Multiphase Multisection Fault Location in Shunt Capacitor Banks

A Dissertation

Presented in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy
with a
Major in Electrical Engineering
in the
College of Graduate Studies
University of Idaho
by
Dereje Jada Hawaz

Major Professor: Brian K. Johnson, Ph.D.
Committee Members: Joseph D. Law, Ph.D., Herbert L. Hess, Ph.D.,
Ahmed A. Ibrahim, Ph.D.
Department Administrator: Joseph D. Law, Ph.D.

August 2021

Authorization to Submit Dissertation

This dissertation of Dereje Jada Hawaz, submitted for the degree of Doctor of Philosophy with a major in Electrical Engineering and titled "Multiphase Multisection Fault Location in Shunt Capacitor Banks," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ______________________________ Date_____

Brian K. Johnson, Ph.D.

Committee Members:

______________________________ Date_____

Joseph D. Law, Ph.D.

______________________________ Date_____

Herbert L. Hess, Ph.D.

______________________________ Date ____

Ahmed A. Ibrahim, Ph.D.

Department Administrator:

______________________________ Date_____

Joseph D. Law, Ph.D.

Abstract

Shunt capacitor banks play a vital role in improving power system capacity. They do so primarily through power factor correction that increases voltage support and improves the overall system voltage profile. Shunt capacitor banks are the most economical devices to increase system capacity by reducing power loss on transmission lines and distribution feeders. The economic benefit of shunt capacitor banks comes because they are inexpensive to install and commission and they can be deployed at any point in the distribution system to enhance the voltage profile.

Since shunt capacitor banks are very important power system components, they need to be protected from faults that occur within the bank or from faults elsewhere in the system that can affect them. Faults in shunt capacitor banks must be monitored, and an alarm or trip initiated to prevent catastrophic damage to the capacitor bank that follows a cascading failure of capacitor elements or units.

The protection method should trip the faulty unit and remove it from the system to mitigate damage to the entire bank that could cause system voltage instability. In addition to shunt capacitor bank protection, a recently developed solution that has grown in popularity identifies faulted phases or sections so a utility crew can pinpoint the location of faulted capacitor elements for speedy maintenance. This faulted phase or section identification solution for shunt capacitor banks was introduced to power systems within the last decade, but it is only limited to locating single-phase faults.

This research presents a multiphase multisection fault location identification approach for ungrounded double-wye capacitor banks with neutral voltage and neutral current monitoring already installed for protection purposes. The proposed approach can locate simultaneous faults in different sections of a capacitor bank. The proposed multiphase multisection fault location identification solution helps operators to quickly identify multiphase fault locations in multiple sections of the double-wye bank to minimize the time it takes to quickly identify faulted elements and units and repair. The solution is even more significant when applied to internally fused and fuseless banks because it

might not be possible to locate faulty elements in closed unit cases until the damage has cascaded to a catastrophic bank failure. Since the unbalance phase angles of the currents and voltages at the neutral are already available from the incumbent protection method the proposed approach does not require additional equipment in the substation. The theoretical and mathematical derivations for the proposed solution will be presented and simulation results obtained with a real-time digital simulator will be used to demonstrate and verify the solution.

Acknowledgments

I would like to express my sincere gratitude to Professor Brian K. Johnson for his diligent support, encouragement, and motivation to help me complete my higher education in electrical and computer engineering. I would also like to thank Dr. Joseph D. Law and Dr. Herbert L. Hess for their support throughout my studies at the university. I am thankful to the members of my committee for their time and support as well. Finally, I would like to thank Dr. Norman Fischer for his encouragement and follow-up and Mr. Satish Samineni for his motivation and support.

Dedication

To my wife, Tigist Hawaz for her love and dedicated support, and my children for their love and sacrifice.

To Jawar Mohammed and the Oromo Qeerroo.

Table of Contents

List of Figures

List of Tables

Definitions

Shunt Capacitor Bank (SCB) – Series, parallel, or series and parallel configured capacitor elements making up capacitor units that in turn are connected in series, parallel or series, and parallel to make a capacitor bank and all supporting accessories.

Capacitor Element – Two electrode plates separated by a dielectric.

Capacitor Unit – A collections of capacitor elements in a case with terminals to be connected to the power circuit.

MVA **-** Megavolt-amperes. Units for apparent power, the product of the total current and voltage in an electrical circuit.

MVAR **-** Mega volt-amperes reactive, the component of power that is reactive.

Capacitor Inrush Current – Transient current when a capacitor bank is switched on or connection made to a voltage source.

Discharge Device – A device that is switched to remove residual voltages from the bank after disconnecting the bank from the power system it's connected to.

Externally Fused Capacitor – A device constructed of one or more series groups of parallel-connected capacitor units. Each capacitor unit is protected with a fuse external to the unit.

Fused Capacitor – A capacitor having fuses mounted on its terminals, inside a terminal enclosure, or inside the capacitor case, to disconnect a failed capacitor element, unit, or group.

Fuseless Capacitor – A capacitor bank with no fuse connected in its internal or external connections.

Internally Fused Capacitor (Unit) – A capacitor unit that is internally fused.

Parallel Connected Capacitor – A capacitor unit where the individual elements are connected in parallel. A capacitor unit that has a single string between capacitor terminals is referred to as a parallel-connected unit.

Series Connected Capacitor – A capacitor unit that the individual elements are connected in series. A capacitor unit that is made up of a single connection of elements between capacitor terminals is referred to as a series-connected unit.

String of Capacitors – Series connected capacitor units between line terminals.

Chapter 1 Introduction

The most economical way of delivering reactive power to a load through a distribution system is to supply it from a nearby source. Generating and transmitting reactive power from distant power plants has many drawbacks including an economical one. One such near-to-load reactive power source is the shunt capacitor bank (SCB).

SCBs play a major role in providing reactive power support that improves the voltage profile, decreases the flow of reactive current, decreases power loss, and as a result, increases power system capacity and energy efficiency. Increasing system capacity, in turn, means a postponement of new system expansion such as new generation and transmission capacity. Figure 1-1 shows the typical substation installation of the shunt capacitor bank.

Figure 1-1 Shunt Capacitor Bank [1]

Because of their importance to system operation, the protection of capacitor banks is crucial. Developing a protection scheme is dependent on the configuration of the bank. High voltage capacitor banks are constructed in various ways with many factors considered. Such factors include footprints, economics, availabilities of equipment such as instrument transformers, fusing, and others. Shunt capacitor banks can be constructed as single-wye, double-wye, or H-bridge and can be grounded or ungrounded. A Capacitor bank's VAR and voltage ratings are dictated by series and parallel connections of elements and units.

The design of the capacitor bank and the knowledge it requires are important considerations for the utilization and protection of SCB. Capacitor bank elements and units are designed with various connections and configurations to meet system requirements. Capacitor units are made up of several capacitor elements connected in series and parallel. Capacitor units are connected in parallel to make up a group and these same groups are connected in series to make up the phase branch [2]. The number of capacitor units that can be connected in parallel or series is an important aspect of capacitor bank configuration and protection. The other important aspect of capacitor bank design is the configuration of fusing. The four fusing options are externally fused, internally fused, unfused, and fuseless. When unbalanced voltages or currents appear at the measurement point due to a fault, capacitor elements and units experience overvoltage conditions. The magnitude change in capacitor elements and units is proportional to the number of elements that failed. The more elements and units fail, the more overvoltage burden there is on the remaining elements and units, which could cause a cascading failure.

The location of faults in externally fused banks are easy to detect where the failed unit disconnects itself from the bank upon blowing a fuse, making it easy to locate. The locations of faults that happen in internally fused, fuseless, and unfused banks are hard to detect because the failed elements can't be seen with the naked eye, resulting in a time-consuming hunt for a fault that happened deep in a series and parallel connected elements. This creates expensive inspections and a prolonged costly outage.

Identifying faulted phases and sections of ungrounded double-wye bank narrows down the search area and helps minimize the outage time. It is prudent to repair capacitor banks promptly so that the proper system voltage profile can be maintained [3].

Typical steps to replace faulty units and put the bank back in service are as follows:

- Take the bank out of service.

- Isolate and ground the bank.
- Disconnect each unit.
- Identify the faulty unit by measuring the capacitance across each unit in the bank.
- Obtain the capacitances of the spare unit.
- Enter the capacitances in a spreadsheet.
- Balance the capacitances in the spreadsheet.
- Replace the faulty unit.
- Move other units within the bank (if required).
- Energize the bank.

The existing state of the art method applied in practice for SCB fault location technique uses the phase angle of unbalance quantity and compares it with a reference quantity angle to determine the fault location [4]. The unbalance quantity is a phasor, and its magnitude measures the unbalance within the bank. This technique exists today and detects faulty units in a single phase of the ungrounded single-wye and double-wye banks. However, in some cases, the concurrent faults can cancel each other's signatures, causing presently used techniques to fail. Finding a solution to that problem is the objective of this research.

1.1 Research Objectives

The primary objective of this research is to further solve the problem of accurately identifying the presence of multiphase multisection faults by accurately identifying fault locations when shunt capacitor banks experience multiphase faults at the same time. The solution this research is presenting can successfully identify multiphase faults on ungrounded wye configured banks. The solution uses the same PTs and CTs the conventional unbalance protection uses for its alarm and trip functions and as a result, it is capital cost-free as no other added equipment or instruments needed. This research analyzes SCBs operating on the fundamental frequency only, and the impacts of harmonics are beyond the scope of this research.

The main objectives of this research are as follows:

- Demonstrate the benefit of shunt capacitor banks in power systems, explain bank design and configurations.
- Demonstrate why a SCB is protected and the current state of the art for SCB protection techniques.
- Demonstrate the importance of locating shunt capacitor bank faults and their impact on the overall reliability of the power system.
- Review currently available solutions for capacitor bank fault location and their limitations.
- Present a new solution to further enhance the bank fault location methods with the addition of a multiphase fault location feature.
- Demonstrate the types of protection methods where the proposed solution can be adopted to run in the same relay.

The research presents mathematical derivations to prove the theoretical basis for this technique. The mathematical model shows the phase and sequence calculation of neutral currents and voltages as well as voltages and currents from the connected bus and bank respectively. It also presents a mathematical derivation for creating factors for balancing inherited differences at the neutral connection due to external system factors. The research also analyzes and describes the fundamentals of capacitance, capacitor bank protection theories, and existing methods of determining single phase-based fault locations in great detail. Hardware-in-the-loop simulating using a Real-Time Digital System (RTDS) is performed to demonstrate the accurate performance of the proposed approach through realistic scenarios and confirms the theoretical analysis and assumptions to prove the proposed solution is able to solve the identified problems.

The following publications from the author are related to the work in this dissertation.

- “Minimizing Capacitor Bank Outage Time Through Fault Location” [4], will be presented in Chapter 5, when a literature survey is presented to demonstrate the currently available solution for bank fault location purposes.

1.2 Thesis Outline

Chapter 2 gives a brief introduction to shunt capacitor banks starting with brief background and describes their benefits to the power system. The chapter will continue discussing the fundamental basis for the protection and fault location solutions through the introduction of bank design, configurations, and fusing.

Chapter 3 presents shunt capacitor bank protection methods which are the basis for the multiphase fault location solution.

Chapter 4 presents literature to review the currently available solutions and point out opportunities that triggered this research to fill the gap.

Chapter 5 presents the existing single-phase fault location identification method that provides a basis for this research.

Chapter 6 introduces the proposed solutions. This chapter explains the theoretical background of the multiphase fault location solution with mathematical derivations.

Chapter 7 will demonstrate the simulation setup and present cases in detail to discuss the relationship between the mathematical assumptions and the simulation results.

Chapter 8 presents the summary of the research, draws conclusions from the research, and suggests future work in the area of this research.

Chapter 2 SCB Background, Configurations, and Fusing

Chapter 2 gives a brief introduction of shunt capacitor banks with some background contexts to show its benefits to the power system and then set the groundwork for the protection and fault location solutions by introducing bank design, configurations, and fusing.

2.1 Benefits of Shunt capacitor banks

Shunt capacitor banks play a vital role in improving power system capacity. They do so primarily through power factor correction that increases voltage support to improve the overall system voltage profile. There are several benefits SCBs provide to the power system, including:

- Power factor correction
- Providing local reactive power
- Boosting voltage and reducing line current
- Reducing line losses
- Improving system capacity
- Can be installed close to a load
- Economic benefits derived from the above benefits

2.1.1 Power factor correction:

The vector sum of the real and reactive power shown in Figure 2-1 creates the apparent power. The magnitude of the reactive power is a function of the angle between the real and the apparent power vectors. As this angle between the two power vectors shrinks, the magnitude of the reactive power also shrinks. As the angle grows, the reactive power grows, and apparent power increases.

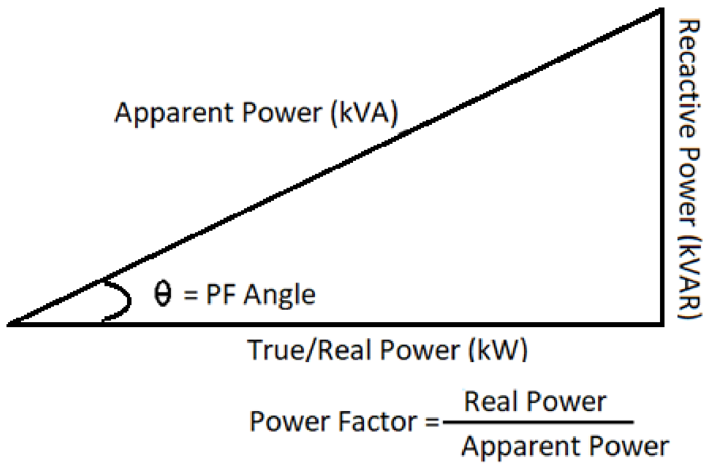


Figure 2-1 Power Triangle

From the power triangle, real power 'P' is the product of the rms voltage and rms current multiplied by the cosine of the angle θ between the voltage and current (which is also the angle between the apparent power and real power).

$$P = Vrms * Irms * (\cos\theta) \qquad (2.1)$$

At cos(0) = 1 and the angle θ shrinks to 0 degrees, there will be no reactive power and what is left is a purely contains real power only.

$$P = Vrms * Irms \text{ (w)} \qquad (2.2)$$

From the power triangle, reactive power 'Q' is the product of the rms voltage and rms current multiplied by the sine of the angle θ between the voltage and current (which is also the angle between the apparent power and real power)..

$$Q = Vrms * Irms * (\sin\theta) \qquad (2.3)$$

At sin(90) = 1 and the angle θ grows to 90 degrees, there will be no real power and what is left is a purely reactive element creating reactive power only.

$$Q = Vrms * Irms \text{ (VA)} \quad (2.4)$$

2.1.2 Providing local reactive power:

Since the reactive power is the sum of the inductive portion of the power (QL) that absorbs reactive power and the capacitive portion of power (QC) that delivers reactive power, the installation of SCB closer to the load enhances the delivery of reactive power. Capacitors and inductors work in canceling each other's current, one as lagging power and the other as leading (capacitors as leading and inductance as lagging). This leading capacitive power characteristic cancels out inductive power and reduces the power factor angle.

2.1.3 Boost Voltage/Reduce Current:

The voltage rise at the capacitor location is approximately equal to the capacitor current IC times the inductive reactance of the system to the capacitor location XL [5]. This voltage rise is caused by the flow of capacitor current (or the reduction of inductive current) through the inductive reactance of the system from the point of installation back to the generation.

$$\Delta V = IC * XL \quad (2.5)$$

where

ΔV *is the change in voltage at the capacitor*
IC *is the capacitor current*
XL *is the inductive reactance of the system*

As the power factor of the power triangle increase to unity, the distribution system capacity increases by reducing the current flow and voltage rise. This makes a shunt capacitor bank a convenient and economical solution for maintaining reliable power delivery.

2.1.4 Reduce Line Loss:

One of the main benefits of applying shunt capacitor banks to the distribution system is that they can reduce distribution line losses. Losses come from current going through the resistance of conductors. Even though part of the current is important to transmit real power, some of the flow supplies reactive power. Therefore, reducing the current reduces line loss. The reduced current going through a line due to a power factor increase, in turn, reduces line loss. Less line loss again increases system capacity.

2.1.5 Improve System Capacity:

Unlike industrial customers who pay for reactive power as tariffs or as a penalty for power quality, residential customers only pay for true/real power only. As a result, industrial customers may provide their own local reactive power compensation, but utilities often pay for the reactive compensation for residential customers as well as for the reactive power consumed by the transmission and distribution systems. As such, utilities build an expensive and complex grid to transport apparent power that contains reactive power as well. Delivering reactive power to the power system, and especially getting it to the load from a faraway generation station requires the production of a larger generation system and a bigger and expensive transmission line. However, if reactive power can be delivered to distribution load from a local source like SCB, then more real power can be delivered from the existing source saving utilities from building or enhancing newer generation and transmission apparatus, increasing system capacity [5]. The estimated optimum economic power factor for a system can be described inequation (2.6).

$$PF = \sqrt{1\left(\frac{C}{S}\right)^2} \tag{2.6}$$

where

C *is the cost per kVAR of capacitor bank*
S *is the cost per kVA of system equipment*
PF *is the optimum power factor*

2.1.6 Installed close to the load:

Shunt capacitor banks can be deployed to any location in the distribution line and enhance the voltage profile. This is the answer to the question of whether there is a way to supply reactive power to a load without generating and transmitting more reactive power from generation stations at a higher cost.

2.1.7 Economical:

In terms of increasing system capacity through reducing power loss, SCBs are the most economical and inexpensive to install and commission devices available. The business aspect of power system utility is to generate, transmit and distribute real power to individual and commercial customers. If SCBs are not installed locally to supply reactive power utilities needs to reinforce the transmission and distribution systems to deliver that reactive power as load grows, and install generation to supply reactive power. Instead, utilities are shutting down older, inefficient plants in urban areas and replacing them with devices able to provide local reactive support.

2.2 Configurations of Shunt Capacitor Banks

Shunt capacitor banks are designed, configured, and protected in various ways depending on requirements and specific applications. This section covers some of the design, connections, and protection aspects and details for purpose of introducing SCBs and identifying suitable protection schemes that this research depends on for measurements for multiphase fault location. The following points are discussed:

- SCB Design
- SCB Configuration

2.2.1 Design:

The connections and protection aspects of SCB are dictated by the fundamentals of capacitor bank construction. As indicated in Figure 2-2, capacitor elements are the smallest unit in the bank. These individual capacitator elements make up the building block of the capacitor bank referred to as capacitor unit. A capacitor is a device for storing electric charge. The two electrodes separated by a dialectic material make a capacitance, and represent the capacity to store charge. Capacitance can be quantified as a ratio of charge in coulombs ‘Q’ to the potential between the two plates in volts ‘V’, measured with a unit of farads.

$$C = \frac{Q}{V} \tag{2.7}$$

The capacitance between the two plates depends on the size, shape, and position of the conductors separated by an insulating dielectric. Therefore, at design, the desired capacitance quantities should consider the area of the plate ‘A’, the distance between the two plates ‘d’, the dielectric constant ‘K’, and the permittivity of the free space $\in_\circ$.

$$C = K \in_\circ \frac{A}{d} \tag{2.8}$$

Before the current methods of manufacturing capacitors, refined Kraft paper and a Polychlorinated Biphenyl (PCB) impregnant were used as both the dielectric and insulating materials. Today, much thinner but evenly distributed Polypropylene film and hydrocarbon dielectric fluid are used to manufacture capacitor elements.

Capacitors are designed to be defect-free. One of the methods in achieving that is packing several layers of aluminum foils on the top of each conducting film and laying polypropylene dielectric film at each layer. The high number of layers of film help avoid imperfection to assure no defective capacitors are produced. The standard element sizes are between 314mm by 508 mm [6].

Capacitors are also designed with a loss of their capacitance characteristics over time in mind. The main concern with the loss of capacitance is discharge resistance loss in ohmic values, dielectric loss, and conductor loss.

In addition, standards require an added resistor that reduces voltage values to 50 volts in 300 seconds when the capacitor is disconnected from the power system [6].

$$V = V_\circ e^{\frac{-t}{RC}} \tag{2.9}$$

$$R = \frac{-t}{C * \ln\left(\frac{V}{V_\circ}\right)} \tag{2.10}$$

Figure 2-2 shows the dielectrically separated conductive capacitance plates that store energy to make the individual capacitor elements. The elements are connected in series and parallel arrangements make the building blocks of a capacitor bank that we call a capacitor unit. The capacitor unit is built in a steel enclosed case and its internal discharge resistor is designed based on equation 2.10.

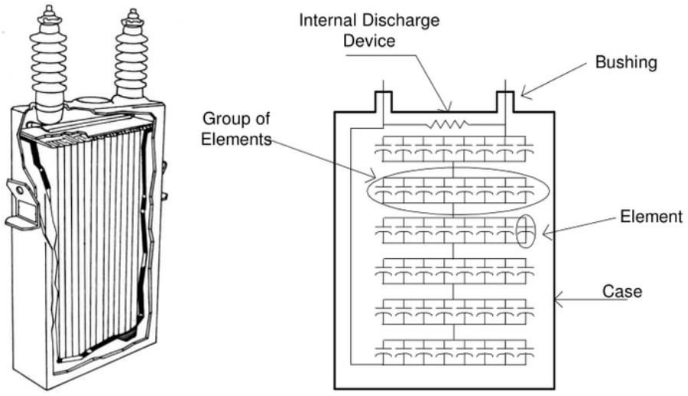


Figure 2-2 Capacitor banks in a distribution substation [13].

The overall bank capabilities and operational boundaries are also part of the bank design. Among the operating conditions, temperature and continuous electrical operations are the main ones of interest. Since capacitors are designed for continuous operation in outdoor settings, climate, weather, and direct sun heat exposures have some impact on them. Capacitors used in SCBs are designed to operate at temperatures down to -40º C.

In continuous operation, capacitors are designed to operate below their rated voltage and frequencies. Capacitor banks provide continuous operation with limits. The following limitations should not exceed [5]:

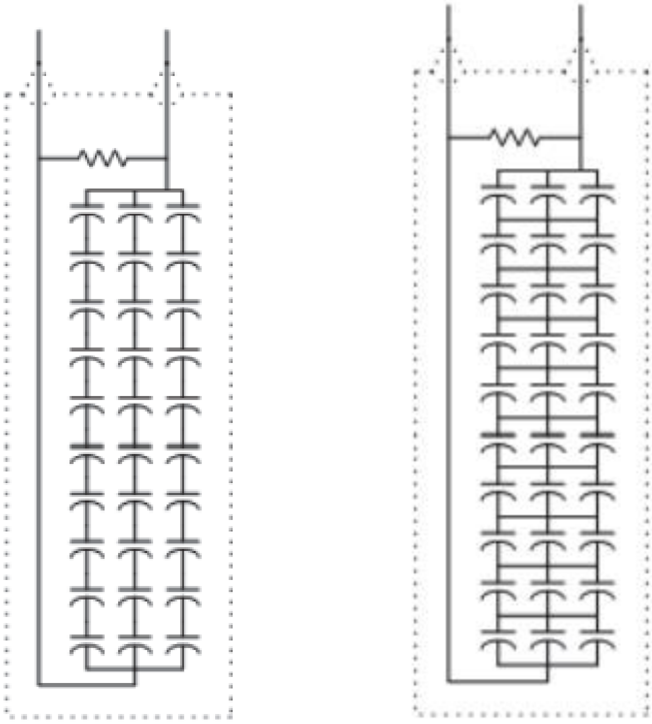
1. 110% of the rated rms voltage.
2. 120% of rated crest voltage.

3. 135% of nominal rms current.
4. 135% of rated kVAR.

For short time transients, capacitors can momentarily withstand switching transient overvoltagess of up to $2 * \sqrt{2}$ time the rated rms voltage.

2.2.2 Configurations:

Just as capacitor elements are connected and made capacitor units, capacitor units are connected in series and parallel to make a shunt capacitor bank. The number of connected series capacitor units and the number of connected parallel capacitor units is dictated by several factors. These factors include voltage ratings, sensitivity for unbalance protection, footprint, and a capacity to carry a charge in the event an adjacent capacitor unit failures. In a parallel-connected capacitor unit, the capacitor elements are connected in parallel groups and these parallel groups are connected in series between the line terminal as shown in Figure 2-3. Capacitor elements are also connected in series with each other between the line terminal and these series-connected elements are connected with one or more series-connected elements in parallel to form the series and parallel connected unit.



a) b)

Figure 2-3 Capacitor unit design [8] (a) parallel (b) series connections.

2.2.3 Fusing:

One of the major factors that dictate the design, application, and protection of shunt capacitor bank is the connections of fuses. Fuses are the first line of defense to capacitor bank elements and units. Capacitor units and elements experience overvoltage conditions due to increased current during faults caused by the clamping of the conductive plates of capacitance of neighboring elements. Fuses prevent this exerted overvoltage condition from moving to neighboring elements and units and respond by blowing to create an open circuit condition to create isolation.

The number of series (rows) and parallel (columns) of SCB is dictated by the fusing method. For example, externally fused banks contain fewer elements in parallel and more elements in series. That is because when any element is shorted, the entire row shorts out. With fewer parallel elements the loss of capacitance is minimum [4].

There are four types of fusing for SCB [9]:

- Externally fused
- Internally fused
- Unfused
- Fuseless

2.3 Types of Fusing in SCB

2.3.1 Externally fused:

Fuses that are connected outside of capacitor units' cases are referred to as external fuses. External fuses remove the entire capacitor unit from the bank to prevent a case rupture and keep the remaining units operational [10]. As Figure 2-3 shows, externally fused banks are made of groups of parallel elements connected in series. The number of capacitor units that make the parallel connections in each series group is determined by the minimum and maximum limitations. The number of capacitor units per group is determined by the desired overvoltage capabilities and kVAR tolerance. The higher the number of units connected in series the less the impact of a nearby blown-off unit. In an externally fused bank with P units, an open fuse caused by a blown-off fault can approximately exert P/P-1 increased voltage level on neighboring units. Therefore, to have the additional overvoltage due to theblown fuse of less than 10%, there need to be 10 or more parallel-connected units [1].

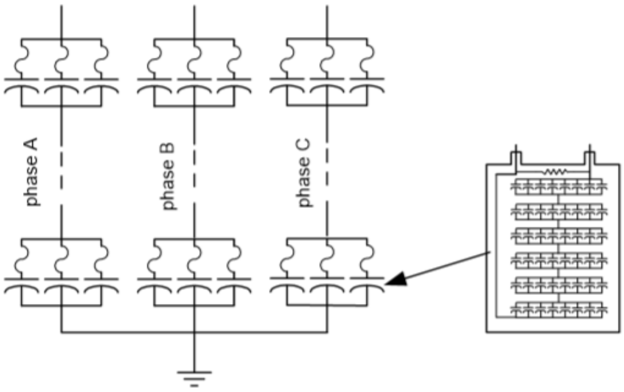


Figure 2-4 Externally fused bank [12].

Externally fused banks have a higher cost to operate but they are beneficial in returning the failed capacitor unit to service quicker because identifying the fault location can be achieved by simple visual inspection without other time and resource-consuming tasks for testing units to determine which has an open fuse. When an externally fused bank unit has failed, the entire unit can be taken out of service for repair, reducing the time the unit is out of service. Fuse ratings on externally fused banks are typically chosen based on currents in the range of 125% to 165% of the nominal capacitor current [5]. As there is an advantage in using externally fused banks, especially if their failure identification is achieved by visual inspection, there are also disadvantages related to their cost and potential failure due to exposure to pollution, corrosion, and vulnerability to climate conditions demanding inspection. Figure 2-4 shows externally fused SCB.

2.3.2 Internally fused:

In contrast, internally fused banks have fewer elements in parallel and more in series. With more elements in parallel, less capacitance is lost when an element is disconnected from the other parallel elements. Because of that, the isolation of an element only removes a small part of elements in the unit as series connections have a small number of elements.

As seen in Figure 2-5, in an internally fused bank, each capacitor element has its own fuse, and the operation of each fuse is intended to isolate the connecting element. There are several advantages in using internally fused banks.

- Fuse rails and insulation assemblies are not required.
- Fuses operate without electrical clearance between units.
- Fewer units are required for a particular bank design.
- Compact bank design for easy insulation and covering is possible.

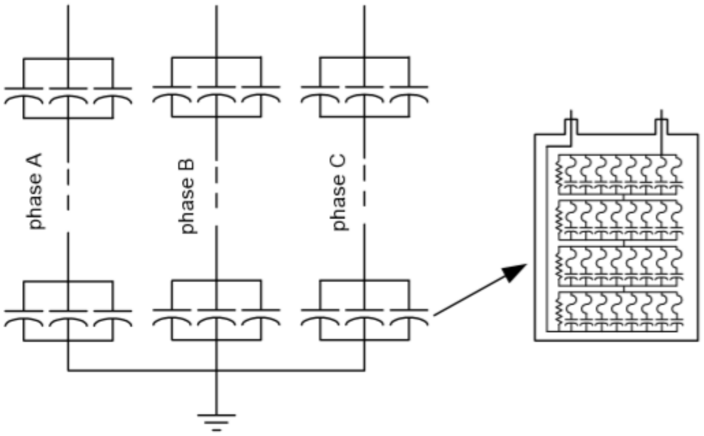


Figure 2-5 Internally fused bank.

2.3.3 Fuseless capacitors banks:

Fuseless capacitors are treated the same way as externally fused capacitor units except no fuses are installed. Because of that, when a fuseless bank fails, the damage is permanent. Fuseless bank design gives the same advantages as the internally fused capacitor bank design. The fuseless design produces fewer losses than the fused design [1]. Unfused SCBs are similar to fuseless banks, but are on their way out of the industry. Figure 2-6 shows a fuseless SCB.

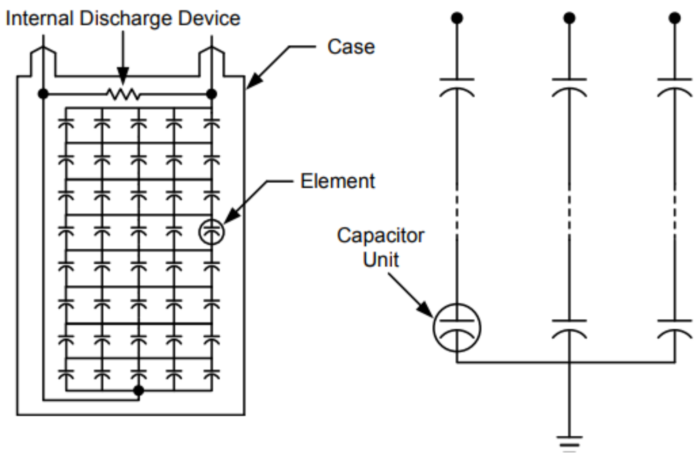


Figure 2-6 Fuseless capacitors bank.

2.3.4 Unfused capacitors banks:

Unlike fuseless capacitor bank configuration where connections are in series, unfused capacitor banks are connected in series/parallel. Unfused capacitor banks are applied in systems that are less than 34.5 kV banks because series string units are impractical.

2.4 Summary

This chapter covered an introduction to capacitor banks starting with the benefits they offer to the power systems, specifically the distribution system. Key benefits are power factor correction, local reactive power support, reduction of line current and line loss, as well us voltage support are presented as benefits to the system. The chapter also covered the economic benefits and the ease to install SCBs anywhere in the power system.

The chapter also covered the design, configuration, and fusing and the impacts and influence they have on the voltage and kVAR ratings.

Types of fuses and the basis to select one type of fuses over another are also explained. The next chapter will pick the subject of protection and current practices.

Chapter 3 SCB Protection: Current Practices

This chapter presents current practices for shunt capacitor bank protection methods that are the basis for the proposed multiphase fault location solution.

Shunt capacitor banks need to be protected as is the case for any power system equipment from damage and system failure. SCBs must be protected from faults that occur within the banks themselves, as well as from external faults that are outside of the banks, which are called external faults. For the external faults that happen anywhere in the power system, the individual apparatus is responsible for protecting its own designated equipment. However, when faults evolve into SCB's protection domain, the SCB protection scheme produces an alarm to warn engineers or trip to clear faults. The two main aspects of protecting shunt capacitor banks are system protection and bank protection. A bus fault or feeder fault that is external to the bank can put extra stress on the bank, and overvoltage or overcurrent conditions can occur in which case disconnecting the bank from the system is necessary. Several conditions cause internal bus faults where dedicated bank protection is required. There are also system faults that occur and directly impact the bank. This chapter will briefly discuss the bank and system protection methods.

3.1 Capacitor Bank Protection Connections

Before discussing these protection aspects, I will show aspects of bank connections and grounding choices that a particular protection method will depend on.

Six common capacitor bank connections can be used based on the preferred requirement for protection and available components such as units that conform with the rated voltage requirements, available fusing methods, and selected protective relay.

Some of the most common connections in the SCB protection method as indicated in Figure 3-1 are delta, grounded single-wye, grounded double-wye, ungrounded single-wye, ungrounded double-wye, and H-bridge.

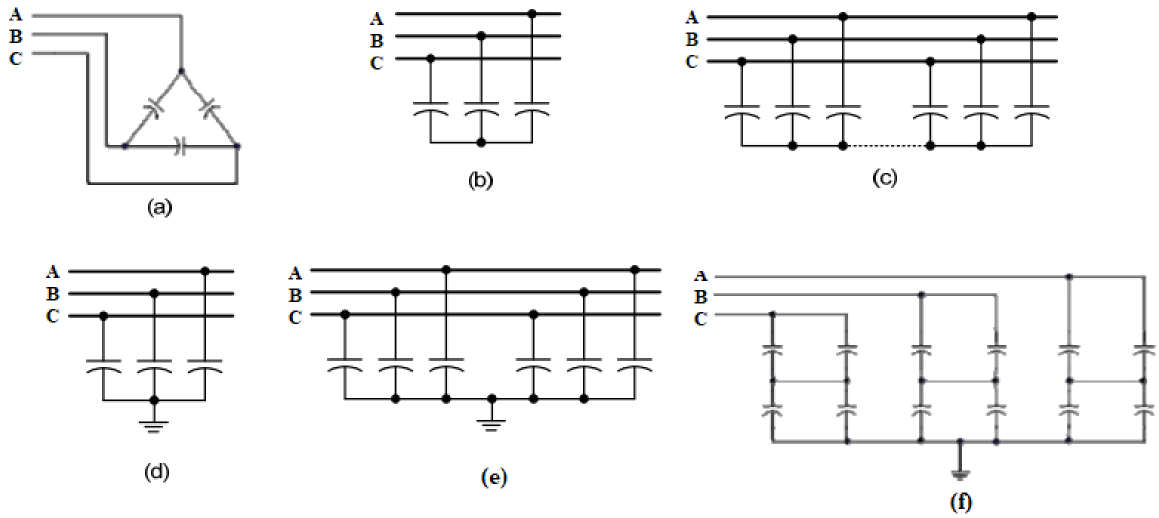


Figure 3-1 Popular capacitor bank connections (a) delta, (b) ungrounded single wye, (c) ungrounded double wye, (d) grounded single wye, (e) grounded double wye, and (f) H-bridge configuration.

There are some advantages and disadvantages to using grounded or ungrounded-single or double-wye capacitor banks. There are certain advantages and disadvantages associated with grounded-versus-ungrounded-wye capacitor banks. The advantages of the grounded-wye arrangement compared to the ungrounded wye are described below.

When using grounded-wye banks cost can be reduced since the neutral doesn't need to be insulated from the ground. The capacitor switching transient recovery voltage is also not as high. But grounded-wye can present disadvantages in measurement instruments since a high inrush current could occur in station grounds and structures. They can also draw zero-sequence harmonic currents to amplify communication interference on phone lines.

Ungrounded-wye can provide an advantage in blocking zero-sequence currents, large switching transient currents, and third harmonic currents. Their neutrals also have to be insulated so it presents some cost issues as a disadvantage over grounded-wye

The multiphase fault location technology that is integral to this research depends on the ungrounded single and double-wye connections, as we will see in the coming chapters.

3.2 Bank Protection

3.2.1 Protection through Fuse

The primary guard to capacitor elements or units during abnormal situations is fusing. However, fusing has to be coordinated with unbalance protection to deliver complete and reliable protection. The various fusing designs discussed in Chapter 2 play a major role in protecting the bank's elements and units in several different ways. In externally fused banks, many capacitor elements have to fail and short circuit the unit before the fuse removes the unit from the bank. The selection requirement of capacitor fusing has to consider speed and reliability to isolate faulted elements and units from elements and units that have the potential to discharge stored energy. Factors to consider for the selection of externally fused capacitor arrangements include ratings, voltage interruption capabilities, security against inrush and outrushes conditions, harmonics, inductive and capacitive current interactions, and their abilities to interact between other methods of protection [5].

An internally fused capacitor bank arrangement is designed to protect the individual elements within the unit. Internally fused banks could be built from capacitor units that are connected in a combination of series and parallel arrangements. In this case, every capacitor element has a fuse connected to it in series. Internally fused arranged banks are configured with a fewer number of units in parallel when compared with externally fused banks. The fuse prevents multiple cascading element failures by isolating faulted elements to save the unit. Factors to consider for the selection of internally fused capacitor arrangements are overvoltage interruption capacity, security against transient conditions, and inrush/ outrush conditions.

The fuseless capacitor bank arrangement doesn't mean removing fuses from capacitor elements and units. Fuses are not used with this arrangement. In this arrangement, each capacitor element is connected in series to create the entire string of the bank's phase. In a fuseless bank, fewer parallel connections result in a reduction in inrush and outrush current. In fuseless capacitor bank protection, the unbalance protection is set up to remove the bank when failed elements create a short circuit current path to create cascading failure.

Capacitor elements can fail from the two dielectrically separated plates welding to each other, resulting in shorting. This leads to increased current and voltage levels on the remaining elements and units. Externally fused and internally fused banks activate fast-acting fuses in coordination with unbalance relay while restraining from tripping during switching surges or external faults. The unbalance protection is coordinated with fuse actions. When a fuse blows in the capacitor element or unit, unbalance conditions are created. From the unbalance quantity magnitude, the unbalance protection determines the number of elements and units blown. The protection is set to operate based on predetermined thresholds for alarm or trip [5].

Faults where capacitor elements short with unit cases, busing failures, or faulty connection do cause tremendous damages on equipment and the system. In such a case, externally fused banks can disconnect the unit from the bank or the system, or the unbalance protection can protect internally fused or fuseless banks with faster response.

3.2.2 Protection through Unbalance Conditions

Unbalance protection detects unbalance conditions and trips the bank from service for any predetermined value of unbalancing a fault created. Both external and internal faults create unbalance conditions, and timely detection and alarming or tripping is the main function of unbalance protection.

There are four commonly used unbalance protection methods:

- Phase voltage unbalance
- Neutral voltage unbalance
- Phase current unbalance
- Neutral current unbalance

The choice of protection method depends on factors such as bank configuration, availability of instrument transformers, sensitivity, and security. Unbalance protection methods use one or more measured quantities such as bus voltages, bank currents, neutral voltage, and neutral current to quantify the unbalance quantity. The unbalance quantity is a phasor, and its magnitude measures the degree of unbalance within the bank. The magnitude of the unbalance quantity directly indicates the number of failed elements or units.

This research primarily focuses on neutral voltage unbalance and neutral current unbalance as the basis for the proposed multiphase fault location identification solution. In the following few sections, a brief introduction to the phase voltage and current unbalance methods will be provided for background.

3.3 Phase voltage unbalance

Phase voltage unbalance or phase voltage differential protection is applied to a wye-connected capacitor bank with a potential transformer (PT) at the tap point, as shown in Figure 3-2. The tap point can be at the midpoint of the bank or a low-voltage capacitor just above the wye connection. The faulty element or unit can be in any of six locations in this bank: in any of the three phases and either above the tap point (top section) or below the tap point (bottom section) of each phase.

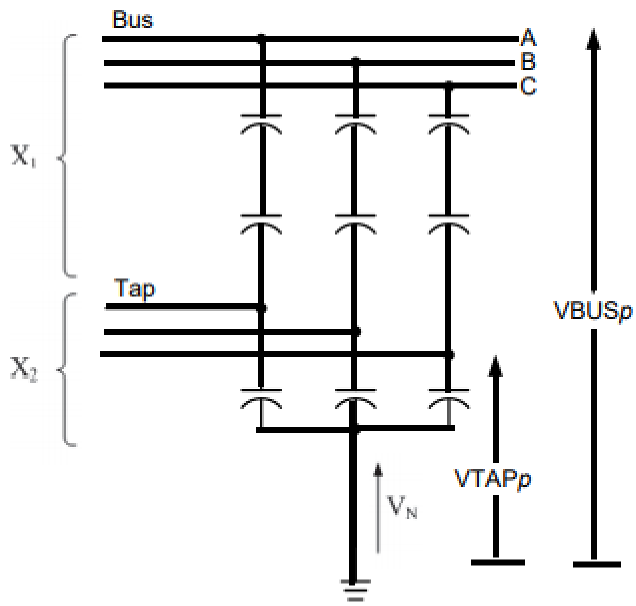


Figure 3-2 Banks using tapped PT-based phase voltage unbalance protection

The protection uses tapped voltage and bus voltage measurements to calculate the unbalance quantity, as shown in (1). For each phase of the bank in Figure 3-2, equation (3.1) holds:

$$\frac{V_{TAP}-V_N}{V_{BUS}-V_N} = \frac{X_2}{X_1+X_2} \tag{3.1}$$

Where:

X_1 and X_2 are capacitance reactance at the top and bottom of the tap.

V_{TAP} is the Phase tap voltage phasor.
V_{BUS} is the Phase bus voltage phasor.
V_N is the Neutral voltage phasor.

If we consider a solidly grounded system where the phases are balanced and the neutral voltage is zero, then equation (3.1) can be expressed as equation (3.2):

$$\frac{V_{TAP}}{V_{BUS}} = \frac{X_2}{X_1+X_2} \tag{3.2}$$

Adding a constant K to represent the reactance ratio:

$$K = \frac{X_2}{X_1+X_2} \tag{3.3}$$

If the bus is balanced and the reactance remains the same from when the protection for phase unbalance is set, then the differential value becomes zero as shown in equation (3.4).

$$DV = |V_{TAP} - K * V_{BUS}| \tag{3.4}$$

The K factor can be also determined by K_{SET} from the measured phase conditions. The voltage unbalance relay continuously measuries and updates the magnitude ratio of the tap voltage over the bus voltage. The difference voltage DV's magnitude is a quantity that the phase unbalance protection uses to set an alarm or trip the bank. The use of the angle of DV will be discussed in depth in Chapter 6 as part of the derivation of the proposed approach.

The K factor's fluctuations from temperature drift or the bank experiencing abnormal conditions can also be expressed as equation (3.5)

$$K_{SET} = \left|\frac{V_{TAP}}{V_{BUS}}\right| \tag{3.5}$$

3.4 Neutral voltage unbalance

3.4.1 Ungrounded bank using neutral voltage single-wye

The proposed multiphase fault location research for voltage unbalance depends partially on neutral voltage unbalance. Neutral voltage unbalance protection is applied to a wye-connected capacitor bank with a neutral PT, as shown in Figure 3-3. The bank can be single or double wye. The faulty element or unit can be in any of three locations (three phases) for a single-wye bank and any of six locations (left or right section of each of the three phases) for a double-wye connected bank.

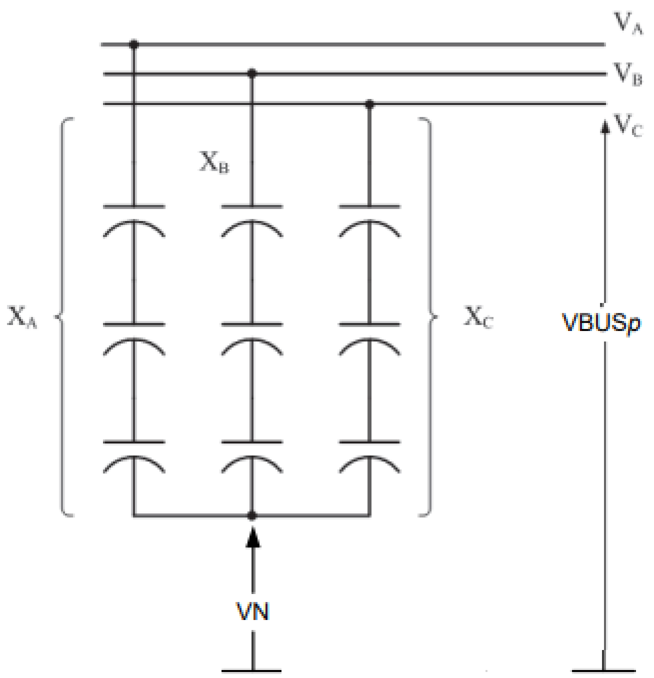


Figure 3-3 Ungrounded bank using neutral voltage unbalance protection single wye

For the ungrounded neutral voltage unbalance circuit in Figure 3-3, the sum of all currents flowing from the bus to neutral point VT is summed to zero as indicated in equation (3.6)

$$I_A + I_B + I_C = 0 \tag{3.6}$$

Expressing the three phases through the voltage across the bank and its impedance as indicated in the equation below:

$$I_A = \frac{V_A - V_N}{-j_X * X_A} \tag{3.7}$$

$$I_B = \frac{V_B - V_N}{-j_X * X_B} \tag{3.8}$$

$$I_C = \frac{V_C - V_N}{-j_X * X_C} \tag{3.9}$$

Substituting equation (2.17), (2.18), (2.19) into equation (3.10):

$$\frac{V_A - V_N}{-j_X * X_A} - \frac{V_B - V_N}{-j_X * X_B} - \frac{V_C - V_N}{-j_X * X_C} = 0 \tag{3.10}$$

Factoring out similar quantities in the three terms:

$$\frac{V_A}{X_A} + \frac{V_B}{X_B} + \frac{V_C}{X_C} - V_N * \left(\frac{1}{X_A} + \frac{1}{X_B} + \frac{1}{X_C}\right) = 0 \tag{3.11}$$

For a balanced bank where $X_A = X_B = X_C$,

$$\left(\frac{1}{X_A} + \frac{1}{X_B} + \frac{1}{X_C}\right) = \frac{3}{X_A} \tag{3.12}$$

Therefore, in a perfectly balanced three-phase capacitive impedance, equation (3.13) simply becomes:

$$3 * V_0 - 3 * V_N = 0 \tag{3.13}$$

PT at the neutral points measures V_N , and the sum of the three-phase bus voltages also measures V_0 to create a balance between the bus voltage and the voltage at the neutral.

With that, the difference voltage at the neutral unbalance voltage for ungrounded wye becomes:

$$DVG = -3 * V_0 - 3 * V_N - (K1 * (V_B - V_N) + K2 * (V_C - V_N)) \tag{3.14}$$

V_A, V_B, V_C *are bus voltages*

$K1, K2$ *are scale factor settings based on relay meausrments*

3.2 Ungrounded bank using neutral voltage double wye

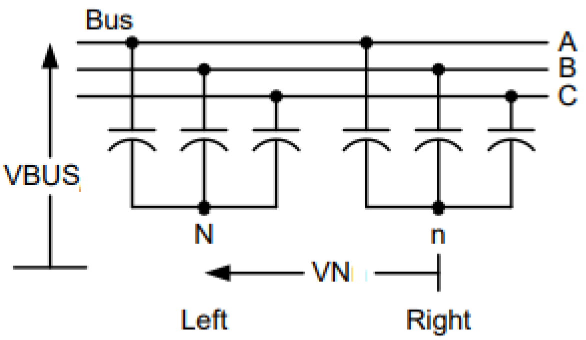


Figure 3-4 Ungrounded bank using neutral voltage unbalance protection double-wye

Neutral voltage unbalance protection is applied to a double-wye-connected capacitor bank with a PT between the neutrals, as shown in Figure 3-4.

The unbalance protection uses a neutral voltage (V_N) measurement to calculate the unbalance quantity as shown in (3.15)

$$DVG = V_N - K * V_{1BUS} \tag{3.15}$$

Where:

V_N is a neutral voltage

V_{1BUS} is the positive − sequence bus voltage

K is the phasor setting based on relay measurements

3.5 Phase current unbalance

Phase current unbalance measures unbalance current per phase for two parallel banks that use window type CT configuration.

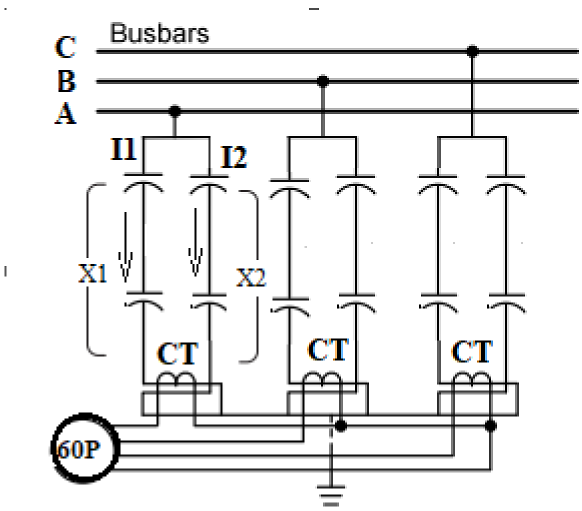


Figure 3-5 Phase current unbalance protection

Figure 3-5 shows an example of phase unbalance differential current measurements. A CT is connected between two equal strings X1 and X2, both on the A phase. I1 and I2 are the two currents split from A-Phase going through two equally split impedances.

From a common voltage applied across X1 and X2 as seen in Figure 3-5, the following equations can be established for the phase unbalance protection. The protection uses balance or bridge-current and bank-current measurements to calculate the unbalance quantity, as shown in equation (3.16).

$$I_1 = \frac{V_{BANK}}{-j_x * X_1} \quad and \quad I_2 = \frac{V_{BANK}}{-j_x * X_2} \tag{3.16}$$

The protection for phase current unbalance acts on the vector value of the difference between the two branches of bank current. The unbalance element shown in Figure 3-6 acts on a quantity shown in equation (3.17) below:

$$I_{DIF} = \frac{V_{BANK}}{-j_x * X_1} - \frac{V_{BANK}}{-j_x * X_2} \tag{3.17}$$

When the current through the two branches is perfectly balanced and the I_{DIF}

is zero, an inherited unbalance current can still be present.

Since the unbalance current I_{DIF} can be expressed as equation (3.18):

$$I_{DIF} = I_{BANK} \frac{X_2 - X_1}{X_2 + X_1} \tag{3.18}$$

When $X_1 = X_2$, $I_{DIF} = 0$. However, When $X_1 \neq X_2$, $I_{DIF} = \neq 0$.

If we let $K = \frac{X_2 - X_1}{X_2 + X_1}$

$$60\text{P} = |I_{DIF} - K * I_{BANK}| \tag{3.19}$$

Here we see K compensating for the inherited unbalance.

Connecting between the two strings near the mid-point, the connection is referred to as the H-Bridge connection.

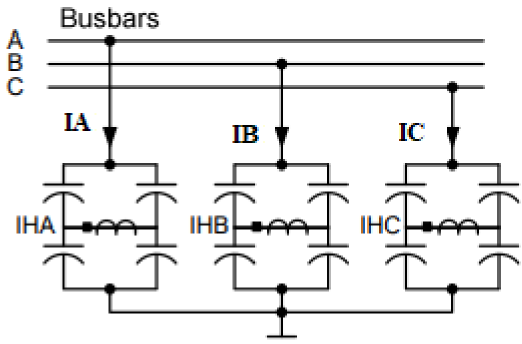


Figure 3-6 H-bridge bank using phase current unbalance protection

$$60P = |I_{HA} - K_A * I_A| \tag{3.20}$$

Where:

I_A is the phase A bank current phasor
I_{HA} is the phase A bridge current phasor
K_A is the phase A setting based on relay measurment of 60P
Phase B and C follow the same calculation as phase A.

3.6 Neutral current unbalance

Neutral current unbalance protection is applied to a double-wye-connected ungrounded capacitor bank with a CT in the common neutral, as shown in Figure 3-7. The differential current measurement is not performed on a per-phase basis as in the phase current unbalance method but between the neutrals of the two banks.

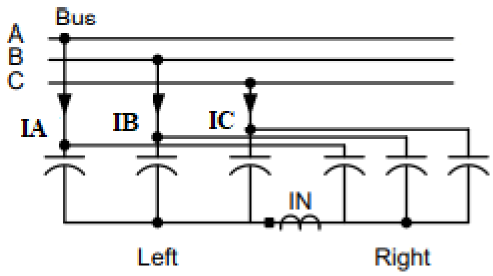


Figure 3-7 Double-wye bank using neutral current unbalance protection

The unbalance protection uses neutral current and bank current measurements to calculate the unbalance quantity for the three phases.

Since the phase current unbalance can be calculated as follow.

$$I_{DIFA} = K_a * I_a, \qquad I_{DIFB} = K_b * I_b, \qquad I_{DIFC} = K_c * I_c,$$

Then the neutral current unbalance and the inherited unbalance compensations can be expressed with equation (3.30)

If:

$$I_a + I_b + I_c = 0$$

From:

$$I_a = -(I_b + I_c)$$

Then:

$$60_N = I_N - (K_1 * I_B + K_2 * I_C) \quad (3.20)$$

Where:

I_a is the phase A bank current phasor
I_N is the neutral current phasor
K_1 and K_2 scale factor settings based on relay measurement of 60N
Phase B and C follow the same calculation as phase A

3.7 Summary

In this chapter, current SCB protection practices were covered. The need to protect SCBs from external and internal faults was examined. The four most popular unbalance protection methods for voltages and currents were explained.

In the next chapter, the research will focus on works previously done for both the protection and the fault location solution highlighting the single-phase fault location methods in the literature.

Chapter 4 Literature survey of approaches for single-phase fault location

This chapter presents a literature survey on the state of research and industrial applicaiton of identifying SCB fault location, and reviews already developed solutions and their limitations. The chapter presents the generalized research, technical papers, industry, and vendor literature in the subjects of shunt capacitor bank fault location solutions.

The utilization of unbalance protection for the shunt capacitor bank is already a subject of several pieces of literature including IEEE Std C37.99. With the recent transitions from externally fused banks to internally fused ones or unfused banks, the requirement to promptly determine fault locations is growing. With solutions developed and available today, identifying fault location and maintaining them quickly became a reality.

However, identification of SCB fault location has much less literature unlike those for the unbalance protection methods. SCB. Few works have been done on the subject of SCB fault location identification and no work has been done on identifying multiphase SCB fault identification.

In this research, this chapter attempts to show solutions that are already implemented to solve the fault location identification problem. The chapter also presents the limitations of existing solutions and shows the motivation for this research to solve more related problems to enhance the overall fault location solution.

The method described in [4] is the foundation of this research. The Chapter 5 will discuss the details of this research and show the proposed solution is a continuation work of fault identification methods. The research analyzes various capacitor bank configurations and proposes an economical method to help locate faulty elements or units for each configuration. These methods are as follows:

- Phase voltage unbalance.
- Neutral voltage unbalance.

- Phase current unbalance.
- Neutral current unbalance

For the banks using phase voltage unbalance protection, the method in [4] uses a tap on a single wye-connected bank and divides the three phases into six places with each phase having a section above and below the tap. The protection in [4] uses tapped voltage and bus voltage measurements to calculate the unbalance quantity. Comparing the phase angle of the unbalance quantity with the phase angle of the bus voltage allows the fault location to be further narrowed down by identifying the section (top or bottom from the tapped point) of the phase.

For the banks using neutral voltage unbalance protection, the method in [4] is applied to a wye-connected capacitor bank with a neutral PT. The bank can be single or double wye. The faulty element or unit can be in any of three locations (three phases) for a single-wye bank and any of six locations (left or right section of each of the three phases) for a double-wye connected bank. The unbalance quantity is not per phase, so the phase that has the faulty unit or element cannot be determined based on the unbalance protection operation. However, by comparing the phase angle of the unbalance quantity with the phase angle of the positive-sequence bus voltage, we can identify the phase that has the faulty unit or element.

For the phase current unbalance protection, the method in [4] is applied to an H-bridge-connected capacitor bank. The faulty element or unit can be in any of 12 locations (any of the three phases and the left, right, top, or bottom section of each phase from the bridge CT). The protection uses balance or bridge current and bank current measurements to calculate the unbalance quantity. The unbalance quantity is per phase and so is the unbalance protection. The phase of the bank with the faulty unit or element is the phase for which the protection has operated (based on unbalance quantity magnitude). By comparing the phase angle of the unbalance quantity with the phase angle of the bank current, we can further narrow down the fault location by identifying the section.

For the neutral current unbalance protection, the method in [4] is applied to a double-wye-connected ungrounded capacitor bank with a CT in the common neutral. The faulty element or unit can be in any of six locations (three phases and either the left or right section of each phase from the neutral CT). The unbalance protection uses neutral current and bank current measurements to calculate the unbalance quantity. The phase angle of the unbalance quantity is referenced to the phase angle of the positive-sequence bank current, and the referenced phase unbalance angle, 60NA, is then checked to determine in which sector of the twelve segments the fault occurred.

The authors of [13] proposes a method that applies dynamic unbalance compensation for detecting more than one failure with negating temperature effects on capacitive reactance to improve existing methods. Detection of more than a single failed element is added to the fault location method. The k-factor resets dynamically between faults to detect consecutive failures between a predetermined time frame. Faults occurring in multiple time frames or changing base setting magnitude indicate more than one failure. The protection technique in [13] is similar to the technique mentioned in [4]

The authors of [11] presents string current unbalance protection and faulted string identification. The faulted string identification is based on unbalance protection concepts. The method presented in [11] detects unbalance current between strings of the same phase and identifies the phase and string in which the faulted units are located.   In the intra-phase string current unbalance protection method, each string in a particular phase Ip1, Ip2, …, IpN (N = number of strings / p=phase A,B,C) is compared twice in a continuous loop around the phase (i.e. Ip1 - Ip2, Ip2 - Ip3, Ip3 - Ip4, . . . , Ip(N-1) - IpN, IpN - Ip1). The method guarantees avoiding ambiguity because every sting in the phase cannot have an equal number of failed capacitor elements.

Among the very few research findings available on the subject of faulted phase identification, the technique in [4] has a solution covering all four unbalance protection methods. As was shown in this chapter, [4] details four unbalance protection methods for its fault identification solutions. In the next chapter, [4] will be presented in detail to examine the two unbalance protection methods it uses for fault location. The neutral voltage unbalances and the neutral current unbalance methods of [4] are the basis of this research and the next chapter will present them to identify possible future developments of this research.

4.1 Summary

This chapter reviewed previous works done in the subject of SCB protection and described the few references describing practice for fault location identification.

The next chapter will detail the single-phase fault location identification solution that was developed and whichlays the groundwork for the subject of this research, the multiphase multisection fault location identification.

Chapter 5 Single Phase Fault Location Identification: Existing Solution

Faulted phase and section identification methods are patented and developed into products for single-phase faults in single or double-wye arranged banks. The choice of protection method depends on factors such as bank configuration, availability of instrument transformers, sensitivity, and security. The unbalance protection methods use one or more of the measured quantities from bus voltages, bank currents, neutral voltage, and neutral current to use for protection and fault location purposes. Reference [4] is coauthored by the author of this research and as a basis for the proposed approach, it will be extensively reviewed in this chapter.

The method presented in [4] uses the unbalance phasor quantity, and the resulting magnitude is used for protection while the angles are sued for fault location. The magnitude of the unbalance quantity in this case directly indicates the number of failed elements or units. The authors of [4] propose a fault location technique that uses the phase angle of the unbalance quantity and compares it with a reference quantity phase angle [12] [13]. The reference quantity can be a phase voltage (bus), phase current (bank), positive-sequence bus voltage, positive-sequence bank current, and so on. If the bank is protected with the phase voltage or phase current unbalance protection method, then use phase voltage (bus) or phase current (bank) as the reference quantity. If the bank is protected with the neutral voltage or neutral current unbalance protection method, then use positive-sequence bus voltage or positive-sequence bank current as of the reference quantity. The proposed fault location technique in [4] helps identify the phase and section of the bank that has the faulty element or unit. The fault location information can be included as part of the event report and can be used by the utility crew to perform planned maintenance.

For sensitivity, the fault location technique is supervised with an alarm or trip condition from unbalance protection. For security, a ±15-degree blinder is applied to exclude unbalances not resulting from capacitor failures, such as instrument transformer errors. The fault location technique is embedded as part of the unbalance protection and does not require additional sensors, and hence, it is an economical solution.

The fault location technique is affected by the fusing method of the bank (i.e., whether it is fused or fuseless). Figure 5-1, Figure 5-2, and Figure 5-3 illustrate an example to show impedance, voltage, and current distribution for fused or fuseless banks. The three figures show four series groups of ten capacitors in parallel to demonstrate the three stages of fuse operation. A capacitor symbol represents either one row of an internally fused unit or a complete unit in an externally fused bank. Figure 5-1 shows the normal state. Figure 5-2 shows the circuit just after a short circuit occurs but before the fuse operates. Figure 5-3 shows the final state of an externally or internally fused bank after the fuse operation. Impedance increases after the fuse operation. Figure 5-2 represents the final state of a fuseless bank. Impedance decreases after a short circuit. This impedance variation affects the current and voltage distribution. Because the fault location technique is based on phase angle comparison, the current and voltage distribution affects the fault location.

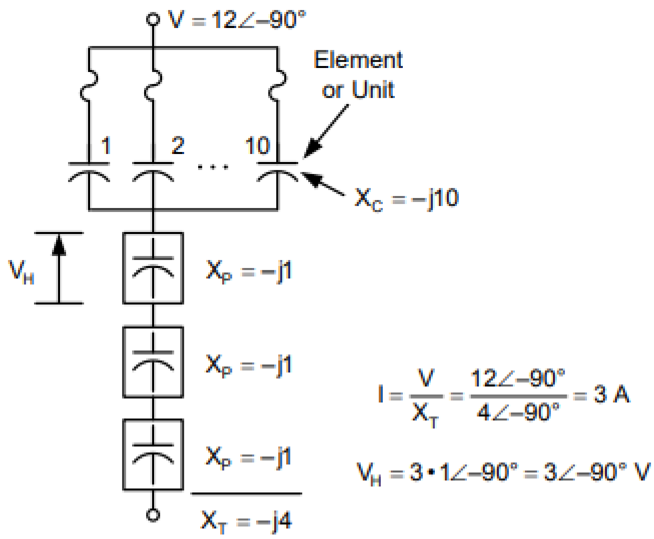


Figure 5-1 Healthy system

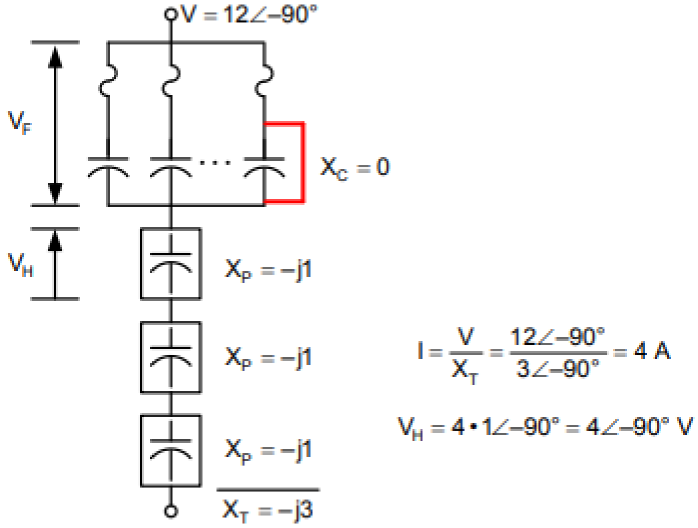


Figure 5-2 System with short circuit

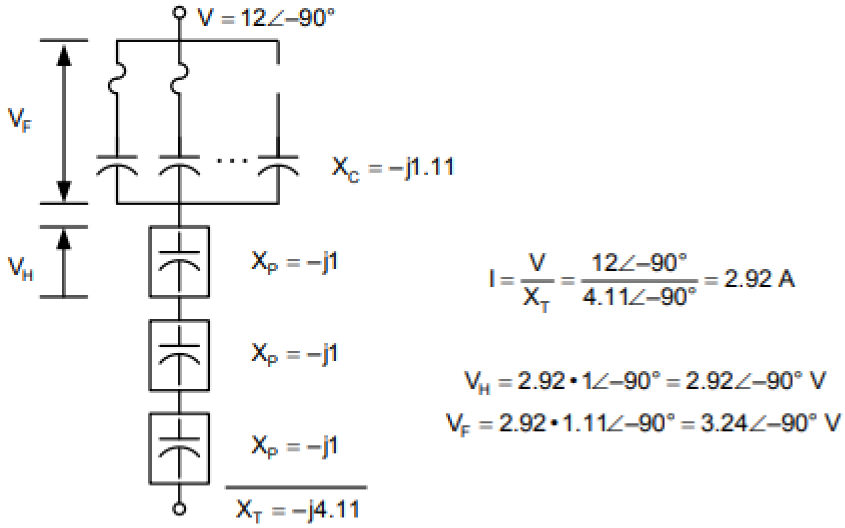


Figure 5-3 A system with a blown fuse

The fault location technique is not affected by the inherent unbalance as long as the unbalance protection compensates for it. Unbalance protective relays are often provided with a manual command to reset the inherent unbalance to improve sensitivity and security. The inherent unbalance can be from the variation on capacitor units within manufacturing tolerances, temperature changes, aging effects, and so on. A bank with element or unit failures that cause acceptable overvoltage can be left in operation for some time awaiting scheduled or emergency maintenance. This can cause an unbalance alarm that needs to be reset by the protective relay so that subsequent failures are detected with maximum sensitivity. The fault location information needs to be saved before resetting the unbalance alarm. When a second failure happens, which results in an alarm or trip, the fault location technique is accurate for the second failure despite the preexisting failure. When the bank is taken out of service, personnel must search for two failures using the original and subsequent fault location information. The following sections explain this fault location technique that can be used for various capacitor bank configurations, depending on the type of unbalance protection method used.

5.1 Banks Using Neutral Voltage Unbalance Protection

5.1.1 Protection Theory and Fault Location Principle

Neutral voltage unbalance protection is applied to a wye-connected capacitor bank with a neutral PT, as shown in Figure 5-4. The bank can be single or double wye. The faulty element or unit can be in any of three locations (three phases) for a single-wye bank and any of six locations (left or right section of each of the three phases) for a double-wye connected bank.

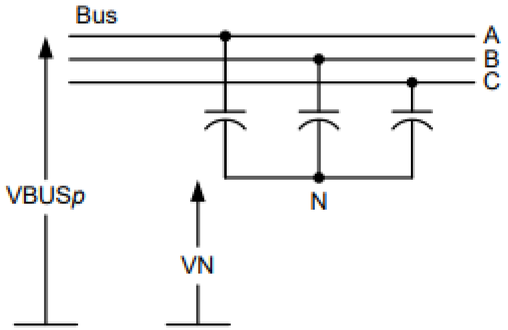


Figure 5-4 Ungrounded bank using neutral voltage unbalance protection

The unbalance protection uses the neutral voltage and bus voltage measurements to calculate the unbalance quantity as shown in (5.1)

$$DVG = VBUSA + VBUSB + VBUSC - 3 * VN - (K1 * (VBUSB - VN) + K2 * (VBUSC - VN)) \tag{5.1}$$

where:

VBUSp is the Phase p bus voltage phasor.

VN is the neutral voltage phasor.

K1 and K2 are the scale factor settings based on the relay measurements that reset DVG.

Let VAG, VBG, and VCG be the voltages measured at the bus. Then equation (5.2) provides zero-sequence voltage at the bus.

$$VAG + VBG + VCG = 3V0 \tag{5.2}$$

We know that bus voltage is the sum of bank-phase-to-neutral voltage and neutral-to-ground voltage. Let VAN, VBN, and VCN be the bank-phase-to-neutral voltages and VNG be the neutral-to-ground voltage.

Then by substitution, we get equation (5.3):

$$(VAG + VNG) + (VBG + VNG) + (VCG + VNG) = 3V0 \tag{5.3}$$

By further substitution

$$VAN + VBN + VCN + 3VNG = 3V0 \tag{5.4}$$

After rearrangement, we obtain the following:

$$3VNG - 3V0 = -(VAN + VBN + VCN) \tag{5.5}$$

Now the bank voltage can be represented in terms of currents and capacitance-reactance dominated impedance.

$$IA + IB + IC = 0$$

And IA can be expressed as:

$$IA = -(IB + IC) \qquad (5.6)$$

By substitution:

$$3VNG - 3V0 = (ZA - ZB) * IB + (ZA - VC) * IC \qquad (5.7)$$

$$3VNG - 3V0 = (ZA - ZB) * \frac{(VBG - VNG)}{\mathrm{ZB}} + (ZA - ZC) * \frac{(VCG - VNG)}{\mathrm{ZC}} \qquad (5.8)$$

$$VNG - V0 = (VNG - VBG) = \frac{(ZB - ZA)}{\mathrm{ZB}} + (VNG - VCG) = \frac{(ZC - ZA)}{\mathrm{ZC}*3} \qquad (5.9)$$

$$VNG = V0 + (VNG - VBG) * KG1 + (VNG - VCG) * KG2) \qquad (5.10)$$

The neutral to ground voltage, VNG, has two components:

- System zero-sequence voltage
- Inherent unbalance within the capacitor bank itself

The difference between the two components from VNG is the true unbalance due to the capacitance element of the bank unit fault.

$$DVG = VBUSA + VBUSB + VBUSC - 3 * VN - (K1 * (VBUSB - VN) + K2 * (VBUSC - VN)) \qquad (5.11)$$

Matching

$$DVG = VNG - V0 - (VNG - VBG) * KG1 + (VNG - VCG) * KG2)$$
(5.12)

The unbalance quantity is not per phase, so the phase that has the faulty unit or element cannot be determined based on the unbalance protection operation. However, by comparing the phase angle of the unbalance quantity with the phase angle of the positive-sequence bus voltage, we can identify the phase that has the faulty unit or element.

Figure 5-5 shows the fault location technique for ungrounded banks using neutral voltage unbalance protection. The phase angle of the unbalance quantity is referenced to the phase angle of the positive-sequence bus voltage. The referenced phase unbalance angle, DVGA, is then checked to determine if it is in Sector 1 (0° ± 15°), Sector 2 (180° ± 15°), Sector 3 (–120° ± 15°), Sector 4 (60° ± 15°), Sector 5 (120° ± 15°), or Sector 6 (–60° ± 15°). For a fuseless bank, if DVGA is in Sector 1, then the faulty unit or element is in Phase A. If DVGA is in Sector 3, then the faulty unit or element is in Phase B. If DVGA is in Sector 5, then the faulty unit or element is in Phase C.

For a fused bank, if DVGA is in Sector 2, then the faulty unit or element is in Phase A. If DVGA is in Sector 4, then the faulty unit or element is in Phase B. If DVGA is in Sector 6, then the faulty unit or element is in Phase C.

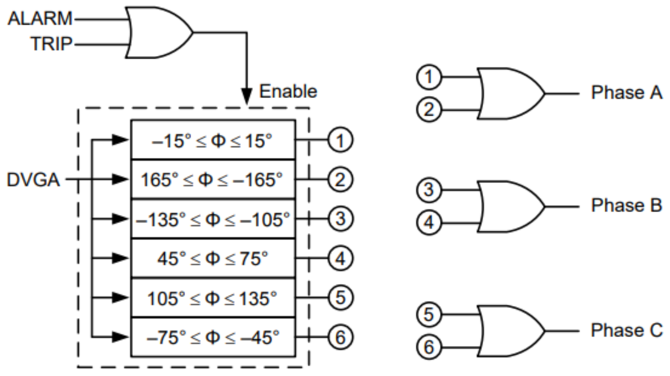


Figure 5-5 Fault location for single-wye banks using neutral voltage unbalance protection

This fault location technique reduces investigation time by 66.6 % (one out of three possible faulted phases) for a single-wye ungrounded bank that uses neutral voltage unbalance protection. This fault location technique can be applied to a double-wye ungrounded bank with a common neutral and a single neutral PT for neutral unbalance protection. In this case, however, the fault location technique cannot identify the section of the bank that has the fault. It can still identify the phase of the bank, resulting in a 66.6 % (two out of six possible fault locations) reduction in investigation time.

5.1.2 Simulation Using the RTDS

A 230 kV, 108.53 MVAR capacitor bank was modeled in the RTDS. A logic consisting of digital bits, logic gates, analogs, timers data acquisition was built to simulate the proposed solution. The bank is a single-wye ungrounded configuration and has a neutral PT for neutral unbalance protection. The bank is fuseless and consists of 192 capacitor units. Figure 5-6 shows a representation of the bank. Each phase of the bank has eight parallel strings with eight units connected in series, for a total of 64 units per phase. Each capacitor unit consists of a single string of eight elements in series. The capacitor unit is rated at 17.8 kV and 650 kVAR.

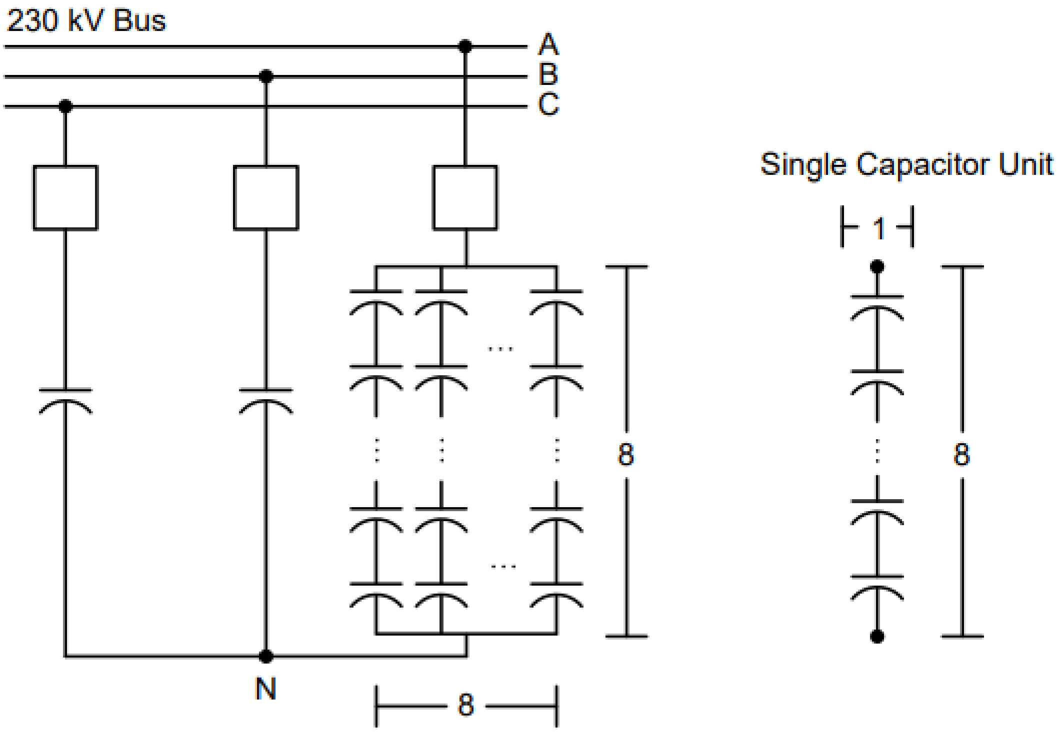


Figure 5-6 Capacitor bank model for neutral voltage unbalance fault location

Figure 5-7 shows the bus voltages and neutral voltage measured by the bus and neutral PTs. The secondary voltages are fed to a relay model that provides unbalance protection. Figure 5-7 also shows the neutral voltage unbalance magnitude and the unbalance angle referenced to positive-sequence bus voltage from the relay model. An internal fault is simulated by shorting two elements in a unit in Phase A of the healthy bank, resulting in an unbalance voltage magnitude of 0.24 V secondary and an angle close to 0 degrees. The relay is set to assert an alarm above 0.2 V after a time delay. Figure 5-7 shows the relay correctly asserts ALARM and PHASE A, indicating the faulty element or unit is in Phase A.

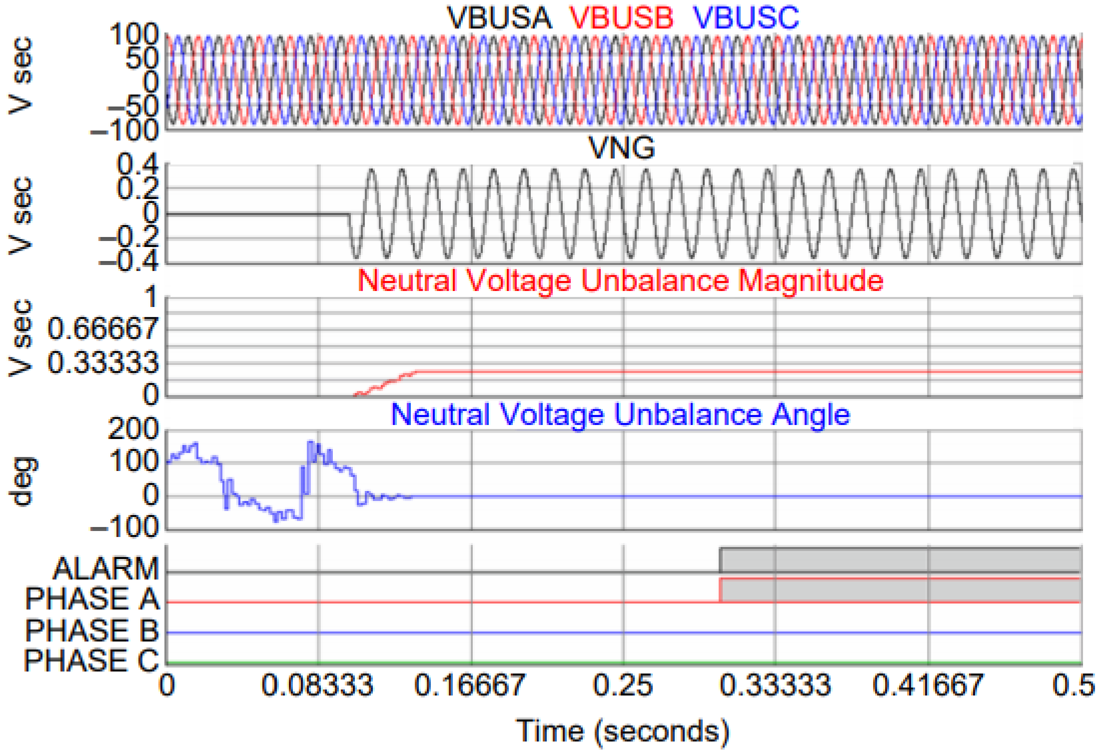


Figure 5-7 Fault in phase A of a bank using neutral voltage unbalance protection

An internal fault is simulated by shorting two elements in a unit in Phase C of the healthy bank. The fault results in an unbalance voltage magnitude of 0.24 V secondary and an angle close to 120 degrees. Figure 5-8 shows the relay correctly asserts ALARM and PHASE C, indicating the faulty element is in Phase C.

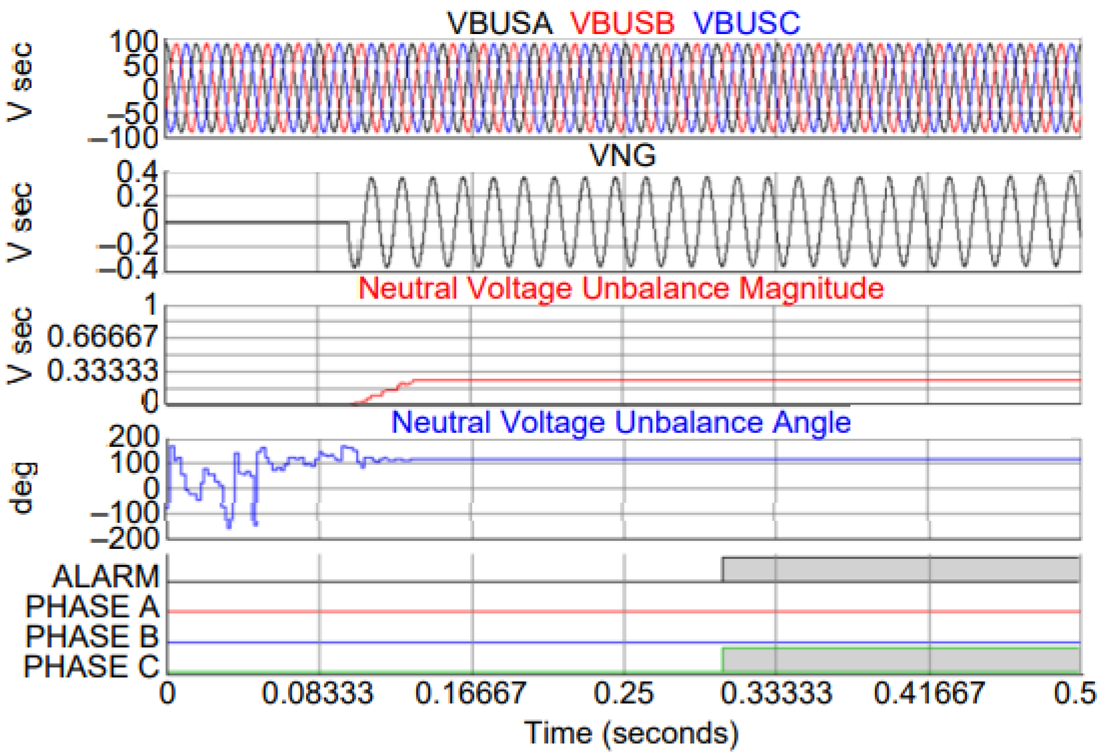


Figure 5-8 Fault in phase c of a bank using neutral voltage unbalance protection

5.1.3 Double-Wye Bank with PT Between Neutrals: Protection Theory and Fault Location Principle

Neutral voltage unbalance protection is applied to a double-wye-connected capacitor bank with a PT between the neutrals, as shown in Figure 5-9. The faulty element or unit can be in any of six locations (three phases and the left or right section of each phase from the neutral PT).

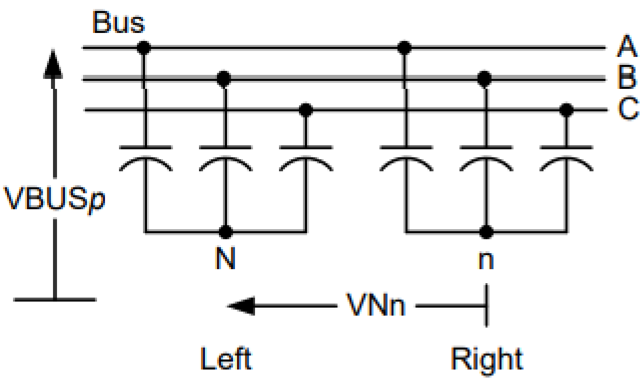


Figure 5-9 Double-wye bank with a neutral PT using neutral voltage unbalance protection

The unbalance protection uses a neutral voltage (VNn) measurement to calculate the unbalance quantity as shown in equation (5.13)

$$DVG = VNn - Kn * V1BUS \tag{5.13}$$

where:

VNn is the neutral voltage phasor.

V1BUS is the positive-sequence bus voltage phasor.

Kn is the phasor setting based on relay measurements that reset DVG.

Figure 5-10 shows the fault location technique for double-wye ungrounded banks with a PT between the neutrals and using neutral voltage unbalance protection. The phase angle of the unbalance quantity is referenced to the phase angle of the positive-sequence bus voltage, and the referenced phase unbalance angle, DVGA, is then checked to determine if it is in Sector 1 (0° ± 15°), Sector 2 (180° ± 15°), Sector 3 (–120° ± 15°), Sector 4 (60° ± 15°), Sector 5 (120° ± 15°), or Sector 6 (–60° ± 15°). For a fuseless bank, if DVGA is in Sector 1, then the faulty unit or element is in Phase A and the left section of the bank. If DVGA is in Sector 2, then the faulty unit or element is in Phase A and the right section of the bank. Similar logic applies to Phase B and Phase C. For a fused bank, if DVGA is in Sector 2, then the faulty unit or element is in Phase A and the left section of the bank.

If DVGA is in Sector 1, then the faulty unit or element is in Phase A and the right section of the bank. Similar logic applies to Phase B and Phase C.

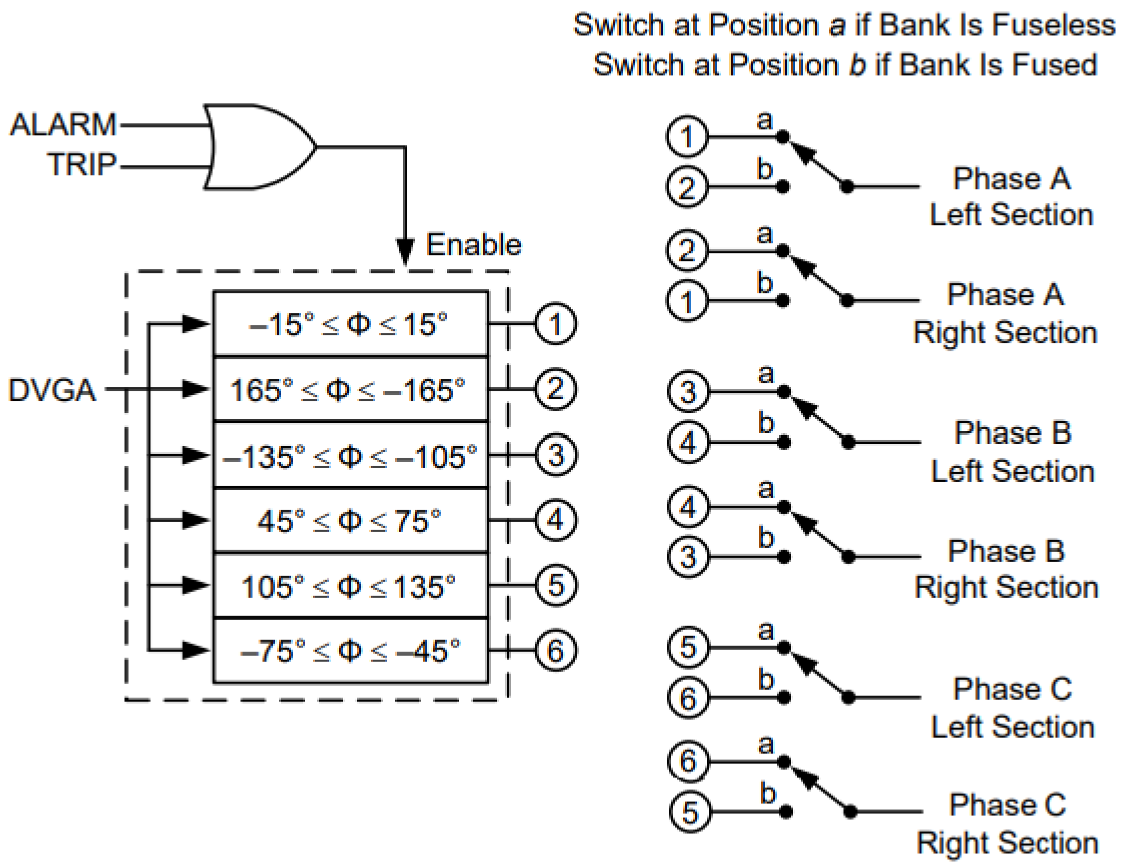


Figure 5-10 Fault location for double-wye banks using neutral voltage unbalance protection

This fault location technique reduces investigation time by 83.3 % (one out of six possible fault locations) for a double-wye ungrounded bank with a PT between the neutrals that use neutral voltage unbalance protection.

5.2 Banks Using Neutral Current Unbalance Protection

5.2.1 Double-Wye Bank with a CT in the Common Neutral: Protection Theory and Fault Location Principle

Neutral current unbalance protection is applied to a double-wye-connected ungrounded capacitor bank with a CT in the common neutral, as shown in Figure 5-11. The faulty element or unit can be in any of six locations (three phases and either the left or right section of each phase from the neutral CT)

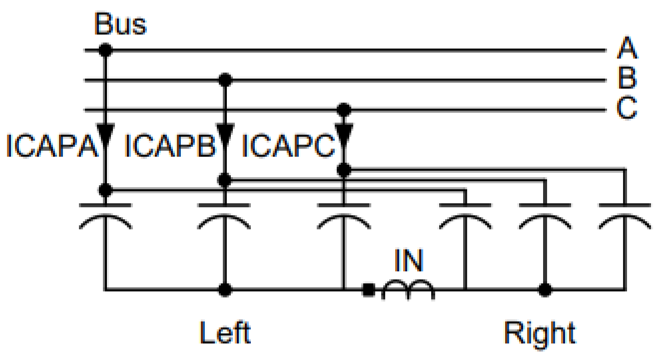


Figure 5-11 Double-wye bank using neutral current unbalance protection

The unbalance protection uses neutral current and bank current measurements to calculate the unbalance quantity as shown in equation (5.14).

$$60N = IN - (K1 * ICAPB + K2 * ICAPC) \qquad (5.14)$$

where:

ICAPp is the Phase p bank current phasor.
IN is the neutral current phasor.
K1 and K2 are the scale factor settings based on the relay measurements that reset 60N.

Figure 5-11 shows the fault location technique for double-wye ungrounded banks with a CT in the common neutral and using neutral current unbalance protection. The phase angle of the unbalance quantity is referenced to the phase angle of the positive-sequence bank current (derived from ICAPp), and the referenced phase unbalance angle, 60NA, is then checked to determine if it is in Sector 1 (0° ± 15°), Sector 2 (180° ± 15°), Sector 3 (–120° ± 15°), Sector 4 (60° ± 15°), Sector 5 (120° ± 15°), or Sector 6 (–60° ± 15°). For sensitivity, the fault location technique is supervised with an alarm or trip condition from the unbalance protection. For security, a ±15-degree blinder is applied for unbalances not resulting from capacitor failures. For a fuseless bank, if 60NA is in Sector 1, then the faulty unit or element is in Phase A in the left section of the bank. If 60NA is in Sector 2, then the faulty unit or element is in Phase A in the right section of the bank. Similar logic applies to Phase B and Phase C. For a fused bank, if 60NA is in Sector 2, then the faulty unit or element is in Phase A in the left section of the bank. If 60NA is in Sector 1, then the faulty unit or element is in Phase A in the right section of the bank. Similar logic applies to Phase B and Phase C.

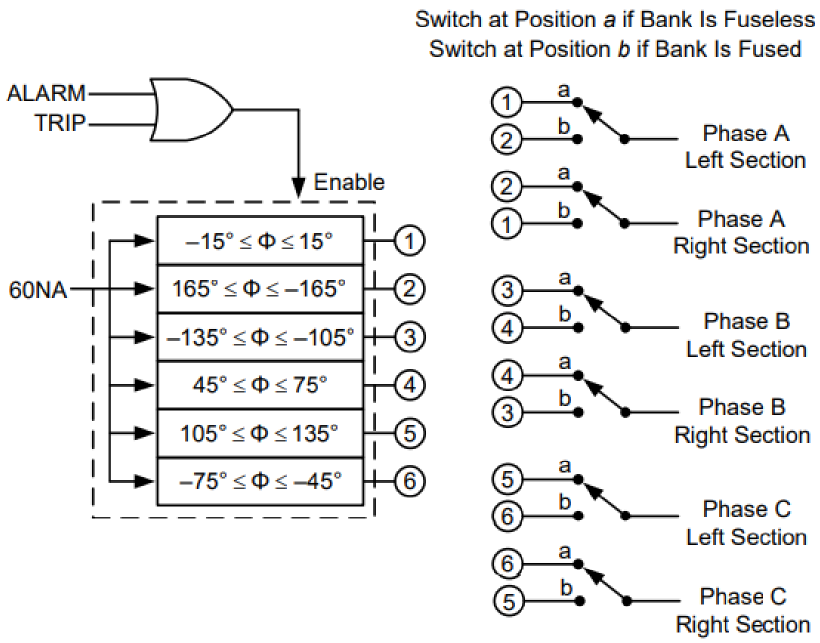


Figure 5-12 Fault location for double-wye banks using neutral current unbalance protection

This fault location technique reduces investigation time by 83.3 % (one out of six possible fault locations) for a double-wye-connected ungrounded bank that uses neutral current unbalance protection.

5.2.2 Double-Wye Bank with a CT in the Common Neutral: Simulation Results Using the RTDS

A 33 kV, 9.54 MVAR capacitor bank was modeled in the RTDS. The bank is a double-wye ungrounded configuration and has a CT between the neutrals for neutral current unbalance protection. The bank consists of 18 capacitor units and is internally fused. Figure 5-13 shows the representation of the bank. Each capacitor unit consists of five series groups with each series group consisting of 15 elements connected in parallel. The capacitor unit is rated at 10.987 kV and 705 kVAR.

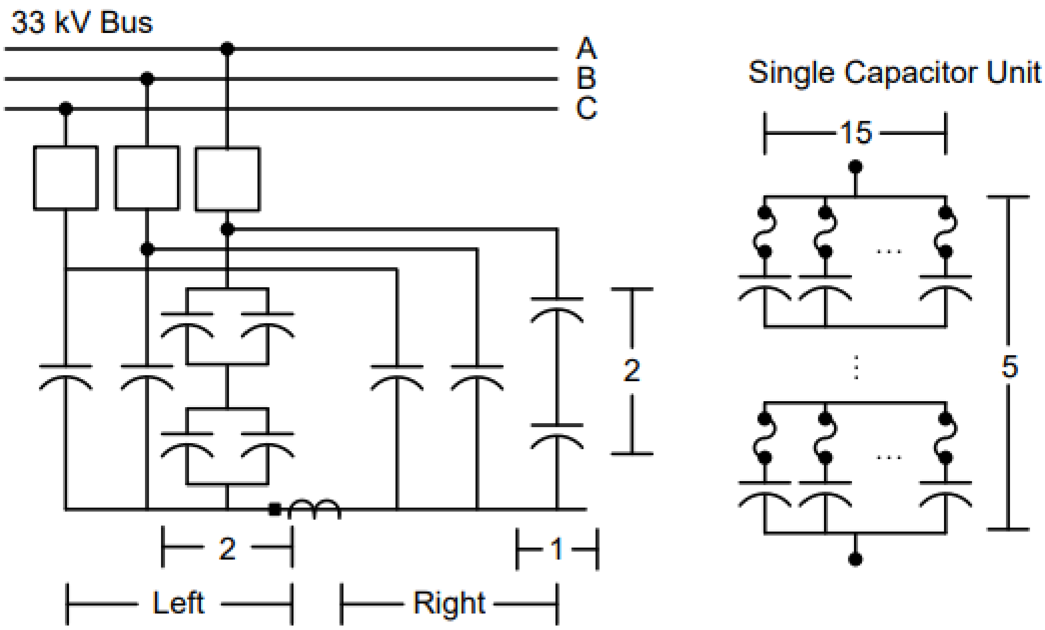


Figure 5-13 Capacitor bank model for neutral current unbalance fault location

Figure 5-13 shows the bank and neutral currents measured by the bank and neutral CTs. They are input to a relay model that provides unbalance protection. Figure 5-14 shows neutral current unbalance magnitude and neutral current unbalance angle referenced to the positive-sequence bank current from the relay model. An internal fault is simulated by shorting two elements in a unit in Phase B and the left section of the healthy bank. The fault is cleared by blowing the appropriate fuses for the shorted elements, resulting in an unbalance current magnitude of 24 mA secondary and an angle close to 60 degrees. The relay is set to assert an alarm if the unbalance current magnitude is above 20 mA alarm after four cycles of delay. Figure 5-14 shows the relay correctly asserts 60ALARM, PHASE B, and LEFT, indicating the faulty element or unit is in Phase B in the left section. Figure 5-14 shows that the bank has some inherent unbalance (there is a neutral current before the internal fault), which was compensated by the unbalance protective relay with new K1 and K2 factors. Th relay monitors for any settings changes, temperature effects and post external disturbance and automatically resets the K values. The relay also can be manually set to reset K factors by demand with a command. This demonstrates that the fault location technique is not affected by the inherent unbalance as long as it is compensated.

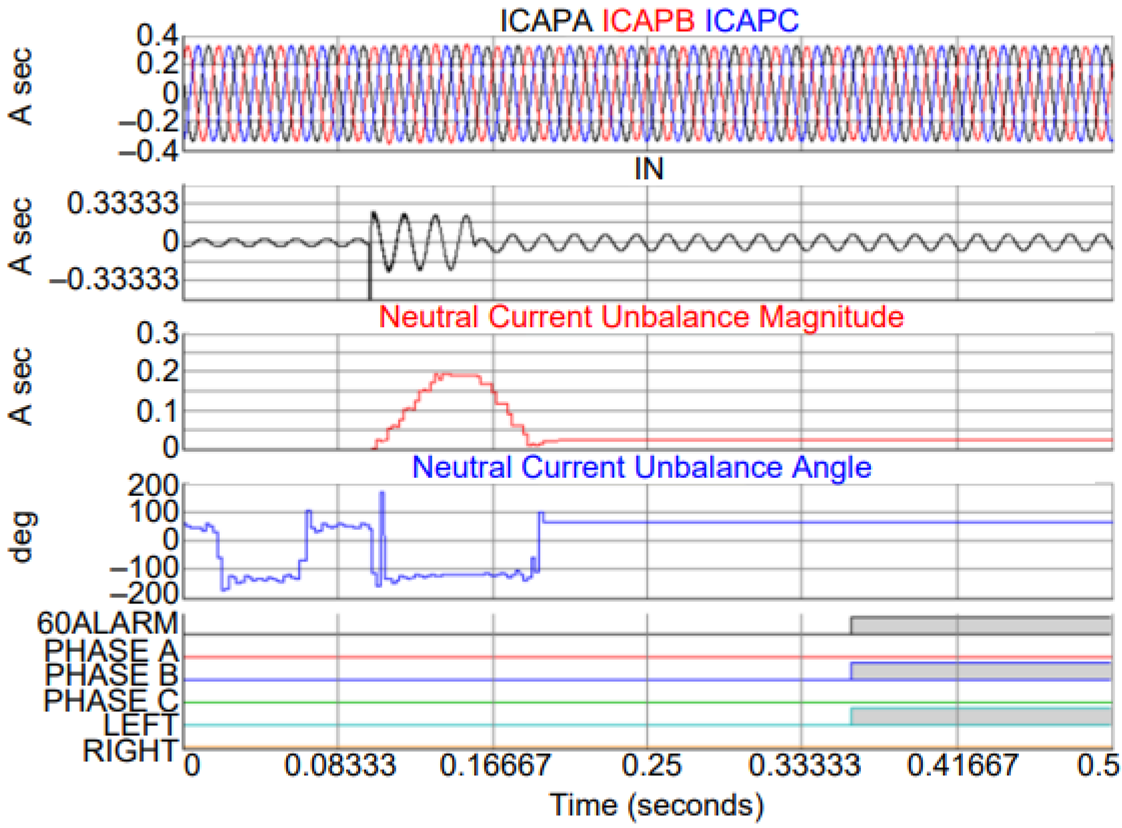


Figure 5-14 Fault in phase B and left section of a bank using neutral current unbalance protection

An internal fault is simulated by shorting two elements in a unit in Phase C and the right section of the healthy bank. The fault results in an unbalance current magnitude of 48 mA secondary and an angle close to 120 degrees, as shown in Figure 5-15. Figure 5-15 also shows the relay correctly asserts 60ALARM, PHASE C, and RIGHT, indicating the faulty element or unit is in Phase C and the right section.

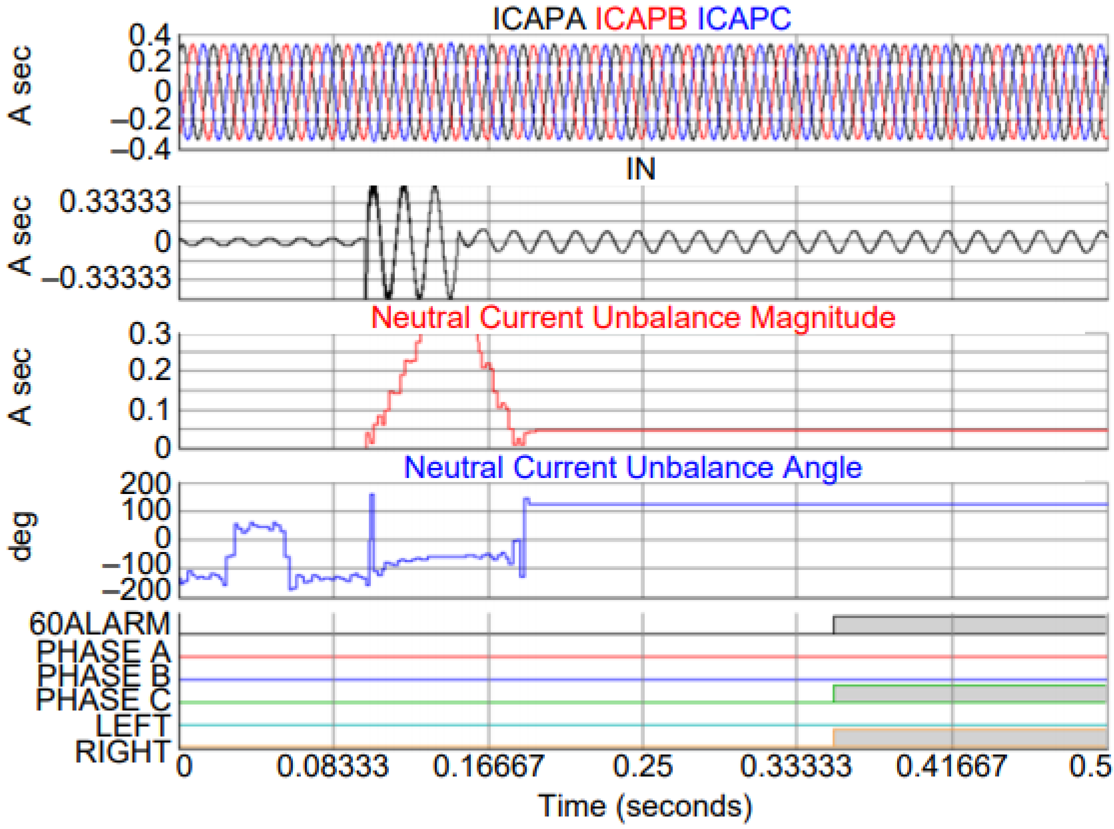


Figure 5-15 Fault in phase C and right section of a bank using neutral current unbalance protection

The neutral current, neutral voltage, phase current, and phase voltage unbalance protection methods we reviewed in this chapter explained the theoretical and mathematical derivations and demonstrated their performance through simulations.

The magnitude of the quantities for all four methods is used for alarm and trip purposes and the angle of the quantities is used for fault location purposes.

5.3 Importance of this Approach

Locating a faulty unit in a capacitor bank is a time-consuming process. The fault location technique proposed in this paper identified the phase and section of the bank with the faulty unit, thereby reducing the investigation time between 50 and 92 percent. The fault location technique is embedded as part of the unbalance protection, making it an economical solution. It can be applied to banks with various configurations and different fusing methods. The fault location technique is not affected by the inherent unbalance as long as the unbalance protection compensates it. The fault location technique helps in providing advance alarms for planned maintenance. It can be used to detect element failures in an externally fused bank before the fuse operates and therefore provide fuse savings and safety from case rupture. Using multiple unbalance protection methods helps to improve the reliability of protection and fault location.

5.4 Limitations in the Existing Solution and New Opportunities to Improve Fault Location Performance.

Identifying SCB fault locations promptly translates into maintaining and returning the bank to service with minimum outage time possible. SCB faults do happen in multiphase branches and identifying multiphase faults can expedite the prevention of cascading failure that could result in a total bank loss. Identifying faulted elements and units in multiple phases at the same time increases the benefit of quick action before multiphase cascading faults happen.

The existing solutions discussed in this chapter only detect and identify a single-phase fault on single or double-wye neutral voltage and current unbalance banks.

When multiphase faults happen, the number of involved elements and units can be double or more than the effect of a single-phase fault. Therefore, identifying double phase faults and locating which phases are faulted can increase reliable SCB protection.

A single-phase fault identification (currently available solution) alone cannot be a comprehensive solution. Faults can happen to multiple phases within wye-connected banks or across a section of double wye-connected banks.

The novel solution that deals with identifying multiphase fault identification will be presented in the next chapter.

5.5 Impact on Reliability and Resiliency

The United States Energy Policy Act of 2005 (PL. 109-58; EPACT05) authorizes the Federal Energy Regulatory Commission (FERC) to oversee the reliability of the bulk power system. [14] The policy is to prevent instability and cascading failure due to sudden disturbance in the power system. Shunt capacitor banks are a good example of components that impact system reliability as they are a local source of increased capacity and stability. The solution being developed by this research increases the reliability of SCB as a method for locating a fault promptly and helping SCBs to come back to service quickly adds great value to the resiliency of the power system.

5.6 Summary

This chapter introduced and analyzed an existing fault location solution that is the basis for this research. The protection theory of [4] was presented, and the fault location solutions for ungrounded phase and neutral voltage and current unbalance protection were described. The single-phase fault location method was presented in detail and simulation results from RTDS were presented.

The next chapter will present the main topic of this research, the multiphase multisection fault location identification.

Chapter 6 Multiphase Fault Location: Proposed Solution

This chapter introduces the proposed solutions to improve multiphase and multisection fault location identification. The chapter derives a theoretical background of the multiphase fault location solutions with mathematical derivation and simulation setups.

The research investigates the relationship between the unbalance voltage and current angles at the neutral of single or double-wye capacitor banks and then relates these quantities with reference quantities to determine the phases involved in the fault.

The solutions presented in this chapter are based on the existing single-phase fault identification solution presented in Chapter 5. This chapter builds on that method to cover multiphase fault location solutions. The two popular protection methods, the neutral voltage-unbalance, and the neutral current-unbalance protection methods are the source of measurements and they provide phasor quantities whose magnitude is used for protection as the angle to identify fault locations. Since the fault identification solution does not have a separate device or require separate equipment beyond the standard protection package, the improved fault identification solution is cost-free. As the neutral unbalance protection measures through PTs and CTs, the angles of these quantities will be the input to fault location identification logic. The complete result of this research is obtained from both PTs and CTs placed at the neutral of single or double-wye banks. A logic based on the inputs from measured and compared angles asserts to declare multiphase fault locations with built-in security and dependability. The following points summarize what the proposed solution accomplishes.

a) Identify the faulted section of the bank (left or right of double-wye configuration)
b) Identify the particular phase or multiphase within the same section (left or right of double-wye configuration or single-wye configuration)
c) Identify simultaneous fault between two different (left or right of double-wye configuration) sections of the double-wye configuration.

6.1 Banks using neutral voltage or current unbalance protection

6.1.1 Single- or double-wye banks with neutral-to-ground PT

6.1.1.1 Protection method and fault location identification principle

Neutral voltage unbalance protection is applied to a wye-connected capacitor bank with a neutral PT, as shown in Figure 6-1. The bank can be single or double-wye, but the double-wye type is demonstrated below. The faulty element or unit can be in any of the three locations for a single-wye bank and any of six locations (left or right section of each of the three phases) for a double-wye connected bank as seen in Figure 6-1.

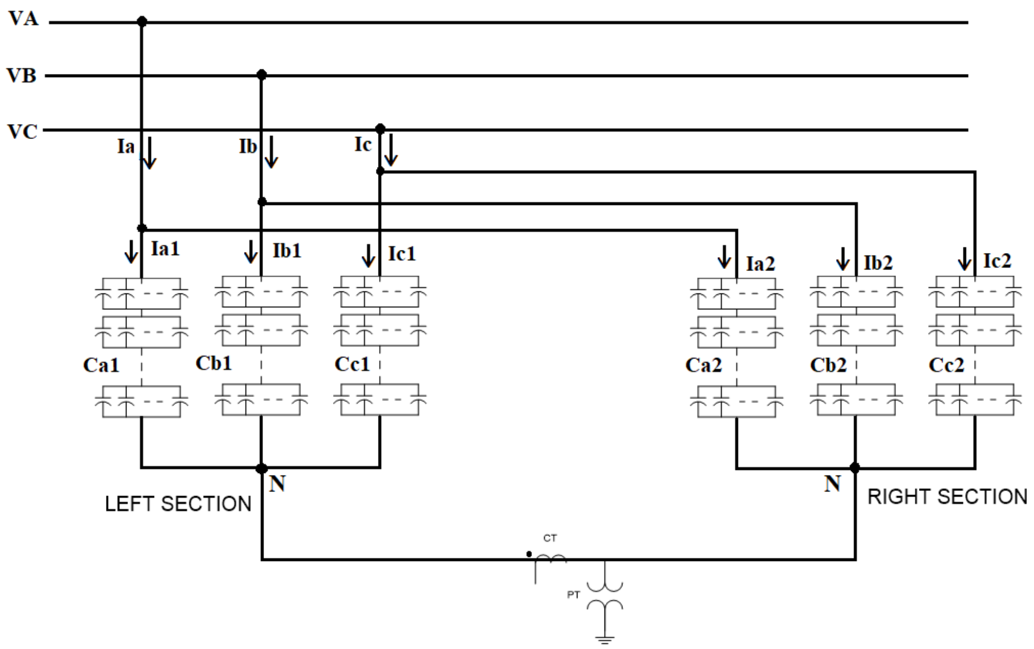


Figure 6-1 Ungrounded double-wye bank using neutral voltage or/and neutral current unbalance protection

6.1.1.2 Neutral Unbalance Current

Using the current divider rule, the currents flowing through the banks are indicated in the equations below:

$$I_{an} = \frac{C_{an}}{C_{a1}+C_{a2}} I_a \qquad (6.1)$$

$$I_{bn} = \frac{C_{bn}}{C_{b1}+C_{b2}} I_b \tag{6.2}$$

$$I_{cn} = \frac{C_{cn}}{C_{c1}+C_{c2}} I_c \tag{6.3}$$

Where:

n = 1, 2

The impedance of each phase is equal to the other two.

$$C_a = C_b = C_c \tag{6.4}$$

Because $C_p = C_{p1} // C_{p2}$

Where

p is phase a, b or c

At each branch, the left and the right sections of the double-wye bank, the unbalance current is also summed to zero.

The unbalance current of the left section:

$$\mathrm{I}_{L\_unb} = \mathrm{I}_{a1} + \mathrm{I}_{b1} + \mathrm{I}_{c1} \tag{6.5}$$

The current at the neutral CT is the sum of the three bank phase currents under normal conditions, it's zero.

$$\mathrm{K}_A * \mathrm{I}_A + \mathrm{K}_B * \mathrm{I}_B + \mathrm{K}_C * I_C = \mathrm{I}_N \tag{6.6}$$

Unbalance quantities come from two posibilities. One is an unbalance quantity that is present at the neutral point when a capacitor element or unit is faulted. The second unbalance comes from several sources such as instrument transformers error, temperature fluctuations, and other non-fault-related sources. The K factor value is used by the protective device to track this inherent unbalance quantity at the neutral point and compensate so the unbalance protection is armed with a different quantity of zero at the set time.

For example, K_A, the K factor for phase A can be calculated as:

$$K_A = \frac{K^{left}{}_A}{K^{left}{}_A + K^{right}{}_A} \qquad (6.7)$$

$$K_A = K_B = K_C \qquad (6.8)$$

The current at the neutral can be calculated as equation (6.9):

$$I_N = I_B * (K_B - K_A) + I_C * (K_C - K_A) \qquad (6.9)$$

In this case, K_1 and K_2 can be expressed as:

$$\begin{aligned} K_1 &= K_B - K_A \\ K_2 &= K_C - K_A \end{aligned} \qquad (6.10)$$

The unbalance protection uses neutral current and bank current measurements to calculate the unbalance quantity as

shown in (6.12):

$$K_1 * I_A + K_B * I_B + K_C * I_C = I_N \qquad (6.11)$$

$$60_N = I_N - (K_1 * I_B + K_2 * I_C) \qquad (6.12)$$

Where

60_N is the unbalance neutral current

I_B and I_C are bank current phasors

I_N is the neutral current phasor

K_1 and K_2 are the scale factor settings based on the relay measurements that reset 60_N

6.2 Neutral unbalance voltage

The unbalance protection uses the neutral voltage and bus voltage measurements to calculate the unbalance quantity as shown in (6.13).

$$DVG = VBUSA + VBUSB + VBUSC - 3 * VN - (\mathrm{K}_1 * (VBUSB - VN) + \mathrm{K}_2 * (VBUSC - VN)) \tag{6.13}$$

where:

DVG is the unbalance voltage at the neutral

VBUSp is the Phase p bus voltage phasor (p = A, B, C)

VN is the neutral voltage phasor

K_1 and K_2 are the scale factor settings based on the relay measurements that reset DVG

The bus voltage is the sum of the bank's phase to neutral voltage and neutral to ground voltage. AN, VBN, and VCN are the bank phase to neutral voltages and VNG is neutral to ground voltage. Then by substitution, we get:

$$(VAG + VNG) + (VBG + VNG) + (VCG + VNG) = 3V0 \tag{6.14}$$

Where

3V0 is the zero-sequence voltage

The zero-sequence voltage in equation (6.14) is the sum of the bank's phase to ground voltage.

$$VAG + VBG + VCG = 3V0 \tag{6.15}$$

After rearrangement, we obtain the following:

$$3VNG - 3V0 = -(VAN + VBN + VCN) \tag{6.16}$$

Where

VNG is the neutral to ground voltage

Now the bank voltage can be represented in terms of currents and reactance-dominated impedance.

$$IA + IB + IC = 0 \tag{6.17}$$

And IA can be expressed as equation (6.18):

$$IA = -(IB + IC) \tag{6.18}$$

By substitution:

$$3VNG - 3V0 = (ZA - ZB) * IB + (ZA - VC) * IC \tag{6.19}$$

$$3VNG - 3V0 = (ZA - ZB) * \frac{(VBG - VNG)}{\mathrm{ZB}} + (ZA - ZC) * \frac{(VCG - VNG)}{\mathrm{ZC}} \tag{6.20}$$

$$VNG - V0 = (VNG - VBG) = \frac{(ZB - ZA)}{\text{ZB}} + \ (VNG - VCG) = \frac{(ZC - ZA)}{\text{ZC} * 3}$$

(6.21)

$$VNG = V0 + (VNG - VBG) * KG1 + (VNG - VCG) * KG2)$$

(6.22)

At this point, the neutral to ground voltage, VNG, has two components:

1. System zero-sequence voltage
2. Inherent unbalance within the capacitor bank itself

When we subtract these two components from the neutral-to-ground voltage, the remaining quantity represents the true unbalance resulting from the element or unit failure within the bank. We call that quantity neutral-to-ground differential voltage or neutral voltage unbalance DVG as seen in equation (6.23).

$$DVG = VBUSA + VBUSB + VBUSC - 3 * VN - (K1 * (VBUSB - VN) + K2 * (VBUSC - VN))$$

(6.23)

6.3 Mapping angular ranges to fault locations

The phase angle of the unbalance quantities of 60_N and DVG are referenced to the phase angles of the positive-sequence bank current and positive sequence bus voltage to create the referenced unbalance angle 60_{N_ang} and DVG$_{ang}$ respectively.

The 60_{N_ang} and DVG$_{ang}$ quantities are then checked to determine the sector of Figure 6-2 the angle falls to identify the faulted phases and sections.

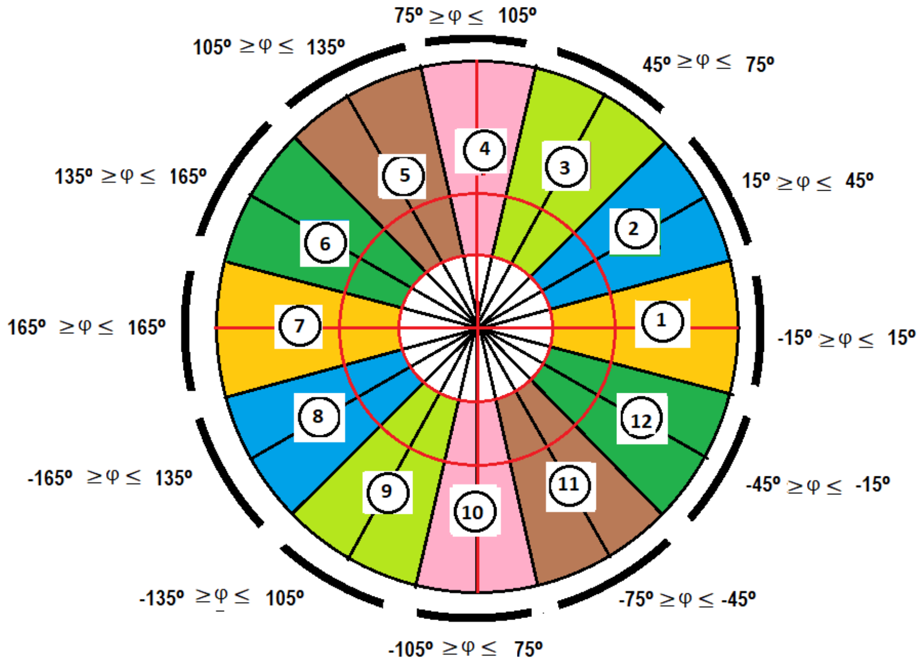


Figure 6-2 Sectors identifying phase relationships between 60_{N_ang} and the positive sequence bank current angle

The twelve outputs of 60_{N_ang} and DVG_{ang} neutral current and neutral voltage unbalance angles on Figure 6-3 are designated with index numbers 1–12. The receipt of an alarm or trip enables the output and each of the twelve (+/- 15 degrees) ranges that are in increments of 30 degrees starting from 0 degrees. The numbers labeled as 1–12 are indexes and used in the current and voltage unbalance fault identification logic as a subscript to indicate precise and unique phase and phase-to-phase faults on both sides (left and right) of double-wye banks.

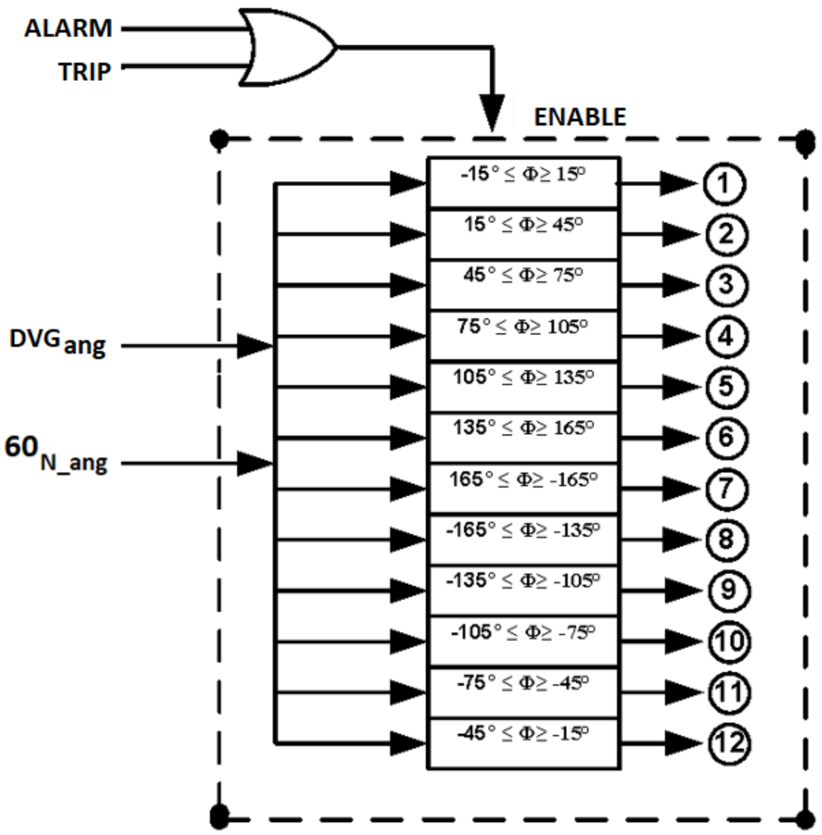


Figure 6-3 phase angle ranges for fault location using neutral phase current unbalance protection in double-wye banks

6.4 Multiphase fault identification

There are three different types of fault location arrangements to identify multiphase and multisection faults for the ungrounded double-wye bank. Based on which type is selected, the particular fault location arrangement requires a CT, a PT, or a combination of CT and PT at the neutral of the single or double-wye bank. For ungrounded single or double-wye banks equipped with both CTs and PTs, all three methods operate with the same setup and same configuration. The three multi-phase fault location categories are:

- Simultaneous multiphase faults on both left and right sides of the double-wye.
- Simultaneous multiphase faults only on the left side of the double-wye.
- Simultaneous multiphase faults only on the right side of the double-wye.

All three categories are explained in the sections below. All three categories are evaluated under the assumption of fused banks.

The multiphase multisection fault location solution works for both fused and fuseless banks. After the neutral unbalance angle obtained from instrumental transformers is compared with the reference angle to get the fault location indicator angle for a fused bank, just adding 180-degrees to that value indicates the same fault location for a fuseless bank. For example, let's assume a multiphase fault indicator $\mathbf{60}_{N\_ang}$ or $\mathbf{DVG}_{ang}$ is at 30 degrees sector to indicate the A phase fault at the left side of a fused bank and B phase fault at the right side of a fused bank. In this case, then the angle for the same fault location for unfused bank becomes -150 degrees.

6.5 Multiphase faults occur on both the left and right sides of the double-wye.

Banks using the neutral current unbalance method as the only protection method can still detect and identify a simultaneously occurring fault between the two double-wye sectors. The measurement of PT or reference of voltage is not used to identify two single-phase faults happening at both sides of the double-wye at the same time. Therefore, the multiphase multisection fault for multiple faults at the left and right sides of the double-wye banks can't be detected by PT detections.

From Figure 6-4, LBRA (Left phase B and Right phase A) indicates a simultaneous multiphase fault occurring at the left and right sides of the double-wye bank. LBRA is declared when the phase angle of $\mathbf{60}_{N\_ang}$ is at subscript 2 of Figure 6-3 indicating a 30-degrees deviation from the reference angle ranging between 15-degrees and 45-degrees (notice a +/- 15-degrees window for 30 degrees expected angle). Again, the subscript number associated with $\mathbf{60}_{N\_ang}$ of Figure 6-4 refers to phase angle ranges from Figure 6-3 in an increment of 60 degrees around the circle.

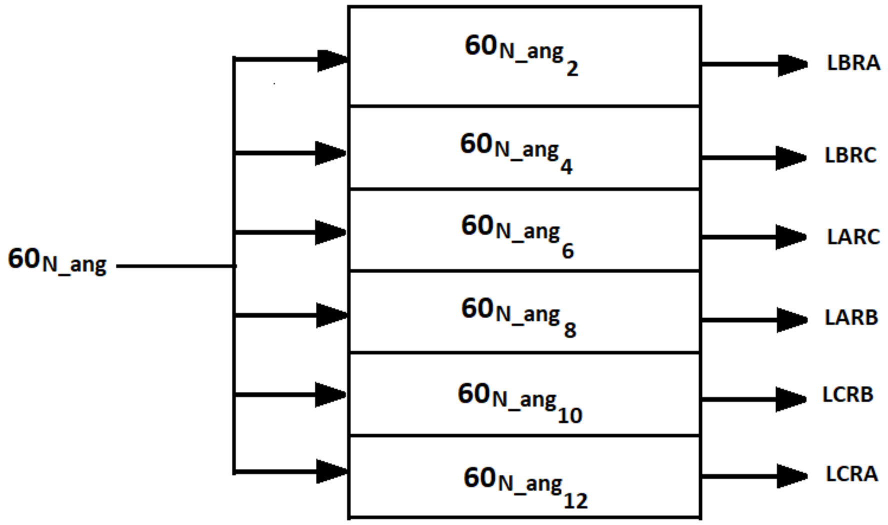


Figure 6-4 double-wye neutral current unbalance compared to a positive sequence bank current

6.6 Multiphase faults occur on the left side of the double-wye.

6.6.1 For banks using either CTs or PTs or both CTs and PTs at the neutral

When multiphase faults occur on the left side of the double-wye bank, the fault identifier voltage angle DVG_{ang} and the fault identifier current angle 60_{N_ang} are at the same angle. Therefore, using either one of the angles can indicate the two faulted phases on the left side of the wye bank.

Figure 6-5 shows the faulted multiphase location is at the left side of the double-wye section. LEFT_AB is a multiphase fault occurring on phase A-B at the left side of the ungrounded double-wye bank. The left side multiphase fault of the double-wye bank uses either the neutral CT or neutral voltage PT or both with an OR gate logic as seen in Figure 6-5. Either 60_{N_ang} or DVG_{ang} are evaluated to match the angle range indicated in Figure 6-3.

The multi-phase fault at the left section is declared when the phase angle of either 60_{N_ang} or DVG_{ang} are at the angle indicated by the subscript respectively.

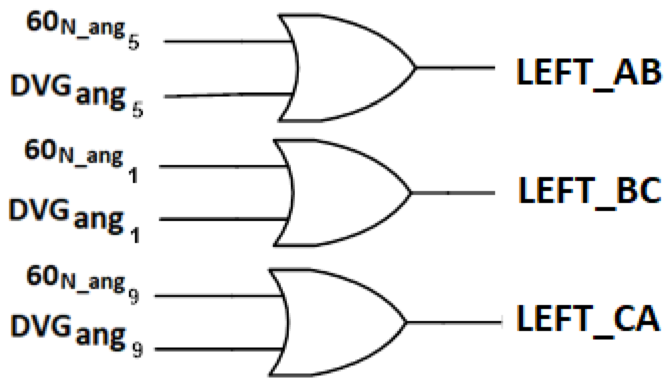


Figure 6-5 double-wye bank with a neutral PT using neutral voltage identifying left side of PT fault location.

6.7 Multiphase faults occur at the right side of the double-wye.

When multiphase faults occur on the right side of the double-wye bank, the fault identifier voltage angle DVG_{ang} and the fault identifier current angle 60_{N_ang} are at a different angle. This multiphase fault location cannot be detected accurately if only a CT or a PT are used at the neutral unbalance protection.

Banks using both CTs and PTs for their neutral current and neutral voltage unbalance protection can detect and identify a simultaneously occurring fault between any two phases at the right side of the double-wye bank.

Figure 6-5 shows the faulted multiphase location is at the right side of the double-wye section. RIGHT_AB is a multiphase fault occurring on phase A-B at the right side of the ungrounded double-wye bank. The right-side multiphase fault of the double-wye bank must use both the neutral CT and neutral PT with an AND gate logic as seen in Figure 6-6. Both 60_{N_ang} and DVG_{ang} are evaluated to match the angle range indicated in Figure 6-6.

The multi-phase fault at the right section is declared when the phase angle of both 60_{N_ang} and $\text{DVG}_{ang}$are at the angles indicated by the subscript respectively. Only when the 60_{N_ang} and DVG_{ang} angles are at their designated phase angle ranges that the multiphase fault identification for the right side of the double-wye bank declared fault location accurately and.

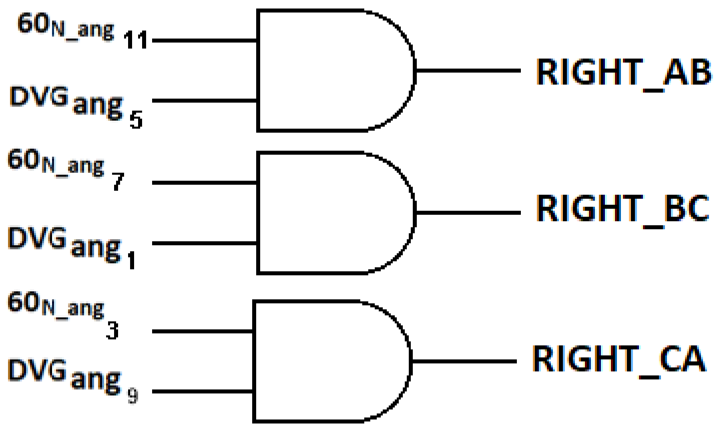


Figure 6-6 Multiphase fault location for Simultaneous fault on right-side of the double-wye.

6.8 Simulation setup

A 33 kV, 50 MVAR capacitor bank was modeled in the RTDS. The bank is a double-wye ungrounded configuration and has a CT and PT between the neutrals for neutral current and voltage unbalance protection. The bank consists of 18 capacitor units and is internally fused. Figure 6-7 shows the representation of the bank. Each capacitor unit consists of five series groups with each series group consisting of 15 elements connected in parallel. The capacitor unit is rated at 10.987 kV and 705 kVAR.

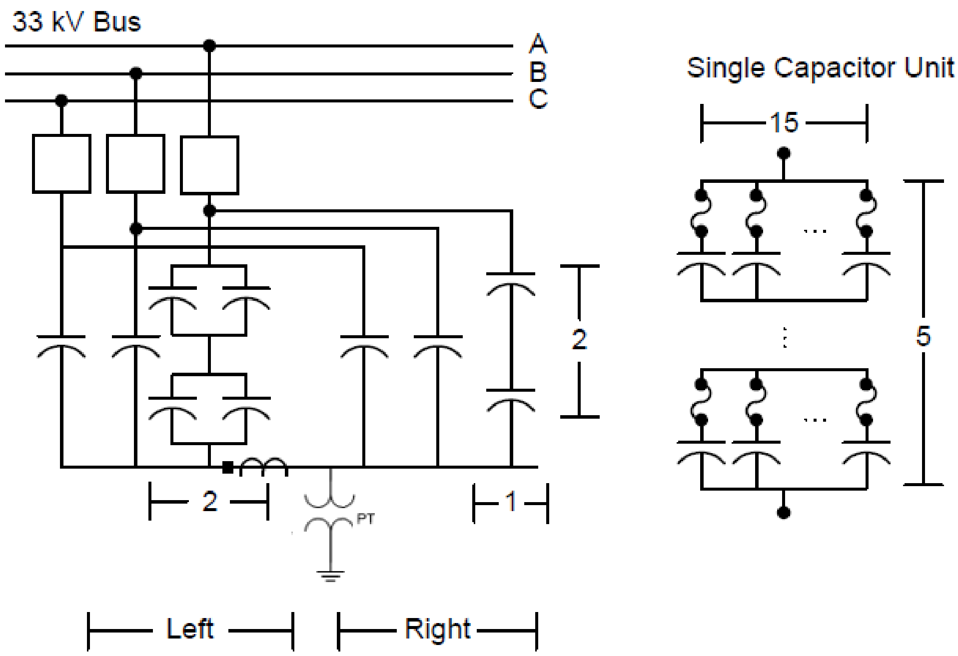


Figure 6-7 Capacitor bank model for neutral voltage and current unbalance fault location

Figure 6-8 shows the one-line diagram of the RSCAD simulation schematic. The bottom portion of the figure (the two boxed parts) shows the left and the right side of the double-wye bank. Both PT and CT are placed at the neutral of the bank for voltage and current unbalance protection. The capacitance reactance values of the left and right sides of the double wye are identical for each phase. For example, the capacitance reactance of the parallel group units that are connected in series at the left side of the A-phase has an identical reactance value as the series-connected A phase reactance at the right side.

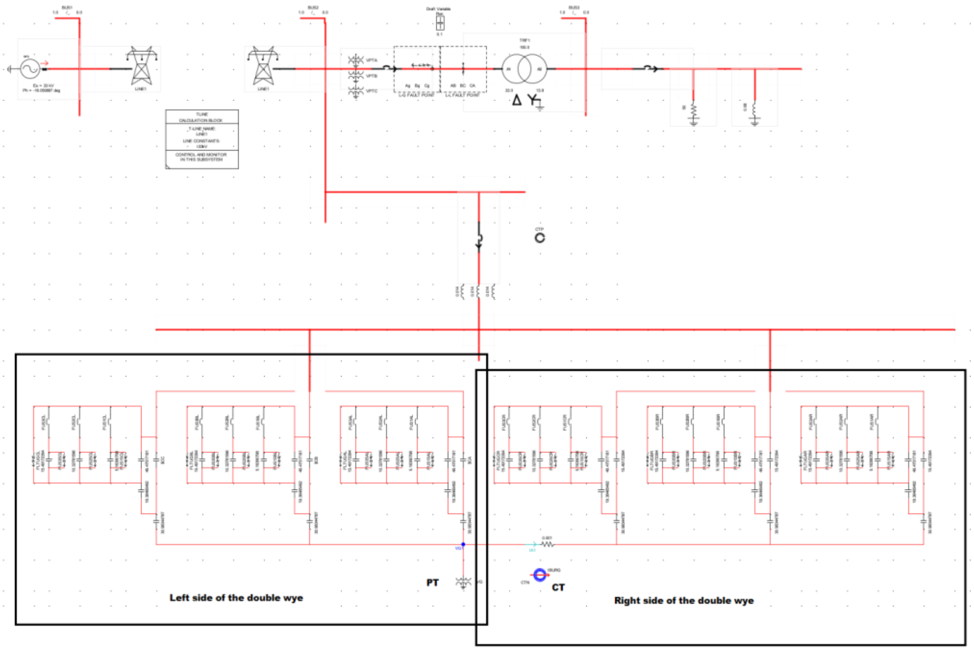


Figure 6-8 RTDS RSCAD one-line diagram for double-wye neutral unbalance.

Figure 6-9 shows the control panel to simulate the proposed solution. The plot displays bus voltages (N1, N2, N3), bank currents (ICAPA, ICAPB, ICAPC), and neutral voltage and neutral current values. The two pushbuttons reset the K factors and eliminate the inherited unbalance before the protection is armed. The K factor push button must be applied every time a configuration has changed to clear non-fault-related unbalances to rearm the protection. The switches toggle to short a capacitor element and create a fault at any single or multiphase section of the phase. For example, in Figure 6-8, two switches (A and B phases) are flipped to simulate a multiphase fault occurring at A-B phases of the left section of the wye bank. The digital plot indicates whether the fault is at the left or right side of the bank and the bar line (AB, BC, CA) displays which phase-to-phase fault occurred for which section (in the Figure 6-9 LEFT and PHASEAB are asserted). All 12 multiphase fault locations are simulated, and results will be discussed in the next chapter.

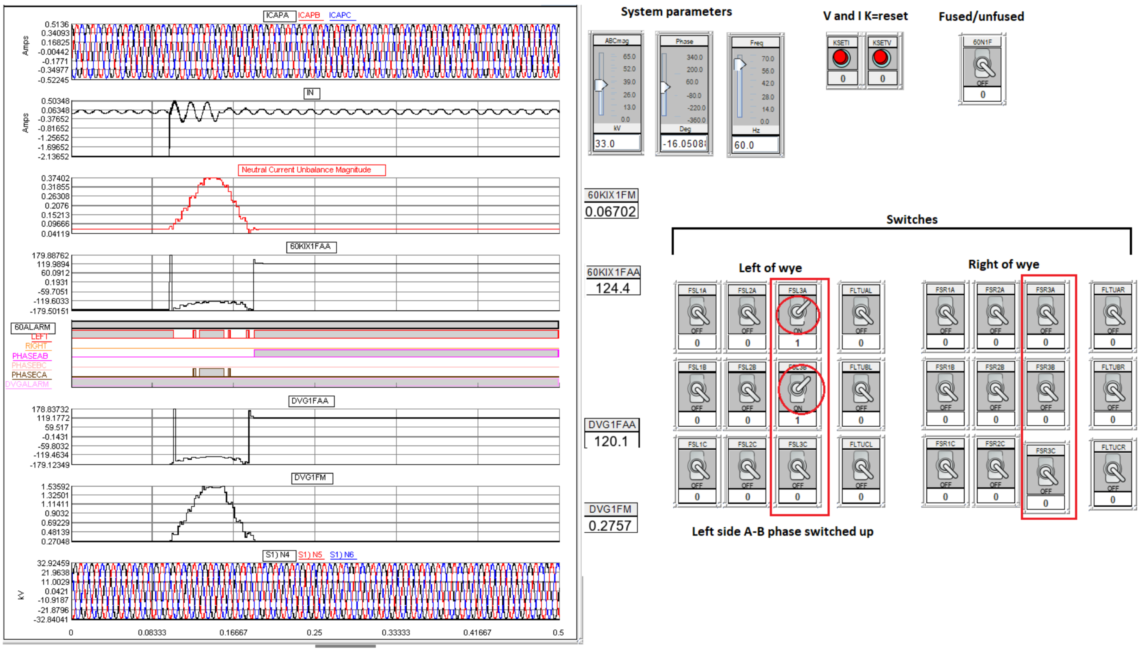


Figure 6-9 RTDS control for double-wye neutral unbalance

6.9 Summary

This chapter introduced the proposed solution for multiphase multisection fault location. Banks using neutral voltage and currents on ungrounded double-wye banks were reintroduced and the application of the multiphase fault location was described. Three methods covering of multiphase multisection solutions for different classes of faults-fault at the left of the double-wye, fault at the right side of the double-wye, and faults at both right and left sections of the wye-were presented. The simulation setup for this solution was also presented.

The next chapter will present RTDS simulation results and discuss each case.

Chapter 7 Simulation Results: Evaluation and Discussions.

This chapter will present the results of the simulation cases in detail and discuss the relationship between the mathematical assumption and the simulation results.

As stated in Chapter 6, Section 6.3 with Figure 6-3, the phase angle of the unbalance phasor is mapped to its corresponding multiphase fault. Figure 6-3 showed the fault identification is enabled by alarm and trip digital bits. The logic built-in RTDS to simulate the fault declaration uses 60ALARM for unbalance current and DVGALARM for unbalance voltage.

7.1 Multiphase faults occur simultaneously on the left and right sides of the double-wye.

7.1.1 For banks using only CTs at the neutral

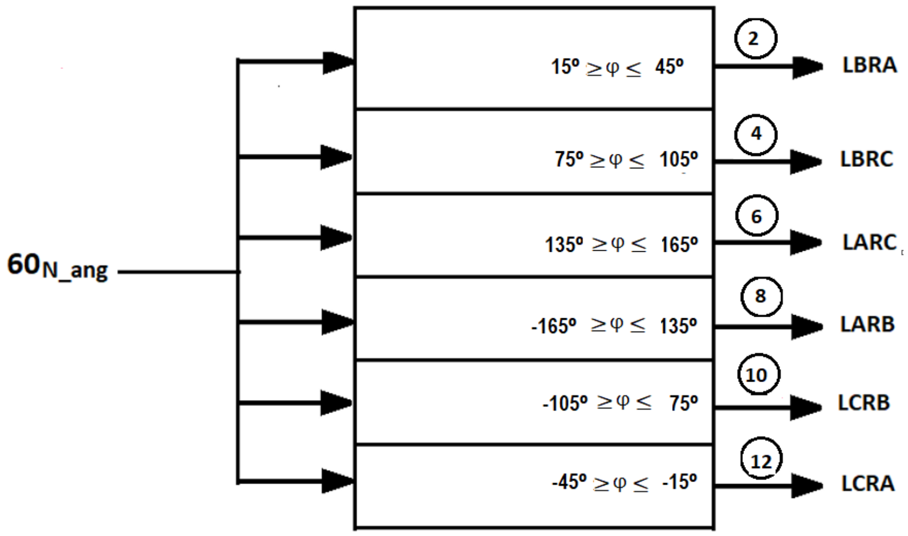


Figure 7-1 Neutral current unbalance angle after referenced with the positive sequence bank current angle

Case 1: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase B of the left side and Phase A of the right side. The fault results in an unbalance current magnitude of 0.1153 A secondary with an angle of 35.91 degrees. The magnitude of the unbalance current is of interest for the unbalance protection and the number of capacitor elements that failed can be determined based on this magnitude value so the protection method could send an alarm or trip signal when a predetermined threshold passed. From the same phasor of the unbalance quantity, the angle is the interest for the multiphase multisection fault location logic to determine accurate location. Digital logic is set in the RSCAD schematic to assert its corresponding digital element to alarm engineers when the unbalance current passes above 20 mA for about 4 cycles. Figure 7-2 shows the logic correctly asserting 60ALARM and LBRA, indicating the faulty element or units are in Phase B of the left side and Phase A of the right side.

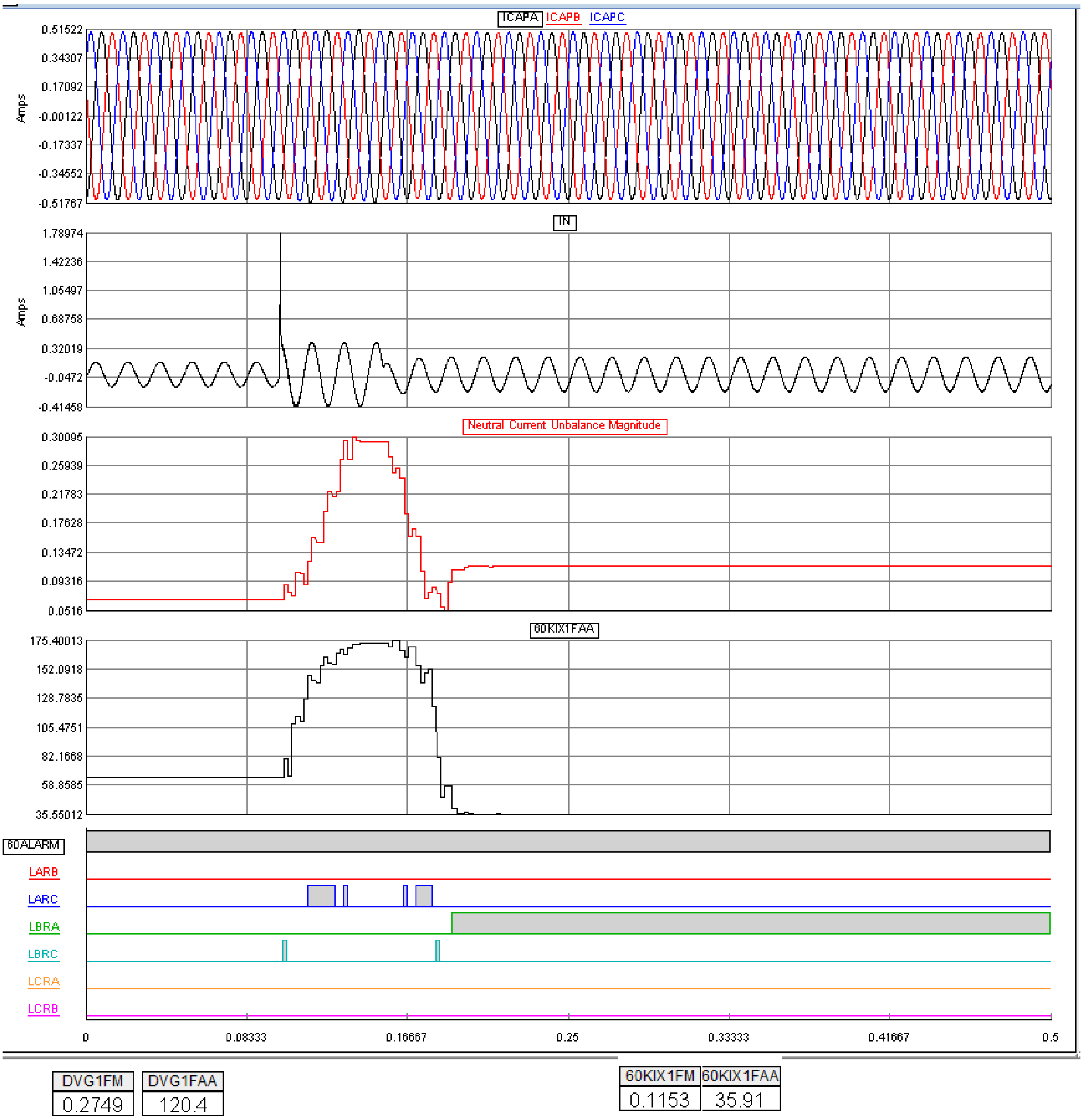


Figure 7-2 Fault in phase B left section and phase A right section of ungrounded double-wye neutral current unbalance protection

Case 2: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase B of the left side and Phase C of the right side. The fault results in an unbalance current magnitude of 0.1155 A secondary with an angle of 95.34 degrees. The magnitude is of interest for the unbalance protection and the number of capacitor elements that failed can be determined based on this magnitude value so the protection method could send an alarm or trip signal when a predetermined threshold passed. From the same phasor of the unbalance quantity, the angle is of interest for the multiphase, multisection fault location logic to determine accurate location. Digital logic is set in the RSCAD schematic to assert its corresponding digital element to alarm engineers when the unbalance current passes above 20 mA for about 4 cycles. Figure 7-3 shows the logic correctly asserting 60ALARM and LBRC, indicating the faulty element or units are in Phase B of the left side and Phase C of the right side.

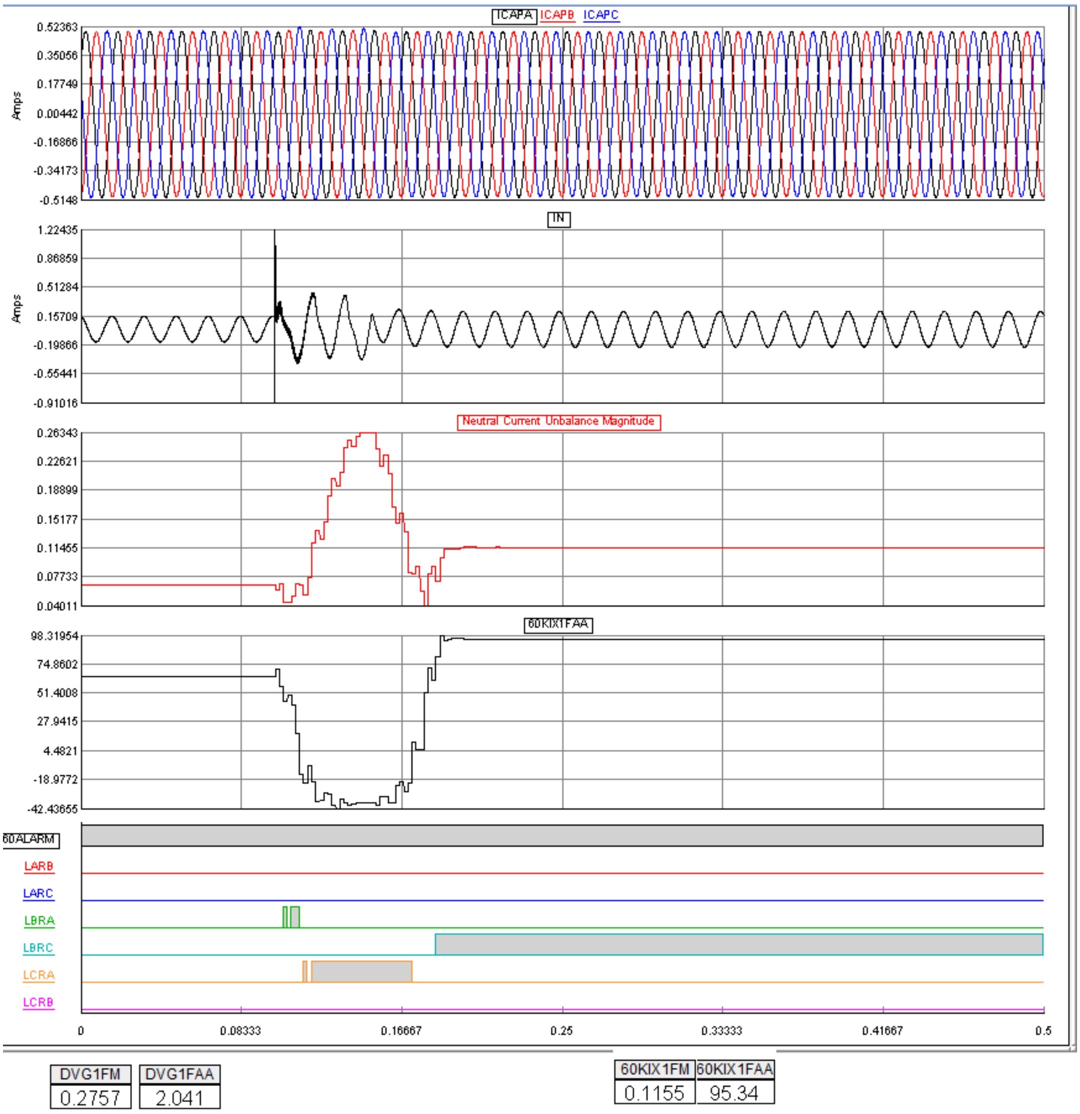


Figure 7-3 Fault in phase B left section and phase C right section of ungrounded double-wye neutral current unbalance protection

Case 3: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase A of the left side and Phase C of the right side. The fault results in an unbalance current magnitude of 0.1144 A secondary with an angle of 155.44 degrees. The magnitude is of interest for the unbalance protection and the number of capacitor elements that failed can be determined based on this magnitude value so the protection method could send an alarm or trip signal when a predetermined threshold passed. From the same phasor of the unbalance quantity, the angle is of interest for the multiphase, multisection fault location logic to determine accurate location. Digital logic is set in the RSCAD schematic to assert its corresponding digital element to alarm engineers when the unbalance current passes above 20 mA for about 4 cycles. Figure 7-4 shows the logic correctly asserting 60ALARM and LARC, indicating the faulty element or units are in Phase A of the left side and Phase C of the right side.

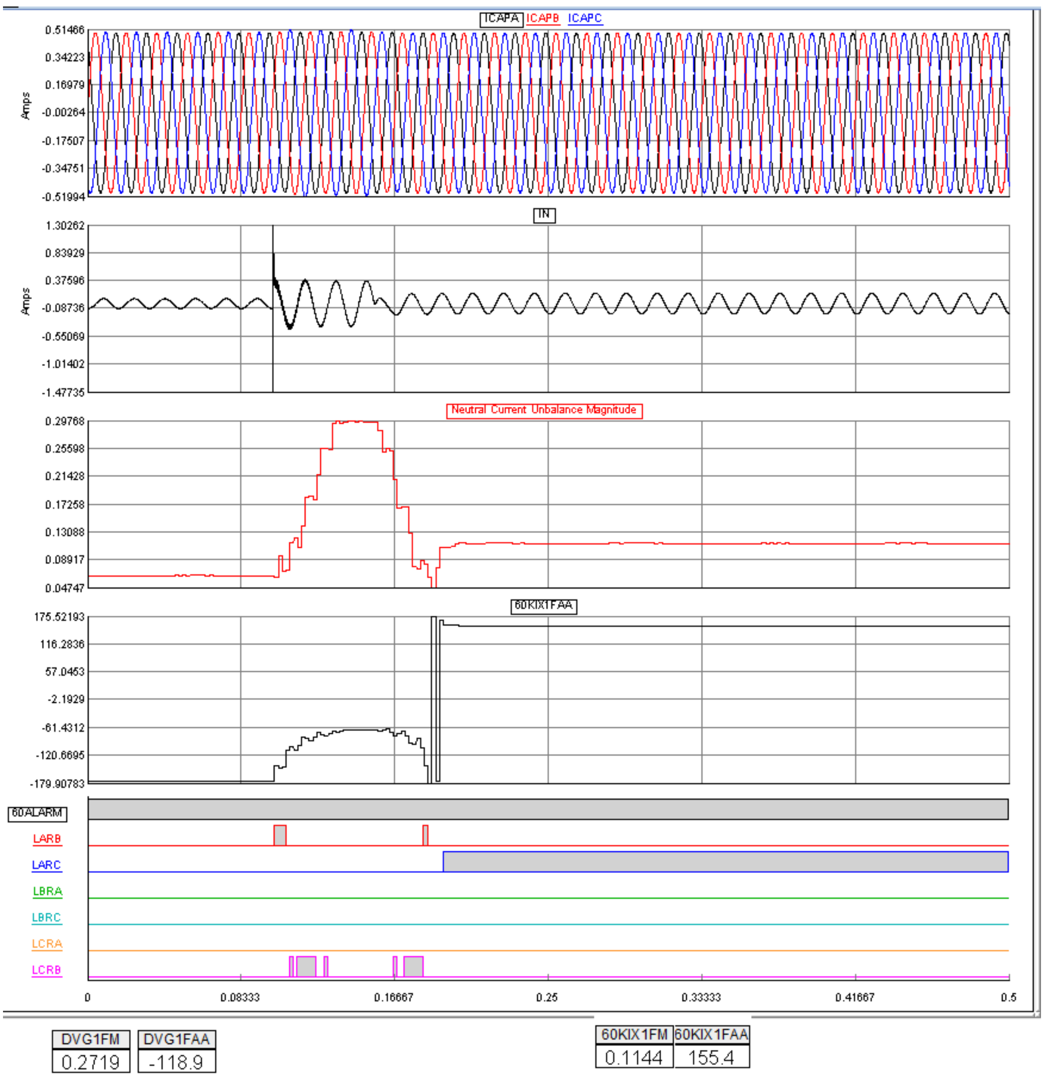


Figure 7-4 Fault in phase A left section and phase C right section of ungrounded double-wye neutral current unbalance protection

Case 4: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase A of the left side and Phase B of the right side. The fault results in an unbalance current magnitude of 0.1136 A secondary with an angle of -144.70 degrees. The magnitude is of the unbalance current is of interest for the unbalance protection and the number of capacitor elements that failed can be determined based on this magnitude value so the protection method could send an alarm or trip signal when a predetermined threshold passed. From the same phasor of the unbalance quantity, the angle is of interest for the multiphase, multisection fault location logic to determine accurate location. Digital logic is set in the RSCAD schematic to assert its corresponding digital element to alarm engineers when the unbalance current passes above 20 mA for about 4 cycles. Figure 7-5 shows the logic correctly asserting 60ALARM and LARB, indicating the faulty element or units are in Phase A of the left side and Phase B of the right side.

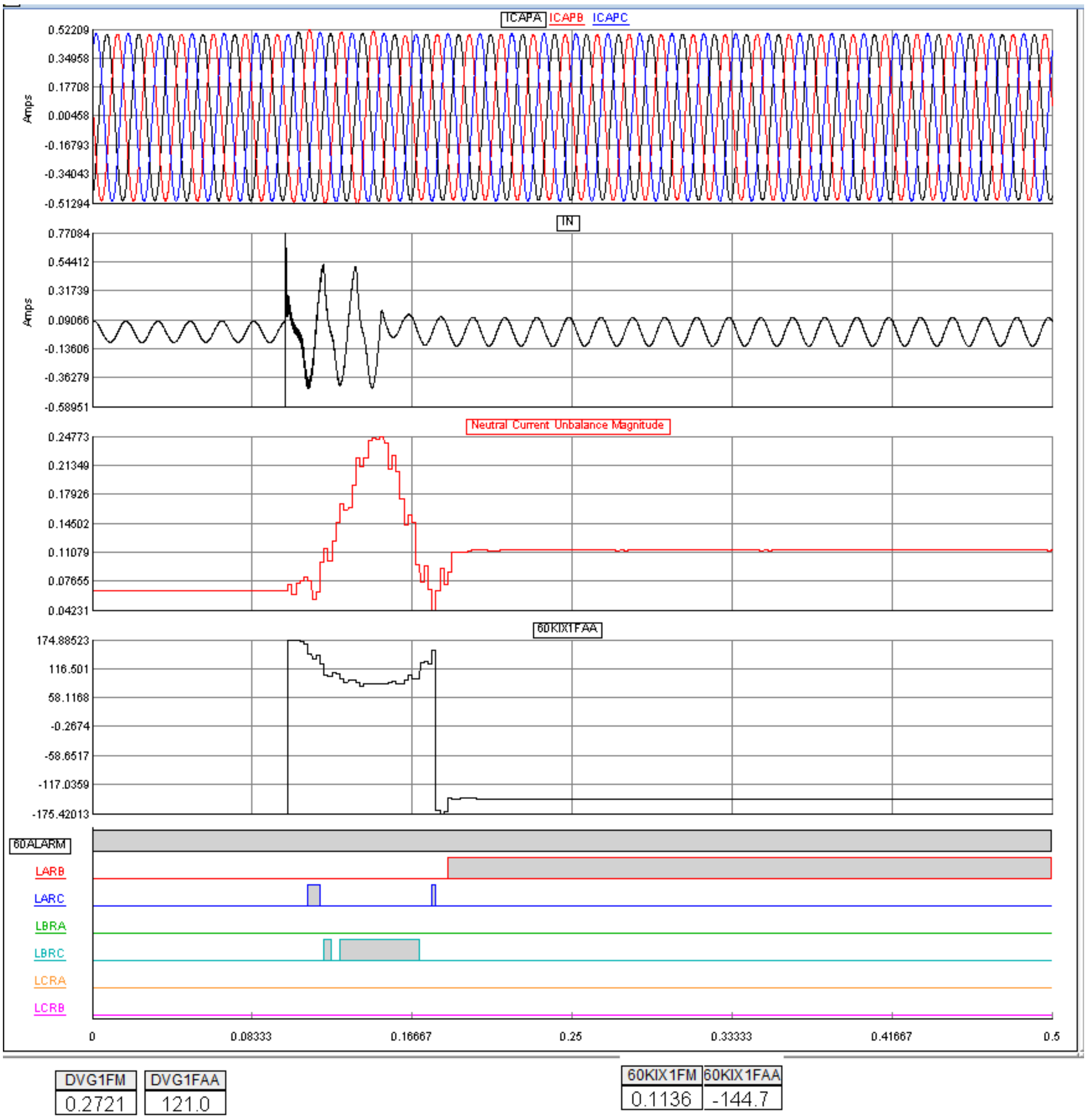


Figure 7-5 Fault in phase A left section and phase B, right section of ungrounded double-wye neutral current unbalance protection

Case 5: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase C of the left side and Phase B of the right side. The fault results in an unbalance current magnitude of 0.1142 A secondary with an angle of -84.56 degrees. The magnitude is of interest forthe unbalance protection and the number of capacitor elements that failed can be determined based on this magnitude value so the protection method could send an alarm or trip signal when a predetermined threshold passed. From the same phasor of the unbalance quantity, the angle is of interest for the multiphase, multisection fault location logic to determine accurate location. Digital logic is set in the RSCAD schematic to assert its corresponding digital element to alarm engineers when the unbalance current passes above 20 mA for about 4 cycles. Figure 7-6 shows the logic correctly asserting 60ALARM and LCRB, indicating the faulty element or units are in Phase C of the left side and Phase B of the right side.

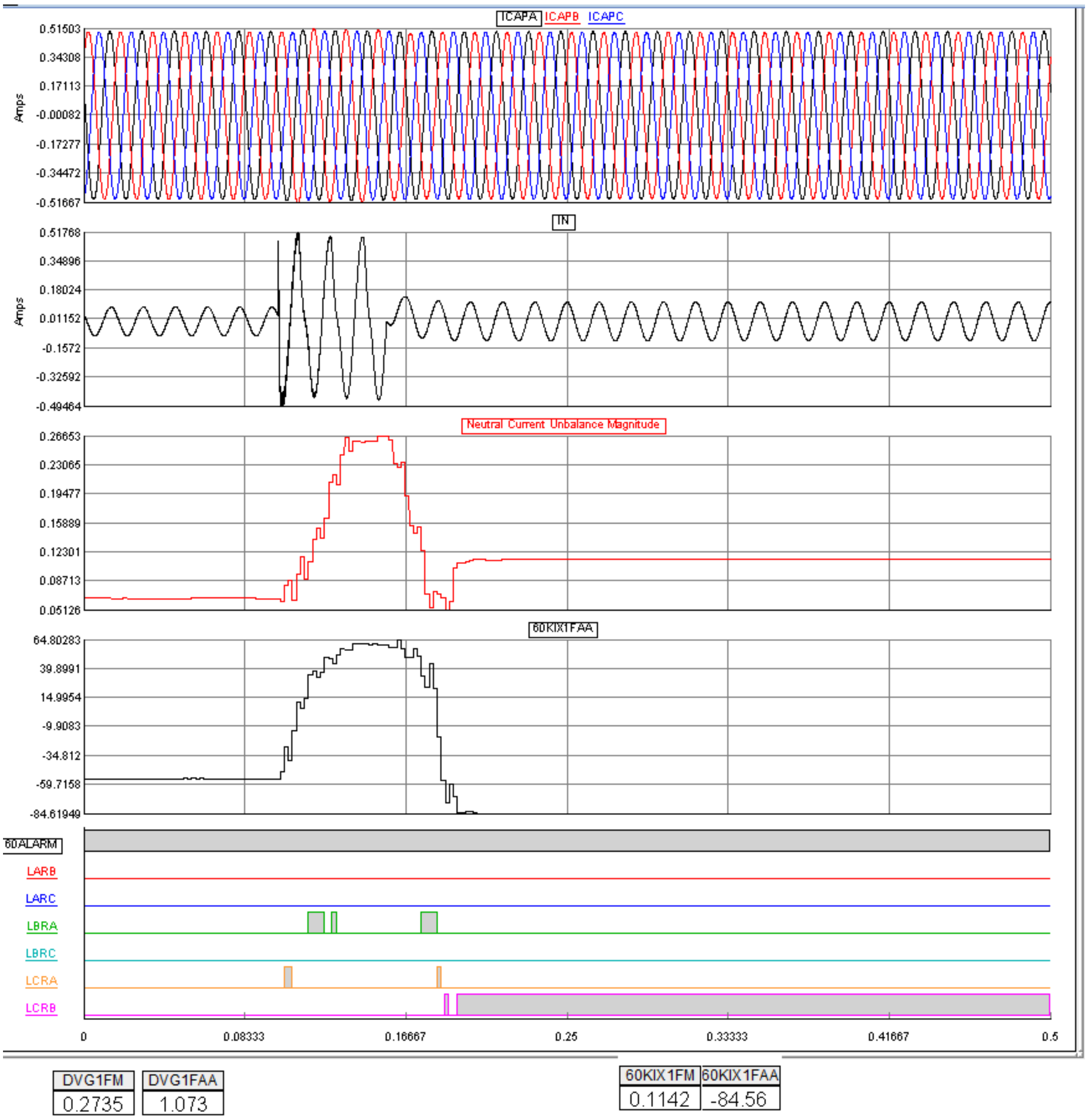


Figure 7-6 Fault in phase C left section and phase B, right section of ungrounded double-wye neutral current unbalance protection

Case 6: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase C of the left side and Phase A of the right side. The fault results in an unbalance current magnitude of 0.1142 A secondary with an angle of -24.45 degrees. The magnitude is of interest for the unbalance protection and the number of capacitor elements that failed can be determined based on this magnitude value so the protection method could send an alarm or trip signal when a predetermined threshold passed. From the same phasor of the unbalance quantity, the angle is of interest for the multiphase, multisection fault location logic to determine accurate location. Digital logic is set in the RSCAD schematic to assert its corresponding digital element to alarm engineers when the unbalance current passes above 20 mA for about 4 cycles. Figure 7-7 shows the logic correctly asserting 60ALARM and LCRA, indicating the faulty element or units are in Phase C of the left side and Phase A of the right side.

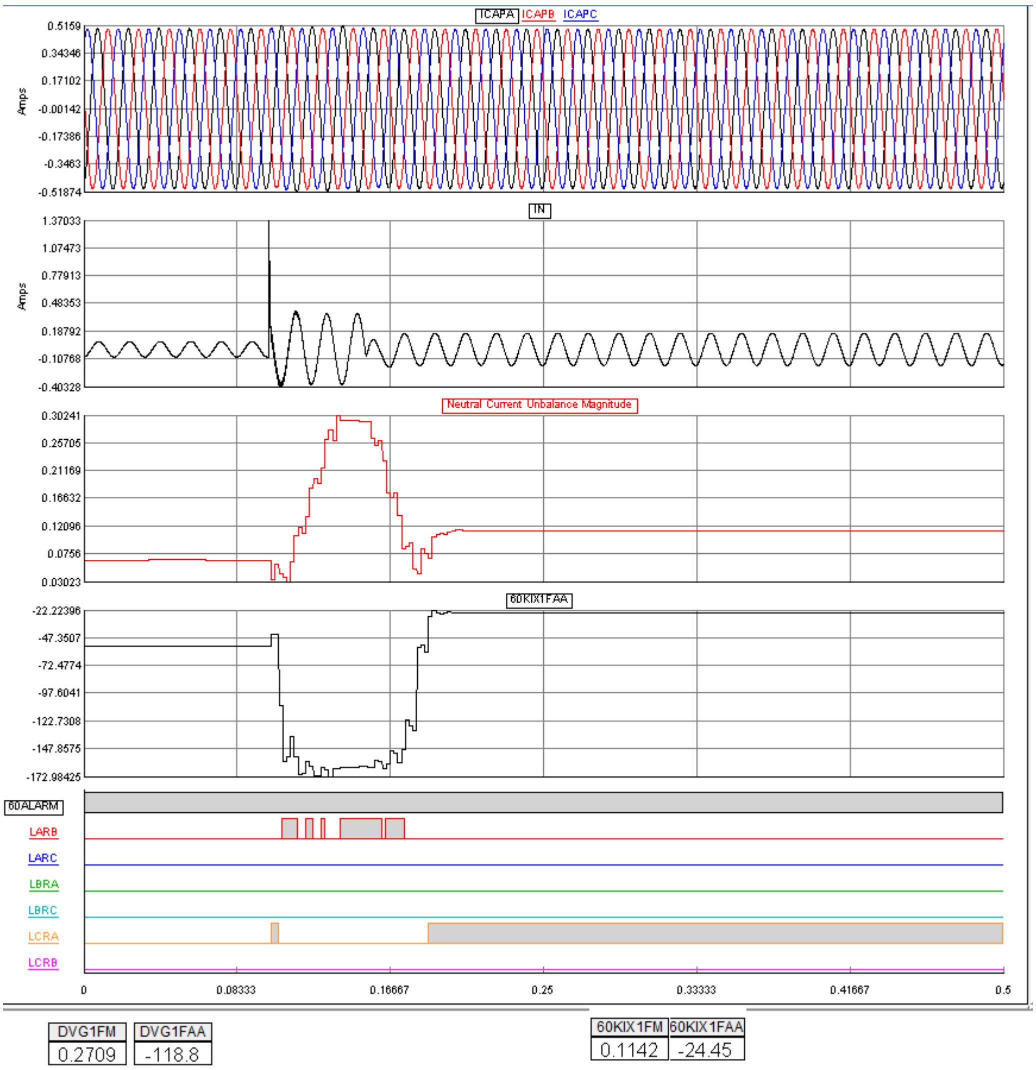


Figure 7-7 Fault in phase C left section and phase A right section of ungrounded double-wye neutral current unbalance protection

The simulation for this section verifies the proposed solution for multiphase simultaneous fault location after fault happened between two phases across the double-wye bank.

7.2 Multiphase faults occurring on the left side of the double-wye.

7.2.1 For banks using either CTs or PTs at the neutral

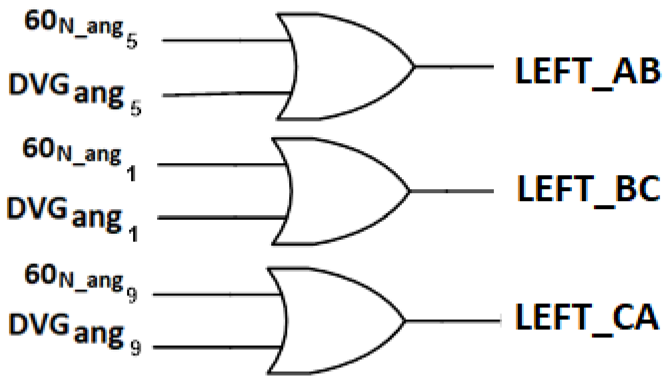


Figure 7-8 Double-wye bank with a neutral PT or CT using neutral voltage identifying left side of fault location.

Case 7: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase AB of the left. The fault results in an unbalance current magnitude of 0.0668 A secondary with an angle of approximately 123.30 degrees **or** unbalance voltage magnitude of 0.2742 V secondary with an angle of approximately 120.3 degrees.

Since this selector operates on OR logic, the solution of detecting multiphase fault at the left side of the unbalance can be achieved by either of the following assert: DVG_{ang}, where only PT is available at the neutral point, or 60_{N_ang}, when only CT is available at the neutral point. If both CT and PT are installed at the neutral point, ORing the two results with the same angle quantity as an output. Figure 7-9 shows the logic correctly asserts 60ALARM, DVGALARM, LEFT, and PHASEAB, indicating the faulty element or units are in Phase AB of the left side.

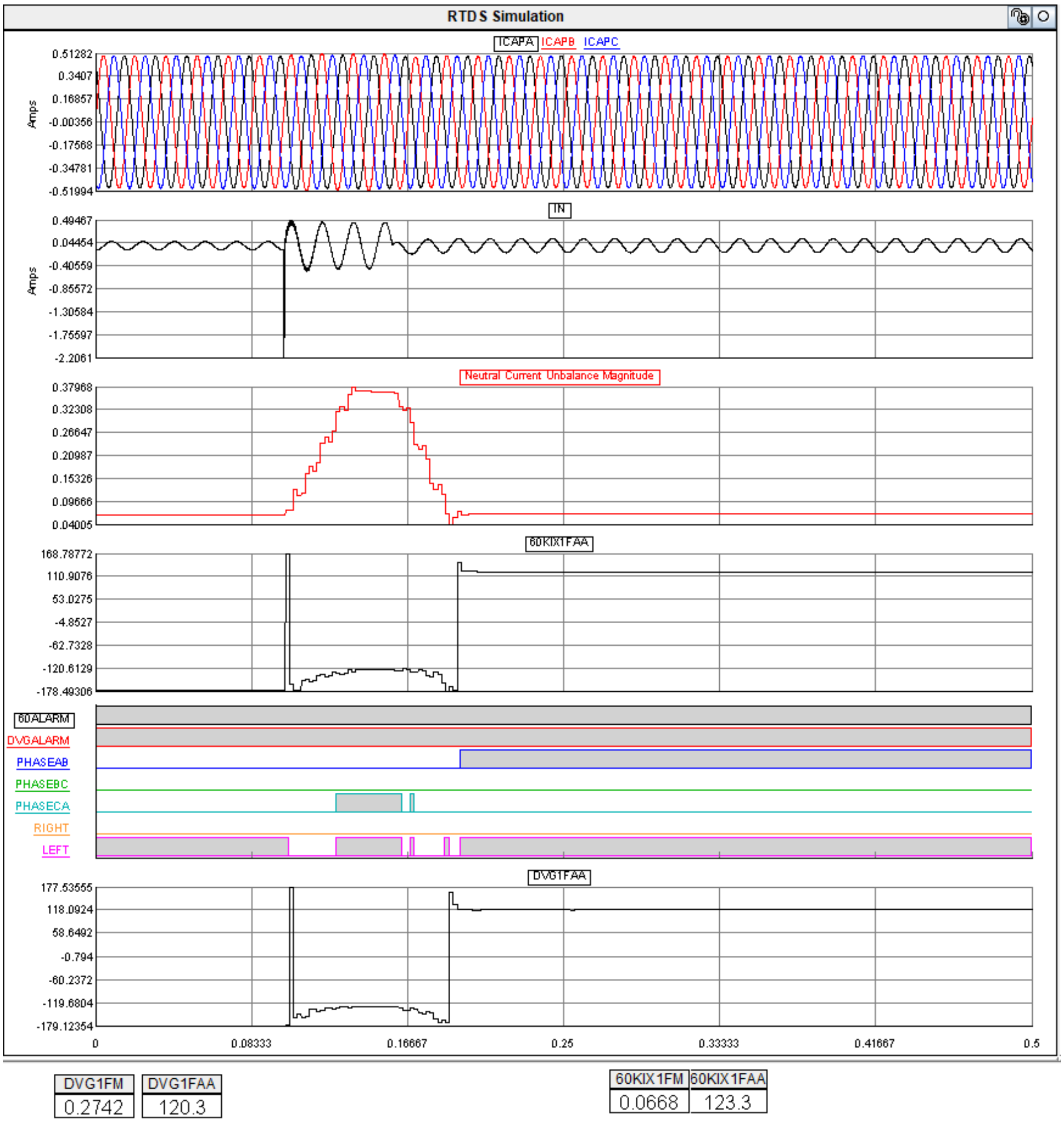


Figure 7-9 Fault in phase AB at the left section of ungrounded double-wye neutral current/voltage unbalance protection

Case 8: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase BC of the left. The fault results in an unbalance current magnitude of 0.0665 A secondary with an angle of approximately 6.65 degrees **or** unbalance voltage magnitude of 0.27412 V secondary with an angle of approximately 1.92 degrees.

Since this selector operates on OR logic, the solution of detecting multiphase fault at the left side of the unbalance can be achieved by either of the following assert: DVG_{ang}, where only PT is available at the neutral point, or 60_{N_ang}, when only CT is available at the neutral point. If both CT and PT are installed at the neutral point, ORing the two results with the same angle quantity as an output. Figure 7-10 shows the logic correctly asserts 60ALARM, DVGALARM, LEFT, and PHASEBC, indicating the faulty element or units are in Phase AB of the left side.

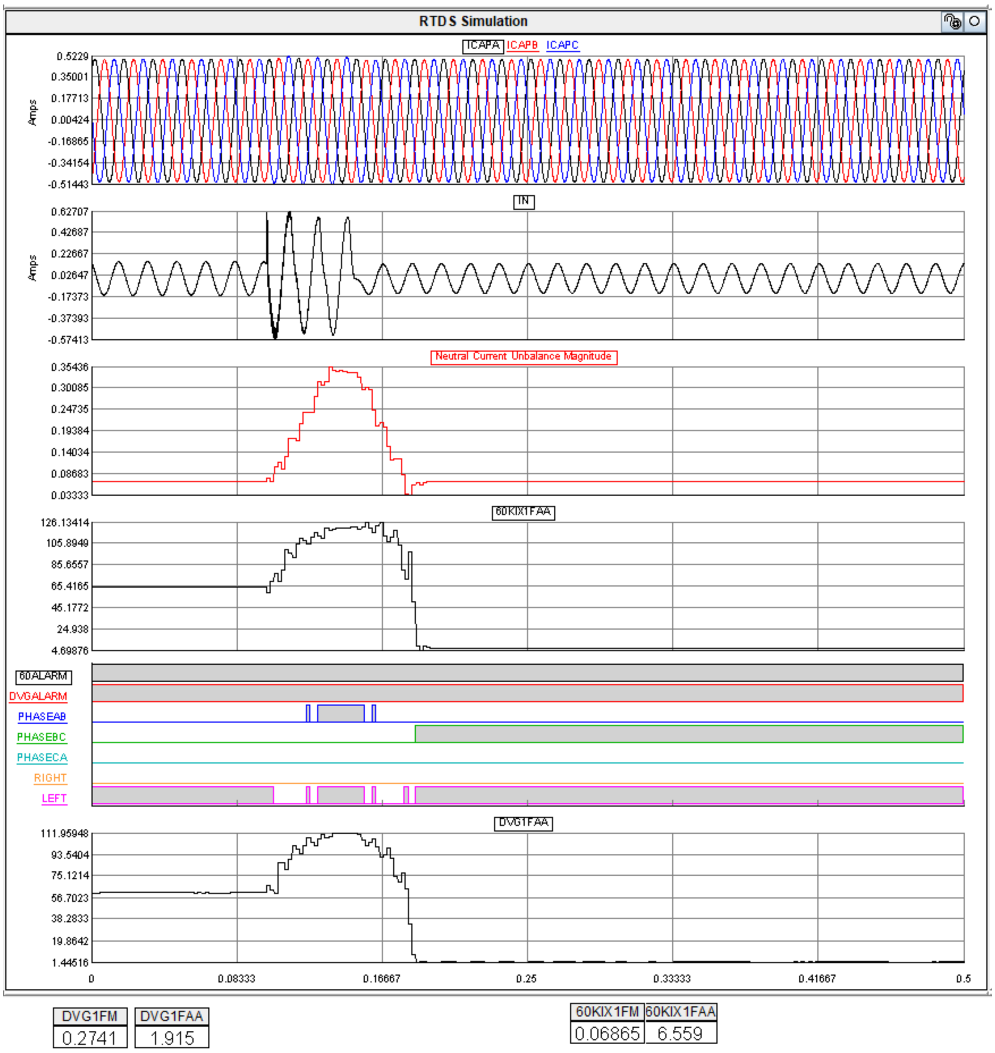


Figure 7-10 Fault in phase BC at the left section of ungrounded double-wye neutral current/voltage unbalance protection

Case 9: An internal fault is simulated in the double-wye current unbalance protection by shorting elements in the healthy bank of units at Phase CA of the left. The fault results in an unbalance current magnitude of 0. 06553 A secondary with an angle of approximately -113.50 degrees **or** unbalance voltage magnitude of 0. 2712 V secondary with an angle of approximately -119.00 degrees.

Since this selector operates on OR logic, the solution of detecting multiphase fault at the left side of the unbalance can be achieved by either of the following assert: DVG_{ang}, where only PT is available at the neutral point, or 60_{N_ang}, when only CT is available at the neutral point. If both CT and PT are installed at the neutral point, ORing the two results with the same angle quantity as an output. Figure 7-11 shows the logic correctly asserts 60ALARM, DVGALARM, LEFT, and PHASECA, indicating the faulty element or units are in Phase AB of the left side.

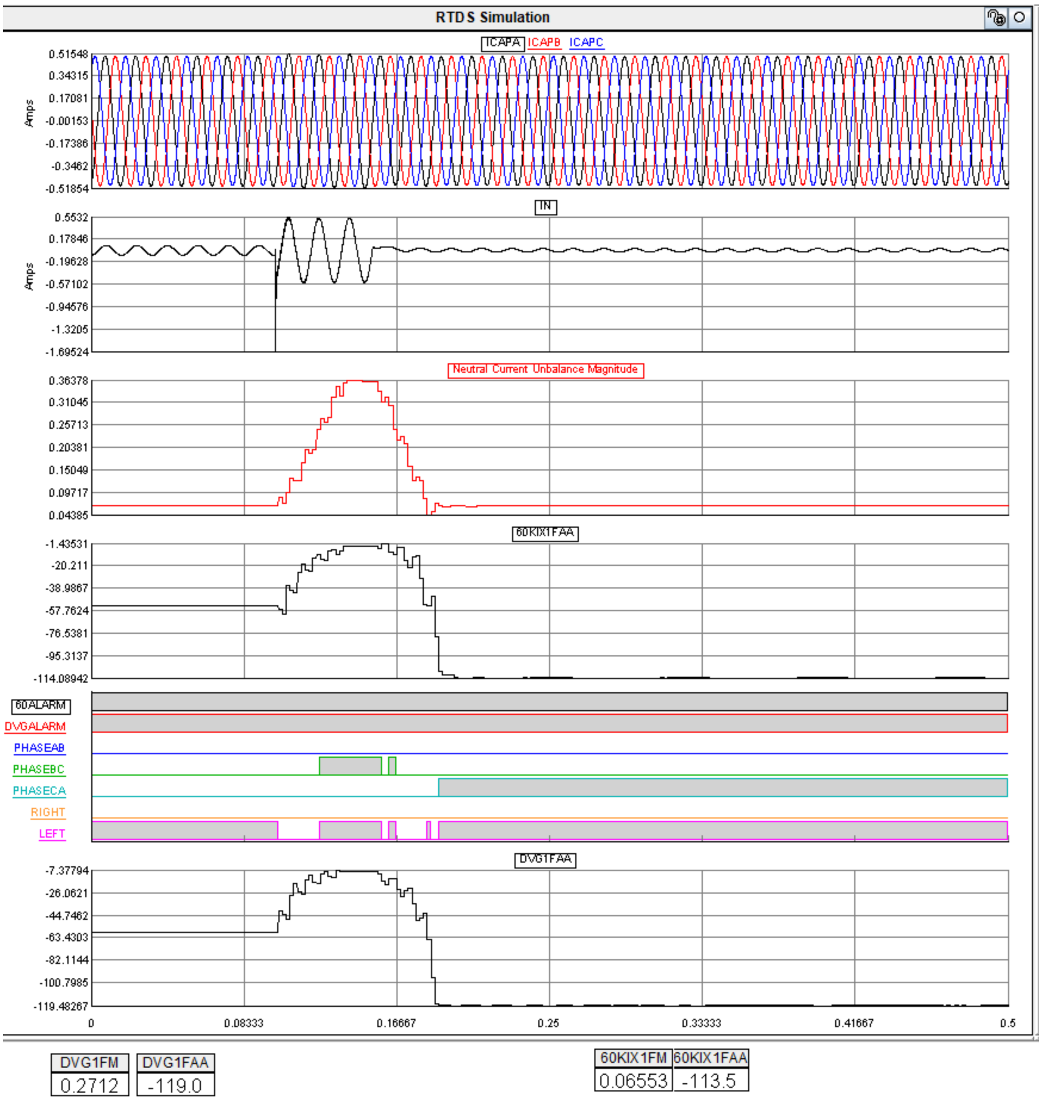


Figure 7-11 Fault in phase CA at the left section of ungrounded double-wye neutral current/voltage unbalance protection

The simulation for this section verifies the proposed solution for multiphase simultaneous fault location after fault happened between two phases at the left side of the double-wye bank.

7.3 Multiphase faults occur at the right side of the double-wye.

7.3.1 For banks using CTs and PTs together at the neutral

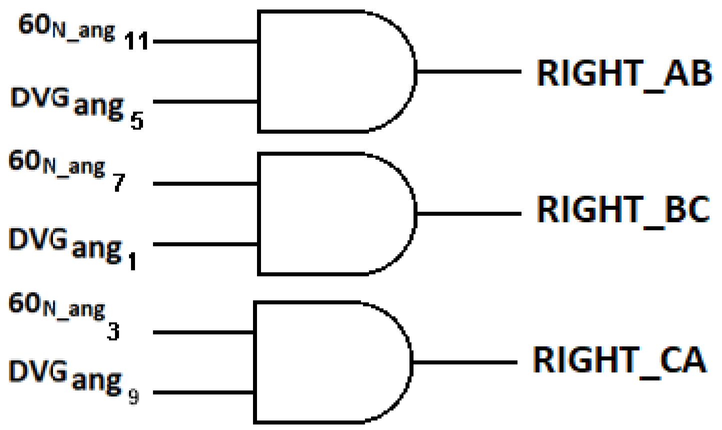


Figure 7-12 Multiphase fault location for a simultaneous fault on both left side and right side sections.

This detector requires having inputs from both a PT and a CT at the neutral point of the double-wye ungrounded unbalance protection. As shown in Figure 7.12, DVG_{ang} and 60_{N_ang} must be inputs of AND gate logic and the measurement of both quantities is a must to detect the right side of multiphase fault location. In this case, the use of both a PT and a CT at the neutral of the double-wye unbalance protection method is essential, and not just for the purpose of security or to have one as a backup to the other. Using just a PT alone or a CT alone cannot accurately detect multiphase faults at the right side of the wye as it produces duplicate angle quantities to result in an error.

Case 10: An internal fault is simulated in the double-wye voltage and current unbalance protection by shorting elements in the healthy bank of units at Phase AB of the right side. The fault results in an unbalance current magnitude of 0.06719 A secondary and an angle close to -53.60 degrees and an unbalance voltage magnitude of 0.272 V secondary and an angle close to -121.1 degrees. Since this section’s logic operates on AND logic, the solution of detecting multiphase fault at the right side of the unbalance can only be detected with both DVG_{ang} and 60_{N_ang} being at unique angle quantities as indicated by the index number subscripts in Figure 7-12.

Figure 7.13 shows the logic correctly asserts 60ALARM, DVGALARM, RIGHT, and PHASEAB, indicating the faulty element or units are in Phase AB of the right side.

by the index number subscripts in Figure 7-12.

Figure 7-13 shows the logic correctly asserts 60ALARM, DVGALARM, RIGHT, and PHASEAB, indicating the faulty element or units are in Phase AB of the right side.

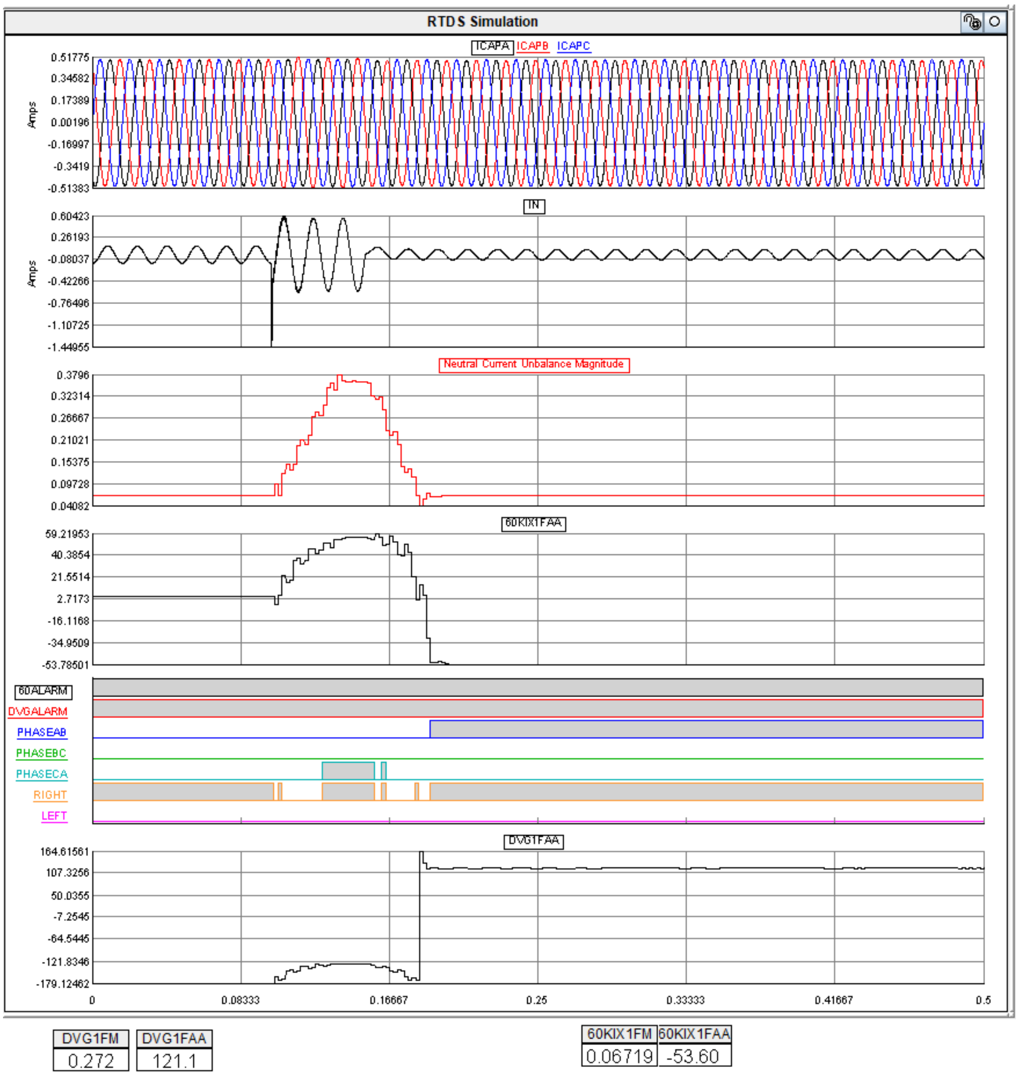


Figure 7-13 Fault in phase AB at the right section of ungrounded double-wye neutral current/voltage unbalance protection

Case 11: An internal fault is simulated in the double-wye voltage and current unbalance protection by shorting elements in the healthy bank of units at Phase BC of the right side. The fault results in an unbalance current magnitude of 0.06491 A secondary and an angle close to -174.9 degrees and an unbalance voltage magnitude of 0.2728 V secondary and an angle close to 1.308 degrees. Since this section's logic operates on AND logic, the solution of detecting multiphase fault at the right side of the unbalance can only be detected with both DVG$_{ang}$ and 60$_{N_ang}$ failing at their prospective angles as indicated by the index numbers subscript in Figure 7.12.

Figure 7.14 shows the logic correctly asserts 60ALARM, DVGALARM, RIGHT, and PHASEBC, indicating the faulty element or units are in Phase BC of the right side.

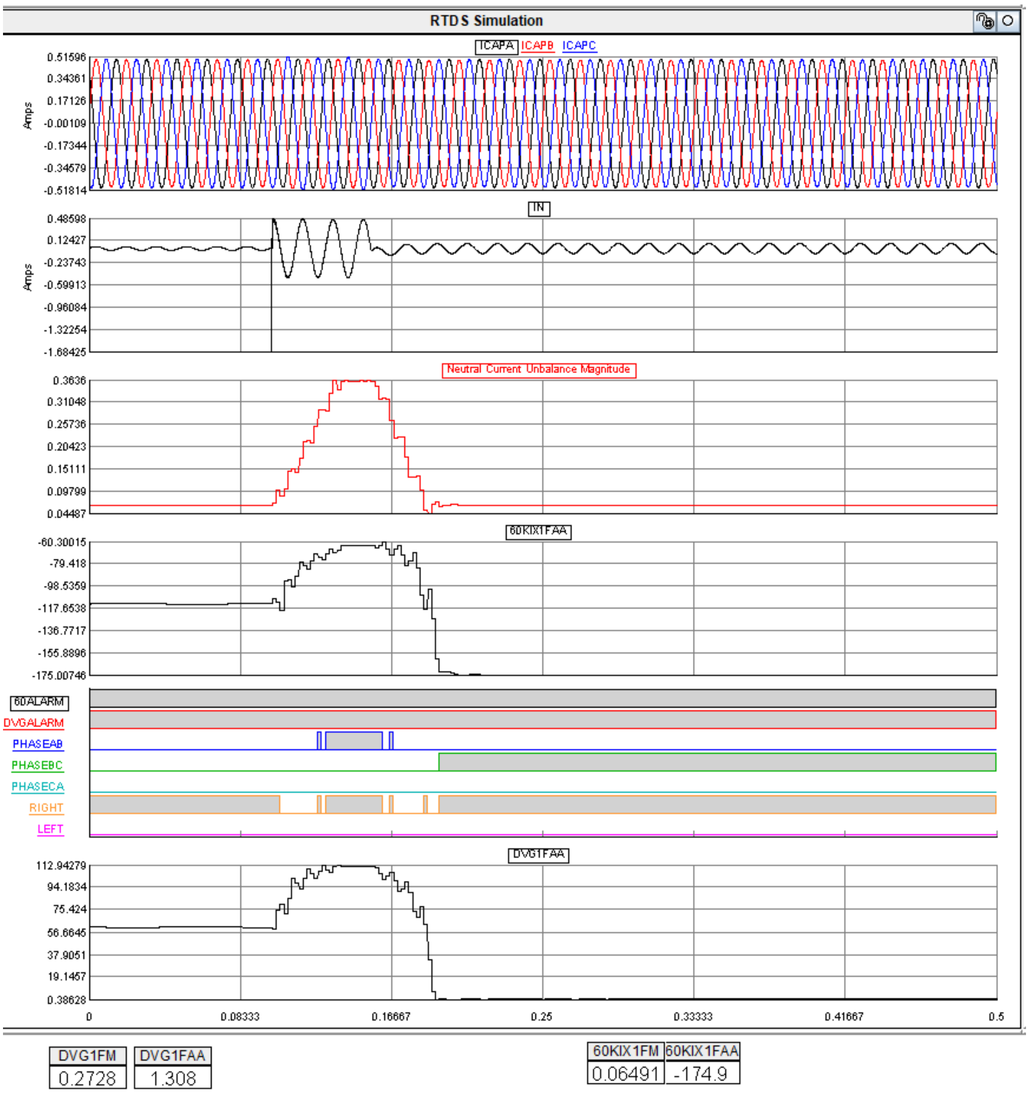


Figure 7-14 Fault in phase BC at the right section of ungrounded double-wye neutral current/voltage unbalance protection

Case 12: An internal fault is simulated in the double-wye voltage and current unbalance protection by shorting elements in the healthy bank of units at Phase CA of the right side. The fault results in an unbalance current magnitude of 0.06699 A secondary and an angle close to 64.43 degrees and an unbalance voltage magnitude of 0.2709 V secondary and an angle close to -118.8 degrees. Since this section’s logic operates on AND logic, the solution of detecting multiphase fault at the right side of the unbalance can only be detected with both DVG_{ang} and 60_{N_ang} failing at their prospective angles as indicated by the index number subscripts in Figure 7.12.

Figure 7.15 shows the logic correctly asserts 60ALARM, DVGALARM, RIGHT, and PHASECA, indicating the faulty element or units are in Phase CA of the right side.

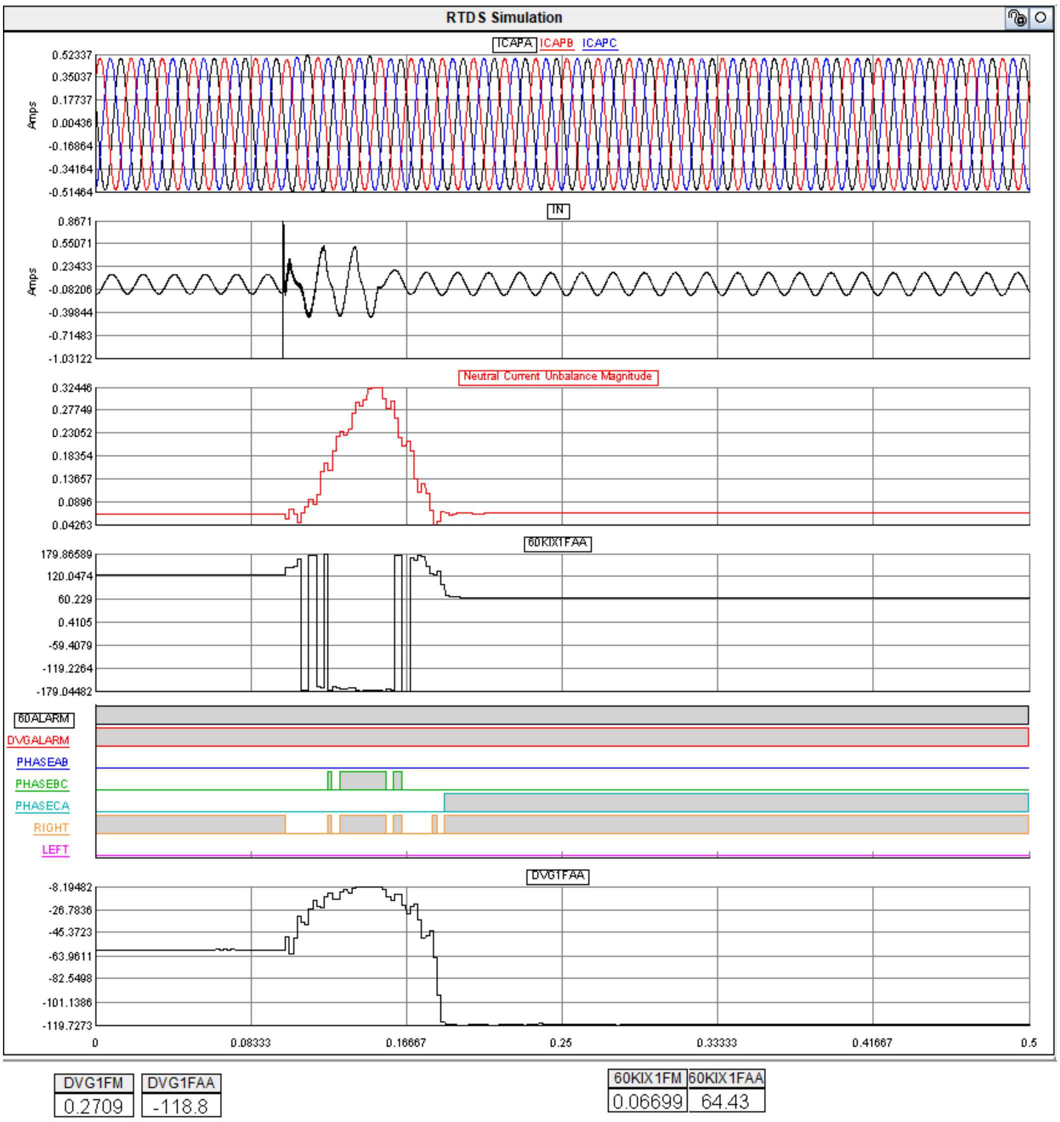


Figure 7-15 Fault in phase CA at the right section of ungrounded double-wye neutral current/voltage unbalance protection

The simulation for this section verifies the proposed solution for multiphase simultaneous fault location after fault happened at the right side of the double-wye bank.

7.4 Summary

In this chapter, the simulation for the solution for multiphase multisection fault location detection was presented. The simulation results verified the research's mathematical deviations and the theoretical assumptions were correct and the solution works to solve real world problems that were identified. The simulation for the three multiphase, multisection fault detection presented in this chapter, Sections 7.1, 7.2, and 7.3 are interrelated by the use of CTs and PTs. The difference is only in the availability of instrument transformers. In a case where both CTs and PTs are installed at the neutral of the ungrounded single or double-wye banks, all three scenarios mentioned can be used within the same configuration. However, if only a CT or only a PT is installed their usage varies.

For example, to detect multiphase fault location at the left side of the double wye bank, only a CT is required as this fault location cannot be detected by a PT.

When detection is for a simultaneous multiphase, multisection fault location across the two sections (for example, the A-phase from the left and B phase from the right), either a CT alone or a PT alone can be used to detect the location. Having both, CT and PT also work for this fault detection and either one of them, or both at the same time (ORed) can be used as the referenced angle from both points to exactly at the same sector.

The fault detection for the right side section must use both CT and PT referenced angles (ANDed). Otherwise, using just a CT or a PT referenced angles alone give ambiguous angles that point to multiple sectors and impossible to detect the exact fault location.

Chapter 8 Summary, Conclusions, and Future Work

This chapter presents the summary of the research, conclusions drawn from research, and possible future research in the area of shunt capacitor bank protection and fault identification

8.1 Summary

This thesis proposed, tested, and verified research for the identification of multiphase multisection SCB faults. Chapter 1 presented the objectives of the research and the research outline was introduced. In Chapter 2, the research covered several topics around SCB, beginning with explaining the main benefits of capacitor banks with examples and illustrations. Power factor correction, local reactive power support, reduction of line current and line loss as well as local voltage support were presented as main benefits to the power system. The research also covered the economic benefits and the ease of installing SCB anywhere in the power system. The design, configuration, fusing of SCBs were presented, followed by the impacts and effects these choices have on the voltage and reactive power ratings, protection methods.

Chapter 3 presented current practices of SCB protection.The protection requirements for internal and external system faults were defined. Unbalance protection methods were also examined and the four most popular unbalance protection methods that use measured voltages and currents were described.

Chapter 4 analyzed previous research on the subject of SCB protection and presented a literature review for the current state of the art in research and in practice for SCB fault location identification.

Chapter 5 introduced and analyzed the existing single-phase fault location solution from [4] that is the basis for the proposed solution. The protection theory was presented, and fault location solutions using ungrounded phase and neutral voltage and current unbalance protection were described. The single-phase fault location method was presented in detail and simulation results from RTDS were discussed.

Chapter 6 introduced the proposed solution for multiphase multisection fault location. Banks using neutral voltage and currents on ungrounded double-wye banks were described and the development and application of the multiphase multisection fault location was described. The three classes of multiphase multisection solutions, (fault at the left side of the double-wye, fault at the right side of the double-wye, and faults at both the right and left sections of the double-wye bank) were presented. The simulation setup for this solution was also presented.

Chapter 7 presented simulation results for the proposed solutions. The simulation results verified that the operation of each case is consistent with the theory presented.

8.2 Conclusions

The objective of this dissertation was the development of a fault location method to accurately determine that simultaneous multiphase multisection faults are present in shunt capacitor banks and accurately identifying fault locations. Three approaches were developed in Chapter 6. The simulation results for the three different sections of multiphase fault detection presented and analyzed in Chapter 7, demonstrated that the proposed method solves this problem.

Identifying fault locations in an internally fused or unfused bank without a method like the one in this research can be complex and time-consuming. Not knowing the failure of capacitor elements or units could increase the likelihood of losing the entire bank through cascading failures. Damage on SCB that is catastrophic could create a loss of the bank itself and its associated equipment. This can lead to longer downtime and the system could lose this critical asset with all the benefits described in Chapter 2 for a longer period.

The solution verified in this research has no additional cost as it’s part of the protection system. Two methods developed can operate with just a CT only or a PT only. For example, only a CT is required to detect multiphase fault location at the left side of the double wye bank.

When detection is for a simultaneous multiphase, multisection fault location across the two sections (for example, the A-phase from the left and B phase from the right), either a CT alone or a PT alone can be used to detect the location. Having both a CT and PT also work for this fault detection since either measurementcan be used to determine reference angle to determine fault location and faulted phase. The resulting reference angle from the CT measurement and PT measurement fall at the same sector.

The fault detection for the right side section must use both CT and PT referenced angles with their output ANDed together. Otherwise, using just a CT or a PT referenced angles alone give ambiguous angles that point to multiple sectors, making it impossible to detect the exact fault location.

The solution developed by this research is one more tool the power system industry could use to make electric power both economical and reliable.

8.3 Future Work

Advances in digital signal processing and fast and modern communications have opened up new opportunities for faster, more accurate, and more versatile protection and fault location methods. New utility communication based on IEC-61850 Sample Values can access remote readings from merging units at multiple locations in the substation. Application of IEC 61850 GOOSE messaging message protocols provides access to information from other relays or intelligent automation devices in the local substation or remote stations. The use of either or both these protocols can facilitate further improvements to shunt capacitor bank protection and fault identifications. Information from CTs, PTs, and other remote sensing devices could be shared between protection relays and control stations across a region to control and coordinate operations. Digital secondaries, such as merging units can utilize Sampled Values and GOOSE messages to transmit and receive analog and digital values between primary devices and control rooms where coordination and protection decisions are made.

Another area should be explored is the application of traveling wave (TW) based measurements for shunt capacitor protection and fault location identification. TW-based protection schemes are already on the rise in commercial application and the general fault location method designed for transmission and distribution systems can be scaled down to to identify faults happening within a bank to differentiate them from external faults that impact shunt capacitor banks.

The multiphase, multisection fault identification solution developed by this research applies to ungrounded double-wye shunt capacitor banks by using neutral current and voltage unbalance protection. The solution from this research can be extended to grounded double-wye banks, or combined wye and delta connected banks as well. Both propose challenges that are not present with the ungrounded double-wye banks.

The proposed approach could also be applied to capacitor banks installed as part of shunt harmonic filters. The harmonic filter application has the added challenge is large current current and amplitudes in the design frequency range.

Bibliography

[1] R. Moxley, J. Pope, and J. Allen, "Capacitor Bank Protection for Simple and Complex Configurations," in *Protective Relay Engineers, 2012 65th Annual Conference for, April 2012, pp. 436–441.*

[2] B. Kasztenny, J. Schaefer, and E. Clark, "Fundamentals of Adaptive Protection of Large Capacitor Banks - Accurate Methods for Canceling Inherent Bank Unbalances," in *Protective Relay Engineers, 2007. 60th Annual Conference for, March 2007, pp. 126–157.*

[3] *S. Samineni and C. A. Labuschagne, Apparatus and Method for Identifying a Faulted Phase in A Shunt Capacitor Bank*. US Patent 8 575 941, November 2013.

[4] J. Schaefer, S. Samineni, C. Labuschagne, S. Chase, and D. Hawaz, "Minimizing Capacitor Bank Outage Time Through Fault Location," in *Protective Relay Engineers, 2014 67th Annual Conference for, March 2014, pp. 72–83.*

[5] *IEEE Guide for the Application of Shunt Power Capacitors*. IEEE Std 1036-2010 (Revision of IEEE Std 1036-1992), pp. 1–88, Jan 2011.

[6] D. Chapman, *Power Quality Application Guide. Copper Development Association, United Kingdom*, : http://copperalliance.org.uk/uploads/2018/03/21-the-cost-of-poor-power-quality.pdf, last accessed October 2018.

[7] G. Brunello, B. Kasztenny, C. Wester "Shunt Capacitor Bank Fundamentals and Protection" in *Protective Relay Engineers, April 8-10, 2003, College Station, TX*.

[8] *IEEE Guide for the Protection of Shunt Capacitor Banks*. IEEE Std C37.99-2012 (Revision of IEEE Std C37.99-2000), pp. 1–151, March 2013.

[9] S. Samineni, C. Labuschagne, J. Pope, and B. Kasztenny, “Fault Location in Shunt Capacitor Banks,” in *Developments in Power System Protection (DPSP 2010). Managing the Change, 10th IET International Conference on, March 2010, pp. 1–5.*

[10] B. Kasztenny, D. McGinn, and I. Voloh, “Enhanced Adaptive Protection Method for Capacitor Banks,” in *Developments in Power System Protection, 2008. DPSP 2008. IET 9th International Conference on, March 2008, pp. 269–274.*

[11] E. Price and R. Wolsey, “String Current Unbalance Protection and Faulted String Identification for Grounded-Wye Fuseless Capacitor Banks,” *in 65th Annual Georgia Tech Protective Relaying Conference, May 2011.*

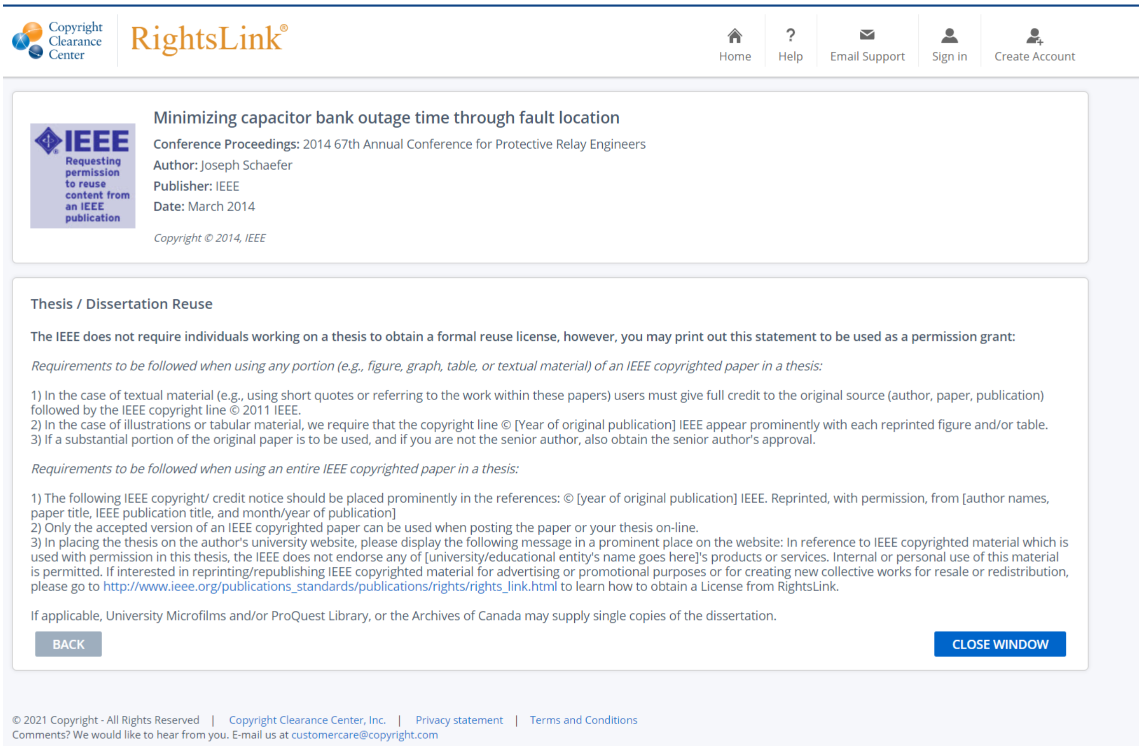
[12] S. Samineni and C. A. Labuschagne, *Apparatus and Method for Identifying a Faulted Phase in A Shunt Capacitor Bank*. US Patent 8 575 941, November 2013.

[13] H. J. Moghaddam, T. S. Sidhu “Enhanced Fault-Location Scheme for Double-wye Shunt Capacitor Banks,” *IEEE transactions on Power Delivery,* vol. 32, no. 4, August 2017, pp. 1872-1880.

[14] Name Redacted *Electric Reliability and Power System Resilience*, Congressional Research Service, May 2, 2018

Appendix A

The material covered in chapter 5 was co-authored by the same author of this research. Chapter 5 presented [4] extensively as the solution developed it is the basis for this research. [4] presented the currently available solution for a single-phase capacitor bank fault location and this research is an extension of that solution in locating multiphase multisection capacitor bank fault. To reuse [4], IEEE's copyright permission was requested and the permission in Figure A1- is granted.


Copyright Clearance Center RightsLink®

Home | Help | Email Support | Sign in | Create Account

IEEE Requesting permission to reuse content from an IEEE publication

Minimizing capacitor bank outage time through fault location

Conference Proceedings: 2014 67th Annual Conference for Protective Relay Engineers

Author: Joseph Schaefer

Publisher: IEEE

Date: March 2014

Copyright © 2014, IEEE

Thesis / Dissertation Reuse

The IEEE does not require individuals working on a thesis to obtain a formal reuse license, however, you may print out this statement to be used as a permission grant:

Requirements to be followed when using any portion (e.g., figure, graph, table, or textual material) of an IEEE copyrighted paper in a thesis:

1) In the case of textual material (e.g., using short quotes or referring to the work within these papers) users must give full credit to the original source (author, paper, publication) followed by the IEEE copyright line © 2011 IEEE.
2) In the case of illustrations or tabular material, we require that the copyright line © [Year of original publication] IEEE appear prominently with each reprinted figure and/or table.
3) If a substantial portion of the original paper is to be used, and if you are not the senior author, also obtain the senior author's approval.

Requirements to be followed when using an entire IEEE copyrighted paper in a thesis:

1) The following IEEE copyright/ credit notice should be placed prominently in the references: © [year of original publication] IEEE. Reprinted, with permission, from [author names, paper title, IEEE publication title, and month/year of publication]
2) Only the accepted version of an IEEE copyrighted paper can be used when posting the paper or your thesis on-line.
3) In placing the thesis on the author's university website, please display the following message in a prominent place on the website: In reference to IEEE copyrighted material which is used with permission in this thesis, the IEEE does not endorse any of [university/educational entity's name goes here]'s products or services. Internal or personal use of this material is permitted. If interested in reprinting/republishing IEEE copyrighted material for advertising or promotional purposes or for creating new collective works for resale or redistribution, please go to http://www.ieee.org/publications_standards/publications/rights/rights_link.html to learn how to obtain a License from RightsLink.

If applicable, University Microfilms and/or ProQuest Library, or the Archives of Canada may supply single copies of the dissertation.

BACK | CLOSE WINDOW

© 2021 Copyright - All Rights Reserved | Copyright Clearance Center, Inc. | Privacy statement | Terms and Conditions
Comments? We would like to hear from you. E-mail us at customercare@copyright.com

Figure 16 IEEE Copywrite permission to reuse [4]

Appendix B

Table B-1, show the magnitude and angle of the neutral voltage unbalance values for all possible fault types between the double-wye banks (left and right). The data in this table show the redundancy of phase angle values for more than one fault location. Without the use of both CTs and PTs values in ANDed logic, the solution to detect simultaneous faults for the left d right side of the section would have misoperated.

	TERMIA	60KIX1	60KIX1	DVG1M	DVG1A
1	LA	0.0661	-174.8	0.2722	-179.1
2	LB	0.0675	65.43	0.2768	61.02
3	LC	0.0663	-54.4	0.2709	-58.56
4	RA	0.0662	5.4	0.2705	-178.9
5	RB	0.0660	-114.4	0.272	60.98
6	RC	0.0662	125.6	0.2717	-58.72
7	LAB	0.0672	124.3	0.2743	120.2
8	LBC	0.0673	6.413	0.2744	2.007
9	LCA	0.0663	-114.5	0.2709	-119
10	RAB	0.0665	-54.42	0.2731	121
11	RBC	0.0663	-174.6	0.2719	1.306
12	RCA	0.0663	65.35	0.2711	-119.7
13	LARB	0.1137	-144.5	0.2721	121.1
14	LARC	0.1710	-156.7	0.2543	61.26
15	LBRA	0.1153	35.69	0.276	120.3
16	LBRC	0.1153	95.09	0.2759	2.099
17	LCRA	0.1141	-24.47	0.2718	-119
18	LCRB	0.1141	-84.36	0.2733	1.3
19	RALB	0.1139	-144.8	0.2737	120.1
20	RALC	0.1142	155.5	0.2712	-118.9
21	RBLA	0.1138	-144.6	0.2733	121.2
22	RBLC	0.1141	-84.47	0.2728	1.175
23	RCLA	0.1141	155.5	0.2707	-118.8
24	RCLB	0.1154	95.26	0.2748	2.13
25	LARA	0.0001	-155	0.5429	-179.1
26	LBRB	0.0016	63.2	0.5463	61.36
27	LCRC	0.0000	87.58	0.5424	-58.85

Table B-1 Simulation data for neutral voltage unbalance

	TERMIA	60KIX1	60KIX1	DVG1M	DVG1A
1	LA	0.0661	-174.8	0.2722	-179.1
2	LB	0.0675	65.43	0.2768	61.02
3	LC	0.0663	-54.4	0.2709	-58.56
4	RA	0.0662	5.4	0.2705	-178.9
5	RB	0.0660	-114.4	0.272	60.98
6	RC	0.0662	125.6	0.2717	-58.72
7	LAB	0.0672	124.3	0.2743	120.2
8	LBC	0.0673	6.413	0.2744	2.007
9	LCA	0.0663	-114.5	0.2709	-119
10	RAB	0.0665	-54.42	0.2731	121
11	RBC	0.0663	-174.6	0.2719	1.306
12	RCA	0.0663	65.35	0.2711	-119.7
13	LARB	0.1137	-144.5	0.2721	121.1
14	LARC	0.1710	-156.7	0.2543	61.26
15	LBRA	0.1153	35.69	0.276	120.3
16	LBRC	0.1153	95.09	0.2759	2.099
17	LCRA	0.1141	-24.47	0.2718	-119
18	LCRB	0.1141	-84.36	0.2733	1.3
19	RALB	0.1139	-144.8	0.2737	120.1
20	RALC	0.1142	155.5	0.2712	-118.9
21	RBLA	0.1138	-144.6	0.2733	121.2
22	RBLC	0.1141	-84.47	0.2728	1.175
23	RCLA	0.1141	155.5	0.2707	-118.8
24	RCLB	0.1154	95.26	0.2748	2.13
25	LARA	0.0001	-155	0.5429	-179.1
26	LBRB	0.0016	63.2	0.5463	61.36
27	LCRC	0.0000	87.58	0.5424	-58.85

Table B-2 shows the same scenario as for Table B-1, except this is for neutral current unbalance.