega^2 L_s L_r - jr_s\omega_r L_r + \omega\omega_r L_s L_r + \omega^2 {L_m}^2 - \omega\omega_r {L_m}^2$$

$$r_s r_r + jr_r\omega L_s + jr_s\omega L_r - \omega^2\left(L_s L_r - {L_m}^2\right) - jr_s\omega_r L_r + \omega\omega_r\left(L_s L_r - {L_m}^2\right)$$

$$r_s r_r + j\omega(r_r L_s + r_s L_r) + jr_s\omega L_r - \omega^2\sigma L_s L_r - jr_s\omega_r L_r + \omega\omega_r\sigma L_s L_r$$

$$r_s r_r - \omega\sigma L_s L_r(\omega - \omega_r) + j(r_s L_r(\omega - \omega_r) + r_{rs}\omega L_r)$$

Therefore

$$\lambda^2\sigma L_r L_m + \lambda\left(r_r L_s + r_s L_r + j\sigma L_s L_r\,(2\omega - \omega_r)\right) + r_s r_r - \omega\sigma L_s L_r(\omega - \omega_r) +$$

$$j(r_s L_r(\omega - \omega_r) + r_{rs}\omega L_r) = 0$$

This is a quadratic equation and using the standard solution for the quadratic equation,

$$\lambda = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

We solve for λ

Where:

$$a = \lambda^2 \sigma L_r L_m$$

$$b = \lambda\big(r_r L_s + r_s L_r + j\sigma L_s L_r\,(2\omega - \omega_r)\big)$$

$$c = r_s r_r - \omega\sigma L_s L_r(\omega - \omega_r\,) + \; j(r_s L_r(\omega - \omega_r) + r_{rs}\omega L_r\,)$$

Solving for $\frac{-b}{2a}$;

$$= \frac{r_r L_s + r_s L_r + j\sigma L_r L_s(2\omega - \omega_r)}{2\sigma L_r L_s}$$

$$= -\frac{r_r L_s}{2\sigma L_r L_s} - \frac{r_s L_r}{2\sigma L_r L_s} - \frac{j\sigma L_r L_s(2\omega - \omega_r)}{2\sigma L_r L_s}$$

$$= \frac{-1}{2\sigma\tau_r} - \frac{1}{2\sigma\tau_s} - \frac{j(2\omega - \omega_r)}{2}$$

$$= -\frac{1}{2}\left(\frac{1}{\tau_r{'}} + \frac{1}{\tau_s{'}}\right) + j\left(\frac{\omega_r}{2} - \omega\right)$$

Where: $\tau_r' = \sigma\tau_r$ = rotor short circuit time constant

$\tau_s' = \sigma\tau_s$ = stator short circuit time constant

Solving for $\frac{\sqrt{b^2-4ac}}{2a}$;

$$\frac{\sqrt{b^2 - 4ac}}{2a} = \sqrt{\frac{b^2 - 4ac}{4a^2}} = \sqrt{\frac{b^2}{4a^2} - \frac{c}{a}}$$

Determining; $\frac{b^2}{4a^2} = \left(\frac{-b}{2a}\right)^2$

$$= \left\{-\frac{1}{2}\left(\frac{1}{\tau_r'} + \frac{1}{\tau_s'}\right) + j\left(\frac{\omega_r}{2} - \omega\right)\right\}^2$$

$$= \left\{\left(-\frac{1}{2}\left(\frac{1}{\tau_r'} + \frac{1}{\tau_s'}\right)\right)^2 + 2\left(-\frac{1}{2}\left(\frac{1}{\tau_r'} + \frac{1}{\tau_s'}\right)\right)\left(j\left(\frac{\omega_r}{2} - \omega\right)\right) + \left(j\left(\frac{\omega_r}{2} - \omega\right)\right)^2\right\}$$

$$= \left\{\frac{1}{4}\left(\frac{1}{\tau_r'} + \frac{1}{\tau_s'}\right)^2 - j\left(\frac{1}{\tau_r'} + \frac{1}{\tau_s'}\right)\left(\frac{\omega_r}{2} - \omega\right) - \left(\frac{\omega_r}{2} - \omega\right)^2\right\}$$

Determining; $\frac{c}{a}$

$$= \frac{r_s r_r - \omega\sigma L_s L_r(\omega - \omega_r) + j(r_s L_r(\omega - \omega_r) + r_r \omega L_s)}{\sigma L_s L_r}$$

$$= \frac{1}{\sigma\tau_s\tau_r} - \omega(\omega - \omega_r) + j\frac{(\omega - \omega_r)}{\sigma\tau_s} + j\frac{\omega}{\sigma\tau_r}$$

Let, $\sigma\tau_r = \tau_r'$ and $\sigma\tau_s = \tau_s'$

$$= \frac{\sigma}{\tau_s'\tau_r'} - \omega(\omega - \omega_r) + j\frac{(\omega - \omega_r)}{\tau_s'} + j\frac{\omega}{\tau_r'}$$

Therefore $\left(\frac{-b}{2a}\right)^2 - \frac{c}{a}$ is;

$$= \frac{1}{4}\left(\frac{1}{\tau_r'} + \frac{1}{\tau_s'}\right)^2 - j\left(\frac{1}{\tau_r'} + \frac{1}{\tau_s'}\right)\left(\frac{\omega_r}{2} - \omega\right) - \left(\frac{\omega_r}{2} - \omega\right)^2 - \frac{\sigma}{\tau_s'\tau_r'} + \omega(\omega - \omega_r)$$
$$- j\frac{(\omega - \omega_r)}{\tau_s'} - j\frac{\omega}{\tau_r'}$$

$$= \frac{1}{4}\left(\frac{1}{\tau_r{}'} + \frac{1}{\tau_s{}'}\right)^2 - j\left(\frac{\omega_r}{2\tau_r{}'} - \frac{\omega}{\tau_r{}'} - \frac{\omega}{\tau_s{}'} + \frac{\omega_r}{2\tau_s{}'}\right) - \left(\frac{\omega_r{}^2}{2} - \omega_r\omega + \omega^2\right) - \frac{\sigma}{\tau_s{}'\tau_r{}'} + \omega^2 - \omega_r\omega \; -$$

$$j\frac{\omega}{\tau_s{}'} + j\frac{\omega_r}{\tau_s{}'} - j\frac{\omega}{\tau_r{}'}$$

$$= \frac{1}{4}\left(\frac{1}{\tau_r{}'} + \frac{1}{\tau_s{}'}\right)^2 - j\frac{\omega_r}{2\tau_r{}'} + j\frac{\omega_r}{2\tau_s{}'} - \frac{\omega_r{}^2}{4} - \frac{\sigma}{\tau_r{}'\tau_s{}'}$$

$$= \frac{1}{4}\left(\frac{1}{\tau_r{}'} + \frac{1}{\tau_s{}'}\right)^2 - \frac{\omega_r{}^2}{4} - \frac{\sigma}{\tau_r{}'\tau_s{}'} + j\frac{\omega_r}{2}\left(\frac{1}{\tau_s{}'} - \frac{1}{\tau_r{}'}\right)$$

Therefore $\sqrt{\frac{b^2}{4a^2} - \frac{c}{a}}$ is;

$$= \pm\frac{1}{2}\sqrt{\left(\frac{1}{\tau_r{}'} + \frac{1}{\tau_s{}'}\right)^2 - \omega_r{}^2 - \frac{4\sigma}{\tau_r{}'\tau_s{}'} + j2\omega_r\left(\frac{1}{\tau_s{}'} - \frac{1}{\tau_r{}'}\right)}$$

And finally $-\frac{b}{2a} \pm \sqrt{\frac{b^2}{4a^2} - \frac{c}{a}}$ gives us the value for λ1 and λ2 where,

$$\lambda_1 = -\frac{1}{2}\left(\frac{1}{\tau_r{}'} + \frac{1}{\tau_s{}'}\right) + j\left(\frac{\omega_r}{2} - \omega\right) + \frac{1}{2}\sqrt{\left(\frac{1}{\tau_r{}'} + \frac{1}{\tau_s{}'}\right)^2 - \omega_r{}^2 - \frac{4\sigma}{\tau_r{}'\tau_s{}'} + j2\omega_r\left(\frac{1}{\tau_s{}'} - \frac{1}{\tau_r{}'}\right)}$$

and

$$\lambda_2 = -\frac{1}{2}\left(\frac{1}{\tau_r{}'} + \frac{1}{\tau_s{}'}\right) + j\left(\frac{\omega_r}{2} - \omega\right) - \frac{1}{2}\sqrt{\left(\frac{1}{\tau_r{}'} + \frac{1}{\tau_s{}'}\right)^2 - \omega_r{}^2 - \frac{4\sigma}{\tau_r{}'\tau_s{}'} + j2\omega_r\left(\frac{1}{\tau_s{}'} - \frac{1}{\tau_r{}'}\right)}$$

Appendix B: Determining the equation for computing C1–C4:

The transient equations for the induction motors rotor and stator are as given by equations [39] and [40]. Using the transient equation for the stator, equation [39];

$$i_{qds}(t) = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + I_{ss} e^{j\omega t}$$

We can say that at time, t=0 that the current is;

$$i_{qds}(0) = C_1 + C_2 + I_{ss} \tag{B.1}$$

And that of the derivative of the current is;

$$pi_{qds}(0) = \lambda_1 C_1 + \lambda_2 C_2 + j\omega_e I_{ss} \tag{B.2}$$

Manipulating equation (B.2) to obtain C_1,

$$C_1 = i_{qds}(0) - C_2 - I_{ss} \tag{B.3}$$

Substituting equation (B.3) into equation (B.2) and solve for C_2,

$$pi_{qds}(0) = \lambda_1 i_{qds}(0) - \lambda_1 C_2 - \lambda_1 I_{ss} + \lambda_2 C_2 + j\omega_e I_{ss}$$

$$C_2(\lambda_2 - \lambda_1) = pi_{qds}(0) - \lambda_1 i_{qds}(0) + \lambda_1 I_{ss} + j\omega_e I_{ss}$$

$$C_2 = \frac{pi_{qds}(0) - \lambda_1 i_{qds}(0) + (\lambda_1 - j\omega_e) I_{ss}}{(\lambda_2 - \lambda_1)} \tag{B.4}$$

Substituting (B.4) into equation (B.3) and solving for C_1,

$$C_1 = i_{qds}(0) - \frac{pi_{qds}(0) - \lambda_1 i_{qds}(0) + (\lambda_1 - j\omega_e) I_{ss}}{(\lambda_2 - \lambda_1)} - I_{ss}$$

$$C_1 = \frac{i_{qds}(0)(\lambda_2 - \lambda_1) - \; pi_{qds}(0) + \lambda_1 i_{qds}(0) - \; (\lambda_1 - j\omega_e)I_{ss} - I_{ss}\,(\lambda_2 - \lambda_1)}{(\lambda_2 - \lambda_1)}$$

$$C_1 = \frac{-pi_{qds}(0) + \lambda_2 i_{qds}(0) + (j\omega_e - \lambda_2)I_{ss}}{(\lambda_2 - \lambda_1)}$$

If we now use the transient equation [40] for the rotor transient current and follow the same procedure

$$i_{qdr}(t) = C_3 e^{\lambda_1 t} + C_4 e^{\lambda_2 t} + I_{sr} e^{j\omega t}$$

Where at time zero, t=0, the rotor current can be expressed as;

$$i_{qdr}(0) = C_3 + C_4 + I_{sr} \tag{B.5}$$

And the derivative of the rotor current as;

$$pi_{qdr}(0) = \lambda_1 C_3 + \lambda_2 C_4 + j\omega_e I_{sr} \tag{B.6}$$

Rewriting equation (B.5) so that C$_3$ is the subject,

$$C_3 = i_{qdr}(0) - C_4 - I_{sr} \tag{B.7}$$

Substituting equation (B.7) into equation (B.6) and solving for C$_4$;

$$pi_{qdr}(0) = \lambda_1 i_{qdr}(0) - \lambda_1 C_4 - \lambda_1 + \lambda_2 C_4 + j\omega_e I_{sr}$$

$$C_4(\lambda_2 - \lambda_1) = pi_{qdr}(0) - \lambda_1 i_{qdr}(0) + \lambda_1 I_{sr} - j\omega_e I_{sr}$$

$$C_4 = \frac{pi_{qdr}(0) - \lambda_1 i_{qdr}(0) + (\lambda_1 - j\omega_e)I_{sr}}{(\lambda_2 - \lambda_1)} \tag{B.8}$$

Substituting equation (B.8) into equation (B.7) and solving for C3;

$$C_3 = i_{qdr}(0) - \left(\frac{pi_{qdr}(0) - \lambda_1 i_{qdr}(0) + (\lambda_1 - j\omega_e)I_{sr}}{(\lambda_2 - \lambda_1)}\right) - I_{sr}$$

$$C_3 = \frac{i_{qdr}(0)(\lambda_2 - \lambda_1) - pi_{qdr}(0) + \lambda_1 i_{qdr}(0) - (\lambda_1 - j\omega_e)I_{sr} - I_{sr}}{\lambda_2 - \lambda_1}$$

$$C_3 = \frac{-pi_{qdr}(0) + \lambda_2 i_{qdr}(0) + (j\omega_e - \lambda_2)I_{sr}}{\lambda_2 - \lambda_1}$$

Appendix C: Deriving the equations for computing the derivatives of the stator and rotor currents for the condition of the motor reconnected to the supply

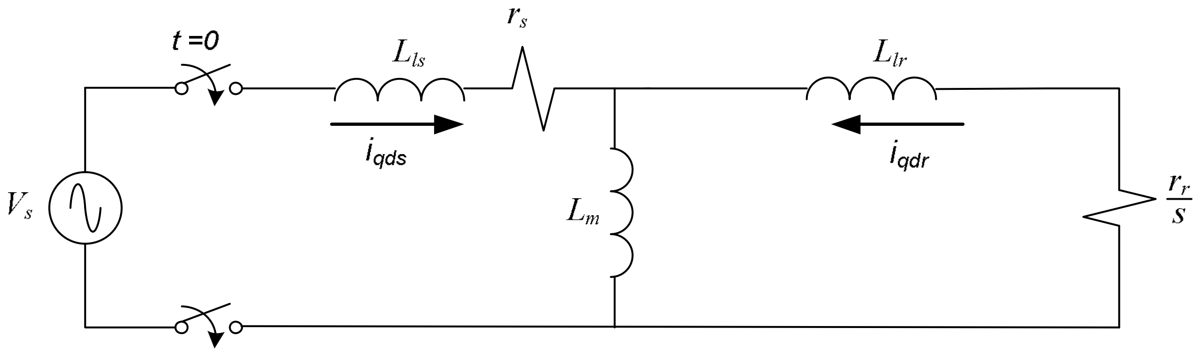

Fig. C.1 The equivalent circuit model of an induction motor used to calculate the derivatives of the stator and rotor currents after the motor has been connected to an alternative power supply

Using the complex induction motor equations given by equations [23] and [24] and the initial condition we can determine the equations to calculate the derivatives of the stator (pi_{qds}) and rotor (pi_{qdr}) currents.

$$v_S = \{r_s + L_s(p + j\omega)\} \cdot i_{qds} + L_m(p + j\omega) \cdot i_{qdr} \tag{C.1}$$

$$0 = \{L_m(p + j(\omega - \omega_r))\} \cdot i_{qds} + \{r_r + L_r(p + j(\omega - \omega_r))\} \cdot i_{qdr} \tag{C.2}$$

Where v_S is the supply voltage when the motor is reconnected, using the rotor reference frame ($\omega = \omega_r$) equations (C.1) and (C.2) become,

$$v_S = \{r_s + L_s(p + j\omega_r)\} \cdot i_{qds} + L_m(p + j\omega_r) \cdot i_{qdr} \tag{C.3}$$

$$0 = L_m \cdot i_{qds} + \{r_r + L_r p\} \cdot i_{qdr} \tag{C.4}$$

Extracting the derivative terms,

$$\begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} pi_{qds} \\ pi_{qdr} \end{bmatrix} = \begin{bmatrix} -(r_s + j\omega_r L_s) & -j\omega_r L_r \\ 0 & r_r \end{bmatrix} \begin{bmatrix} i_{qds} \\ i_{qdr} \end{bmatrix} + \begin{bmatrix} V_s \\ 0 \end{bmatrix}$$

Letting $L = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix}$ and $Z = \begin{bmatrix} -(r_s + j\omega_r L_s) & -j\omega_r L_r \\ 0 & r_r \end{bmatrix}$

Resulting in,

$$\begin{bmatrix} pi_{qds} \\ pi_{qdr} \end{bmatrix} = L^{-1} Z \begin{bmatrix} i_{qds} \\ i_{qdr} \end{bmatrix} + L^{-1} \begin{bmatrix} V_s \\ 0 \end{bmatrix}$$

Where:

$$L^{-1} = \frac{1}{L_s L_r - {L_m}^2} \begin{bmatrix} L_r & -L_m \\ -L_m & L_s \end{bmatrix}$$

The coupling coefficient (σ) is defined as

$$\sigma = 1 - \frac{{L_m}^2}{L_s L_r}$$

$$L_s L_r - {L_m}^2 = L_s L_r \left(1 - \frac{{L_m}^2}{L_s L_r} \right) = \sigma L_s L_r$$

Giving,

$$\begin{bmatrix} pi_{qds} \\ pi_{qdr} \end{bmatrix} = \begin{bmatrix} \frac{1}{\sigma L_s} & \frac{-L_m}{\sigma L_s L_r} \\ \frac{-L_m}{\sigma L_s L_r} & \frac{1}{\sigma L_r} \end{bmatrix} \begin{bmatrix} -(r_s + j\omega_r L_s) & -j\omega_r L_m \\ 0 & -r_r \end{bmatrix} \begin{bmatrix} i_{qds} \\ i_{qdr} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & \frac{-L_m}{\sigma L_s L_r} \\ \frac{-L_m}{\sigma L_s L_r} & \frac{1}{\sigma L_r} \end{bmatrix} \begin{bmatrix} V_s \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} \frac{-L_r(r_s + j\omega_r L_s)}{\sigma L_s L_r} & \left(\frac{-j\omega_r L_r L_m + r_r L_m}{\sigma L_s L_r}\right) \\ \frac{L_m(r_s + j\omega_r L_s)}{\sigma L_s L_r} & \frac{j\omega_r {L_m}^2 - r_r L_s}{\sigma L_s L_r} \end{bmatrix} \begin{bmatrix} i_{qds} \\ i_{qdr} \end{bmatrix} + \begin{bmatrix} \frac{L_r V_s}{\sigma L_s L_r} \\ \frac{-L_m V_s}{\sigma L_s L_r} \end{bmatrix}$$

Therefore the derivative terms are as follows:

$$pi_{qds} = \frac{-L_r(r_s + j\omega_r L_s)}{\sigma L_s L_r} i_{qds} + \left(\frac{-j\omega_r L_m L_r + r_r L_m}{\sigma L_s L_r}\right) i_{qdr} + \frac{L_r V_s}{\sigma L_s L_r}$$

$$pi_{qdr} = \frac{L_m(r_s + j\omega_r L_s)}{\sigma L_s L_r} i_{qds} + \left(\frac{j\omega_r {L_m}^2 - r_r L_s}{\sigma L_s L_r}\right) i_{qdr} - \frac{L_m V_s}{\sigma L_s L_r}$$

Appendix D: Calculating the magnitude of vector using two consecutive samples

Assume we had to consecutive sample as shown in Fig. D.1, these consecutive samples can be identified as V_k and V_{k-1} respectively.

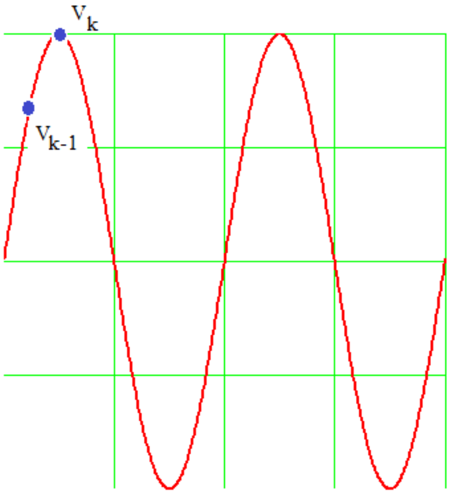

Fig. D.1 A simple sketch showing two consecutive samples of a sinusoidal voltage or current waveform.

We can express V_k and V_{k-1} as follows:

$$V_k = V\sin(\omega t_k) \tag{D.1}$$

$$V_{k-1} = V\sin(\omega t_{k-1})$$

$$= V\sin[\omega(t_k - \Delta t)]$$

$$= V\sin(\omega t_k)\cos(\omega\Delta t) - V\sin(\omega\Delta t)\cos(\omega t_k) \tag{D.2}$$

Substituting equation (D.1) into equation (D.2)

$$V_{k-1} = V_k \cos(\omega\Delta t) - V \sin(\omega\Delta t)\cos(\omega t_k)$$

$$V\cos(\omega t_k) = \frac{V_k \cos(\omega\Delta t) - V_{k-1}}{\sin(\omega\Delta t)} \tag{D.3}$$

Squaring Equation (D.3)

$$V^2\cos^2(\omega t_k) = \left[\frac{V_k \cos(\omega\Delta t) - V_{k-1}}{\sin(\omega\Delta t)}\right]^2 \tag{D.4}$$

If we now add V_k^2 to both side of the equation we obtain

$$V^2\cos^2(\omega t_k) + V_k^2 = V_k^2 + \left[\frac{V_k \cos(\omega\Delta t) - V_{k-1}}{\sin(\omega\Delta t)}\right]^2 \tag{D.5}$$

But from equation (D.1) we know that

$${V_k}^2 = V^2\sin^2(\omega t_k) \tag{D.6}$$

If we now substitute equation (D.6) into the LHS of equation (D.5)

$$V^2\cos^2(\omega t_k) + V^2\sin^2(\omega t_k) = V_k^2 + \left[\frac{V_k \cos(\omega\Delta t) - V_{k-1}}{\sin(\omega\Delta t)}\right]^2 \tag{D.7}$$

If we expand equation (D.7)

$$V^2\cos^2(\omega t_k) + V^2\sin^2(\omega t_k) = V_k^2 + \frac{{V_k}^2\cos^2(\omega\Delta t) - 2V_kV_{k-1}\cos(\omega\Delta t) + {V_{k-1}}^2}{\sin^2(\omega\Delta t)} \tag{D.8}$$

But we know that

$$V^2\cos^2(\omega t_k) + V^2\sin^2(\omega t_k) = V^2 \tag{D.9}$$

Substitute equation (D.9) in equation (D.8) and bringing everything on the RHS under a common denominator

$$\mathrm{V}^2 = \frac{V_k^2 \sin^2(\omega\Delta t) + {V_k}^2 \cos^2(\omega\Delta t) - 2V_k V_{k-1} \cos(\omega\Delta t) + {V_{k-1}}^2}{\sin^2(\omega\Delta t)} \qquad \text{(D.10)}$$

Taking the square root of equation (D.10), and reducing the first to numerator terms on the RHS of the equation:

$$\mathrm{V} = \sqrt{\frac{V_k^2 - 2V_k V_{k-1} \cos(\omega\Delta t) + {V_{k-1}}^2}{\sin^2(\omega\Delta t)}} \qquad \text{(D.11)}$$

Where:

$$\omega\Delta t = \frac{2\pi f}{f_s}$$

f = nominal system frequency

f_s = sampling frequency

Equation (D.11) is what is used to calculate the magnitude from two consecutive samples.

Appendix E: Results

The following section contains all the results for when the power line is subjected to a single-line-to-ground fault or three phase fault prior to the motor bus being isolated. Once the motor bus is isolated the in-phase transfer algorithm is enabled and the motor bus is transferred to the alternative power source. This section contains the following data, the transient torque developed by the motor during the fault condition, the voltage and frequency on the motor bus prior to the motor bus being transferred to the alternative. Once the motor bus has been transferred the transient torque develop by the motor, the steady state voltage on the following the motor bus transfer and whether the voltage on the bus remained within the ITI curve limits.

Sections E1 and E2, document the results for the in-phase motor bus transfer following the isolation of the motor bus. For the single line to ground fault test cases (Section E.1) all motor bus transfer where successful. In each of the cases the transient torque developed by the motor following the in-phase transfer where less than 6.0 p.u. For the three phase fault test cases (Section E.2) all of the majority of the test cases where successful the exception being the following test cases:

- Case 319 to case 324, case 349 to case 360 and case 373 to case 378, the reason for these cases failing to execute a successful in-phase motor bus transfer was that the voltage across the motor magnetizing branch was lower than 0.33 V p.u. The reason that the voltage across the motor magnetizing branch fell below the allowable in-phase transfer limit was that the bus was only isolated from the three phase fault 4 cycles after the fault was initiated (fault clearing time was 4 cycles) . In conjunction with the slow isolation of the motor bus the bus was loaded at 75% of it rating. The combination of the slow clearing time of the motor bus and the heavy loading of the bus resulted in the voltage across the magnetizing branch being lower than 0.33 V p.u when the motor bus voltage and alternative source voltage came into phase with each and prevent an in-phase bus transfer.

E.1 Single Line to Ground Faults (SLG):

Case 1:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 4.24 p.u., -2.05 p.u., -5.17 p.u.

Reclose Frequency and Voltage (motor bus) = 51.84Hz; 0.780 kV

Steady State Voltage = 1.318 kV (99.2%)

Meet ITI specification = yes

Case 2:

Fault Duration ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.86 p.u., -1.72 p.u., -4.95 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3Hz, 0.698 kV

Steady State Voltage = 1.311 kV (98.7%)

Meet ITI specification = yes

Case 3:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.79 p.u., -2.0 p.u., -5.3 p.u,

Reclose Frequency and Voltage (motor bus) = 51.92 Hz, 0.753 kV

Steady State Voltage = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 4:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.52 p.u., -1.83 p.u., -5.07 p.u,

Reclose Frequency and Voltage (motor bus) = 52.2 Hz, 0.730 kV

Steady State Voltage = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 5:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -5.82 p.u., -1.90 p.u., -5.4 p.u,

Reclose Frequency and Voltage (motor bus) = 51.9 Hz, 0.764 kV

Steady State Voltage = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 6:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -5.5 p.u., -1.90 p.u., -5.17 p.u,

Reclose Frequency and Voltage (motor bus) = 52.2 Hz, 0.726 kV

Steady State Voltage = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 7:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.0 p.u, -1.2 p.u, -4.6 p.u.

Reclose Frequency and Voltage (motor bus) = 51.6 Hz, 0.576 kV

Steady State Voltage = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 8:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.9 p.u, -1.0 p.u, -4.5 p.u.

Reclose Frequency and Voltage (motor bus) = 51.47 Hz, 0.523 kV

Steady State Voltage = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 9:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.95 p.u, -1.29 p.u, -4.42 p.u.

Reclose Frequency and Voltage (motor bus) = 51.05 Hz, 0.562 kV

Steady State Voltage = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 10:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.52 p.u, -1.17 p.u, -4.4 p.u.

Reclose Frequency and Voltage (motor bus) = 51.47 Hz, 0.510 kV

Steady State Voltage = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 11:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -5.2 p.u, -1.17 p.u, -4.2 p.u.

Reclose Frequency and Voltage (motor bus) = 51.05 Hz, 0.553 kV

Steady State Voltage = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 12:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -5.1 p.u, -1.12 p.u, -4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 51.4 Hz, 0.517 kV

Steady State Voltage = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 13:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.0 p.u, -0.8 p.u, -4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 51.05 Hz, 0.466 kV

Steady State Voltage = 1.296 kV *(97.4%)*

Meet ITI specification =yes

Case 14:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.64 p.u, -0.63 p.u, -4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 51.57 Hz, 0.411 kV

Steady State Voltage = 1.288 kV *(97%)*

Meet ITI specification = yes

Case 15:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.31 p.u, -0.91 p.u, -4.1 p.u.

Reclose Frequency and Voltage (motor bus) = 51.05 Hz, 0.455 kV

Steady State Voltage = 1.296 kV *(97.4%)*

Meet ITI specification = yes

Case 16:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.0 p.u, -0.8 p.u, -4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 50.87 Hz, 0.425 kV

Steady State Voltage = 1.288 kV *(97%)*

Meet ITI specification = yes

Case 17:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.63 p.u, -0.9 p.u, -3.7 p.u.

Reclose Frequency and Voltage (motor bus) = 51.05 Hz, 0.455 kV

Steady State Voltage = 1.296 kV *(97.4%)*

Meet ITI specification = yes

Case 18:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.46 p.u, -0.8 p.u, -3.63 p.u.

Reclose Frequency and Voltage (motor bus) = 50.9 Hz, 0.410 kV

Steady State Voltage = 1.288 kV *(97%)*

Meet ITI specification = yes

Case 19:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -3.75 p.u., -1.72 p.u., -4.85 p.u.

Reclose Frequency and Voltage (motor bus) = 52.63 Hz, 0.731 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.5%)*

Meet ITI specification = yes

Case 20:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -3.64 p.u., -1.51 p.u., -4.7 p.u.

Reclose Frequency and Voltage (motor bus) = 52.26 Hz, 0.684 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(97.8%)*

Meet ITI specification = yes

Case 21:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -4.8 p.u., -1.9 p.u., -5.0 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.731kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.5%)*

Meet ITI specification = yes

Case 22:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -4.7 p.u., -1.67 p.u., -4.9 p.u.

Reclose Frequency and Voltage (motor bus) = 52.88 Hz, 0.682 kV

Steady State Voltage (V_{LN}) = 1.299 kV (97.8%)

Meet ITI specification = yes

Case 23:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -5.9 p.u., -1.7 p.u., -4.9 p.u.

Reclose Frequency and Voltage (motor bus) = 51.84 Hz, 0.698 kV

Steady State Voltage (V_{LN}) = 1.309 kV (98.5%)

Meet ITI specification = yes

Case 24:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -5.1 p.u., -1.67 p.u., -4.2 p.u.

Reclose Frequency and Voltage (motor bus) = 52.35 Hz, 0.683 kV

Steady State Voltage (V_{LN}) = 1.299 *(97.8%)*

Meet ITI specification = yes

Case 25:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -3.5 p.u., -1.0 p.u., -4.2 p.u.

Reclose Frequency and Voltage (motor bus) = 51.7 Hz, 0.498 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 26:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -3.54 p.u., -0.8 p.u., -4.1 p.u.

Reclose Frequency and Voltage (motor bus) = 51.7 Hz, 0.507 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 27:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -4.46 p.u., -1.12 p.u., -4.08 p.u.

Reclose Frequency and Voltage (motor bus) = 51.44 Hz, 0.509 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 28:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -4.02 p.u., -0.9 p.u., -4.14 p.u.

Reclose Frequency and Voltage (motor bus) = 51.68 Hz, 0.476 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 29:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -4.7 p.u., -0.95 p.u., -4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 51.45 Hz, 0.52 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 30:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -4.52 p.u., -0.95 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 51.7 Hz, 0.466 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 31:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.0 p.u.

Reclose Torque = -3.47 p.u., -0.58 p.u., -3.75 p.u.

Reclose Frequency and Voltage (motor bus) = 51.32 Hz, 0.400 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 32:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.0 p.u.

Reclose Torque = -3.15 p.u., -0.46 p.u., -3.64 p.u.

Reclose Frequency and Voltage (motor bus) = 51.75 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 33:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.0 p.u.

Reclose Torque = -3.58 p.u., -0.69 p.u., -3.70 p.u.

Reclose Frequency and Voltage (motor bus) = 51.54 Hz, 0.433 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 34:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.0 p.u.

Reclose Torque = -3.53 p.u., -0.58 p.u., -3.64 p.u.

Reclose Frequency and Voltage (motor bus) = 51.4 Hz, 0.382 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 35:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.0 p.u.

Reclose Torque = -4.2 p.u., -0.7 p.u., - 3.27 p.u.

Reclose Frequency and Voltage (motor bus) = 52.23 Hz, 0.400 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 36:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.0 p.u.

Reclose Torque = -3.86 p.u., -0.7 p.u., -3.42 p.u.

Reclose Frequency and Voltage (motor bus) = 51.4 Hz, 0.382 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 37:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.2 p.u.

Reclose Torque = -3.86 p.u., -1.62 p.u., -4.63 p.u.

Reclose Frequency and Voltage (motor bus) = 52.76 Hz, 0.712 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 38:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.1 p.u.

Reclose Torque = -3.37 p.u., -1.34 p.u., -4.35 p.u.

Reclose Frequency and Voltage (motor bus) = 52.52 Hz, 0.698 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 39:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.1 p.u.

Reclose Torque = -4.35 p.u., -1.72 p.u., -4.74 p.u.

Reclose Frequency and Voltage (motor bus) = 52.76 Hz, 0.698 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 40:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.1 p.u.

Reclose Torque = -3.86 p.u., -1.41 p.u., -4.52 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.665 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 41:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.1 p.u.

Reclose Torque = -5.5 p.u., -1.5 p.u., -4.63 p.u.

Reclose Frequency and Voltage (motor bus) = 51.97 Hz, 0.698 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 42:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3.0 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.1 p.u.

Reclose Torque = -4.68 p.u., -1.50 p.u., -4.62 p.u.

Reclose Frequency and Voltage (motor bus) = 52.52 Hz, 0.665 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 43:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.64 p.u., -0.8 p.u., -3.9 p.u.

Reclose Frequency and Voltage (motor bus) = 51.7 Hz, 0.498 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 44:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.28 p.u., -0.6 p.u., -3.8 p.u.

Reclose Frequency and Voltage (motor bus) = 51.92 Hz, 0.479 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 45:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -4.0 p.u., -0.86 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 51.88 Hz, 0.479 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 46:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.6 p.u., -0.74 p.u., -3.8 p.u.

Reclose Frequency and Voltage (motor bus) = 51.89 Hz, 0.452 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 47:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -4.52 p.u., -0.8 p.u., -3.42 p.u.

Reclose Frequency and Voltage (motor bus) = 51.89 Hz, 0.479 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 48:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -4.13 p.u., -0.8 p.u., -3.64 p.u.

Reclose Frequency and Voltage (motor bus) = 51.98 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 49:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -2.86 p.u., -0.35 p.u., -3.43 p.u.

Reclose Frequency and Voltage (motor bus) = 51.75 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 50:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.8 p.u.

Reclose Torque = -2.74 p.u., -0.27 p.u., -3.31 p.u.

Reclose Frequency and Voltage (motor bus) = 51.57 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.242 kV (93.5%)

Meet ITI specification = yes

Case 51:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -3.54 p.u., -0.52 p.u., -3.37 p.u.

Reclose Frequency and Voltage (motor bus) = 51.75 Hz, 0.424 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 52:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -3.2 p.u., -0.4 p.u., -3.35 p.u.

Reclose Frequency and Voltage (motor bus) = 51.7 Hz, 0.38 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 53:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -3.64 p.u., -0.52 p.u., -3.2 p.u.

Reclose Frequency and Voltage (motor bus) = 51.57 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 54:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -3.47 p.u., -0.44 p.u., -3.23 p.u.

Reclose Frequency and Voltage (motor bus) = 51.4 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 55: [Change Inertia of Motor 2 (M2) from 0.75s to 1.15s]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.45 p.u.

Reclose Torque = - 3.97 p.u., -1.67 p.u., -5.1 p.u.

Reclose Frequency and Voltage (motor bus) = 53.05 Hz, 0.744 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 56:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.45 p.u.

Reclose Torque = -3.6 p.u., -1.3 p.u., - 4.8 p.u.

Reclose Frequency and Voltage (motor bus) = 52.84 Hz, 0.735 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 57:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.45 p.u.

Reclose Torque = - 4.57 p.u., -1.78 p.u., -5.17 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.764 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 58:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.45 p.u.

Reclose Torque = -4.6 p.u., -1.67 p.u., - 5.0 p.u

Reclose Frequency and Voltage (motor bus) = 52.8 Hz, 0.734 kV

Steady State Voltage = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 59:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.45 p.u.

Reclose Torque = - 5.85 p.u., -1.95 p.u., -5.4 p.u.

Reclose Frequency and Voltage (motor bus) = 52.4 Hz, 0.744 kV

Steady State Voltage = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 60:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.45 p.u.

Reclose Torque = -5.15 p.u., -1.72 p.u., - 4.3 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.726 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 61:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.40 p.u.

Reclose Torque = -4.0 p.u., -1.3 p.u., - 4.55 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3 Hz, 0.51 kV

Steady State Voltage (V_{LN}) = 1.303 kV (*98.1%)*

Meet ITI specification = yes

Case 62:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.40 p.u.

Reclose Torque = - 3.6 p.u., -0.6 p.u., -4.25 p.u.

Reclose Frequency and Voltage (motor bus) = 52.1 Hz, 0.5 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 63:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.40 p.u.

Reclose Torque = -4.3 p.u., -1.0 p.u., - 4.50 p.u.

Reclose Frequency and Voltage (motor bus) = 52.0 Hz, 0.53 kV

Steady State Voltage (V_{LN}) = 1.303 kV (*98.1%)*

Meet ITI specification = yes

Case 64:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.40 p.u.

Reclose Torque = - 4.0 p.u., -1.12 p.u., -4.47 p.u.

Reclose Frequency and Voltage (motor bus) = 51.2 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*.

Meet ITI specification = yes

Case 65:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.40 p.u.

Reclose Torque = -5.0 p.u., -1.3 p.u., - 4.46 p.u.

Reclose Frequency and Voltage (motor bus) = 52.0 Hz, 0.52 kV

Steady State Voltage (V_{LN}) = 1.303 kV (*98.1%)*

Meet ITI specification = yes

Case 66:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.40 p.u.

Reclose Torque = - 4.7 p.u., -1.20 p.u., -4.35 p.u.

Reclose Frequency and Voltage (motor bus) = 52.1 Hz, 0.495 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 67:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.35 p.u.

Reclose Torque = -3.6 p.u., -0.8 p.u., - 4.2 p.u.

Reclose Frequency and Voltage (motor bus) = 52.0 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4 %)*

Meet ITI specification = yes

Case 68:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.35 p.u.

Reclose Torque = - 3.3 p.u., -0.64 p.u., -4.1 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.42 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 69:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.35 p.u.

Reclose Torque = -3.85 p.u., -0.85 p.u., - 4.21 p.u.

Reclose Frequency and Voltage (motor bus) = 52.1 Hz, 0.42 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4 %)*

Meet ITI specification = yes

Case 70:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.35 p.u.

Reclose Torque = - 3.7 p.u., -0.77 p.u., -4.05 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 71:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.35 p.u.

Reclose Torque = -4.46 p.u., -1.07 p.u., - 4.1 p.u.

Reclose Frequency and Voltage (motor bus) = 51.8 Hz 0.43kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4 %)*

Meet ITI specification = yes

Case 72:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.35 p.u.

Reclose Torque = - 4.15 p.u., -0.93 p.u., -3.95 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 73:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = - 3.64 p.u., -1.56 p.u., -4.7 p.u.

Reclose Frequency and Voltage (motor bus) = 53.2 Hz, 0.765 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 74:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -3.36 p.u., -1.28 p.u., - 4.52 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.665 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(97.8%)*

Meet ITI specification = yes

Case 75:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = - 4.35 p.u., -1.72 p.u., -4.89 p.u.

Reclose Frequency and Voltage (motor bus) = 53.2 Hz, 0.73 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 76:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque 4.2 p.u.

Reclose Torque = -3.8 p.u., -1.39 p.u., - 4.57 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.665 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(97.8%)*

Meet ITI specification = yes

Case 77:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2p.u.

Reclose Torque = - 4.68 p.u., -1.78 p.u., -4.9 p.u.

Reclose Frequency and Voltage (motor bus) = 53.2 Hz, 0.715 kV

Steady State Voltage (V_LN) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 78:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -4.57 p.u., -1.56 p.u., - 4.74 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.682 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(97.8%)*

Meet ITI specification = yes

Case 79:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.43 p.u., -0.9 p.u., - 4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.510 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 80:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1p.u.

Reclose Torque = -3.14 p.u., -0.61 p.u., - 4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3 Hz, 0.48 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 81:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.72 p.u., -0.93 p.u., - 4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.510 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 82:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.45 p.u., -0.8 p.u., - 4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 52.26 Hz, 0.465 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 83:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -4.6 p.u., -1.17 p.u., - 4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 52.1 Hz, 0.505 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 84:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -4.05 p.u., -1.0 p.u., -4.05 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3 Hz, 0.46 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 85:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.0 p.u., -0.47 p.u., -3.76 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 86:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -2.83 p.u., -0.33 p.u., -3.62 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.38 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 87:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.1 p.u., -0.5 p.u., -3.8 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 88:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.21 p.u., -0.58 p.u., -3.66 p.u.

Reclose Frequency and Voltage (motor bus) = 52.4 Hz, 0.365 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 89:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.83 p.u., -0.85 p.u., -3.72 p.u.

Reclose Frequency and Voltage (motor bus) = 52.4 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 90:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.52 p.u., -0.75 p.u., -3.65 p.u.

Reclose Frequency and Voltage (motor bus) = 52.4 Hz, 0.375 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 91:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.2 p.u.

Reclose Torque = -3.53 p.u., -1.4 p.u., -4.52 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.710 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 92:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.2 p.u.

Reclose Torque = -3.07 p.u., -1.1 p.u., -4.17 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.67 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 93:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.2 p.u.

Reclose Torque = -3.86 p.u., -1.54 p.u., -4.5 p.u.

Reclose Frequency and Voltage (motor bus) = 53.3 Hz, 0.715 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 94:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.2 p.u.

Reclose Torque = -3.43 p.u., 1.22 p.u., -4.3 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.655 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 95:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.2 p.u.

Reclose Torque = -4.7 p.u., -1.6 p.u., -4.68 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.68 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 96:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.2 p.u.

Reclose Torque = -4.3 p.u., -1.4 p.u., -4.52 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.67 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 97:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -2.9 p.u., -0.64 p.u. -3.8 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.475 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 98:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -2.77 p.u., -0.51 p.u., -3.62 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.445 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 99:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.05 p.u., -0.75 p.u., -3.8 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 100:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.25 p.u., -0.67 p.u., -3.76 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.465 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 101:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -4.05 p.u., -0.97 p.u., -3.85 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 102:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.62 p.u., -0.81 p.u., -3.81 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.445 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 103:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -2.52 p.u., -0.16 p.u., -3.42 p.u.

Reclose Frequency and Voltage (motor bus) = 52.8 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 104:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -2.56 p.u., -0.23 p.u., -3.32 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.36 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 105:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -3.1 p.u., -0.575 p.u., -3.45 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.345 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 106:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -2.81 p.u., -0.4 p.u., -3.32 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.365 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 107:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -3.24 p.u., -0.65 p.u., -3.42 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 108:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -3.1 p.u., -0.58 p.u., -3.3 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 109: [Change Inertia of Motor 3 (M3) from 0.527s to 1.15s]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 3.72 p.u., -1.67 p.u., -4.9 p.u.

Reclose Frequency and Voltage (motor bus) = 53.1 Hz, 0.78 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 110:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.54 p.u., -1.4 p.u., - 4.64 p.u.

Reclose Frequency and Voltage (motor bus) = 53.5 Hz, 0.71 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 111:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 4.25 p.u., -1.89 p.u., -5.12 p.u.

Reclose Frequency and Voltage (motor bus) = 53.1Hz, 0.765 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 112:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.1 p.u., -1.56 p.u., - 4.8 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.715 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 113:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 5.23 p.u., -1.94 p.u., -5.3 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.75 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 114:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.68 p.u., -1.67 p.u., - 4.95 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.715 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 115:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 3.7 p.u., -1.07 p.u., -4.52 p.u.

Reclose Frequency and Voltage (motor bus) = 52.4 Hz, 0.53 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 116:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.4 p.u., -0.81 p.u., -4.3 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.48 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 117:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 4.0 p.u., -1.12 p.u., -4.57 p.u.

Reclose Frequency and Voltage (motor bus) = 52.4 Hz, 0.565 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 118:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.86 p.u., -1.01 p.u., -4.4 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.5 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 119:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	67(4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 4.9 p.u., -1.34 p.u., -4.45 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3 Hz, 0.54 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 120:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.41 p.u., -1.23 p.u., - 4.41 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.51 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.1%)*

Meet ITI specification = yes

Case 121:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 3.43 p.u., -0.767 p.u., -4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3 Hz, 0.445 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 122:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.17 p.u., -0.575 p.u., - 3.96 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.425 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 123:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 3.64 p.u., -0.85 p.u., -4.17 p.u.

Reclose Frequency and Voltage (motor bus) = 52.3 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 124:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.56 p.u., -0.767 p.u., - 4.05 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.42 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 125:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = - 4.35 p.u., -1.12 p.u., -4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 52.1 Hz, 0.43kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 126:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.56 p.u., -0.767 p.u., - 4.05 p.u.

Reclose Frequency and Voltage (motor bus) = 52.4 Hz, 0.44 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 127:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2 p.u.

Reclose Torque = -3.37 p.u., -1.4 p.u., -4.58 p.u.

Reclose Frequency and Voltage (motor bus) = 53.1 Hz, 0.715 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 128:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2p.u.

Reclose Torque = -3.2 p.u., -1.1 p.u., - 4.34 p.u.

Reclose Frequency and Voltage (motor bus) = 53.5 Hz, 0.645 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(97.8%)*

Meet ITI specification = yes

Case 129:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2p.u.

Reclose Torque = -3.64 p.u., -1.51 p.u., - 4.63 p.u.

Reclose Frequency and Voltage (motor bus) = 53.1 Hz, 0.715 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 130:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2p.u.

Reclose Torque = -3.64 p.u., -1.3 p.u., - 4.46 p.u.

Reclose Frequency and Voltage (motor bus) = 53.5 Hz, 0.645 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(98.6%)*

Meet ITI specification = yes

Case 131:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.2p.u.

Reclose Torque = -5.1 p.u., -1.72 p.u., -4.95 p.u.

Reclose Frequency and Voltage (motor bus) = 53.2 Hz, 0.7 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 132:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.2p.u.

Reclose Torque = -3.15 p.u., -1.45 p.u., -4.6 p.u.

Reclose Frequency and Voltage (motor bus) = 53.5 Hz, 0.645 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(98.6%)*

Meet ITI specification = yes

Case 133:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.2 p.u., -0.72 p.u., -4.1 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.51 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 134:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.07 p.u., -0.58 p.u., -3.93 p.u.

Reclose Frequency and Voltage (motor bus) = 52.8 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 135:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.77 p.u., -0.93 p.u., -4.2 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.51 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 136:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.41 p.u., -0.75 p.u., -4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 52.8 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 137:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -4.3 p.u., -1.13 p.u., -4.17 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.48 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 138:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.76 p.u., -0.97 p.u., -4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 139:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -2.81 p.u., -0.44 p.u., -3.65 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 140:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -2.77 p.u., -0.37 p.u., -3.62 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.425 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 141:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.52 p.u., -0.78 p.u., -3.79 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.425 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 142:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.07 p.u., -0.51 p.u., -3.65 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 143:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	2.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.76 p.u., -0.81 p.u., -3.78 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.395 kV

Steady State Voltage (V_{LN}) = 1.278 kV *(96.2%)*

Meet ITI specification = yes

Case 144:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	2.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.1 p.u.

Reclose Torque = -3.45 p.u., -0.64 p.u., -3.73 p.u.

Reclose Frequency and Voltage (motor bus) = 52.6 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.268 kV *(95.5%)*

Meet ITI specification = yes

Case 145:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.3 p.u.

Reclose Torque = -3.0 p.u., -1.17 p.u., -4.22 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.71 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 146:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.3 p.u.

Reclose Torque = -3.0 p.u., -0.93 p.u., -4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.655 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 147:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.3 p.u.

Reclose Torque = -3.6 p.u., -1.4 p.u., -4.46 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.7 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 148:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.3 p.u.

Reclose Torque = -3.25 p.u., -1.1 p.u., -4.14 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.67 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 149:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.3 p.u.

Reclose Torque = -4.57 p.u., -1.61 p.u., -4.63 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.7 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 150:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.3 p.u.

Reclose Torque = -3.9 p.u., -1.31 p.u., -4.35 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.655 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 151:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.15 p.u., -0.64 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.5 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 152:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -2.78 p.u., -0.44 p.u., -3.62 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.455 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 153:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.55 p.u., -0.89 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.48 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 154:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.0 p.u., -0.58 p.u., -3.68 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.465 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 155:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.73 p.u., -0.92 p.u., -3.9 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 156:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.0 p.u.

Reclose Torque = -3.45 p.u., -0.78 p.u., -3.72 p.u.

Reclose Frequency and Voltage (motor bus) = 53.1 Hz, 0.455 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 157:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -2.83 p.u., -0.4 p.u., -3.45 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 158:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -2.5 p.u., -0.16 p.u., -3.3 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.365 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 159:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -3.07 p.u., -0.51 p.u., -3.56 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 160:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -2.74 p.u., -0.27 p.u., -3.38 p.u.

Reclose Frequency and Voltage (motor bus) = 52.8 Hz, 0.375 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 161:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -3.62 p.u., -0.78 p.u., -3.48 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.5%)*

Meet ITI specification = yes

Case 162:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.9 p.u.

Reclose Torque = -3.14 p.u., -0.5 p.u., -3.42 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.355 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

In the next series of test cases the fault duration is changed from 33 milliseconds (2 cycles) to 67 milliseconds (4 cycles). Stated differently the operation time of the line protection relay and the line circuit breaker is slower than in the first 162 test cases.

Case 163:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.43 p.u., -1.17 p.u., -4.24 p.u.

Reclose Frequency and Voltage (motor bus) = 53.05 Hz, 0.567 kV

Steady State Voltage (V_{LN}) = 1.312 kV *(98.7%)*

Meet ITI specification = yes

Case 164:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25

Reclose Torque = -3.23 p.u., -0.767 p.u., -4.17 p.u.

Reclose Frequency and Voltage (motor bus) = 53.05 Hz, 0.515 kV

Steady State Voltage (V_{LN}) = 1.305 kV *(98.3%)*

Meet ITI specification = yes

Case 165:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.56 p.u., -1.1 p.u., -4.42 p.u.

Reclose Frequency and Voltage (motor bus) = 53.05 Hz (0.567 kV)

Steady State Voltage (V_{LN}) = 1.312 kV *(98.7%)*

Meet ITI specification = yes

Case 166:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25

Reclose Torque = -3.6 p.u., -0.93 p.u., -4.26 p.u.

Reclose Frequency and Voltage (motor bus) = 53.10 Hz, 0.541 kV

Steady State Voltage (V_{LN}) = 1.305 kV *(98.3%)*

Meet ITI specification = yes

Case 167:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.74 p.u., -1.15 p.u., -4.63 p.u.

Reclose Frequency and Voltage (motor bus) = 52.94 Hz, 0.567 kV

Steady State Voltage (V_{LN}) = 1.312 kV *(98.7%)*

Meet ITI specification = yes

Case 168:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	67 (4cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25

Reclose Torque = -4.17 p.u., -1.26 p.u., -4.38 p.u.

Reclose Frequency and Voltage (motor bus) = 53.10 Hz (0.515 kV)

Steady State Voltage (V_{LN}) = 1.305 kV *(98.3%)*

Meet ITI specification = yes

Case 169:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.58 p.u., -0.9 p.u., -4.41 p.u.

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Reclose Frequency and Voltage (motor bus) = 51.68 Hz, 0.492 kV

Meet ITI specification = yes

Case 170:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.53 p.u., -0.79 p.u., -4.24 p.u.

Reclose Frequency and Voltage (motor bus) = 51.96 Hz, 0.462 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 171:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.57 p.u., -1.07 p.u., -4.35 p.u.

Reclose Frequency and Voltage (motor bus) = 51.75 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%*

Meet ITI specification = yes

Case 172:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.13 p.u., -0.95 p.u., -4.24 p.u.

Reclose Frequency and Voltage (motor bus) = 51.46 Hz, 0.462 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 173:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -5.17 p.u., -0.95 p.u., -3.69 p.u.

Reclose Frequency and Voltage (motor bus) = 51.05 Hz, 0.481 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 174:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.63 p.u., -1.01 p.u., -4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 51.22 Hz, 0.462 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 175:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.48 p.u., -0.52 p.u., -4.03p.u.

Reclose Frequency and Voltage (motor bus) = 51.22 Hz, 0.407 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 176:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.31 p.u., -0.41 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 51.57 Hz, 0.396 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 177:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.00 p.u., -0.74 p.u., -3.97 p.u.

Reclose Frequency and Voltage (motor bus) = 51.31 Hz, 0.41 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 178:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.64 p.u., -0.63 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 51.44 Hz, 0.375 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 179:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	67 (4 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.2 p.u., -0.8 p.u., -3.88 p.u.

Reclose Frequency and Voltage (motor bus) = 51.44 Hz, 0.385 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 180:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	67 (4 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -4.08 p.u., -0.68 p.u., -3.64 p.u.

Reclose Frequency and Voltage (motor bus) = 51.53 Hz, 0.385 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

The closing speeds of the transfer circuit breaker is going to change from 33, 50 and 67 milliseconds to 16.67, 33 and 50 milliseconds. The closing speed of 67 milliseconds is going to be replaced by a closing speed of 16.667 millisecond (1 cycle at 60 Hz). In addition to this the system SIR is going to be at either 0.5 or 5.0, this is to very check the performance of the algorithm during two extreme cases a strong source (low SIR) and a weaker source (high SIR).

Case 181:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 4.15 p.u.

Reclose Torque = -2.65 p.u., -1.07 p.u., -4.3 p.u.

Reclose Frequency and Voltage (motor bus) = 52.61 Hz, 0.647 kV

Steady State Voltage (V_{LN}) = 1.309 kV (98.6%)

Meet ITI specification = yes

Case 182:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.15p.u.

Reclose Torque = -2.82 p.u., -0.89 p.u., -4.17 p.u.

Reclose Frequency and Voltage (motor bus) = 52.96 Hz, 0.62 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(97.8%)*

Meet ITI specification = yes

Case 183:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.15 p.u.

Reclose Torque = -4.0 p.u., -1.45 p.u., -4.63 p.u.

Reclose Frequency and Voltage (motor bus) = 52.52 Hz, 0.62 kV

Steady State Voltage (V_{LN}) = 1.309 kV (98.6%)

Meet ITI specification = yes

Case 184:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.15 p.u.

Reclose Torque = -3.47 p.u., -1.18 p.u., -4.3 p.u.

Reclose Frequency and Voltage (motor bus) = 52.96 Hz, 0.595 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(97.8%)*

Meet ITI specification = yes

Case 185:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.15 p.u.

Reclose Torque = -4.41 p.u., -1.56 p.u., -4.68 p.u.

Reclose Frequency and Voltage (motor bus) = 52.52 Hz, 0.62 kV

Steady State Voltage (V_{LN}) = 1.309 kV (98.6%)

Meet ITI specification = yes

Case 186:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.15 p.u.

Reclose Torque = -3.64 p.u., -1.23 p.u., -4.35 p.u.

Reclose Frequency and Voltage (motor bus) = 53.05 Hz, 0.595 kV

Steady State Voltage (V_{LN}) = 1.299 kV *(97.8%)*

Meet ITI specification = yes

Case 187:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -2.83 p.u., -0.4 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 52.35 Hz, 0.436 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 188:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -2.76 p.u., -0.27 p.u., -4.00 p.u.

Reclose Frequency and Voltage (motor bus) = 52.23 Hz, 0.385 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 189:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -2.894 p.u., -0.4 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 52.35 Hz, 0.41 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 190:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -3.1 p.u., -0.56 p.u., -3.76 p.u.

Reclose Frequency and Voltage (motor bus) = 52.28 Hz, 0.385 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 191:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -3.86 p.u., -0.85 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 52.41 Hz, 0.44 kV

Steady State Voltage (V_{LN}) = 1.289 kV *(97.1%)*

Meet ITI specification = yes

Case 192:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -3.53 p.u., -0.4 p.u., -3.75 p.u.

Reclose Frequency and Voltage (motor bus) = 52.28 Hz, 0.385 kV

Steady State Voltage (V_{LN}) = 1.279 kV *(96.3%)*

Meet ITI specification = yes

Case 193:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u

Reclose Torque = -2.81 p.u., -0.4 p.u., -3.45 p.u.

Reclose Frequency and Voltage (motor bus) = 51.97Hz, 0.38 kV

Steady State Voltage (V_{LN}) = 1.278 kV (96.2%)

Meet ITI specification = yes

Case 194:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -2.66 p.u., -0.0 p.u., -3.35 p.u.

Reclose Frequency and Voltage (motor bus) = 51.97Hz, 0.36 kV

Steady State Voltage (V_{LN}) = 1.268 kV (95.5%)

Meet ITI specification = yes

Case 195:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -2.9 p.u., -0.27 p.u., -3.45 p.u.

Reclose Frequency and Voltage (motor bus) = 51.97Hz, 0.38 kV

Steady State Voltage (V_{LN}) = 1.278 kV (96.2%)

Meet ITI specification = yes

Case 196:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u

Reclose Torque = -2.81 p.u., -0.13 p.u., -3.38 p.u.

Reclose Frequency and Voltage (motor bus) = 51.97Hz, 0.34 kV

Steady State Voltage (V_{LN}) = 1.268 kV (95.5%)

Meet ITI specification = yes

Case 197:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -3.35 p.u., -0.44 p.u., -3.43 p.u.

Reclose Frequency and Voltage (motor bus) = 52.17Hz, 0.34 kV

Steady State Voltage (V_{LN}) = 1.278 kV (96.2%)

Meet ITI specification = yes

Case 198:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.08 p.u.

Reclose Torque = -3.03 p.u., -0.27 p.u., -3.35 p.u.

Reclose Frequency and Voltage (motor bus) = 51.97Hz, 0.33 kV

Steady State Voltage (V_{LN}) = 1.268 kV (95.5%)

Meet ITI specification = yes

Case 199: [Change SIR from 5.0 to 0.5 and Inertia of M2 and M3 to 1.15s]

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -4.53 p.u., -3.0 p.u., -4.53 p.u.

Reclose Frequency and Voltage (motor) bus) = 53.52 Hz, 0.7 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 200:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.0 p.u., -1.0 p.u., -4.34 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.65 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 201:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.22 p.u., -1.34 p.u., -4.63 p.u.

Reclose Frequency and Voltage (motor bus) = 53.57 Hz, 0.7 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 202:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.3 p.u., -1.12 p.u., -4.46 p.u.

Reclose Frequency and Voltage (motor bus) = 53.49 Hz, 0.65 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 203:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -4.11 p.u., -1.72 p.u., -4.95 p.u.

Reclose Frequency and Voltage (motor bus) = 52.89 Hz, 0.7 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 204:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.64 p.u., -1.28 p.u., -4.6 p.u.

Reclose Frequency and Voltage (motor bus) = 53.49 Hz, 0.65 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 205:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.07 p.u., -0.68 p.u., -4.26 p.u.

Reclose Frequency and Voltage (motor bus) = 52.63 Hz, 0.52 kV

Steady State Voltage (V_{LN}) = 1.304 kV *(98.2%)*

Meet ITI specification = yes

Case 206:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.0 p.u., -0.56 p.u., -4.05 p.u.

Steady State Voltage (V_{LN}) = 1.297 kV *(97.7%)*

Reclose Frequency and Voltage (motor bus) = 52.96Hz, 0.49 kV

Meet ITI specification = yes

Case 207:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.68 p.u., -0.97 p.u., -4.41 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.52 kV

Steady State Voltage (V_{LN}) = 1.304 kV *(98.2%)*

Meet ITI specification = yes

Case 208:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.2 p.u., -0.68 p.u., -4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 52.87Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.297 kV *(97.7%)*

Meet ITI specification = yes

Case 209:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.97 p.u., -1.12 p.u., -4.46 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.52 kV

Steady State Voltage (V_{LN}) = 1.304 kV *(98.2%)*

Meet ITI specification = yes

Case 210:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.25 p.u.

Reclose Torque = -3.6 p.u., -0.9 p.u., -4.26 p.u.

Reclose Frequency and Voltage (motor bus) = 52.28Hz, 0.47 kV

Steady State Voltage (V_{LN}) = 1.297 kV *(97.7%)*

Meet ITI specification = yes

Case 211:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.0 p.u., -0.47 p.u., -3.89 p.u.

Reclose Frequency and Voltage (motor bus) = 52.76 Hz, 0.415 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 212:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -2.77 p.u., -0.3 p.u., -3.76 p.u.

Reclose Frequency and Voltage (motor bus) = 53.14 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.288 kV (97.0%)

Meet ITI specification = yes

Case 213:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.17 p.u., -0.57 p.u., -3.96 p.u.

Reclose Frequency and Voltage (motor bus) = 52.63 Hz, 0.415 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 214:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -2.9 p.u., -0.37 p.u., -3.8 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.385 kV

Steady State Voltage (V_{LN}) = 1.288 kV (97.0%)

Meet ITI specification = yes

Case 215:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.38 p.u., -0.67 p.u., -4.00 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.41 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 216:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 2.2 p.u.

Reclose Torque = -3.1 p.u., -0.61 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 52.78 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.288 kV (97.0%)

Meet ITI specification = yes

Case 217: [Change system SIR from 0.5 to 5.0]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.15p.u.

Reclose Torque = -2.63 p.u., -0.75 p.u., -3.28 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.63 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 218:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.15p.u.

Reclose Torque = -2.45 p.u., -0.54 p.u., -3.58 p.u.

Reclose Frequency and Voltage (motor bus) = 54.2 Hz, 0.585 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 219:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.15 p.u.

Reclose Torque = -2.69 p.u., -0.83 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.63 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 220:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.15 p.u.

Reclose Torque = -2.69 p.u., -0.61 p.u., -3.72 p.u.

Reclose Frequency and Voltage (motor bus) = 53.75 Hz, 0.585 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 221:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.15 p.u.

Reclose Torque = -3.8 p.u., -1.26 p.u., -4.26 p.u.

Reclose Frequency and Voltage (motor bus) = 53.8 Hz, 0.595 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 222:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.15 p.u.

Reclose Torque = -3.0 p.u., -0.74 p.u., -3.8 p.u.

Reclose Frequency and Voltage (motor bus) = 53.75 Hz, 0.585 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 223:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.15p.u.

Reclose Torque = -2.25 p.u., -0.16 p.u., -3.24 p.u.

Reclose Frequency and Voltage (motor bus) = 53.5 Hz, 0.43 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 224:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.15 p.u.

Reclose Torque = -2.28 p.u., -0.13 p.u., -3.2 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 225:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.15p.u.

Reclose Torque = -2.63 p.u., -0.37 p.u., -3.42 p.u.

Reclose Frequency and Voltage (motor bus) = 53.6 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 226:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.15

Reclose Torque = -2.54 p.u., -0.20 p.u., -3.24 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.41 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 227:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.15p.u.

Reclose Torque = -3.1 p.u., -0.61 p.u., -3.52 p.u.

Reclose Frequency and Voltage (motor bus) = 53.68 Hz, 0.435 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.7%)*

Meet ITI specification = yes

Case 228:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.15 p.u.

Reclose Torque = -2.63 p.u., -0.267 p.u., -3.32 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 229:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -2.01 p.u., -0.18 p.u., -3.0 p.u.

Reclose Frequency and Voltage (motor bus) = 53.61 Hz, 0.345 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.7%)*

Meet ITI specification = yes

Case 230:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -2.07 p.u., 0.1 p.u., -2.86 p.u.

Reclose Frequency and Voltage (motor bus) = 53.57 Hz, 0.33 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 231:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -2.45 p.u., -0.2 p.u., -3.1 p.u.

Reclose Frequency and Voltage (motor bus) = 53.6 Hz, 0.345 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.7%)*

Meet ITI specification = yes

Case 232:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -2.12 p.u., 0.0 p.u., -2.9 p.u.

Reclose Frequency and Voltage (motor bus) = 53.55 Hz, 0.33 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

Case 233:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u.

Reclose Torque = -2.56 p.u., -0.27 p.u., -3.1 p.u.

Reclose Frequency and Voltage (motor bus) = 53.68 Hz, 0.345 kV

Steady State Voltage (V_{LN}) = 1.255 kV *(94.7%)*

Meet ITI specification = yes

Case 234:

Fault Duration (ms)	Inertia Constant (H)	Source Impedance Ratio

	(seconds)	
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 4.85 p.u

Reclose Torque = -2.28 p.u., -0.12 p.u., -2.94 p.u.

Reclose Frequency and Voltage (motor bus) = 53.55 Hz, 0.33 kV

Steady State Voltage (V_{LN}) = 1.242 kV *(93.5%)*

Meet ITI specification = yes

E.2 Three Phase Faults (3ϕ):

Case 235:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.94 p.u., -0.8 p.u., -4.13 p.u.

Reclose Frequency and Voltage (motor bus) = 53.49 Hz, 0.626 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 236:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.94 p.u., -0.64 p.u., -4.1 p.u.

Reclose Frequency and Voltage (motor bus) = 53.41 Hz, 0.585 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 237:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -3.23 p.u., -1.0 p.u., -4.26 p.u.

Reclose Frequency and Voltage (motor bus) = 53.52 Hz, 0.63 kV)

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 238:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -3.02 p.u., -0.77 p.u., -4.1 p.u.

Reclose Frequency and Voltage (motor bus) = 53.43 Hz, 0.585 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 239:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -3.93 p.u., -1.21 p.u., -4.24 p.u.

Reclose Frequency and Voltage (motor bus) = 53.55 Hz, 0.63 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 240:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -3.52 p.u., -1.00 p.u., -4.22 p.u.

Reclose Frequency and Voltage (motor bus) = 53.4 Hz, 0.585 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 241:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.75 p.u.

Reclose Torque = -2.767 p.u., -0.27 p.u., -3.6 p.u.

Reclose Frequency and Voltage (motor bus) = 52.87 Hz, 0.42 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 242:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.75 p.u.

Reclose Torque = -2.73 p.u., -0.2 p.u., -3.55 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 243:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -3.07 p.u., -0.44 p.u., -3.7 p.u.

Reclose Frequency and Voltage (motor bus) = 52.96 Hz, 0.42 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 244:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.9 p.u., -0.27 p.u., -3.65 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 245:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -3.4 p.u., -0.1 p.u., -3.14 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.42 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 246:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -3.28 p.u., -0.4 p.u., -3.65 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 247:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.42 p.u., -0.1 p.u., -3.14 p.u.

Reclose Frequency and Voltage (motor bus) = 52.8 Hz, 0.34 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 248:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.35 p.u., -0.0 p.u., -3.1 p.u.

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.31 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 249:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.6 p.u., -0.17 p.u., -3.21 p.u.

Reclose Frequency and Voltage (motor bus) = 52.76 Hz, 0.34 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 250:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.56 p.u., -0.1 p.u., -3.17 p.u.

Reclose Frequency and Voltage (motor bus) = 52.4 Hz, 0.31 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 251:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.9 p.u., -0.27 p.u., -3.28 p.u.

Reclose Frequency and Voltage (motor bus) = 52.8 Hz, 0.34 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 252:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.76 p.u., -0.2 p.u., -3.21 p.u.

Reclose Frequency and Voltage (motor bus) = 52.36 Hz, 0.31 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 253: [Change inertia of M2 and M3 from 0.75 and 0.527 respectively to 1.15s]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.67 p.u., -0.47 p.u., -3.86 p.u.

Reclose Frequency and Voltage (motor bus) = 54.2 Hz, 0.6kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 254:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.56 p.u., -0.34 p.u., -3.7 p.u.

Reclose Frequency and Voltage (motor bus) = 54.3 Hz, 0.57 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 255:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.86 p.u., -0.56 p.u., -3.93 p.u.

Reclose Frequency and Voltage (motor bus) = 54.2 Hz, 0.595 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 256:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.7 p.u., -0.47 p.u., -3.76 p.u.

Reclose Frequency and Voltage (motor bus) = 54.3 Hz, 0.58 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification =

Case 257:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -3.15 p.u., -0.72 p.u., -4.05 p.u.

Reclose Frequency and Voltage (motor bus) = 54.2 Hz, 0.6 kV

Steady State Voltage (V_{LN}) = 1.318 kV *(99.2%)*

Meet ITI specification = yes

Case 258:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -3.07 p.u., -0.75 p.u., -3.9 p.u.

Reclose Frequency and Voltage (motor bus) = 53.9 Hz, 0.57 kV

Steady State Voltage (V_{LN}) = 1.311 kV *(98.7%)*

Meet ITI specification = yes

Case 259:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.4 p.u., -0.13 p.u., -3.35 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 260:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque =.5.8 p.u.

Reclose Torque = -2.35 p.u., -0.1 p.u., -3.24 p.u.

Reclose Frequency and Voltage (motor bus) = 53.5 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 261:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.56 p.u., -0.3 p.u., -3.38 p.u.

Reclose Frequency and Voltage (motor bus) = 53.8 Hz, 0.42 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 262:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.46 p.u., -0.23 p.u., -3.31 p.u.

Reclose Frequency and Voltage (motor bus) = 53.5 Hz, 0.375 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 263:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.8 p.u., -0.46 p.u., -3.48 p.u

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.43 kV

Steady State Voltage (V_{LN}) = 1.303 kV *(98.1%)*

Meet ITI specification = yes

Case 264:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.67 p.u., -0.3 p.u., -3.42 p.u.

Reclose Frequency and Voltage (motor bus) = 53.6 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.296 kV *(97.6%)*

Meet ITI specification = yes

Case 265:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.7 p.u.

Reclose Torque = -2.25 p.u., 0.14 p.u., -3.17 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.35 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 266:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.7 p.u.

Reclose Torque = -2.25 p.u., 0.14 p.u., -3.11 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.35 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 267:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.7 p.u.

Reclose Torque = -2.4 p.u., 0.08 p.u., -3.21 p.u.

Reclose Frequency and Voltage (motor bus) = 53.9 Hz, 0.345 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 268:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.7 p.u.

Reclose Torque = -2.28 p.u., 0.11 p.u., -3.08 p.u.

Reclose Frequency and Voltage (motor bus) = 53. 8 Hz, 0.32 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 269:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.7 p.u.

Reclose Torque = -2.56 p.u., -0.2 p.u., -3.21 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.33 kV

Steady State Voltage (V_{LN}) = 1.294 kV *(97.4%)*

Meet ITI specification = yes

Case 270:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.7 p.u.

Reclose Torque = -2.45 p.u., -0.17 p.u., -3.14 p.u.

Reclose Frequency and Voltage (motor bus) = 53.3 Hz, 0.32 kV

Steady State Voltage (V_{LN}) = 1.288 kV *(97.0%)*

Meet ITI specification = yes

Case 271: [Change SIR from 0.5 to 5.0]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.9 p.u.

Reclose Torque = -2.84 p.u., -0.64 p.u., -3.76 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.6 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 272:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.9 p.u.

Reclose Torque = -2.56 p.u., -0.58 p.u., -3.62 p.u.

Reclose Frequency and Voltage (motor bus) = 53.2 Hz, 0.57 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 273:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.9 p.u.

Reclose Torque = -2.8 p.u., -0.75 p.u., -3.82 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.615 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 274:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.9 p.u.

Reclose Torque = -2.8 p.u., -0.67 p.u., -3.72 p.u.

Reclose Frequency and Voltage (motor bus) = 53.2 Hz, 0.57 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 275:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.9 p.u.

Reclose Torque = -3.38 p.u., -1.05 p.u., -4.0 p.u.

Reclose Frequency and Voltage (motor bus) = 53.2 Hz, 0.6 kV

Steady State Voltage (V_{LN}) = 1.298 kV *(97.7%)*

Meet ITI specification = yes

Case 276:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.9 p.u.

Reclose Torque = -3.1 p.u., -0.82 p.u., -3.82 p.u.

Reclose Frequency and Voltage (motor bus) = 53.1 Hz, 0.56 kV

Steady State Voltage (V_{LN}) = 1.284 kV *(96.7%)*

Meet ITI specification = yes

Case 277:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.42 p.u., -0.13 p.u., -3.24 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.43 kV

Steady State Voltage (V_{LN}) = 1.271 kV *(95.75)*

Meet ITI specification = yes

Case 278:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.32 p.u., 0.0 p.u., -3.14 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 279:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.56 p.u., -0.23 p.u., -3.24 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.271 kV (95.7%)

Meet ITI specification = yes

Case 280:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.45 p.u., -016 p.u., -3.14 p.u.

Reclose Frequency and Voltage (motor bus) = 52.9 Hz, 0.395 kV

Steady State Voltage (V_{LN}) = 1.258 kV *(94.7%)*

Meet ITI specification = yes

Case 281:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.93 p.u., -0.51 p.u., -3.21 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.4 kV

Steady State Voltage (V_{LN}) = 1.271 kV (95.7%)

Meet ITI specification = yes

Case 282:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.73 p.u., -0.4 p.u., -3.14 p.u

Reclose Frequency and Voltage (motor bus) = 52.5 Hz, 0.38 kV

Steady State Voltage (V_{LN}) = 1.253 kV *(94.4%)*

Meet ITI specification = yes

Case 283:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u

Reclose Torque = -2.15 p.u., 0.11 p.u., -2.8 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.34 kV

Steady State Voltage (V_{LN}) = 1.25 kV *(94.1 %)*

Meet ITI specification = yes

Case 284:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.08 p.u., 0.2 p.u., -2.76 p.u.

Reclose Frequency and Voltage (motor bus) = 52.8 Hz, 0.31 kV

Steady State Voltage (V_{LN}) = 1.237 kV *(93.1%)*

Meet ITI specification = yes

Case 285:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.28 p.u., -0.07 p.u., -2.83 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.33 kV

Steady State Voltage (V_{LN}) = 1.25 kV *(94.1 %)*

Meet ITI specification = yes

Case 286:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.15 p.u., 0.14 p.u., -2.76 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.31kV

Steady State Voltage (V_{LN}) = 1.237 kV *(93.1%)*

Meet ITI specification = yes

Case 287:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.45 p.u., -0.13 p.u., -2.83 p.u.

Reclose Frequency and Voltage (motor bus) = 53.0 Hz, 0.32 kV

Steady State Voltage (V_{LN}) = 1.25 kV *(94.1 %)*

Meet ITI specification = yes

Case 288:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -2.32 p.u., 0.0 p.u., -2.78 p.u.

Reclose Frequency and Voltage (motor bus) = 52.7 Hz, 0.29 kV

Steady State Voltage (V_{LN}) = 1.237 kV *(93.1%)*

Meet ITI specification = yes

Case 289: [Change inertia of M2 and M3 from 0.75 and 0.527 respectively to 1.15s]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.35 p.u., -0.34 p.u., 3.48 p.u.

Reclose Frequency and Voltage (motor bus) = 54.4Hz, 0.58 kV

Steady State Voltage (V_{LN}) = 1.293 *(97.4%)*

Meet ITI specification = yes

Case 290:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.28 p.u., -0.34 p.u., -3.31 p.u.

Reclose Frequency and Voltage (motor bus) = 54.2 Hz, 0.56 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 291:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.5 p.u., -0.44 p.u., -3.52 p.u.

Reclose Frequency and Voltage (motor bus) = 54.3 Hz, 0.58 kV

Steady State Voltage (V_{LN}) = 1.293 *(97.4%)*

Meet ITI specification = yes

Case 292:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.42 p.u., -0.44 p.u., -3.38 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.57 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 293:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.86 p.u., -0.74 p.u., -3.66 p.u.

Reclose Frequency and Voltage (motor bus) = 53.8 Hz, 0.58 kV

Steady State Voltage (V_{LN}) = 1.293 *(97.4%)*

Meet ITI specification = yes

Case 294:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.63 p.u., -0.51 p.u., -3.45 p.u.

Reclose Frequency and Voltage (motor bus) = 54.2 Hz, 0.56 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 295:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = -2.07 p.u., 0.04 p.u., -2.94 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.41 kV

Steady State Voltage (V_{LN}) = 1.266 kV *(95.3%)*

Meet ITI specification = yes

Case 296:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = -2.1 p.u., 0.1 p.u., -2.94 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.37 kV

Steady State Voltage (V_{LN}) = 1.253 kV *(94.3%)*

Meet ITI specification = yes

Case 297:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = -2.19 p.u., -0.06 p.u., -3.0 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.41 kV

Steady State Voltage (V_{LN}) = 1.266 kV *(95.3%)*

Meet ITI specification = yes

Case 298:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = -2.26 p.u., 0.0 p.u., -3.0 p.u.

Reclose Frequency and Voltage (motor bus) = 53.8 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.253 kV *(94.3%)*

Meet ITI specification = yes

Case 299:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = -2.6 p.u., -0.27 p.u., -3.21 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.39 kV

Steady State Voltage (V_{LN}) = 1.266 kV *(95.3%)*

Meet ITI specification = yes

Case 300:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = -2.45 p.u., -0.1 p.u., -3.07 p.u.

Reclose Frequency and Voltage (motor bus) = 53.8 Hz, 0.38 kV

Steady State Voltage (V_{LN}) = 1.253 kV *(94.3%)*

Meet ITI specification = yes

Case 301:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.5 p.u.

Reclose Torque = -1.88 p.u., 0.18 p.u., -2.67 p.u.

Reclose Frequency and Voltage (motor bus) = 54.0 Hz, 0.325 kV

Steady State Voltage (V_{LN}) = 1.25 kV *(94.1%)*

Meet ITI specification = yes

Case 302:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.5 p.u.

Reclose Torque = -1.82 p.u., 0.15 p.u., -2.56 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.315 kV

Steady State Voltage (V_{LN}) = 1.237 kV *(93.1%)*

Meet ITI specification = yes

Case 303:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.5 p.u.

Reclose Torque = -1.98 p.u., 0.0 p.u., -2.69 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1Hz, 0.33 kV

Steady State Voltage (V_{LN}) = 1.25 kV *(94.1%)*

Meet ITI specification = yes

Case 304:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.5 p.u.

Reclose Torque = -1.91 p.u., 0.07 p.u., -2.62 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.3 kV

Steady State Voltage (V_{LN}) = 1.237 kV *(93.1%)*

Meet ITI specification = yes

Case 305:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.5 p.u.

Reclose Torque = -2.15 p.u., -0.1 p.u., -2.75 p.u.

Reclose Frequency and Voltage (motor bus) = 53.9 Hz, 0.31 kV

Steady State Voltage (V_{LN}) = 1.25 kV *(94.1%)*

Meet ITI specification = yes

Case 306:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
33	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.5 p.u.

Reclose Torque = -2.01 p.u., 0.0 p.u., -2.67 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.29 kV

Steady State Voltage (V_{LN}) = 1.237 kV *(93.1%)*

Meet ITI specification = yes

Case 307: [Change Fault duration from 33 milliseconds to 67 milliseconds]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.18 p.u., -0.06 p.u., -3.24 p.u.

Reclose Frequency and Voltage (motor bus) = 54.6 Hz, 0.47 kV

Steady State Voltage (V_{LN}) = 1.316 kV *(99.1%)*

Meet ITI specification = yes

Case 308:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.18 p., -0.13 p.u., -3.11 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 309:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.32 p.u., -0.13 p.u., -3.28 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.47 kV

Steady State Voltage (V_{LN}) = 1.316 kV *(99.1%)*

Meet ITI specification = yes

Case 310:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.28 p.u., -0.16 p.u., -3.17 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.44 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 311:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.66 p.u., -0.5 p.u., -3.38 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.316 kV *(99.1%)*

Meet ITI specification = yes

Case 312:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.50 p.u., -0.27 p.u., -3.25 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.46 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 313:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -1.9.p.u., 0.12 p.u., -2.67 p.u.

Reclose Frequency and Voltage (motor bus) = 54.2 Hz, 0.32 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 314:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.0.p.u., 0.21 p.u., -2.75 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.3 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 315:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.09 p.u., 0.1 p.u., -2.78 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.32 kV

Steady State Voltage (V_{LN}) = 1.3 kV *(97.9%)*

Meet ITI specification = yes

Case 316:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.5 p.u., 0.15 p.u., -2.8 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.3 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 317:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.4 p.u., 0.0 p.u., -2.87 p.u.

Reclose Frequency and Voltage (motor bus) = 54.1 Hz, 0.32 kV

Steady State Voltage (V_{LN}) = 1.3 kV *(97.9%)*

Meet ITI specification = yes

Case 318:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.20 p.u., 0.07 p.u., -2.78 p.u.

Reclose Frequency and Voltage (motor bus) = 53.7 Hz, 0.3 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 319:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque =.Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 320:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 321:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 322:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 323:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 324:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 325: [Change inertia of M2 and M3 from 0.75 and 0.527 respectively to 1.15s]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.15 p.u., 0.0 p.u., -3.04 p.u.

Reclose Frequency and Voltage (motor bus) = 54.6 Hz, 0.46 kV

Steady State Voltage (V_{LN}) = 1.316 kV *(99.1%)*

Meet ITI specification = yes

Case 326:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = 2.15 p.u., 0.15 p.u., -3.0 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.44 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 327:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.18 p.u., 0.0 p.u., -3.04 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.316 kV *(99.1%)*

Meet ITI specification = yes

Case 328:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.25 p.u., 0.08 p.u., -3.08 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 329:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.29 p.u., -0.1 p.u., -3.1 p.u.

Reclose Frequency and Voltage (motor bus) = 54.6 Hz, 0.46 kV

Steady State Voltage (V_{LN}) = 1.316 kV *(99.1%)*

Meet ITI specification = yes

Case 330:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = 2.35 p.u., 0.0 p.u., -3.11 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.46 kV

Steady State Voltage (V_{LN}) = 1.309 kV *(98.6%)*

Meet ITI specification = yes

Case 331:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -1.82 p.u., 0.26 p.u., -2.61 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.31 kV

Steady State Voltage (V_{LN}) = 1.3 kV *(97.9%)*

Meet ITI specification = yes

Case 332:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -1.77 p.u., 0.23 p.u., -2.53 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.3 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 333:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -1.94 p.u., 0.15 p.u., -2.64 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.315 kV

Steady State Voltage (V_{LN}) = 1.3 kV *(97.9%)*

Meet ITI specification = yes

Case 334:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -1.82 p.u., 0.23 p.u., -2.56 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.32 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 335:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -1.98 p.u., 0.07 p.u., -2.67 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.31 kV

Steady State Voltage (V_{LN}) = 1.3 kV *(97.9%)*

Meet ITI specification = yes

Case 336:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = 2.04 p.u., 0.12 p.u., -2.67 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.3 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 337:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 338:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 339:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 340:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 341:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 342:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	0.5

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.72 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 343: [Change SIR from 0.5 to 5.0 and H of M2 and M3 to 0.75s and 1.15s respectively]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -1.95 p.u., -0.07 p.u., -2.86 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.46 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 344:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.05 p.u., 0.08 p.u., -2.9 p.u.

Reclose Frequency and Voltage (motor bus) = 54.3 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 345:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.01 p.u., -0.12 p.u., -2.92 p.u.

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.49 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 346:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.09 p.u., 0.0 p.u., -2.89 p.u.

Reclose Frequency and Voltage (motor bus) = 54.3 Hz, 0.44 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 347:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.45 p.u., -0.27 p.u., -3.14 p.u,

Reclose Frequency and Voltage (motor bus) = 54.5 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 348:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.8 p.u.

Reclose Torque = -2.26 p.u., -0.1 p.u., -2.97 p.u.

Reclose Frequency and Voltage (motor bus) = 54.3 Hz, 0.44 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 349:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 350:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 351:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 352:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 353:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 354:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 355:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 356:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 357:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 358:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 359:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 360:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 0.75 M3 = 0.527	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 361: [Change inertia of M2 and M3 from 0.75 and 0.527 respectively to 1.15s]

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.05 p.u., 0.14 p.u., -2.8 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.455 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 362:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -1.85 p.u., 0.15 p.u., -2.64 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.44 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 363:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.11 p.u., 0.14 p.u., -2.87 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.44 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 364:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = 1.93 p.u., 0.0 p.u., -2.67 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 365:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
3.0 MVA (0.3 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.18 p.u., 0.08 p.u., -2.87 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.45 kV

Steady State Voltage (V_{LN}) = 1.293 kV *(97.4%)*

Meet ITI specification = yes

Case 366:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
3.0 MVA (0.3 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 6.0 p.u.

Reclose Torque = -2.04 p.u., -0.04 p.u., -2.73 p.u.

Reclose Frequency and Voltage (motor bus) = 54.8 Hz, 0.43 kV

Steady State Voltage (V_{LN}) = 1.28 kV *(96.4%)*

Meet ITI specification = yes

Case 367:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -1.63 p.u., 0.37 p.u., -2.31 p.u.

Reclose Frequency and Voltage (motor bus) = 54.9 Hz, 0.3 kV

Steady State Voltage (V_{LN}) = 1.266 kV *(95.3%)*

Meet ITI specification = yes

Case 368:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -1.65 p.u., 0.424 p.u., -2.31 p.u.

Reclose Frequency and Voltage (motor bus) = 54.7 Hz, 0.285 kV

Steady State Voltage (V_{LN}) = 1.253 kV *(94.4%)*

Meet ITI specification = yes

Case 369:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -1.71 p.u., 0.34 p.u., -2.37 p.u.

Reclose Frequency and Voltage (motor bus) = 54.9 Hz, 0.3 kV

Steady State Voltage (V_{LN}) = 1.266 kV *(95.3%)*

Meet ITI specification = yes

Case 370:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -1.65 p.u., 0.37 p.u., -2.34 p.u.

Reclose Frequency and Voltage (motor bus) = 54.7 Hz, 0.285 kV

Steady State Voltage (V_{LN}) = 1.253 kV *(94.4%)*

Meet ITI specification = yes

Case 371:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
6.0 MVA (0.6 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -1.9 p.u., 0.26 p.u., -2.7 p.u.

Reclose Frequency and Voltage (motor bus) = 54.9 Hz, 0.285 kV

Steady State Voltage (V_{LN}) = 1.266 kV *(95.3%)*

Meet ITI specification = yes

Case 372:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
6.0 MVA (0.6 p.u.)	50 (3 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.65 p.u.

Reclose Torque = -1.74 p.u., 0.26 p.u., -2.37 p.u.

Reclose Frequency and Voltage (motor bus) = 54.7 Hz, 0.285 kV

Steady State Voltage (V_{LN}) = 1.253 kV *(94.4%)*

Meet ITI specification = yes

Case 373:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 374:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	16.67 (*1 cycles*)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 375:

Fault Duration (ms)	**Inertia Constant (H) (seconds)**	**Source Impedance Ratio**
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	**Speed of Breaker (Reclose) (ms)**	**Shunt Capacitor Bank (In/Out)**
7.5 MVA (0.75 p.u.)	33 (2 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 376:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 377:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	50 (3 cycles)	In (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer

Case 378:

Fault Duration (ms)	Inertia Constant (H) (seconds)	Source Impedance Ratio
67	M1 = 1.15 M2 = 1.15 M3 = 1.15	5.0

Load on Bus (MVA)	Speed of Breaker (Reclose) (ms)	Shunt Capacitor Bank (In/Out)
7.5 MVA (0.75 p.u.)	33 (2 cycles)	Out (120 kVAR)

Observations: Peak Fault Torque = 5.6 p.u.

Reclose Torque = Failed to Transfer

Reclose Frequency and Voltage (motor bus) = Failed to Transfer

Steady State Voltage (V_{LN}) = Failed to Transfer

Meet ITI specification = Failed to Transfer