Impedance Based Protection for Fuseless Shunt Capacitor Banks

A Thesis
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Abstract

As the grid continues to evolve into the future, shunt capacitor banks continue to be relevant to the power network. Shunt capacitor bank protection is critical to ensuring banks are removed from the grid during faults and ensuring the bank is not removed for conditions in which it is safe for it to operate. The balance between sensitivity and selectivity has always been a challenge for engineers tasked with protecting shunt capacitor banks or any other power apparatus. Fuseless bank designs are becoming increasingly popular for their many benefits; however, one tradeoff with this design is the lack of visible fault indication as is present on fused banks. The protective relays on these banks become the first line of protection and it is imperative they are able to correctly identify bank faults.

This thesis will examine a fuseless shunt capacitor bank connected in a grounded wye configuration and applied to a 345 kV transmission network. Two methods to protect this type of bank are examined. One approach uses the commonly applied voltage differential capacitor bank protection method, and another less commonly used fairly new impedance measurement method. The two methods are analyzed and compared in a software model to prove that the impedance based method offers increased protection and selectivity for the capacitor bank.

Acknowledgments

I would like to thank the members of my committee and my major professor Dr. Brian Johnson for the support and help he has provided me through my time as a graduate student. I would also like to thank the faculty at the University of Idaho for being helpful and providing a way for me to obtain this degree from a remote setting.

I would also like to thank the industry experts that have assisted me. The engineers at Gentec, Inc., SEL, and Eaton (formerly Cooper Power Systems). Without the insight I received from them I would not have been able to get as far as I did with the realistic bank model and relay manuals.

I would also like to thank my employer Groves Electrical Services, formerly William E. Groves Construction, Inc. for providing me a job after my undergraduate degree and allowing me to pursue my graduate degree.

Dedication

I would like to thank my family. Most importantly, my wife and kids for remaining patient with me during my time in graduate school. Their patience and support has helped tremendously.

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Acronyms

IEEE – Institute of Electrical and Electronics Engineers

IEC – International Electrotechnical Commission

PT – Potential Transformer

CT – Current Transformer

LVC – Low Voltage Capacitor

87V – ANSI Device for Differential Element with a Voltage Suffix

21C – ANSI Device for Distance Element with Capacitor Bank Suffix

PSCAD - Power Systems Computer Aided Design

EMTDC – Electromagnetic Transients Including DC

MVAR – Mega Volt-amps Reactive

KVAR – Kilo Volt-amps Reactive

kV – Kilovolts

V – Volts

A - Amperes

Xc – Capacitive Reactance

Chapter 1: Introduction

1.1 Background

Capacitor banks are becoming increasingly important for grid stability and support. Increased supply from renewable sources has brought shunt capacitor banks back into the spotlight. Technology has improved in the design and construction of capacitor units, resulting in increased reliability. With the increased demand for the capacitor banks to remain in service it has become imperative that they are provided with protection schemes that are selective yet remain sensitive.

This thesis will look at single wye grounded shunt capacitor banks that are typically applied to the high voltage transmission networks. The application requirements for these banks is not discussed, rather only the unbalance protection of these devices. A relatively new scheme will be discussed, and its protection performance will be verified against a commonly applied protective scheme. The results will be evaluated to determine if this new scheme offers more sensitivity and selectivity to the protection of the bank. A model bank will be utilized for this thesis which will be discussed in Section 1.3.

1.2 Fuseless Capacitors

Fuseless capacitors are not a new technology. They have been successfully applied for years in installations at higher voltage levels. Fuseless capacitor banks are installed in substations connected to the system bus, where each bank consists of multiple individual units connected together to form the circuit. The circuit consist of capacitor units connected in series to form strings; capacitor strings installed in parallel and connected to a common reference point. This common reference point can be connected to ground potential or left floating, depending on the application requirements. The theory of the fuseless design is that rather than fail in an unstable condition, the capacitor elements will fail in a stable manner allowing the unit to experience minimal changes in current as the result of a failure of individual capacitor elements.

Figure 1.1 illustrates the stages of a fuseless capacitor bank failure. The unit in the figure contains 6 series sections, each with 3 parallel elements. The capacitor unit contains 18 total capacitor elements. The failure case illustrated shows two elements failing within the capacitor. When this happens each element that fails will short out the other two in parallel with it. The result will be a capacitor element with 4 series sections. This is discussed in more detail in Chapter 3 as part of the unbalance protection description.

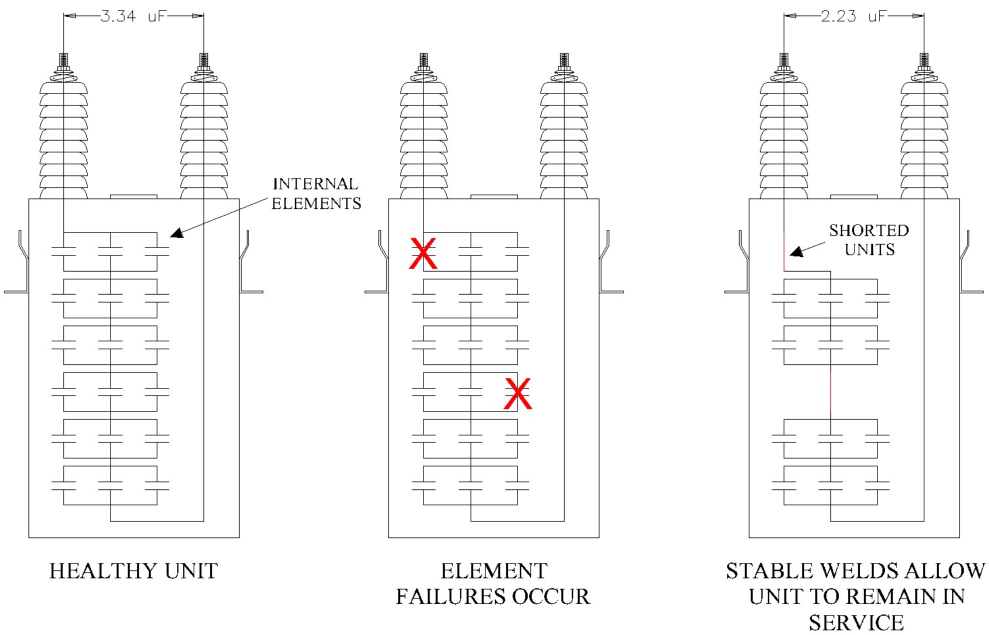


Figure 1.1: Diagram showing a common failure sequence within fuseless capacitors

1.3 Model Bank for the Thesis

A single wye grounded shunt capacitor bank configuration was selected for protection scenarios in this thesis. The bank consists of ten fuseless capacitor units per string with a total of six strings per phase. Each capacitor unit contains 11 series element groups. The capacitor series elements consist of two elements in parallel for a total of 1,320 capacitor units per phase. The chosen bank for the study is currently configured for voltage differential protection and there are two low voltage capacitors per phase. These low voltage capacitors contain 19 elements in parallel, which are of a fuseless design, their purpose is exclusively to support the voltage differential protection scheme which will be discussed in later chapters. A three phase view of the bank is shown in Figure 1.2. A single phase view of the physical layout of the bank is shown in Figure 1.3. The bank model is utilized for analytical calculations and also created using the PSCAD/EMTDC electromagnetic transients program for circuit analysis.

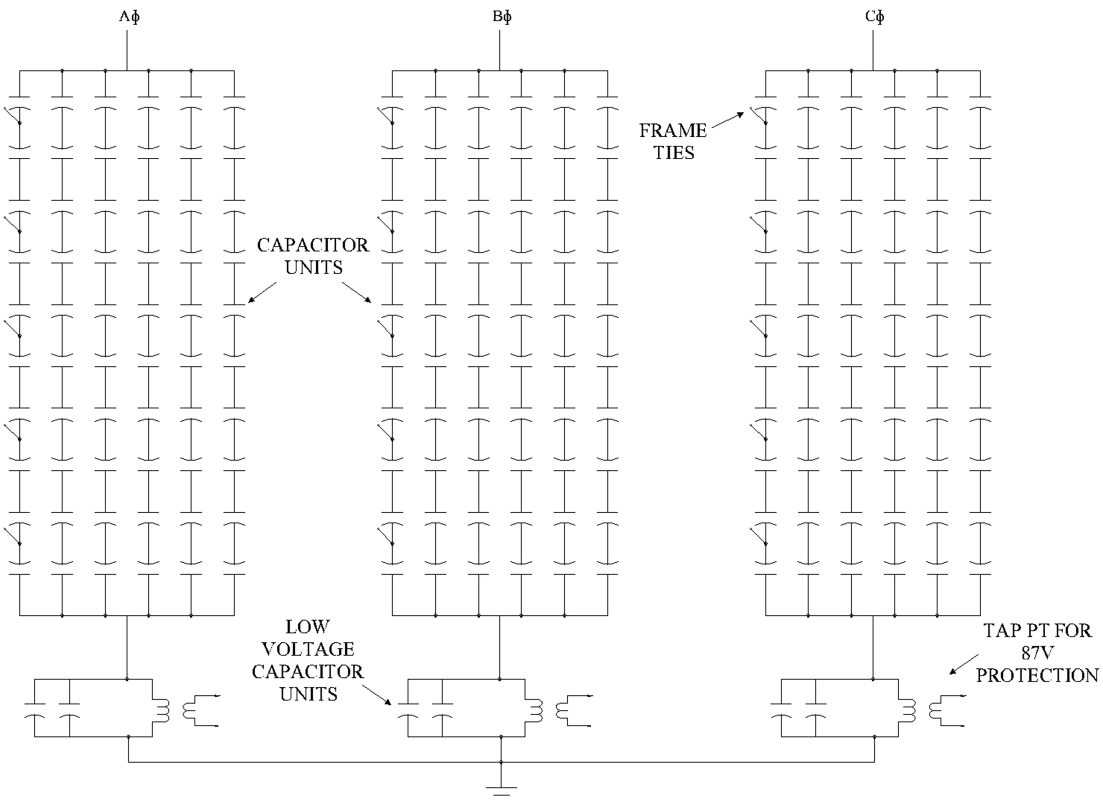


Figure 1.2: Three line diagram view of model capacitor bank utilized for this thesis

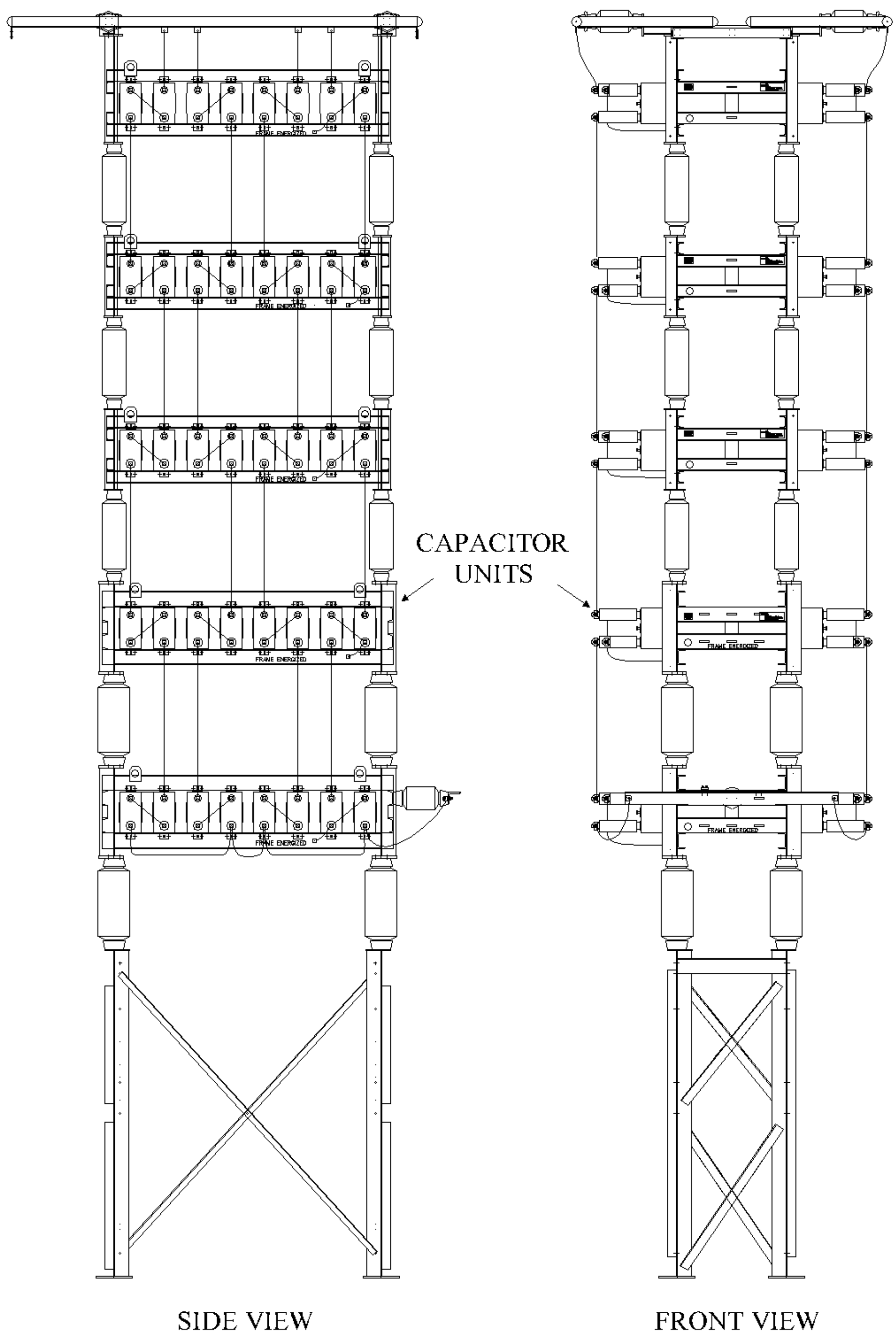


Figure 1.3: Outline view of one phase of the model bank utilized in this study

1.4 Thesis Overview

Chapter 2 will provide background on current protection practices recommended in IEEE standards and provide reviews of current industry articles pertaining to relevant capacitor bank protection.

Chapter 3 will discuss capacitor bank unbalance protection and introduce the scope for this thesis. The model bank will be analyzed to provide the theory for setting protective relay elements for shunt capacitor bank protection. The chapter will also discuss typical faults that a shunt capacitor bank would be exposed to.

Chapter 4 will discuss the voltage differential protection scheme as applied to shunt capacitor banks. The chapter will begin with a review of the voltage differential element theory of operation, protection technology currently used to apply this scheme, and finally discuss how set points will be calculated to apply this protective element to the model bank.

Chapter 5 will discuss an impedance based protection scheme as applied to shunt capacitor banks. The chapter will begin with a review the theory of operation of the impedance based element currently applied protection technology, and discuss how set points will be calculated for four different scenarios of applying this protective element to the model bank.

Chapter 6 introduces the fault study that will be performed utilizing the model bank implemented in PSCAD/EMTDC simulation. The fault study will be described as well as how the faults will be implemented in the model. The implementation of the relay models will also be discussed in this chapter along with a description of the measurements taken from the model bank that will mimic realistic locations for instrument transformers.

Chapter 7 will provide and analyze the results of the fault study. The results will be presented based upon the cases listed in Chapter 6. Each case will be discussed in its own section and summarized in the form of a table. The protection element responses will be discussed, followed by an evaluation of whether or not the impedance based element offers advantages over the industry norm of voltage differential protection for shunt capacitor banks.

Chapter 8 will summarize the work presented in this thesis, discuss conclusions from this thesis and discuss areas that should be the focus of future work concerning this topic.

Chapter 2: Literature Review

This chapter will look at current industry standards and technical articles to assess current practices and research pertaining to shunt capacitor bank unbalance protection. It should be noted that the protection of capacitor banks has historically been a low volume market for relay vendors; therefore, not much research is available. Most of the articles available are focused on basic capacitor bank protection theory or certain protection methods not applicable to the bank configuration type chosen for this thesis. Capacitor banks are available in a broad range of types and configurations, therefore research on them is a very broad topic.

Reviewing literature pertaining to the protection of shunt capacitor banks it appears the common consensus is that unbalance protection is the recommended protection for a variety of potential capacitor bank faults. Literature reviewed contained topics on unbalance protection primarily as it pertains to a voltage differential method as well as an impedance based method.

2.1 Recommendations in Industry Standards

Protection engineers in North America refer to the IEEE standards on shunt capacitor banks for insight on how to select and apply protection. To first understand any protection application, the design constraints that are applicable to the piece of equipment being protected should be determined. The IEEE Standard for Shunt Power Capacitors (IEEE 18-2012) [1] was consulted to understand the design constraints and construction of the capacitor units. From [1] the design constraints on voltage and current handling capabilities of these units were determined. Based on the standard, the manufacturer's tolerances for capacitors is 0-10% of the nameplate ratings. Operating temperature ranges are also given as a reference in the standard.

The next standard reviewed was the IEEE Guide for the Protection of Shunt Capacitor Banks (IEEE C37.99-2012) [2]. Consulting [2] led to a deeper understanding of requirements for protection of shunt capacitor banks. The specific capacitor bank configuration chosen for this thesis was a shunt single-wye grounded bank with fuseless capacitors. Therefore, the sections of the standard studied pertain to the protection requirements for this type of bank. Capacitor bank unbalance theory and application in a protection scheme were also discussed in [2]. From reviewing [2] it was determined that two protection methods offer similar unbalance protection coverage for the model bank. The protection requirement for fuseless banks mentioned in [2] requires that the bank be removed from service when the voltage across any single unit exceeds 110%. The standard also mentions that if a large bank contains a large number of series elements, then a situation could occur where a complete unit is shorted but the voltage across individual elements does not exceed 110%. This is an important fact to remember as this thesis develops unbalance protection calculations and methods.

The theoretical derivations of the voltage differential scheme in [2] will also be explored later in more detail. The IEEE standard presents protection calculations based upon bank design for different configurations, however these are based in per unit capacitances, which can lead to confusion. This thesis will look at calculations involving capacitive reactance versus the per unit equations, which should provide better clarification of the protection quantities needed. The IEEE standard will be used as a building block for the rest of this work.

2.2 Shunt Capacitor Bank Protection Recommendations in Literature

The authors of [3] discuss fuseless capacitors and their application. That paper discusses the construction of fuseless banks and touches on protective relaying requirements. An interesting thing to note in [3] is that for fuseless banks the string current should be limited to 62A. This limit seems arbitrary, but it was determined by that manufacturer to insure stable weld joints in the capacitor elements when they fail. The different types of unbalanced conditions that capacitor banks are exposed to are also mentioned in [3]. These conditions are inherent unbalance, system unbalance, and unbalance due to capacitor unit failures. These unbalances will be discussed in later chapters when the protection theory is examined in more detail. The authors of [3] also reiterate what was mentioned in [2]: that a bank should be removed from service when the voltage across any single capacitor unit exceeds 110% of rated, or when the number of internal series groups equal to one unit have failed, whichever comes first. This is an interesting statement because most technical papers mentioned the 110% limit, but the other limiting factor was overlooked.

The authors of [4] discuss fuseless capacitor design and different commonly used bank configurations. The important information gained from this article was the discussion on complicating factors to implementing successful unbalance protection. The unbalance conditions mentioned in [3] include inherent unbalance and system unbalance, and the complicating factors in [4] pertain to these types of unbalances. The impact of manufacturer's tolerances of 0-10% is discussed, however during bank commissioning the effects of these variations can be nulled out. The impact of solar radiation on drift of capacitance values over time is also discussed. This drift is impacted by the individual bank's physical location relative to the direct sunlight. For example, if a capacitor rack is oriented where the left hand side is exposed to full sunlight but the right side is shaded, there can be changes in the left bank's capacitance. In [4] it is mentioned that the change in capacitance is due to the dielectric film changing with temperature, the fluid changing with temperature, and the heating of the fluid causing the expansion of the unit. The unit expansion will change the dimension between the capacitor plates, thus changing the unit's capacitance. The article also gives some lessons learned in practice on applying the capacitor banks. These stated that current measurements are generally more sensitive than voltage measurements for indicating bank unbalance because low level voltage measurements exhibit more noise than low level current measurements. The authors do however state that voltage based protection elements are as fast as, or faster than current based elements.

The authors of [5] discuss the development of the voltage differential element for capacitor bank protection. This paper is older, and the technology mentioned is obsolete, but the background to this protection is applicable to this paper. As engineers, we must know the history of where we came from to understand how to develop and apply solutions for the future. The paper mentions that prior to applying these relays, shunt capacitor banks required visual inspections to determine if fuses had blown and an unbalance exists. This method would not work for fuseless banks, as they have no visual indication of element failures. It would appear that voltage differential was the best solution for capacitor bank protection for the technology available in the era the paper was written. The relay mentioned was a static type, yet its operating characteristics are still applicable to the voltage differential elements applied today. The difference however is modern day relays utilize numerical methods to compare signals against set points versus using electronic based comparators.

The authors of [6] present an application guide on applying a currently available capacitor bank relay to a grounded fuseless bank. This paper takes a modern-day approach to the design in [5] with discussion of the theory and an example on how it is applied. An interesting artifact from the microprocessor-based protection is that the relay can use the sign of the differential voltage to determine if a fault is located above or below a tap point. For example, a negative value concludes the fault is above the tap point, and a positive value determines that the fault is below the tap point. This method of fault identification was patent pending for the relay utilized at the time this application guide was written [6].

The authors of [7] go into detail on impedance based protection of fuseless capacitors. This protection concept was previously offered in a capacitor bank protective relay; however it did not pick up much use. The paper discusses the application of the impedance based protection. Temperature induced changes in capacitance are also mentioned to be 3.5% across the spread range of capacitor operating temperatures. Discussion of the theory of impedance protection and its advantages are discussed. One advantage of this method is the ability for a relay to see the apparent impedance of either an individual string or multiple strings versus the entire bank. This helps reduce required maintenance callouts as well as misoperations of the capacitor protection. The paper provides a good source of information but does not provide enough data to reinforce its comparisons to the voltage differential method.

Article [8] is a paper produced by a vendor currently producing impedance based protection relays specifically for capacitor banks. The paper discusses the limitations of the voltage differential method and how the impedance based protection overcomes these limitations. The paper also discusses the application of the impedance based protection and the calculations for determining the protection settings. The vendor has also developed an algorithm to compensate for capacitance changes due to temperature and [8] describes how the relay can interpret temperature based changes versus changes due to capacitor element failure. The voltage differential methods available today do not have the capability to compensate for temperature changes, thus making the impedance based method an appealing alternative method. The paper finally discusses advanced monitoring functions for capacitor banks and describes how to retrofit existing banks to accommodate them. There is one note that if the bank is retrofitted with impedance bank protection scheme where the apparent impedance of the entire bank is measured, then there will be no gain on sensitivity of this method. The reasoning behind this behavior will be discussed further in this thesis. The retrofit however will allow the user to take advantage of the temperature-based compensation available with the impedance method as opposed to having no compensation with the voltage differential scheme.

The authors of [9] discuss an alternative to the impedance based and voltage based unbalance schemes that is based solely on current measurements. The method of string current imbalance applies current transformers to the bank strings, similar to practice in the impedance protection. The paper provides good information of capacitor bank string protection, however at this time no vendors offer this method of protection in practice. The discussed approach would however be applicable as a fail-over method for impedance based protection schemes in the event the bus voltage measurements are lost. Upon inspection of this method, it is comparing one string current to another string current so it could experience a compensating failure if simultaneous failures in different strings result in no unbalance signal, as discussed in [2].

Based on this literature review, this thesis will compare the currently used voltage differential elements against the newer impedance based protection methods. This will involve a side-by-side comparison under different operating conditions to determine how the elements respond.

Chapter 3: Unbalance Protection Scope

3.1 Unbalance Protection

After reviewing [2] it has been determined that an unbalance protection scheme should be applied as primary protection of shunt capacitor banks. This will be a focus of the thesis, and this chapter will discuss the initial calculations needed to set this type of protection. The equations from [2] will work as well, but they tend to be non-intuitive and can cause confusion when focusing on multiple methods of protection.

3.2 Calculations for Protection Setting

To first set the capacitor bank protection, calculations have to be made to determine the set points where the protection should operate. Similar to the settings of an overcurrent element, the expected normal values, along with the values at the point the protection should operate should be calculated. An approximate equation is given in [2] for fuseless single wye grounded capacitor banks where Ve is the per-unit voltage across individual elements, Vln is the per-unit line-to neutral voltage, E is the number of series elements in one string, and e is the number of shorted (failed elements). This equation is shown in (3.1), it is rearranged to solve for e as (3.2).

$$Ve = Vln * \frac{E}{E - e} \tag{3.1}$$

$$e = E - \frac{E}{Ve} \tag{3.2}$$

The model capacitor bank for this thesis has 10 capacitor units in series per string, each containing 11 elements. This equates to 110 elements in one series string. Setting Vln equal to 1.0 per unit, Ve equal to 1.1 per unit and E equal to 110 and solving for e, it is determined that 10 shorted elements in one string will result in a 1.1 per unit over voltage across each element.

One thing to note is the line to neutral voltage for the model system is set to 199.19 kV, however our capacitor units are rated at 21,320 V. Dividing the system line to neutral voltage by the 11 will equal a voltage of approximately 1,938 V. This voltage will be applied across all the capacitor elements in one string. To determine a nominal Ve by dividing the line to neutral voltage of 199.19 kV by 110, the resultant voltage will be approximately 1,811 V. Taking this value and multiplying by 1.1 results in 1,992 V. This calculated voltage is below the true 110% rating of each capacitor unit.

It is mentioned in [2], and reiterated in [3], that the bank should be tripped prior to the shorting of one complete capacitor unit, therefore with 11 series elements in one capacitor unit, 10 shorted elements is still a valid set point to remove the capacitor bank from service. Although the capacitor bank may be perfectly healthy, the protective relays cannot discriminate between capacitor unit and bank string faults. For the protection settings in this thesis, we will focus on removing the bank from service using the set point located between the calculated values for 9 shorted elements and for 10 shorted elements in one string.

Once the required number of shorted elements to remove the bank is known, the next step is to determine electrical quantities at a nominal state and also at two failed states. One state with 9 shorted capacitor elements in a string and the other state is with 10 elements shorted. To solve for the nominal quantities, we have gather the following information from the capacitor nameplates and the bank layout.

Voltage Line to Neutral (V_{LN}): 199.19 kV

Capacitor Unit Capacitance (C_U): 3.34 µF

Series Elements in One Capacitor (*Se*): 11

Low Voltage Capacitor Capacitance (C_{LVC}): 650.84 µF

Number of Series Elements Per String (*Ns*): 10

Number of Parallel Strings Per Phase (*N*p): 6

Number of Low Voltage Capacitors in Parallel (N_{LVC}): 2

Circuit analysis methods are used to condense the capacitor bank into an equivalent impedance consisting of the upper and lower sections. From the upper and lower sections, the capacitive reactance *Xc* of the capacitor units are calculated using equation (3.3) below.

$$Xc = \frac{1}{j * 2 * \pi * 60Hz * C} \tag{3.3}$$

The *Xc* of the upper capacitor unit is calculated to be approximately -j72.2 Ω and the Xc for the low voltage capacitor unit is calculated to be approximately -j4 Ω. The upper section consists of 10 elements per string in series and 6 strings in parallel. Using the calculated reactances, the upper section can be further simplified utilizing equation (3.4) below.

$$X1 = \frac{Xc * Ns}{Np} \quad (3.4)$$

From equation (3.4), $Xc * Ns$ is the impedance of one series string, calculated to be approximately -j7941.9 Ω.

The lower capacitor section will consist of 2 low voltage capacitors in parallel, the equivalent capacitive reactance is calculated as the reactance of one unit divided by 2. The upper section *Xc* (X1 in Figure 3.1) is calculated as approximately -j1323.64 Ω. The lower section (X2) is approximately -j2 Ω. This simplified model is shown below in Figure 3.1.

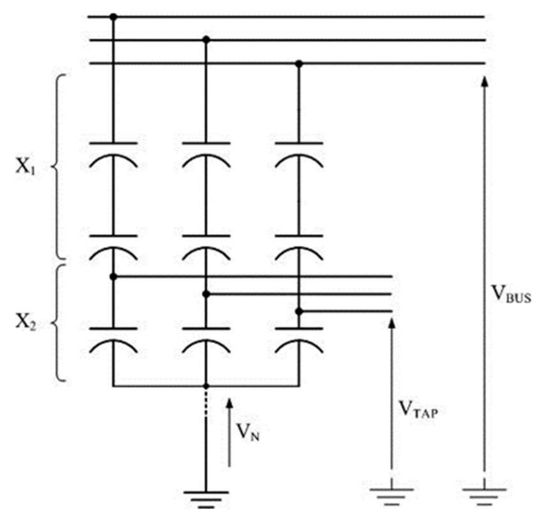


Figure 3.1: Simplified three line diagram of capacitor model from [2]

Once the impedance reduction of the capacitor bank is completed, we can then solve for the upper unit voltage and the lower unit voltage using a voltage divider. Equations (3.5) and (3.6) show how the upper and lower section voltages are calculated.

$$Upper\ V = Vln * \frac{X1}{X1 + X2} \quad (3.5)$$

$$Lower\ V = Vln * \frac{X2}{X1 + X2} \quad (3.6)$$

The upper section voltage is calculated to be 198,578.5 V, while the lower section voltage is calculated to be 306.2 V.

The bank needs to be reexamined with 9 shorted elements and again with 10 shorted elements. As mentioned earlier, the variable e is used to represent the number of shorted elements in the upper bank. The effective reactance, $X1$, as e is varied is derived in equation (3.7).

$$X1 = \left(\frac{1}{\frac{Xc}{Np - 1}} + \frac{1}{Xc * ((Ns * Se) - e)} \right)^{-1} \quad (3.7)$$

From equation (3.7) $Xc * \big((Ns * Se) - e\big)$ is equal to the reactance of the shorted string.

The equations assume all the shorted elements are in one string while the other strings remain equivalent to the normal string reactance. X2 will remain the same at -j2 Ω. From equation (3.7) the following reactances and voltage values are calculated.

<u>9 Shorted Elements:</u>

X1: -j1304.3 Ω

Xc of Shorted String: -j7292.1 Ω

Upper Section Voltage: 198,879.3 V

Lower Section Voltage: 310.7 V

<u>10 Shorted Elements:</u>

*X*1: -j1301.9 Ω

Xc of Shorted String: -j7219.9 Ω

Upper Section Voltage: 198,878.7 V

Lower Section Voltage: 311.3 V

The above calculated values will be utilized in the following chapters to determine the protection settings for the relay elements that are applied for protection of this bank. The protection set points will be set between the values calculated for 9 shorted capacitor elements and for 10 shorted capacitor elements. These calculated values will also be utilized to verify if our PSCAD/EMTDC model is operating correctly. The equations used thus far assume that the capacitor units are of the parallel connected capacitor unit design, which is more commonly applied. The series connected design is a specialty from certain vendors and requires that the capacitor unit be examined in more detail because of internal series strings, which is beyond the scope of this thesis. Application of series connected units with the settings calculated in this thesis would result in erroneous results.

3.3 Fault Types of Shunt Capacitor Banks

The previous section examined the failure of elements in one string of the capacitor bank. A capacitor bank however can be subjected to a multitude of different types of faults. While these fault types are not utilized to calculate the protection set points, they are important to understand to study how the capacitor bank protection responds and determine what faults cause unintended results from the relays.

String Element Failures

String element failures are the result of capacitor elements failing in one string. These were discussed in the previous section and are a common fault that shunt capacitor banks are exposed to. As the elements fail, they will fail in a shorted manner, as can be seen in Figure 1.1. This failure results in the upper section voltage dividing across the remaining elements and causes them to be exposed to an increased potential difference. This increased potential difference becomes an issue when enough capacitor units are shorted to expose capacitor elements to voltages exceeding their design criteria. As discussed earlier in [2] and [3], it is good practice to remove a capacitor bank when the number of shorted elements in a string is equal to the total number of elements or series sections in one unit. The reasoning for this is because if one capacitor unit failed completely it will act as a very low impedance conductor in an oil filled enclosure. If this capacitor unit was the first unit in a string and there is a phase to ground fault on the bank side bushing, the capacitor unit could experience bus phase to ground fault current levels. This current would cause super heating of the capacitor dielectric oil and potentially rupture the case causing significant damage.

Distributed Element Failures

Distributed capacitor element failures are the same as string element failures with the exception that they are not localized to one string. This is a more realistic approximation of a bank because capacitor elements will fail at random without external factors. An example would be that one string will have 5 elements shorted and the other strings each have 2 shorted each for a total of 15 total capacitor elements shorted in the bank. This phenomenon will be examined during the protection analysis. In this scenario, none of the individual elements are exceeding their voltage limits so the bank can remain in service. But as will be discussed later, some of protection schemes will trip the entire bank for this scenario.

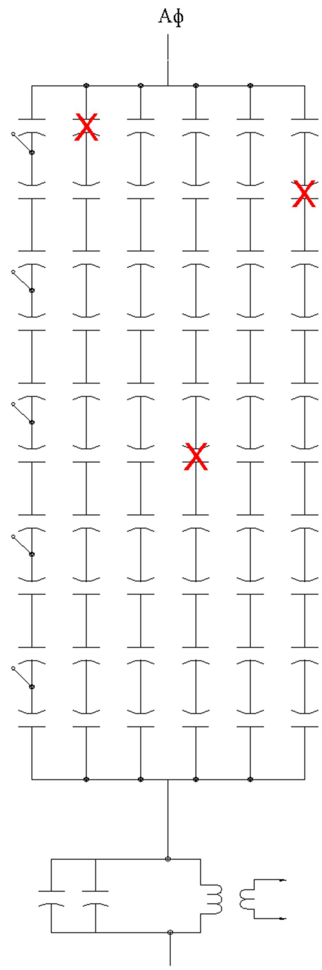


Figure 3.2: Single phase view of bank detailing distributed failures

Low Voltage Capacitor Failures

Low voltage capacitors are not required for correct capacitor bank operation. The low voltage capacitors are installed only for the voltage differential protection scheme. The low voltage capacitors in our model bank have one series group, therefore if one element fails it will short out the entire low voltage tap. When the low voltage capacitor fails it will not negatively affect the bank's performance or subject it to danger, however it has the potential to disable the protection scheme or cause a relay misoperation. The protection response will be discussed more in Chapter 4.

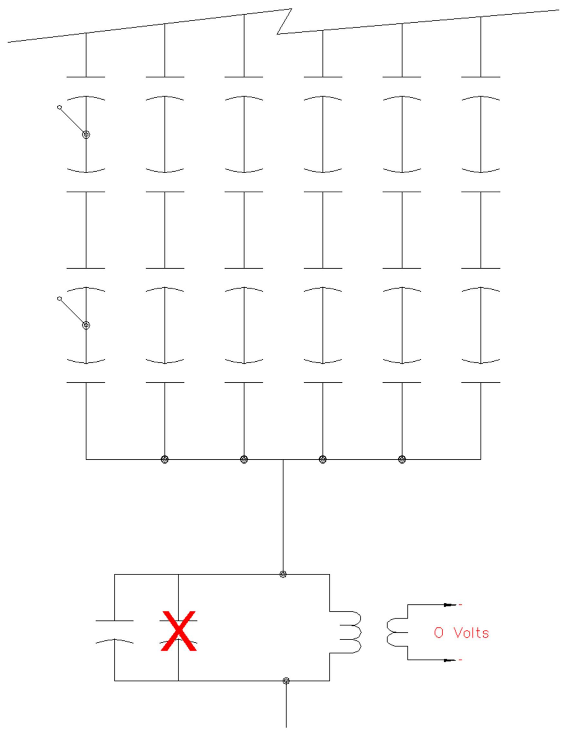


Figure 3.3: Single phase view detailing a low voltage capacitor failure

String to String Faults

Capacitor banks are installed on racks with unit spacing in accordance with [1]. The frame is energized from a wire connection from one string. This can lend itself to provide an easy path for string to string faults. Capacitor units located in areas with high conductive contamination exposure or large climbing animal populations are especially prone to these types of faults. Examining the physical layout of the bank as shown in Figure 3.4 it is proven that string to string faults have a high likelihood to occur. In the capacitor model for this work, two different string to string faults have been evaluated, for one fault with a string to string short at the midpoint and another fault with an off midpoint short. Utilizing hand calculations and circuit analysis it can be proven that a string to string fault can expose some units to excessive over voltages without much difference in the total upper and lower section voltages. This is an interesting discovery as string to string faults are not mentioned much in literature except for phase to phase fault situations. The simulation model will replicate and prove this observation in Chapter 7.

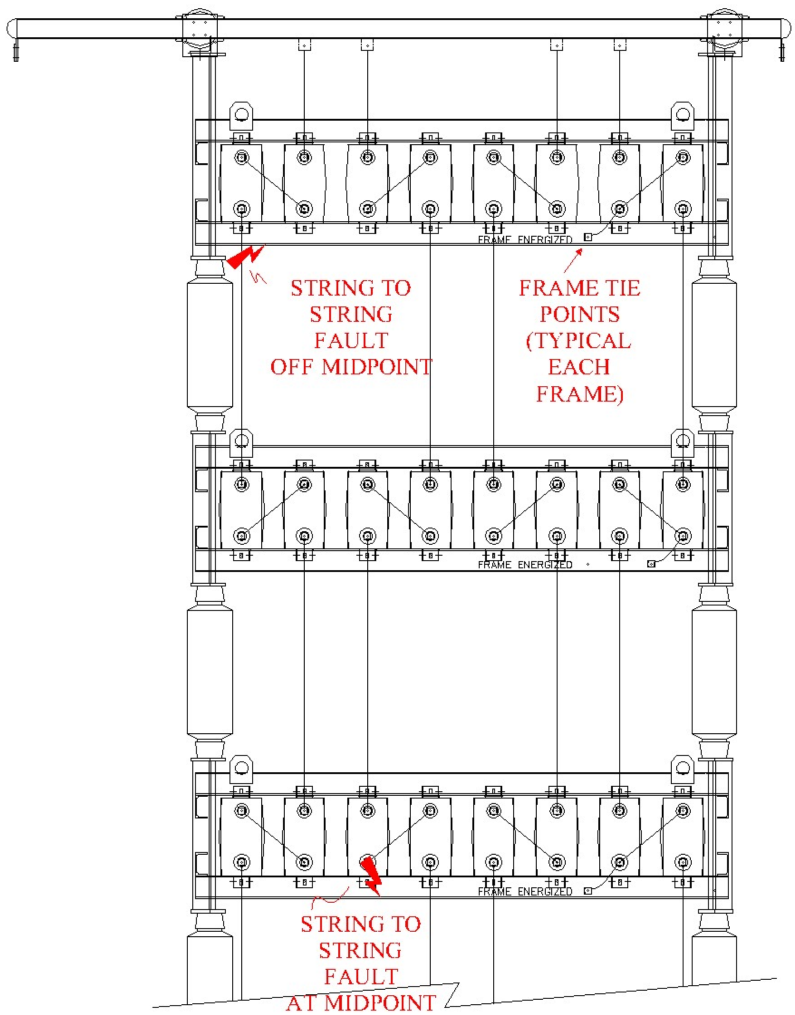


Figure 3.4: Side view of one phase describing string to string fault locations

Phase to Ground Faults

Capacitor banks are located outdoors in substation yards. These capacitor banks are exposed to weather conditions and they can be subjected to phase to ground faults. The model for this thesis will subject the bank to a phase to ground fault at a common location and note the response on the protective relays. By inspection of the bank layout, it is determined that if a phase to ground fault occurs at the bottom of one string above the low voltage capacitor tap point, as shown in Figure 3.5, then the response would replicate a failure of a low voltage capacitor.

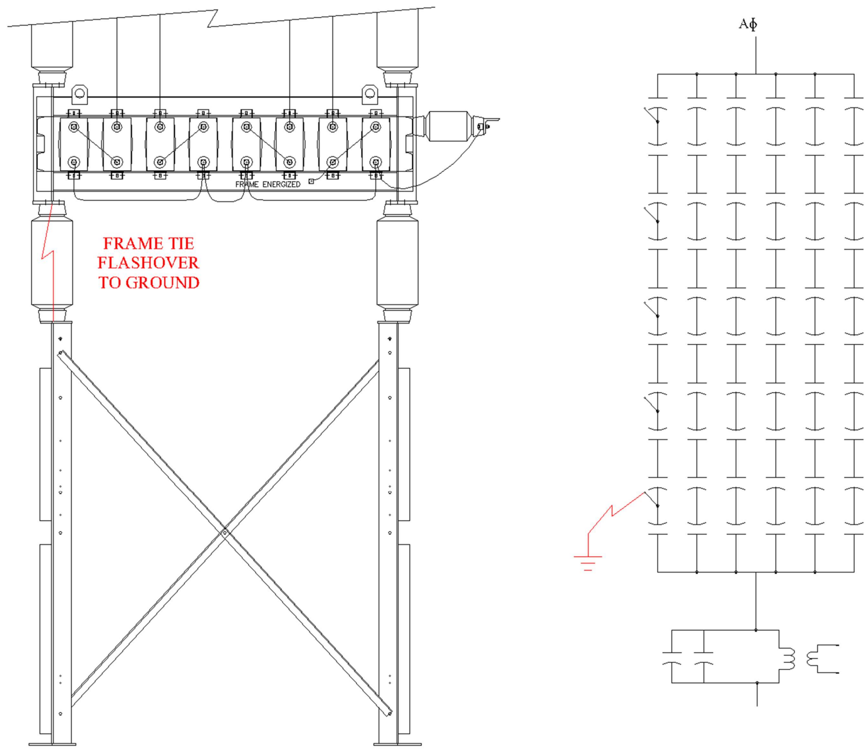


Figure 3.5: Physical layout and single phase schematic view of phase to ground fault

<u>Phase to Phase Faults</u>

Phase to phase faults on outdoor capacitor banks where the phases are located on separate structures would be an uncommon occurrence. The phase to phase faults will still be analyzed to judge the unbalance protection schemes in the event this fault was to occur. Recommendations in [2] suggest that the capacitor bank's inherent unbalance should be factored in, and a negative sequence overcurrent element should be set to protect the bank at 10% nominal phase current assuming the system is perfectly balanced.

From the fault cases above it is concluded that analytically examine a capacitor bank in the various situations would require an extensive set of calculations to capture all fault scenarios. The majority of engineers do not have time to analytically examine all possible operating conditions and faults to analyze the protection response for each capacitor bank that is to be protected. This thesis will develop a computer model of a real capacitor bank and use models of the protective relays to verify their response in all the scenarios. Chapter 6 will discuss this model and provide the results from the above-mentioned faults applied to the capacitor bank.

Chapter 4: Voltage Differential Protection

4.1 Voltage Differential Protection Theory

The voltage differential function, commonly referred to as the ANSI 87V, is an impedance comparison function rather than a true differential scheme. This protection scheme is a per-phase method that utilizes three protection elements, one for each phase, that are independent of each other. This allows the scheme to not be affected by system imbalances. The inputs for the voltage differential element are from a bus potential transformer (PT) located on the system bus and a tap PT located across the low voltage capacitor. The scheme works using the electrical relationship that a balanced capacitor bank has a known ratio between the bus voltage and the tap voltage. This ratio is dependent on the upper and lower impedances of the bank. To further explain this, [2] is referenced and its derivation of the voltage differential scheme. A three-line diagram of the voltage differential scheme is shown in Figure 1.2.

From Equation (3) in [2] we see the relationship between the bus and tap voltages in (4.1).

$$\frac{Vtap}{Vbus} = \frac{X2}{X1 + X2} \tag{4.1}$$

This relationship shows that as the impedance of the bank changes, the relationship between these two voltages changes. To generate a protection signal from this behavior, a balance equation is written as Equation (4) in [2].

$$Vtap - k * Vbus = 0 \tag{4.2}$$

$$k = \frac{X2}{X1 + X2} = \frac{Vtap}{Vbus} \tag{4.3}$$

From equation (4.2), a constant referred to as the k value is used to null out the equation to zero to cancel standing imbalance during commissioning, and we can write the operating signal using Equation (5) from IEEE C37.99 [2] as follows, and numbered as equation (4.4) in this work.

$$Vop = |Vtap - k * Vbus| \tag{4.4}$$

This is similar to equation (5.1) in [10], which is provided by a relay vendor to set their 87V relay, which is equation (4.5) in this thesis. The difference between equation (4.4) and the relay vendor's equation is that equation (4.5) does not take the absolute value of the operate quantity, as will be discussed later. The relay vendor also swaps the *Vtap* and *Vbus* values in their equation, which will result in a change in the calculation of the *k* constant. From the above description it is proven that the voltage differential scheme is simply using the principle of a voltage divider to calculate impedance changes in a bank.

Equation (5.1) from [10] can put into common terms used in this work:

$$DV\ (Vop) = Vbus - k * Vtap \tag{4.5}$$

Where the k is now defined for the relay in [10] as:

$$k = \frac{Vbus}{Vtap} \tag{4.6}$$

The voltage differential protection scheme requires the following components when applied to fuseless banks: bus PTs, tap PTs, and low voltage capacitors. The PTs are installed to step down the bus and tap voltages to tolerable voltages for the relays and to provide galvanic isolation. The low voltage capacitors are installed to provide a reference impedance for the protection comparison.

4.2 Current Protection Technology for Voltage Differential

Currently two relay vendors produce voltage differential relays for capacitor bank protection. One vendor's manual is referenced in [10]. Both relays offer the same functionality so only one was chosen for representation. The modern voltage differential relay builds its foundation on the original static relay discussed in [5]. The relay allows the user to dynamically compensate for inherent unbalances during capacitor bank commissioning. The relay also uses the calculated sign of the voltage difference to allow two protective set points depending on the location of the fault relative to the tap point voltage.

For inherent unbalances, the relay utilizes a function that will take readings from a healthy bank in service and automatically null out the balance equation by internally calculating the k value. This procedure allows for very precise setting of the voltage differential set point without errors associated with hand calculations of the k value. For modeling purposes in this work, this k factor will be hand calculated and input into the model to simulate a nulled scheme.

Another function provided by the relay vendor is the ability to apply multiple voltage differential set points to account for different fault locations. As discussed in [6], the relay will report the fault is above the tap point if a negative operating quantity is calculated. If a positive operating quantity is calculated then the relay will report the fault below the tap point. The relay also uses the sign of the operating quantity in logic to determine which set point to utilize. An example of this would be if the fault is below the tap the relay will enable a set point of 3 V for comparison, but if it is below the tap it will utilize a set point of 5 V. This however can cause issues on fuseless banks with low voltage capacitors because if the low voltage capacitor fails then the differential voltage will be at a value equivalent to the bus secondary voltage. If that happens, the protection element will have no reference to produce any operating quantity on the upper section. From the previous reasoning it is proven that a failure of the low voltage capacitor would disable the protection.

One potential downfall of the voltage differential scheme is the possibility for the scheme to incorrectly respond to changes in capacitance due temperature gradients within the bank. The capacitors have a manufacturing tolerance of 0-10% [1]. This error will be nulled out during commissioning, so it has no effect on the protection scheme. One thing to consider on this is if a capacitor is replaced in the field, the voltage differential scheme will then need to be nulled again. This nulling is to offset any changes from the new unit that is installed. The bank is nulled only during commissioning; so any temperature deviations or shorted elements will generate a voltage mismatch in the relay. Another benefit of the newer relays is that they offer special logic such as loss of potential logic and customizable user logic that allows the element to be applied to meet specific needs.

4.3 Setting the 87V Relay

In order to set the relay we need to determine the initial k factor setting to utilize. This *k* factor constant will be used as a starting point in practice, and also in our model. This *k* factor constant will be used to null equation (4.5) to equal zero in normal conditions. Using (3.2) we have already calculated the tap voltage as 306.2 V when the bus voltage is at 199.19 kV. These voltages will be the values used in equation (4.5) to calculate the *k* factor constant; except they need to be in PT secondary values. The scheme's potential transformer ratios are utilized to convert these values to secondary values. For our model capacitor bank the bus PTs will have a ratio of 3000:1 and the tap PT will have a ratio of 3.2:1. The secondary voltages are calculated using equation (4.7).

$$Vsec = \frac{Vpri}{PTR} \tag{4.7}$$

Using equation (4.7), we determine the *Vbus* secondary to be 66.4 Vln and the *Vtap* is calculated to be 95.7 V. Entering these values into equation (4.6), the *k* factor constant can be determined.

$$k = \frac{Vbus}{Vtap} = \frac{66.4\,V}{95.7\,V} = 0.693 \tag{4.8}$$

Once we have the initial *k* factor constant the set point for the voltage differential function can be determined by taking the values calculated in Section 3.2 for 9 and 10 shorted elements, and then set the relay to operate between these points. Writing equation (4.5) for each scenario we obtain the following.

$$dV(9\ shorts) = 66.4\ V - 0.693 * \frac{310.7}{3.2} = -0.88\ V \quad (4.9)$$

$$dV(10\ shorts) = 66.4\ V - 0.693 * \frac{311.3}{3.2} = -1\ V \quad (4.10)$$

The operating voltage will be set between these values as an average, as shown in equation (4.10).

$$87TP2P = \frac{|dV\ (10\ shorts) + dV\ (9\ shorts)|}{2} = 0.95\ V \quad (4.11)$$

Based on the above calculation it is proven that our differential voltage element should be set at -0.95 V. Per the recommendation in [10] a 3 cycle delay should also be set. This value will however only apply to the second trip level in the relay. The relay will only utilize this trip set point when the differential voltage is less than or equal to 0. For values greater than 0 the relay identify faults below the tap, which will signify a failed low voltage capacitor. This value will be equal to the bus voltage as calculated with equation (4.5). A conservative set point would be to divide this by two and set the 87TP1P to 33.2 V if the intention to trip the bank for a failed low voltage capacitor. It should be noted that if the low voltage capacitor fails the relay will not be able to provide protection of upper section faults. It will be up to the protection engineer to decide if this pickup will be used for tripping or for alarm only. If the bank is left in service with a shorted low voltage capacitor the relay will not respond to faults in the upper section unless they produce enough operating quantities to result in the pickup of other protective elements in the system.

Chapter 5: Impedance Based Unbalance Protection

5.1 Capacitor Bank Impedance Protection Theory

Impedance based protection of capacitor banks is a relatively new concept made possible by advances in microprocessor-based relay technology. Impedance based protective relays have been applied to transmission lines for decades. Although the technology has been available with the electromechanical counterparts, the cost and space needed to provide this type of protection to a capacitor bank made this protection unfeasible to apply.

The impedance based protection elements is referred to as a 21C device number. The element contains an inward-looking mho element that calculates the apparent impedance of the capacitor bank. This apparent impedance is compared to a mho circle in a R-X plane. When the apparent impedance is located inside of this mho circle the element is in a normal state. When the apparent impedance crosses out of this defined circle the element will operate and declare a trip. This element is shown below in Figure 5.1.

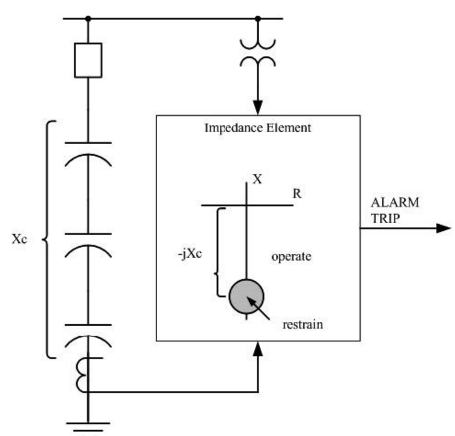


Figure 5.1: Single line detail of impedance based protection from [2]

The element uses measurements from bus PTs and from current transformers (CTs) located in the bank. Since the impedance based element is calculating the apparent impedance, the sensitivity depends on the number and location of these CTs. The capacitor bank breaker bushing CT’s can be used to calculate the apparent impedance of the entire bank. As an alternative, CTs can be located on the grounded end of each string, in which case the relay will calculate the apparent impedance of each string.

The theory behind the operation of this element is very intuitive as the apparent impedance is the measured secondary bus voltage divided by the measured CT secondary current. Relay set points to obtain the center and trip radius of the mho element are calculated similar to those for the voltage differential function. The circle for the mho element will be centered at the nominal impedance and its radius will be a percentage of this impedance. Relay set points will be calculated using equations from [11], as will be discussed later in this chapter.

The CTs can also be located in the bushing of the breaker looking at the capacitor bank, on each string, or surrounding multiple strings for "lumped" impedance measurements. The model utilized for this thesis examines four methods of impedance measurements based on different CT locations. One with bushing CTs measuring the entire capacitor bank current (per phase method), one with individual string measurements (per string method), one with 2 strings per CT (lumped 2 string method), and one with 3 strings per CT (lumped 3 string method). From the set point calculations, it is observed that the relay with the individual string method has the highest sensitivity, and that sensitivity decreases as more capacitor strings are added to a CT. If the CT's measurements are made on the grounded side of the string, lower insulation class CTs can be utilized providing cost savings.

5.2 Current Protection Technology for Impedance Based Protection

Currently one vendor on the market produces a relay to perform capacitor bank impedance protection (21C). The instruction manual for this relay is referenced in [11] and is used here to set the model elements for the bank under study in this thesis. This relay has up to 18 current inputs that would allow 6 three phase groups to be protected by the relay. The model bank for this thesis contains six strings so this relay will be adequate to perform full protection, however multiple relays can be specified if additional strings are required.

Impedance based capacitor bank protection is mentioned in [2] without going into much detail. The relay vendor in [8] and [11] go into deeper discussion on this protection method. A large advance available for the relay in [8] and [11] is that the manufacturer has developed an algorithm that will allow the mho circle to shift as the relay reads impedance changes that appear to be signatures of drift with temperature changes. Figure 5.2 shows how this element responds to impedance changes due to temperature swings. The authors in [8] show how impedance changes due to temperature changes differ from impedance changes due to failed capacitors and explain how the relay responds to these types of changes appropriately. This temperature compensation function adds a feature that is not currently available in a voltage differential capacitor protection scheme.

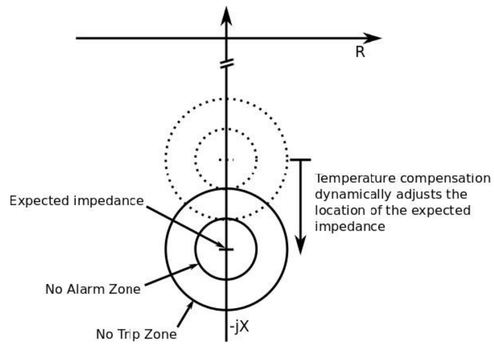


Figure 5.2: Diagram showing the 21C element mho characteristic changes with temperature from [8]

One feature the voltage differential relays offer that the impedance based scheme also provides is the ability to do online commissioning of the bank. The relay allows the user to dial in the expected impedance to values based on values measured in the field with more accuracy for that specific bank than the data sheet values. This result will set the relay exactly at the measured apparent impedance, thus mitigating any measurement errors relative to the calculated values. Rather than using a scaling factor, the relay adjusts the center point of the mho circle to a measured actual value. The tripping radius will then be based on the percent change of this impedance value that is calculated.

Another feature added by impedance based protection is that the relay allows remote access to investigate the actual measured impedances of the bank. This allows an operator diagnose an alarm signal without sending a technician to the site to investigate. A HMI can be developed to display the capacitor bank status and measured values. The relays in [8] utilizing this element also offer advanced features such as user customizable logic, as well as blocking logic based on voltage and current levels. Blocking logic based upon measured values is utilized in the relay to enable the protective relay to differentiate a faulted condition from a non-faulted condition. One example of this would be if the bank is switched offline the relay will block its protection from operating upon a loss of current or voltage measurements.

5.3 Setting the 21C Relay

The first step to set the impedance based capacitor bank relay is to determine what apparent impedances will be seen by the relay based on the current measurement points. Once these current measurement points are located, the nominal currents at these points are calculated and utilized to calculate the impedance protection set points. Equation (8) in [11] is used to calculate the apparent impedance as shown in equation (5.1)

$$Zn = \frac{Vbus}{In} \tag{5.1}$$

Where *In* is the measured current in secondary amps from the CT. The set points are then calculated per equation (9) in [11] as in equation (5.2).

$$\Delta Zn(\%) = \frac{|Zexp - Zn|}{|Zn|} x100\% \tag{5.2}$$

Where *Zexp* is the expected impedance calculated from the bus voltage divided by the expected current at the measurement point. The expected current is the value of current generated from circuit analysis of the bank or measurements made on a healthy bank. The measured current will be the actual value measured by the current transformers. In a healthy state, the expected current will equal the measured current. *Zn* is designated as the measured impedance. Using these two values the relay can then be set. For the model bank an initial set point configuration will determine these values, but in practice, the relay will measure the current of the bank once it is put into service and utilize this measured value to calculate the expected impedance. Due to the multiple options for CT locations used in this research, the setting calculations will be broken down into four segments.

5.3.1 Per Phase Setting (CTs Looking at Entire Bank)

The predicted nominal current the CT will measure is determined as a first step toward calculating the per phase set points. It is assumed the CT will be see the current for the entire bank since it is located in the breaker bushings. This method is designated as the per phase method, which has a similar view of the bank as the voltage differential scheme. To calculate the bank current, the value for the upper section voltage calculated in Section 3.2 is divided by the upper section impedance. This calculation for the primary side current is shown in equation (5.3).

$$Ibank = \frac{Vbus}{X1} = \frac{199.19\ kV}{-j1323.64\ \Omega} = j150.5\ A \tag{5.3}$$

Based on this calculated value, a CT ratio of 200:5 is selected. This will give a secondary current calculated using equation (5.4)

$$Ibank, sec = \frac{Ibank}{CTR} = \frac{j150.5\ A}{40} = j3.76\ A \tag{5.4}$$

Based on the calculated secondary current and the secondary voltage calculated using equation (4.6), the expected secondary impedance can be calculated using equation (5.1).

$$Zexp = \frac{66.4\ V}{j3.76\ A} = -j17.66\ \Omega \tag{5.5}$$

A trip radius in percent of nominal impedance can now be determined.

Next, the bank currents with 9 shorted turns and with 10 shorted turns are calculated using equation (5.3). The relay is set for a current between these points.

$$Ibank\ (9\ shorts) = \frac{Vbus}{X1(9\ shorts)} = \frac{199.19\ kV}{-j1304.3\ \Omega} = j152.7\ A \tag{5.6}$$

$$Ibank\ (10\ shorts) = \frac{Vbus}{X1(10\ shorts)} = \frac{199.19\ kV}{-j1301.9\ \Omega} = j152.9\ A \tag{5.7}$$

The average between these two values is taken and used to determine the value *Zn* using secondary voltage and current. The average current value is 152.8 A, by inspection. The secondary current is calculated using the CTR in equation (5.4).

$$Ibank, sec = \frac{j152.8\ A}{40} = j3.82\ A \tag{5.8}$$

Using the calculated secondary current, the expected secondary impedance is calculated using equation (5.1).

$$Zn = \frac{66.4\ V}{j3.82\ A} = -j17.40\ \Omega \tag{5.9}$$

This value is applied to equation (5.2), resulting in.

$$\Delta Zn(\%) = \frac{|-j17.66\ \Omega - -j17.40\ \Omega|}{|-j17.40\ \Omega|} x100\% = 1.5\% \tag{5.10}$$

Using the above calculation of *Zexp* and *ΔZn* we can then set the relay's 21C element for the per phase method. If the relay from [11] is used, there will a sufficient number of current inputs to allow protection of 5 more capacitor banks using the per phase method.

5.3.2 Per String Method (CTs Measurement Currents on Individual Strings)

The per string method will require the exact same calculations as above. The difference is that the currents provided to the relay are from one string rather than the entire capacitor bank. Using symmetry of the capacitor bank, it is assumed there are 6 identical strings. From this symmetry assumption it is concluded that the current will divide evenly between all six strings. The nominal string current is calculated below.

$$Ist = \frac{Ibank}{Np} = \frac{j150.5\ A}{6} = j25\ A \tag{5.11}$$

Each string will draw 25 A of current. We will select a CT ratio of 100:5 to allow future expansion if necessary, without need to upgrade the protection equipment. The string secondary current is calculated as:

$$Ist, sec = \frac{j25\ A}{20} = j1.25\ A \tag{5.12}$$

The expected string apparent impedance is calculated from equation (5.1).

$$Zn = \frac{66.4\ V}{j1.25\ A} = -j53.12\ \Omega \tag{5.13}$$

A trip radius in percent of nominal impedance is determined. To do this the currents in the affected string with 9 shorted units and with 10 shorted are calculated using equation (5.3). The relay will be set between these points as was done above.

$$Ist\ (9\ shorts) = \frac{Vupper}{Xst(9\ shorts)} = \frac{198{,}879.3\ V}{-j7292.1\ \Omega} = j27.3\ A \tag{5.14}$$

$$Ist\ (10\ shorts) = \frac{Vupper}{Xst(10\ shorts)} = \frac{198{,}878.7\ V}{-j7219.9\ \Omega} = j27.5\ A \tag{5.15}$$

From the above calculations the average between these values is used as the current value for *Zn* using secondary voltage and current. This value, by inspection, is 27.4 A. The secondary current is.

$$Ist, sec = \frac{j27.4}{20} = j1.37\ A \tag{5.16}$$

From the above calculated secondary current, the expected secondary impedance is calculated using equation (5.1).

$$Zn = \frac{66.4\ V}{j1.37\ A} = -j48.46\ \Omega \tag{5.17}$$

This value of *Zn* is inputted into equation (5.2).

$$\Delta Zn(\%) = \frac{|-j53.12\ \Omega - -j48.46\ \Omega|}{|-j48.46\ \Omega|} x100\% = 9.6\ \% \tag{5.18}$$

Using the above calculation of *Zexp* and *ΔZn* we can then set the relay's 21C element for the per string method. The model bank has six strings so all current inputs in the relay from [11] are utilized for this protection scheme.

5.3.3 Lumped 2 String Method

The lumped 2 string method will be implemented with the conductors from two strings passing through the primary for one window CT. The 2 strings will be combined at the grounded end of the capacitor bank to allow the conductors to be connected together without causing a string to string fault. The relay set points will be calculated similarly to the above methods. It is assumed the healthy single string current will remain at approximately 25 A. The CT ratio remains at 20 and the healthy and faulted string currents add together through the CT. A shortcut can be utilized on the above equations to calculate the apparent impedance.

First the secondary current seen by the relay is calculated by equation (5.19), with results shown in (5.20).

$$I2st, sec = Ist1, sec + Ist2, sec \tag{5.19}$$

$$I2st, sec = j1.25\ A + j1.25\ A = j2.5\ A \tag{5.20}$$

From the above calculated secondary current, the expected secondary impedance is calculated using equation (5.1).

$$Zn = \frac{66.4\ V}{j2.5\ A} = -j26.56\ \Omega \tag{5.21}$$

From the string protection calculations, the string current in a failed string between 9 and 10 shorts was determined to be 27.4 A. The healthy string is assumed to remain constant at 25 A. From the above reasoning, the secondary current seen using (5.19) is.

$$I2st, sec = j1.37\ A + j1.25\ A = j2.62\ A \tag{5.22}$$

From the above calculated secondary current, the expected effective secondary impedance is calculated using equation (5.1).

$$Zn = \frac{66.4\ V}{j2.62\ A} = -j25.34\ \Omega \tag{5.23}$$

Plugging this value into equation (5.2), the percent change is calculated.

$$\Delta Zn(\%) = \frac{|-j26.56\ \Omega - -j25.34\ \Omega|}{|-j25.34\ \Omega|} x100\% = 4.8\ \% \tag{5.24}$$

By inspection it is noticed that this value is half of the percent change required in the single string method.

5.3.4 Lumped 3 String Method

The lumped 3 string method is identical to the lumped 2 string method except 3 strings are monitored in one CT, versus the 2 monitored above. We will perform the calculations similarly. First the nominal secondary current is calculated using equation (5.25).

$$I3st, sec = Ist1, sec + Ist2, sec + Ist3, sec \tag{5.25}$$

$$I3st, sec = j1.25\ A + j1.25\ A + j1.25\ A = j3.75\ A \tag{5.26}$$

From the above calculated secondary current, the expected effective secondary impedance is calculated using equation (5.1).

$$Zn = \frac{66.4\ V}{j3.75\ A} = -j17.71\ \Omega \tag{5.27}$$

From the single string protection calculations we determined the string current in a failed string between 9 and 10 shorts to be 27.4 A. It is still assumed the healthy strings will remain constant at 25 A. From the above reasoning the secondary current is calculated using equation (5.25).

$$I3st, sec = j1.37\ A + j1.25\ A + j1.25\ A = j3.87\ A \tag{5.28}$$

From the above calculated secondary current, the expected effective secondary impedance is calculated using equation (5.1).

$$Zn = \frac{66.4\ V}{j3.87\ A} = -j17.16\ \Omega \tag{5.29}$$

Plugging this value into equation (5.2) the percent change is calculated.

$$\Delta Zn(\%) = \frac{|-j17.71\ \Omega - -j17.16\ \Omega|}{|-j17.16\ \Omega|} x100\% = 3.2\ \% \tag{5.30}$$

This percentage change is lower than the 1 and 2 string methods but still higher than the per phase. All of these current measurement methods are studied in our model to verify the results and sensitivities of the protection scheme. The lumped 2 and 3 string methods would typically be utilized when a capacitor bank contains multiple strings per phase and only one protective relay is available. An example of this would be a 12 string bank could be protected by the relay mentioned in [11] by lumping 2 strings per CT input.

In summary, this chapter has demonstrated that the calculations for the 21C element are intuitive and do not require advanced software or studies to complete. As opposed the calculations in Chapter 4 for the 87V relay, these calculations do not require additional analysis of the bank, rather only require solving for additional variables of current using readily available information from the specifications for the bank. The apparent impedance is calculated utilizing this solved current value. Applied in practice, these calculations will serve as baseline values for initial settings for the relay. Per [11] the relay contains a commissioning tool that will adjust the impedance set points based on the actual measured apparent impedance for the bank. The commissioning tool will account for any inherent unbalances in the system.

Chapter 6: Capacitor Bank Fault Study

PSCAD/EMTDC was utilized to develop a model for the capacitor bank suitable for internal fault studies, as mentioned in Chapter 1. This chapter will discuss the model and apply it to analyze relay response to internal capacitor bank faults. A screenshot of the PSCAD/EMTDC circuit schematic is shown in Appendix-A.

6.1 Capacitor Bank System Model

The bank units modeled are nameplate rated at 573 kVAR at a voltage of 21,320 V across the unit bushings and 3.34 μF total capacitance per can with ten cans in series. The capacitor kVAR rating is dependent on the voltage, since this system operates 345 kV, the capacitor units in this model will be derated to approximately 500 kVAR. The effective kVAR rating of the bank can then be calculated to be 90 MVAR. Using equation (6.1) we can calculate the nominal line current of the capacitor bank.

$$Ibank = \frac{kVAReffective}{\sqrt{3} * kV_{LL}} \tag{6.1}$$

The PSCAD/EMTDC model will be utilized to verify the operation of the protective elements discussed in this thesis. The study system contains a three phase circuit model of the Y-grounded bank with the phase A bank expanded to show individual strings. Circuit breakers are utilized in the model to simulate faults at various locations within the bank, as discussed in Chapter 3. To verify that the bank model in the simulation will reproduce accurate results, we analytically solve for the steady state bank current under normal conditions using equation (6.1). The resulting current is approximately 150.6 A. Current meters in the simulation model verified that the steady state current matches this calculated value. Additional verification will be provided as part of the unbalance calculations in Chapter 7.

6.2 Modeling Internal Bank Faults

The capacitor bank was built utilizing components available in PSCAD/EMTDC. This research was primarily concerned with steady state fault behavior, but a PSCAD/EMTDC model was utilized because of the ability to model individual strings, internal faults, take measurements, and simulate relay responses in one common interface. The faults introduced in Chapter 3 are discussed in this section to describe how they will be simulated in the software. Voltage and current meters were placed within the model to take measurements used for protection and analysis. Due to the number of cases and configurations, analytically solving all of these cases would be a tedious and time-consuming effort, which reinforces utilizing PSCAD/EMTDC for the analysis.

String Element Failures

Capacitor string element failures were modeled utilizing one string with the individual capacitor units represented to model the internal elements. Circuit breakers were installed in parallel to these elements which are normally in an open state. Closing one of these breakers simulates the failure mode of a fuseless capacitor with a low resistance shorted element. A total of 11 breakers were utilized in one string to simulate up to 11 total element failures in one entire unit.

Distributed Element Failures

The capacitor string element failures model described above is utilized for this case as well, with the addition of another capacitor string. A parallel connected breaker simulates the shorting of 5 elements in the added string. This set of cases examines the response of different protective relay functions when there are shorted capacitor elements in locations throughout the bank versus only shorted capacitors on one individual string.

Low Voltage Capacitor Failures

A normally open breaker is installed in parallel with the low voltage capacitor to simulate a case when an element fails shorted in the low voltage capacitor section.

String to String Faults

Two normally open breakers are used to simulate string to string faults at different locations in the strings. To examine mid-point string to string faults one breaker was placed between the midpoints of two parallel strings. To examine the off mid-point string to string faults another breaker was installed between the midpoint of one string and at a point above the midpoint in the other string.

Phase to Ground Faults

To examine phase to ground faults, a low voltage capacitor shorting breaker is be utilized to simulate a ground fault at the bottom of a capacitor string. The next case examined is a lower frame tie to ground fault. This is simulated by a normally open breaker shorting out the units in that string to ground.

Phase to Phase Faults

Phase to phase faults are simulated similar to the string-to-string faults. The implementation differs in that normally open breakers are now utilized to tie the strings of different phases together.

6.3 Modeling Relay Response

To model the relay response of the voltage differential and the impedance based capacitor bank protective relay, models for the elements are developed to examine their pickup response. PSCAD/EMTDC does not have a preconfigured block for the voltage differential function, so available components are utilized to develop a model. A simplified model of the relay logic for the voltage differential element from [10] is shown in Figure 6.1. The differential voltage calculation from equation (4.5) is implemented utilizing a constant input for the k-factor and PSCAD/EMTDC math blocks the differential voltage calculation, as shown in Figure 6.2. The solved differential voltage is then inputted into comparators to mimic the relay's tripping decision logic. This trip logic is shown in Figure 6.3 which contains the two tripping levels from Figure 6.1 [10]. The output values of these trip levels are written to graphical outputs to observe the relay response. The calculated differential voltage is also displayed in the simulation graphical interface for a visualization of its value.

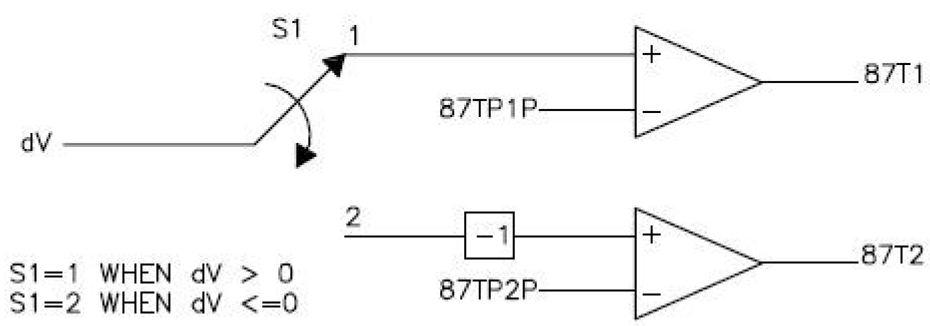


Figure 6.1: Simplified 87V element logic

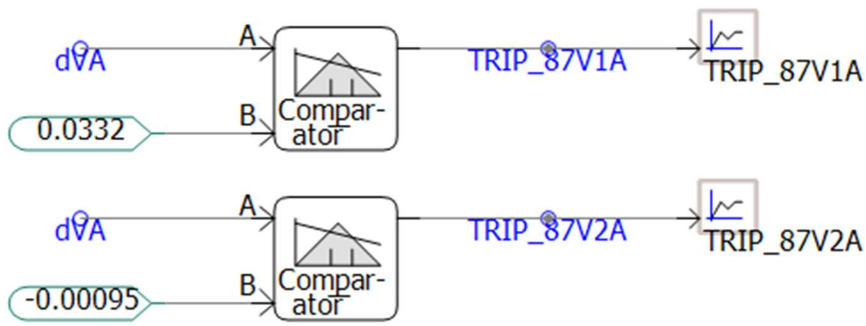


Figure 6.2: PSCAD representation of the 87V relay (set points scaled by 1000)

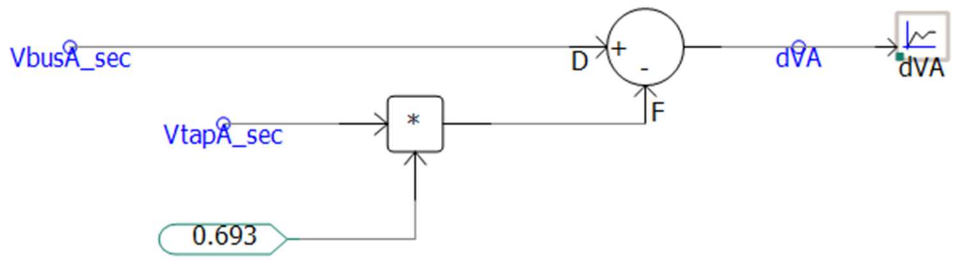


Figure 6.3: PSCAD math blocks for differential voltage calculation (k-factor set as constant)

The PSCAD/EMTDC interface offers a preconfigured mho relay block that is utilized in this work for simulating the capacitor bank impedance relay, as shown in Figure 6.4. The mho element block has inputs that require settings for the mho circle radius and the x-y coordinates of the mho circle center. The apparent impedance is calculated in the software using another preconfigured block that will take single phase voltage and current measurements and convert them to equivalent R-X values. These values are inputted into the mho characteristic as shown in Figure 6.5. The protection setting for the trip radius to set the relay is calculated with equation (5.2). However this does not map correctly to the PSCAD/EMTDC mho element model. A conversion is required to convert the percentage of the expected impedance to the actual element radius; this conversion is shown in equation (6.2).

$$Trip\ Radius = Zexp * \frac{\Delta Zn(\%)}{100} \tag{6.2}$$

The mho characteristic in PSCAD/EMTDC is configured by default to model a typical line distance relay response. This element generate a logical output of 1 for a trip when the apparent impedance is located inside of the circle. The 21C element is configured as an inward looking mho element to generate a logic output of 1 when the apparent impedance is located outside of the circle, so the output will need to be inverted. The trip signal output is sent to a graphical interface to examine the relay response. The output impedance is also monitored for quick inspection. The apparent impedance is graphically shown on an R-X diagram using the element set points in the simulation graphical interface.

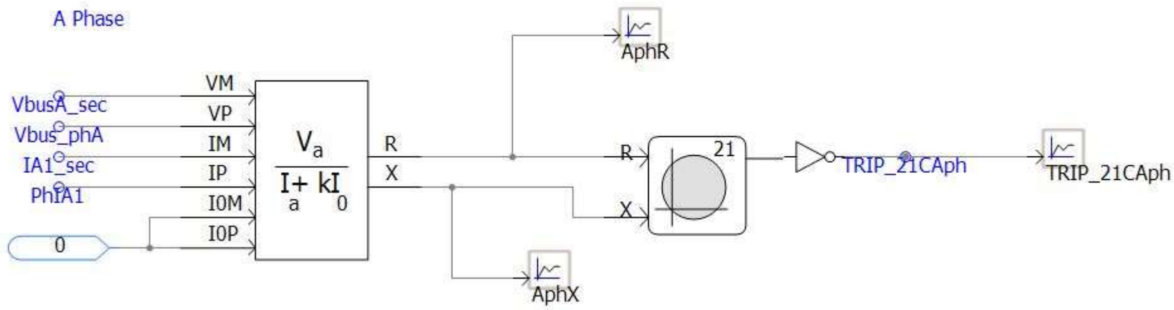


Figure 6.4: PSCAD implementation of 21C Element

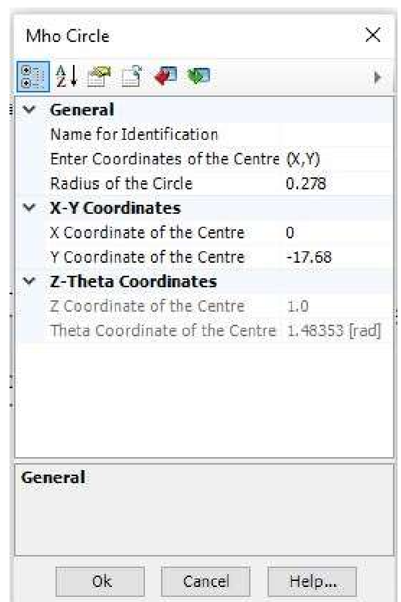


Figure 6.5: PSCAD inputs required for setting 21C element

6.4 Bank Measurements

The capacitor bank modelled in PSCAD/EMTDC contains multiple measurement points as inputs for the protection scheme and for evaluation of the simulation results. The voltage measurements consist of the bus voltage, tap point voltage, and four capacitor element voltage measurements located throughout the bank. The bus and tap voltages were scaled through their respective PT ratios. The element voltage measurements are used to determine the voltage distribution throughout the bank and determine if there are any units exposed to voltages exceeding 110% of their rating.

Current measurements are taken on each phase for the total bank current, with additional current measurements on each individual string on A phase. These measurements are scaled by the appropriate CT ratios. The lumped string protection methods utilize the mathematical sum of each string's individual current. The distributed element failures scenario will examine two cases for each lumped string method, one with failures in the same group of lumped strings, and one with failures in separate groups of lumped strings.

Instrument transformer measurement errors due to instrument transformer transient response are known to occur in certain applications. However, the goal of this thesis is not to evaluate these schemes for security during transients, and therefore transient response analysis should be reserved for future enhancements and analyses of these schemes. The CT and PT models in the computer simulation simply take the measured value scaled by the ratio of the instrument transformer utilized. To verify the scaling factors, the simulation results are compared to the calculated values as summarized in Table 6.1. The data in Table 6.1 verifies that the PSCAD/EMTDC model matches the circuit model used in the hand calculations. The differential voltage, dV, measurement of 0.11 volts is an artifact of the simulation model representing some inherent imbalance that is due to the model being represented with the expanded phase and strings.

Table 6.1: Comparison of PSCAD/EMTDC results with the calculated values for normal bank operation

Relay Element	Measured Value		Calculated Value	
Ia	-j3.75	A	-j3.76	A
I1	3.75	A	3.76	A
I2	0	A	0	A
I0	0	A	0	A
Va	66.39	V	66.4	V
VtapA	95.64	V	95.7	V
Xbank	-j17.66	Ω	-j17.66	Ω
X (3 Strings)	-j17.69	Ω	-j17.71	Ω
X (2 Strings)	-j26.51	Ω	-j25.56	Ω
X (String)	-j53.15	Ω	-j53.12	Ω
dV	0.11	V	0	V

6.5 Performing the Study

A graphical user interface was created utilizing breaker control interfaces in PSCAD/EMTDC to perform the study. The simulations were ran and the appropriate breakers are closed to represent the respective faults under study. Once the breakers were in the state for the study the relay responses are noted as well as the measurements of the relay operating quantities. The first case for string element failures is utilized to further verify performance of the bank circuit model against the analytical calculations. The comparisons between the simulations measurements and the calculated measurements are discussed in the next chapter, followed by an evaluation of relay responses.

Chapter 7: Fault Study Results

The results for the fault study are summarized in this chapter. The results are used to analyze the operation of the voltage differential relay as well as performance of the impedance based capacitor bank relay under the conditions introduced in Chapter 3. The fault results are presented in sets of tables organized per the fault type that will present calculated quantities, measured quantities, and relay element pickup response. Individual element voltages are analyzed in these results to determine the voltages across capacitor elements compared to their nominal voltages. The relay element response is referred to as a pickup response in the presented results because the motivation for this thesis is based on the relay being able to identify faulted conditions based upon the measured quantities. The outputs of these pickup responses are then be applied to logical equations in the relay to declare a trip condition.

7.1 String Element Failure Results

The string element failure case is utilized to calculate the relay protection set points, therefore the relay responses are expected to operate as calculated. From Chapter 3, the protection is set to operate between 9 and 10 failed elements. Utilizing our PSCAD/EMTDC model the breakers located in the string with expanded capacitor elements will be utilized to short out individual elements. The relay should not pickup with nine shorted elements, but when the 10^{th} element is shorted, the relay should operate. The measurements from cases with 9, 10 and capacitor elements shorted are listed in Table 7.1 and the relay element pickup results are listed in Table 7.2.

Table 7.1: Relay measurements taken from the A phase in response to failures in one string

Relay Element	Calculated Nominal Value		Measured Value (9 Shorts)		Measured Value (10 Shorts)		Measured Value (11 Shorts)	
Ia	-j3.76	A	-j3.82	A	-j3.82	A	-j3.83	A
Va	66.4	V	66.4	V	66.4	V	66.4	V
VtapA	95.7	V	97.06	V	97.24	V	97.4	V
Xbank	-j17.66	Ω	-j17.40	Ω	-j17.37	Ω	-j17.34	Ω
X (3 Strings)	-j17.71	Ω	-j17.17	Ω	-j17.12	Ω	-j17.05	Ω
X (2 Strings)	-j26.56	Ω	-j25.41	Ω	-j25.27	Ω	-j25.14	Ω
X (String)	-j53.12	Ω	-j48.78	Ω	-j48.29	Ω	-j47.8	Ω
dV	0	V	-0.87	V	-0.99	V	-1.11	V

Table 7.2: A phase relay element responses to faults within one series string

Relay Element	Pickup Value (9 Shorts)	Pickup Value (10 Shorts)	Pickup Value (11 Shorts)
87TP1	0	0	0
87TP2	0	1	1
21C (Entire Bank)	0	1	1
21C (3 Strings)	0	1	1
21C (2 Strings)	0	0	1
21C (1 String)	0	0	1

The results in Table 7.2 demonstrate that the relay elements are operating correctly. Upon initial inspection of the results it appeared that the settings were misapplied on the elements covering individual strings and the elements protecting 2 strings. However looking at these it appears the percent impedance change is not large enough to clearly identify the fault, as will be discussed in more detail below.

To analyze the performance of the voltage differential relay and impedance relay responses, their respective operating quantities are plotted. The voltage differential output is plotted as the differential voltage (dV) versus time. The simulation was set up to short one capacitor element at a time to show how the differential voltage or the effective impedance varies with the number of shorted capacitor elements. The protection elements generate trip signals when the operate quantity crosses a trip threshold.

The differential voltage plot is shown in Figure 7.1. The top trace shows dV as the number of shorted elements increases. The lower trace indicates that a trip signal is generated when the tenth capacitor is shorted.

Figure 7.2 describes the impedance relay characteristic plotted in an R-X diagram. This diagram shows the offset mho characteristic as well as the impedance trajectory of the measured apparent impedance. Plotting the effective impedance against the R-X diagram shows how the shorting of elements causes the impedance trajectory to take a vertical path towards to R axis.

Looking at this in detail in Figure 7.3 we can see where 10 shorts is not enough to push the impedance measurement out of the restraint region, however Figure 7.4 shows 11 shorted elements will leave into the operate region. Looking back at the settings calculation philosophy from Chapter 3, the bank will still be protected for any number of shorted elements over 10, which is the design intent was for pickup setting.

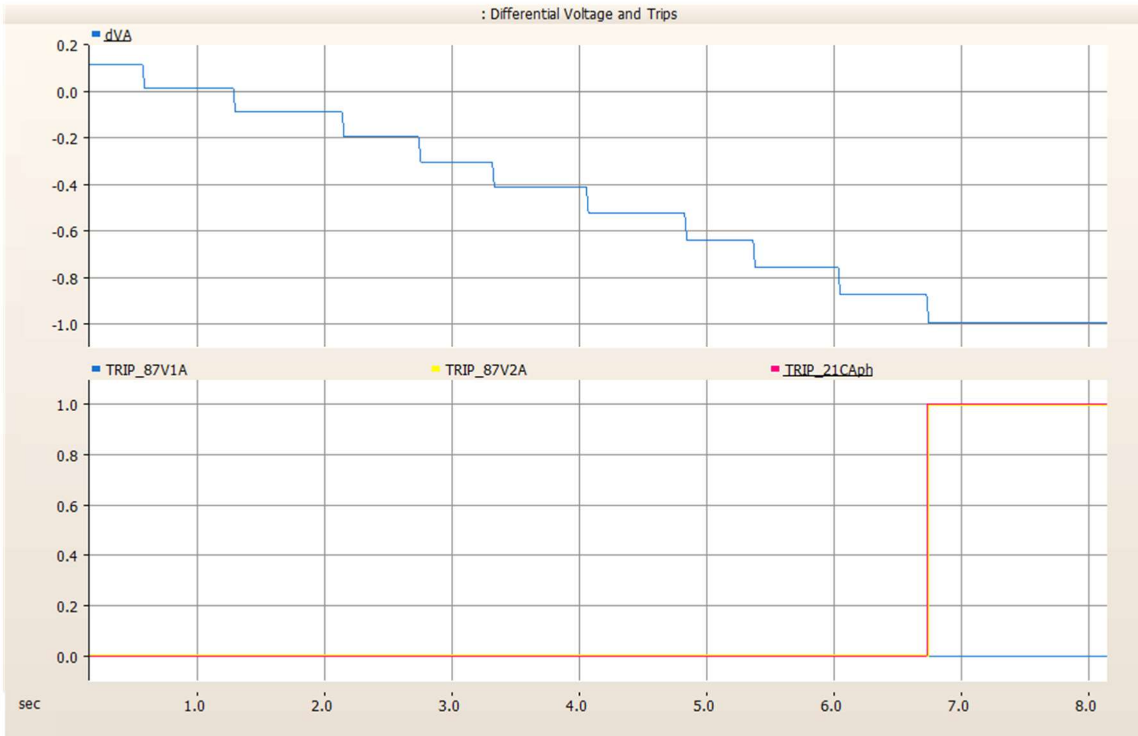


Figure 7.1: Differential voltage and trip signals versus time illustrating 10 element failures with time delays between failures

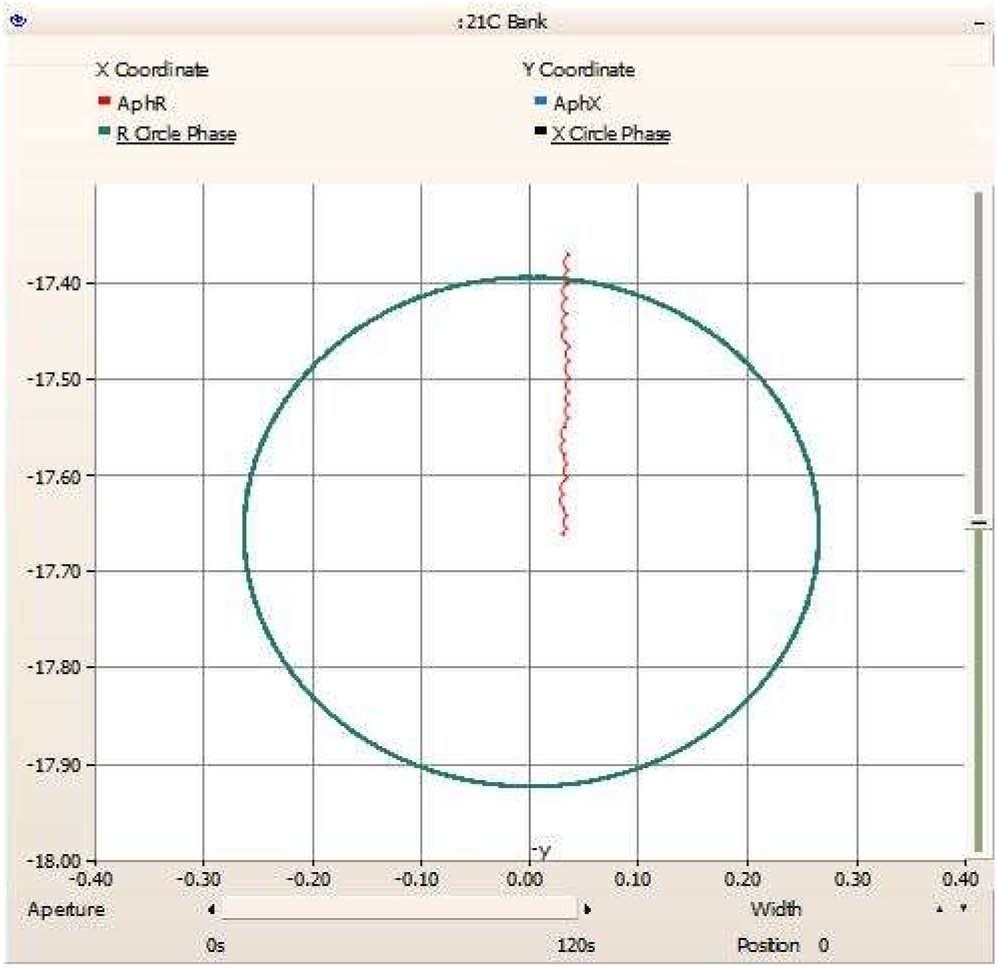


Figure 7.2: 21C operating characteristic for the entire bank element in the R-X plane, showing the impedance trajectory going outside of the restraint region for 10 elements shorted

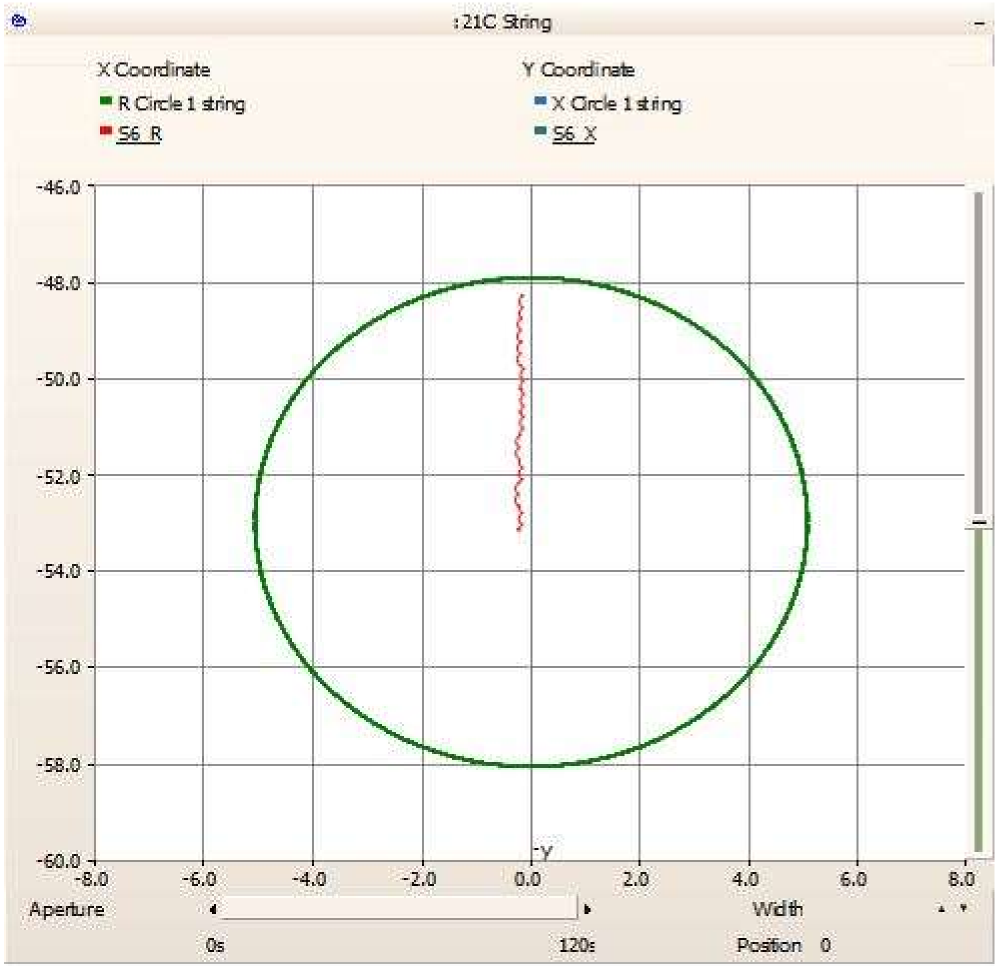


Figure 7.3: R-X diagram of the per string element illustrating that the measured impedance with 10 shorted capacitor elements does not leave restraint region

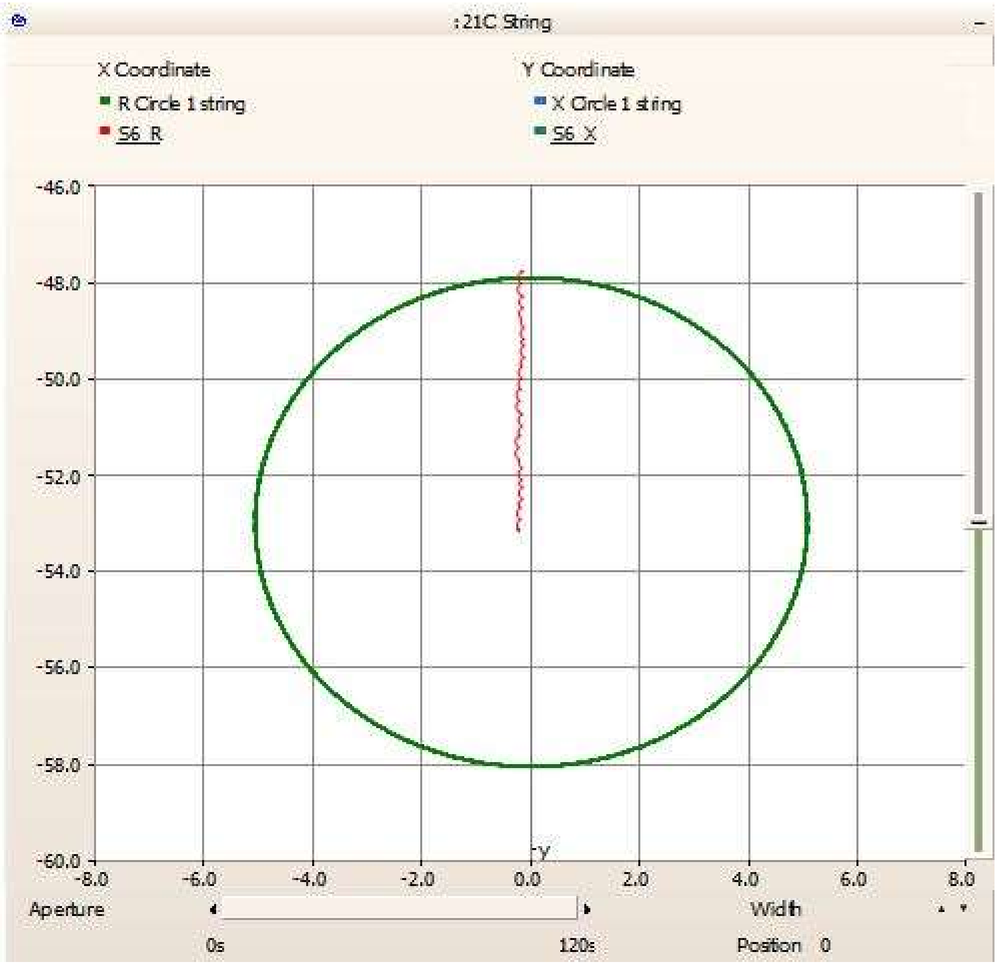


Figure 7.4: R-X diagram of per string element illustrating measured impedance with 11 shorted capacitor elements entering the operate region

To summarize the behavior of the elements on this situation, it is concluded that the relay operates as intended and is set to protect the bank for unbalance per the requirements set forth in [2]. The results in Table 7.1 demonstrate that the measured results obtained from the simulations are very close to the calculations used for setting the relay. The results were anticipated, however we know that the simulation model is operating correctly. This will build the foundation for the examination of the operation of the relay elements during the remaining fault cases.

7.2 Distributed Element Failure Results

Distributed element failures, as discussed in Chapter 3, are modeled in PSCAD/EMTDC. To simulate this event 5 capacitor elements are shorted in string 1 and 6 capacitor elements are shorted in string 6. The measurement results are obtained in Table 7.3 and the relay element pickup results are shown in Table 7.4. Once again, the relay quantities are plotted graphically. Figure 7.5 illustrates the differential voltage response, while Figure 7.6 illustrates the 21C response.

The top trace in Figure 7.5 shows that the differential voltage versus time. The lower traces in Figure 7.5 shows the output of the trip logic for the two differential elements, along with the output of the per phase impedance element 21CAph. Note that the differential voltage element trips, as does the per phase impedance element. Although, one additional capacitor element needs to be shorted for the impedance element to pick up.

In Figure 7.6 the apparent impedance of the phase A per phase element is shown next to the apparent impedance of per string element on string 6. Examining the left side of Figure 7.6 we can see that the per phase 21C element will calculate with the failure of 11 elements. Note that the apparent impedance enters the operate region in this case. The per string element will just calculate the apparent impedance of string 6 and it will remain in the restraint region as shown on the right side of Figure 7.6. From the figures, it should be noted that the large jump in the differential voltage and impedance trajectory is due to the model shorting five strings at once in string 1.

Table 7.3: Relay measurements taken from the A phase in response to distributed failures in string 1 and in string 6

Relay Element	**Calculated Nominal Value**		**Measured Value**	
Ia	-j3.76	A	-j3.82	A
Va	66.4	V	66.4	V
VtapA	95.7	V	97.3	V
Xbank	-j17.66	Ω	-j17.36	Ω
X (3 Strings Failures in same CT set)	-j17.71	Ω	-j17.08	Ω
X (3 Strings Failures in opposite CT set)	-j17.71	Ω	-j17.39	Ω
X (2 Strings Failures in same CT set)	-j26.56	Ω	-j25.21	Ω
X (2 Strings Failures in opposite CT set)	-j26.56	Ω	-j25.79	Ω
X (String)	-j53.12	Ω	-j50.23	Ω
dV	0	V	-1.05	V

Table 7.4: A phase relay element responses to distributed failures

Relay Element	Pickup Value (9 Shorts)
87TP1	0
87TP2	1
21C (Bank)	1
21C (3 Strings failures in same CT set)	1
21C (3 Strings failures in opposite CT set)	0
21C (2 Strings failures in same CT set)	1
21C (2 Strings failures in opposite CT set)	0
21C (String)	0

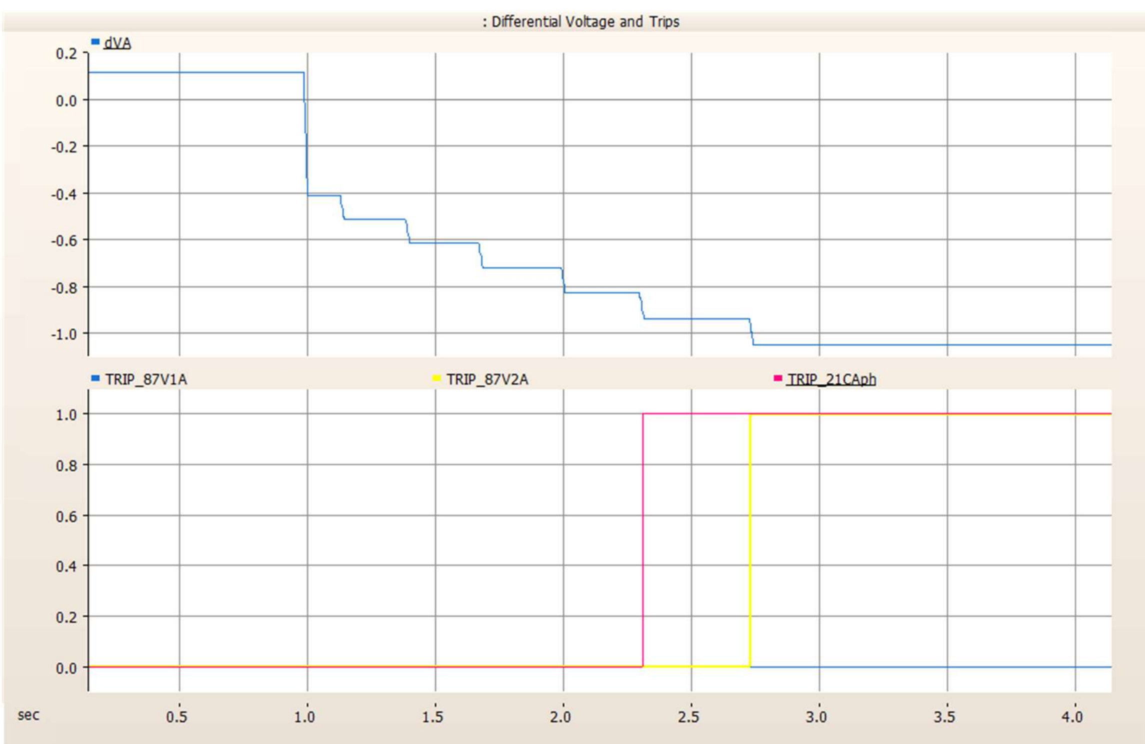


Figure 7.5: Differential voltage and trip signals versus time illustrating distributed failures

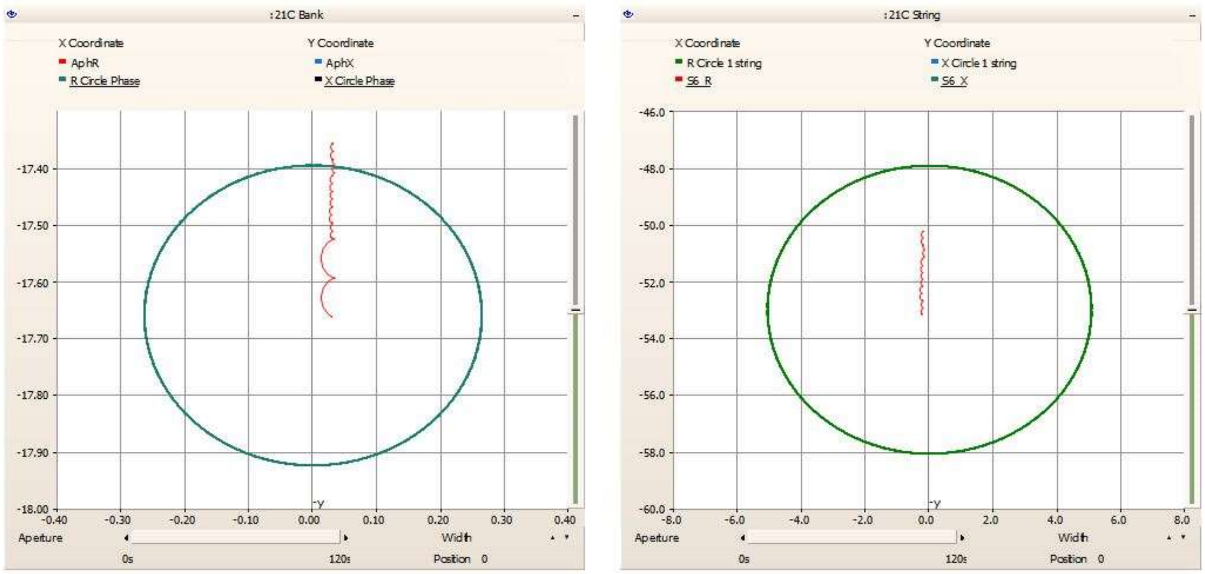


Figure 7.6: R-X diagrams of the phase element (left) and string element (right) apparent impedance trajectories due to distributed failures

Analyzing the results of this case it was determined that the differential voltage element as well as the phase impedance element are not able to determine where capacitor element failures are located. This failure to discriminate capacitor failures will cause unintended operations of the capacitor bank relay. The case with multiple strings is also examined to see the effect of failures within string sets common to one CT. The impedance elements measuring one, two, or three strings are shown to operate similarly to the phase element in determination of shorted capacitor elements. A capacitor bank trip will occur if the distributed failures are common to a lumped string group contained monitored by one CT. Summarizing these results it can be concluded that the per string element offers a significant advantage over the other methods as it can determine if the failures are common to one string.

The lumped string methods offer better protection than the total bank element, however they can still be prone to false positive operations when a capacitor bank can be left in service. If the per phase impedance element CT connection is utilized it offers the exact same protection as the voltage differential element. This result is expected as the voltage differential is operating on the same change in the percent impedance. Analyzing the bank under this type of situation, it is concluded that the bank remains safe for operation under distributed failures as long as the capacitor failures per string remain less than 11 elements.

7.3 Low Voltage Capacitor Failure Results

A failure of the low voltage capacitor was simulated to examine the effects this would have on the protection elements. For the voltage differential scheme equation shown in Figure 6.3 it can be seen that if the low voltage capacitor is shorted the positive differential voltage equal to the bus voltage. A common trend in industry is to alarm only on a low voltage capacitor failure. This has been proven to result in leaving the bank vulnerable to failures between the time of the failure and when personnel can service the bank in response to the alarm. A second simulation case was used to demonstrate that the bank is left unprotected after a low voltage capacitor failure when using the voltage differential method. This second case creates additional failures after the low voltage capacitor is shorted.

The results of the first case can be seen in Table 7.5 and Table 7.6. Figure 7.7 plots the differential voltage graphically after a low voltage capacitor failure and it will be shown again in Figure 7.9 to examine the operation of the differential voltage after a failure of an element in the upper section with the low voltage capacitor shorted. Tables 7.7 and 7.8 show the results for the second case, with the results for the 21C element for the low voltage capacitor failure plotted in Figure 7.8. Figure 7.10 shows the view the results with shorted bank element failures in the upper section after low voltage capacitor is shorted.

Table 7.5: Relay measurements taken from the A phase in response to a LVC failure

Relay Element	**Nominal Value**		**Measured Value (LVC Failure)**	
Ia	-j3.76	A	-j3.76	A
Va	66.4	V	66.4	V
VtapA	95.7	V	0	V
Xbank	-j17.66	Ω	-j17.63	Ω
X (3 Strings)	-j17.71	Ω	-j17.66	Ω
X (2 Strings)	-j26.56	Ω	-j25.5	Ω
X (String)	-j53.12	Ω	-j53.07	Ω
dV	0	V	66.23	V

Table 7.6: A phase relay element responses to a LVC failure

Relay Element	**Pickup Value (LVC Failure)**
87TP1	1
87TP2	0
21C (Bank)	0
21C (3 Strings)	0
21C (2 Strings)	0
21C (String)	0

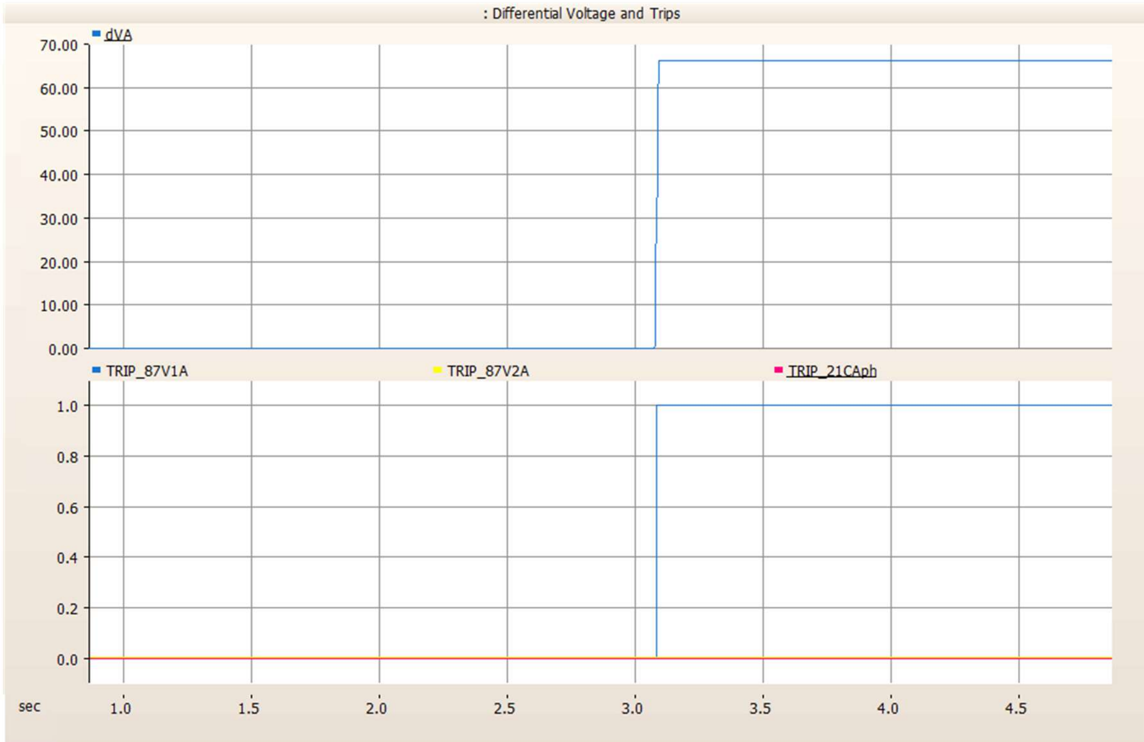
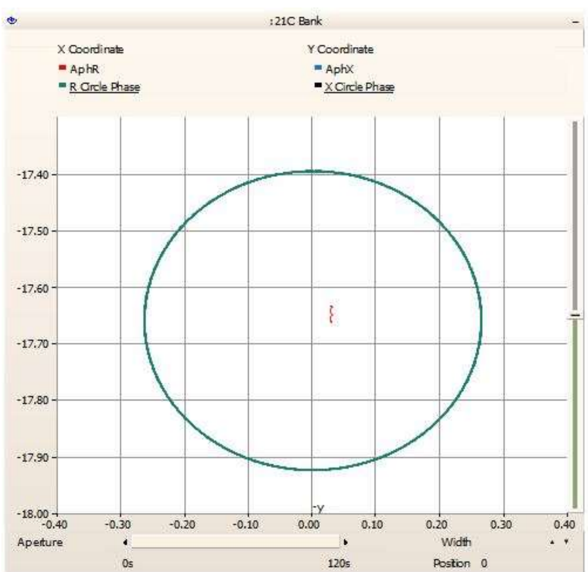


Figure 7.7: Differential voltage and trip signals versus time illustrating a low voltage capacitor (LVC) failure



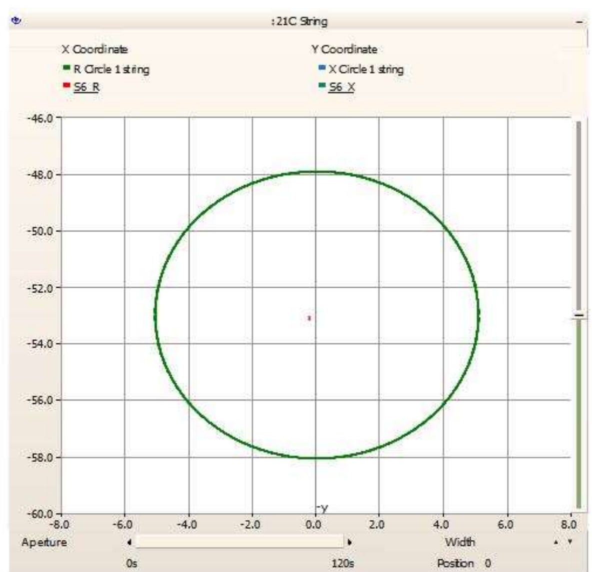


Figure 7.8: R-X diagrams of the phase element (left) and per string element (right) apparent impedance trajectories due to a low voltage capacitor failure

Table 7.7: Relay measurements taken from the A phase in response to a LVC failure with additional bank element failures

Relay Element	Calculated Nominal Value		Measured Value (LVC Failure)	
Ia	-j3.76	A	-j3.83	A
Va	66.4	V	66.4	V
VtapA	95.7	V	0	V
Xbank	-j17.66	Ω	-j17.31	Ω
X (3 Strings)	-j17.71	Ω	-j17.02	Ω
X (2 Strings)	-j26.56	Ω	-j25.10	Ω
X (String)	-j53.12	Ω	-j47.73	Ω
dV	0	V	66.23	V

Table 7.8: A phase relay element responses to a LVC failure with additional bank element failures

Relay Element	Pickup Value (LVC Failure)
87TP1	1
87TP2	0
21C (Bank)	1
21C (3 Strings)	1
21C (2 Strings)	1
21C (String)	1

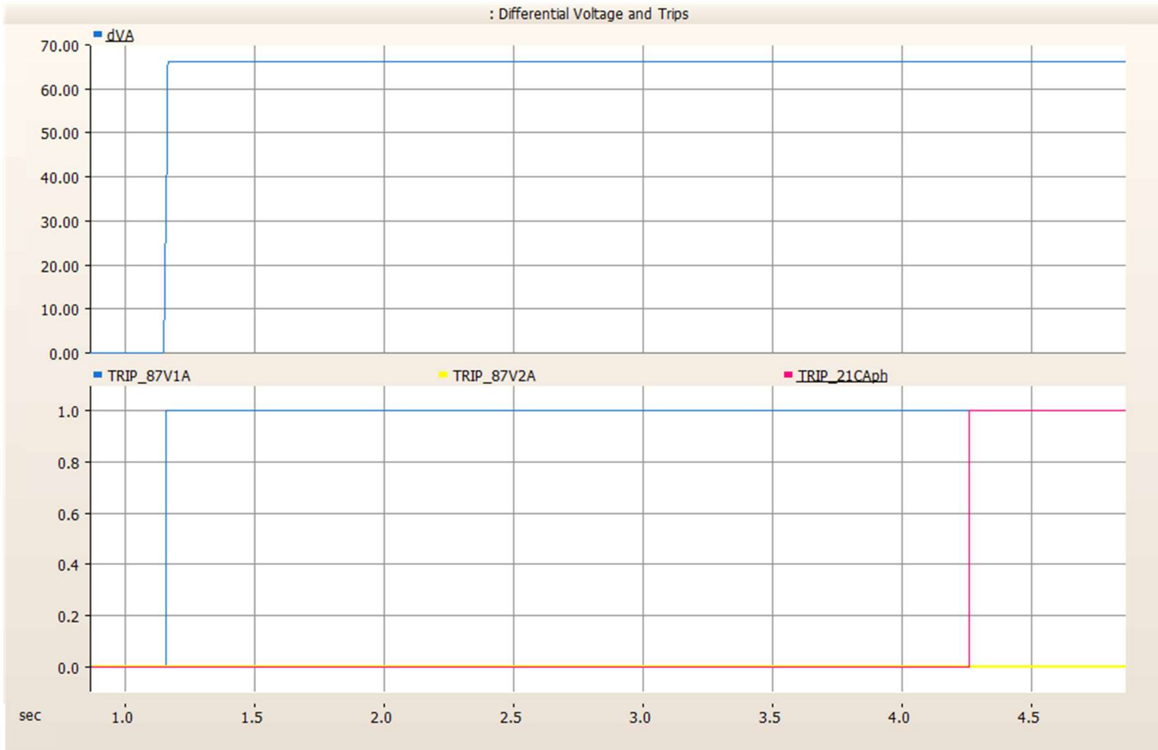
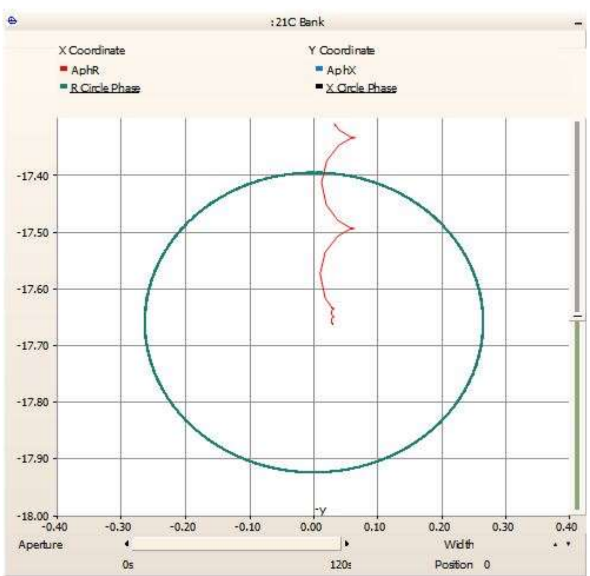


Figure 7.9: Differential voltage and trip signal versus time illustrating a LVC failure with additional bank element failures



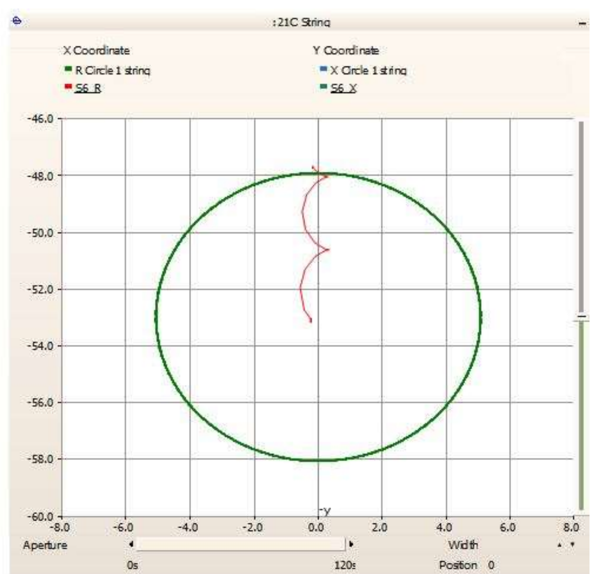


Figure 7.10: R-X diagrams of the phase element (left) and per string element (right) apparent impedance trajectory due to a LVC failure with additional bank element failures

Analyzing the results from the two cases with low voltage capacitor failures it is demonstrated that this type of failure will disable a voltage differential scheme. Reiterating, since the purpose for the low voltage capacitor is to provide a reference voltage for the voltage differential scheme this result was expected. The impedance based protection scheme does not operate during a low voltage capacitor failure since the change of impedance is not large enough, but it will still provide protection after this event for bank elements. This is one of the advantages of the 21C protection scheme. It was also proven that the bank will suffer no detrimental effects due to shorting of the low voltage capacitor, thus it is safe to remain in service after this type of fault. For banks not utilizing differential voltage protection the low voltage capacitor is not required.

7.4 String to String Fault Results

String to string faults were analyzed using this model with fault initiation as discussed in Chapter 6. Two situations were studied, one with a string to string fault at the midpoint of the bank and the other with a string to string fault off the bank's midpoint. The importance of using the simulation model for this type of fault is that hand calculations would become very tedious and exhausting.

For the first case involving a string to string fault at the bank midpoint we can reference a common externally fused bank configuration referred to as the H-bridge connection where a tap is connected between strings. During normal operation the capacitors are balanced above and below this connection, therefore no current will flow between the two. Our study has confirmed that a string to string fault at the midpoint operates like an H-bridge connection. The relay measurements from this case are shown in Table 7.9 and the operating pickup quantities are shown in Table 7.10. The results from this case show that this failure case does not cause any changes in the operating quantities therefore, their graphs are omitted. This failure does not cause damaging overvoltages on the individual capacitor units.

For the second case with the string to string fault off the bank midpoint the results are presented in Tables 7.11 and 7.12 respectively. Looking into the voltage measurements across each element it can be seen that in one string the voltage across the elements reaches 2,711 V. This voltage is approximately 140% higher than the unit's rated voltage, which is a condition that the unbalance protection is intended to protect against. The bank should have tripped for this type of operating condition. The graphs of the operating quantities are also referenced with the differential voltage in Figure 7.11 and the apparent impedance trajectory of the bank element in Figure 7.12. Strings 5 and 6 apparent impedance trajectories are shown in Figure 7.13.

Analyzing these results, it can be seen that the voltage differential element sees a slight change, while the impedance elements notices this change. The fault is simulated between string 5 and string 6 which are both shown in Figure 7.13 to notice changes in the apparent impedance. From Figure 7.13 we can conclude that string 6 will see an increase in current, causing the magnitude of the apparent impedance to approach to decrease and approach trip zone in that direction, while string 5 will notice a decrease in current, causing the apparent impedance to increase and approach the trip zone in the opposite direction.

Table 7.9: Relay measurements taken from the A phase in response to a midpoint string to string fault

Relay Element	**Calculated Nominal Value**		**Measured Value (S-S Midpoint)**	
Ia	-j3.76	A	-j3.76	A
Va	66.4	V	66.4	V
VtapA	95.7	V	95.6	V
Xbank	-j17.66	Ω	-j17.66	Ω
X (3 Strings)	-j17.71	Ω	-j17.68	Ω
X (2 Strings)	-j26.56	Ω	-j26.52	Ω
X (String)	-j53.12	Ω	-j53.09	Ω
dV	0	V	0.11	V

Table 7.10: A phase relay element responses to a midpoint string to string fault

Relay Element	**Pickup Value (S-S Midpoint)**
87TP1	0
87TP2	0
21C (Bank)	0
21C (3 Strings)	0
21C (2 Strings)	0
21C (String)	0

Table 7.11: Relay measurements taken from the A phase in response to an off midpoint string to string fault

Relay Element	**Calculated Nominal Value**		**Measured Value (S-S Off-Midpoint)**	
Ia	-j3.76	A	-j3.78	A
Va	66.4	V	66.4	V
VtapA	95.7	V	96.3	V
Xbank	-j17.66	Ω	-j17.54	Ω
X (3 Strings)	-j17.71	Ω	-j17.22	Ω
X (2 Strings)	-j26.56	Ω	-j26.01	Ω
X (String 5)	-j53.12	Ω	-j55.26	Ω
X (String 6)	-j53.12	Ω	-j49.17	Ω
dV	0	V	-0.33	V

Table 7.12: A phase relay element responses to an off midpoint string to string fault

Relay Element	Pickup Value (S-S Off-Midpoint)
87TP1	0
87TP2	0
21C (Bank)	0
21C (3 Strings)	0
21C (2 Strings)	0
21C (String)	0

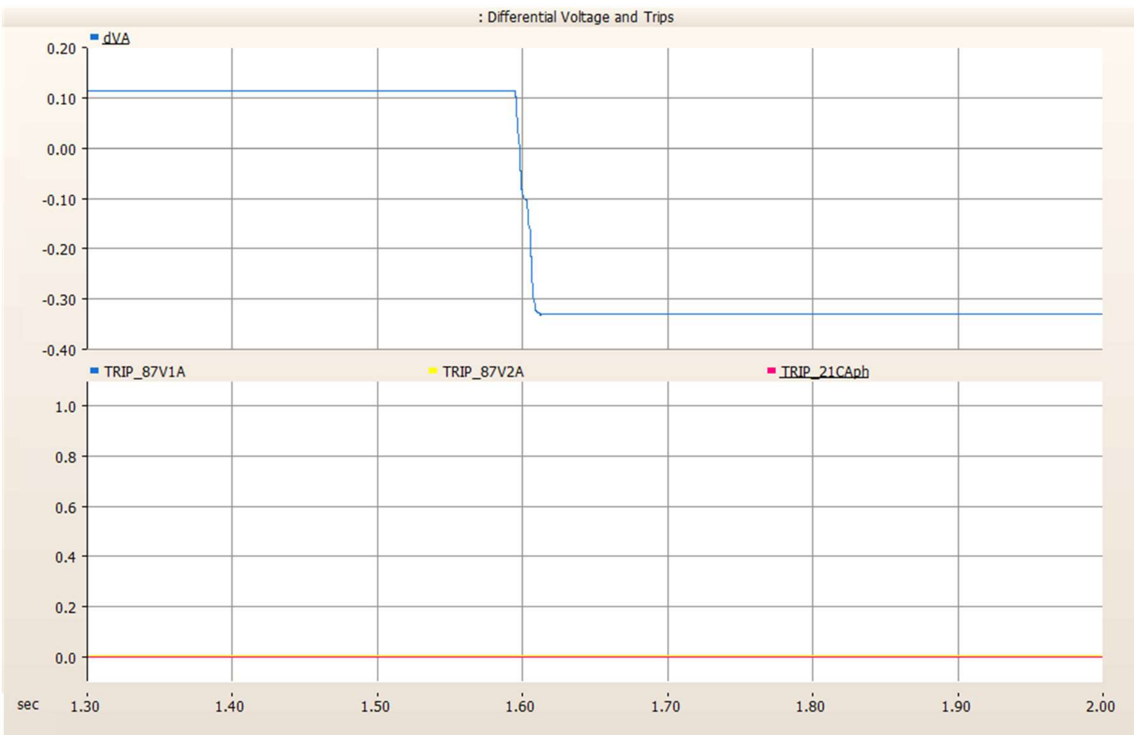


Figure 7.11: Differential voltage and trip signal versus time in response to a string to string off midpoint fault

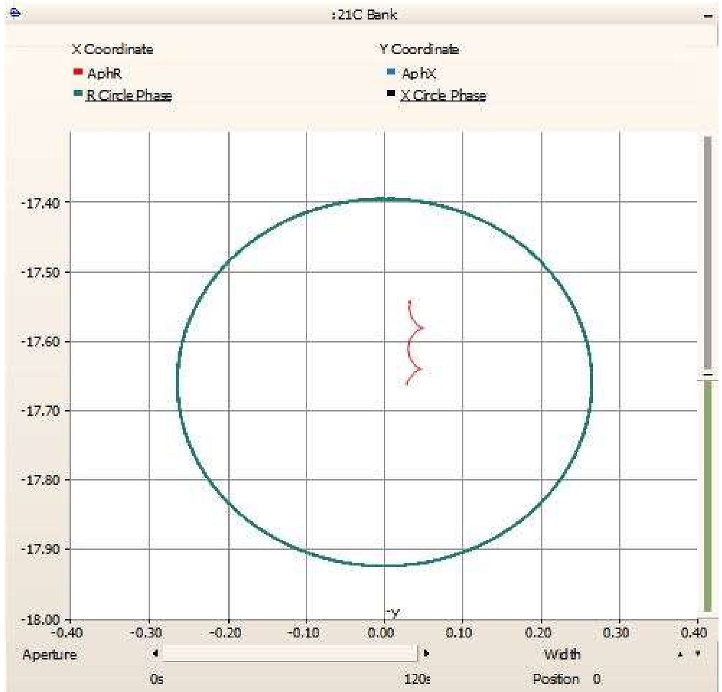


Figure 7.12: R-X diagrams of the phase element apparent impedance trajectory due to a string to string off midpoint fault

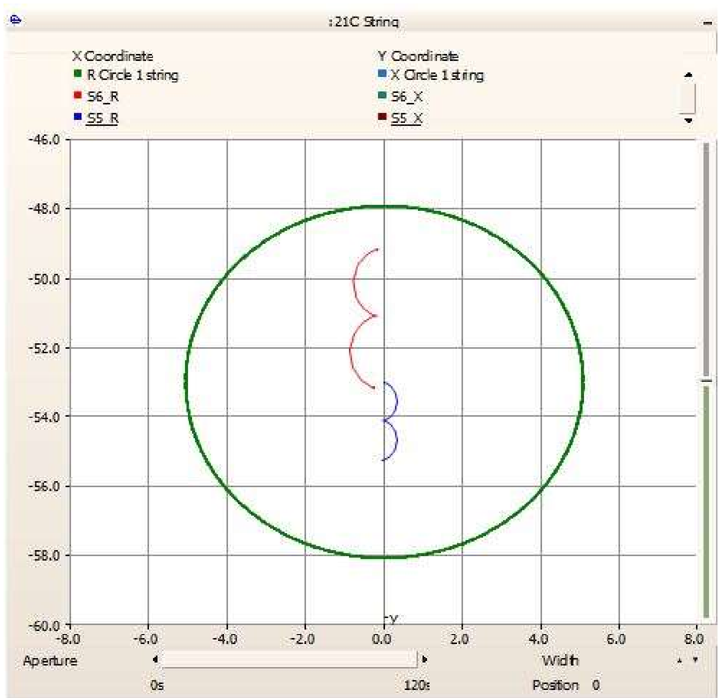


Figure 7.13: R-X diagrams of the string element apparent impedance trajectory due to a string to string off midpoint fault, string 6 impedance (red) moves towards R axis while string 5 impedance (blue) approaches the opposite direction

Reviewing the results from the string to string fault cases it is concluded that the per string impedance based element has an upper hand over the voltage differential element. The voltage differential element or the phase impedance elements do not provide enough change in the operating characteristic to detect a string to string fault. One thing noted on the per string impedance based elements is the phenomenon where the two affected strings have impedance changes in the opposite direction. Depending on the relative fault location in each string the direction of the impedance trajectory will change. Using this observed phenomenon additional work could done to design an element to allow a relay to use this characteristic for identification of a string to string fault. This will be discussed in the future work section as the findings demonstrate that the bank will experience an event where it should be removed from service, however none of the elements used in this study will respond to this condition. The string midpoint to string midpoint fault it is proven to behave like an H-bridge bank connection and does not cause inadvertent effects on the bank as long as the capacitors in both strings remain healthy above and below the midpoint.

7.5 Phase to Ground Fault Results

As discussed in previous chapters, a phase to ground fault is not a common occurrence, but still a possibility. The fault location will affect the fault current as the impedance between the source will vary with the fault location in the bank. For this study it will be assumed that a flashover of an insulator stack will occur in the bottom section of the bank. This would expose the frame tie point to ground. Figure 3.5 and Figure A.1 show the location of the phase to ground fault in the model bank. Faults to ground between the bank capacitors and low voltage capacitors are not studied here since they would have characteristics the same as the low voltage capacitor failure case.

The measured values for the ground fault cases are shown in Table 7.13 and the relay element pickup values are noted in Table 7.14. The symmetrical component quantities were analyzed on the model for this case and there were no significant amounts of negative or zero sequence current measured by the relay. The bank element voltage levels show that this type of fault will result in the voltage across some capacitor elements to be approximately 115% of their rated voltage. One other thing noted was the differential voltage that the relay calculated was a positive value, which would normally only occur during a LVC failure. Depending on how the element is set, the positive differential voltage will not result in a trip for the bank if the bank was set to not trip on a LVC failure. Figure 7.14 displays the positive differential voltage response, while Figure 7.15 displays the apparent impedance response.

This is the first fault case studied where CT location has a significant effect on the results. The plot of the bank impedance element shows that as the bank A phase current increases, the the impedance trajectory to move towards a smaller impedance magnitudes, while the response of string impedance element for the string that contains the fault approaches a higher impedance magnitudes. This is due to the installation of CT for the string element on the grounded side of the bank. The ground fault current will bypass this CT, it will see a sudden decrease in current, and the impedance will fall out of the restraint region. If the CT was to be located on the end of the string towards the 345 kV bus the response of the string element would follow a similar pattern to the bank element due to increased current.

Table 7.13: Comparison of relay measurements taken from the A phase in response to a phase to ground fault

Relay Element	Calculated Nominal Value		Measured Value	
Ia	-j3.75	A	-j3.83	A
I1	3.75	A	3.78	A
I2	0	A	0.03	A
I0	0	A	0.025	A
Va	66.39	V	66.4	V
VtapA	95.64	V	79.5	V
Xbank	-j17.66	Ω	-j17.33	Ω
X (3 Strings)	-j17.69	Ω	-j26.34	Ω
X (2 Strings)	-j26.51	Ω	-j52.34	Ω
X (String)	-j53.15	Ω	4142	Ω
dV	0	V	11.27	V

Table 7.14: A phase relay element responses to a phase to ground fault

Relay Element	Pickup Value (Phase to Ground Fault)
87TP1	0
87TP2	0
21C (Bank)	1
21C (3 Strings)	1
21C (2 Strings)	1
21C (String)	1

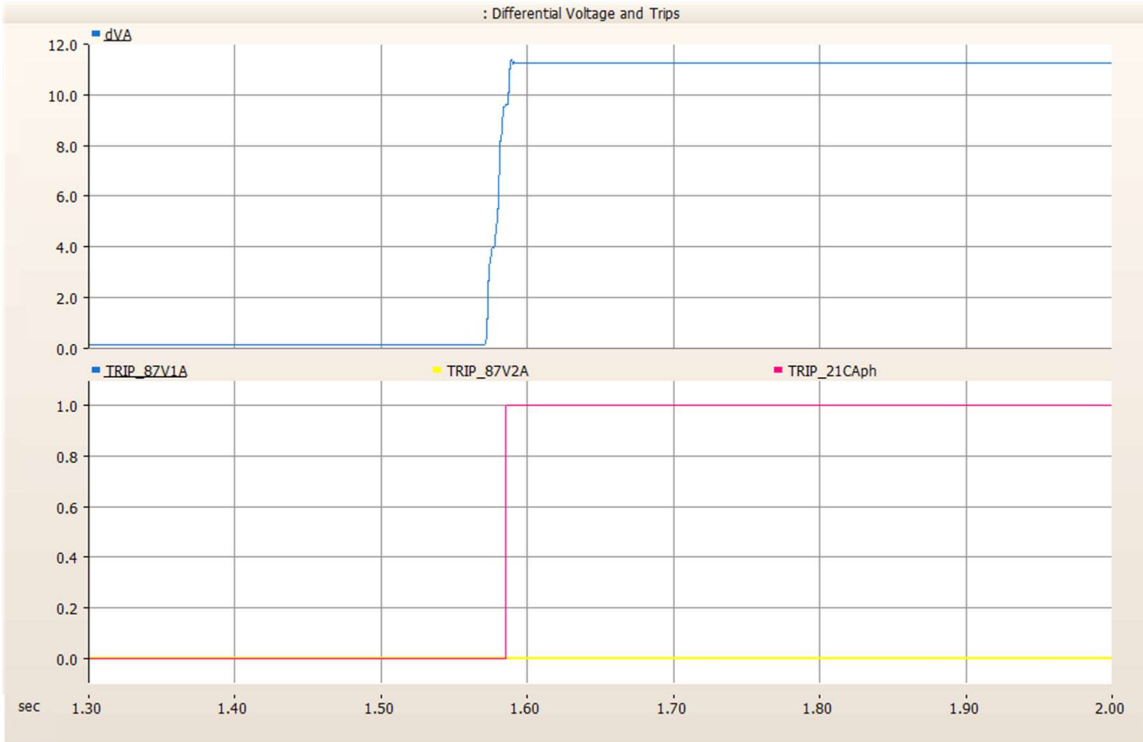


Figure 7.14: Differential voltage and trip signals versus time illustrating response to a phase to ground fault

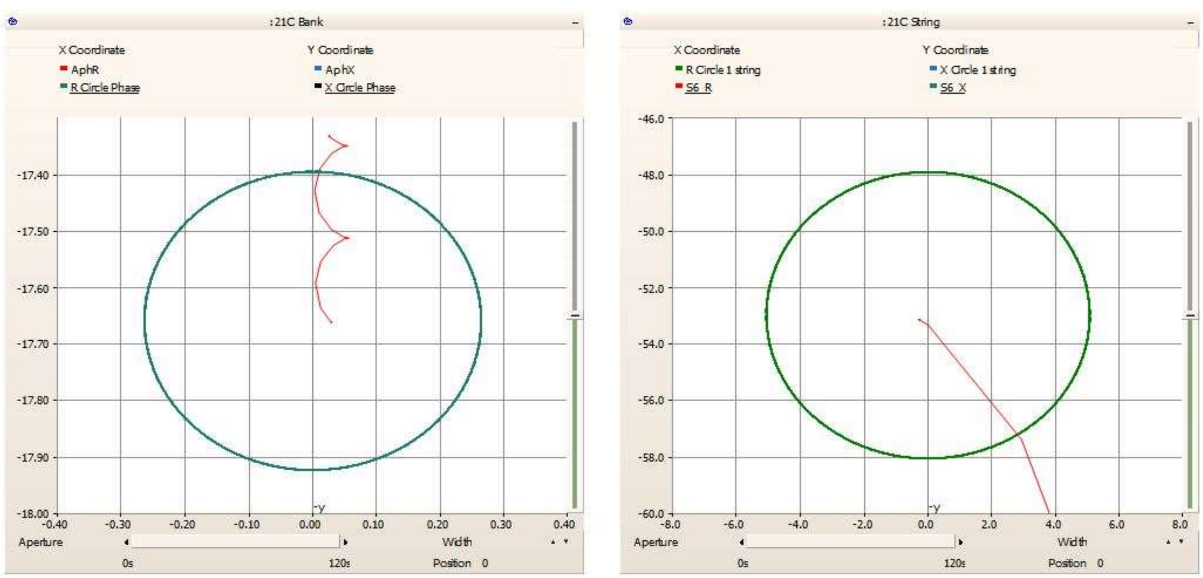


Figure 7.15: R-X diagrams of the phase element (left) and string element (right) apparent impedance trajectories due to a phase to ground fault

Reviewing the results it is proven that the impedance based elements offer a significant advantage over the voltage differential scheme. Looking at the differential voltage calculated during this event we can conclude that the relay would have identified this fault as below the tap point with a different voltage magnitude less than the recommended trip value. The impedance based relays will see this fault and respond because the fault current will drive the impedance out of the restraint region.

7.6 Phase to Phase Faults

Phase to phase faults are extremely uncommon in this type of bank configuration where each phase is located on its own support structure. However, some capacitor banks are constructed on the same structure in a phase-over-phase configuration, which is why this situation is considered. Based on the recommendation in [2], a negative sequence element is utilized and set to pick up at 10% of the normal load current to protect against these faults. Two situations were modeled, one with a phase to phase fault at a string midpoint, and one with a phase to phase fault off the string midpoint. Due to this fault type being uncommon it was not studied in too much detail, however the results are still of interest for comparison.

The results from both cases appeared very similar to the phase to ground fault in which the voltage differential element saw the fault as below the tap point, while the impedance elements all operated. Figure 7.16 shows the response of the differential voltage element for a phase to phase fault occurring off each phase's string midpoint. Figure 7.17 shows the impedance element response against the setting characteristics. One interesting note was for the midpoint phase to phase fault case is that the negative sequence current magnitude calculated by the relay was approximately 8% of the nominal phase current. This magnitude is not be sufficient to result in a pickup if the negative sequence element is set to pick up at 10% of I1 per [2]. The voltages across elements in the bank reach 178% of their rated value in this case, but only the impedance based elements picked up, neither the negative sequence protection nor the voltage differential scheme would pick up for this fault. The results from this once again conclude that the impedance based elements offer significant advantages. Although the voltage differential relay sees a change in the operating quantity, it does not pick up since the differential voltage is positive and is too small to even generate an alarm for a shorted low voltage capacitor.

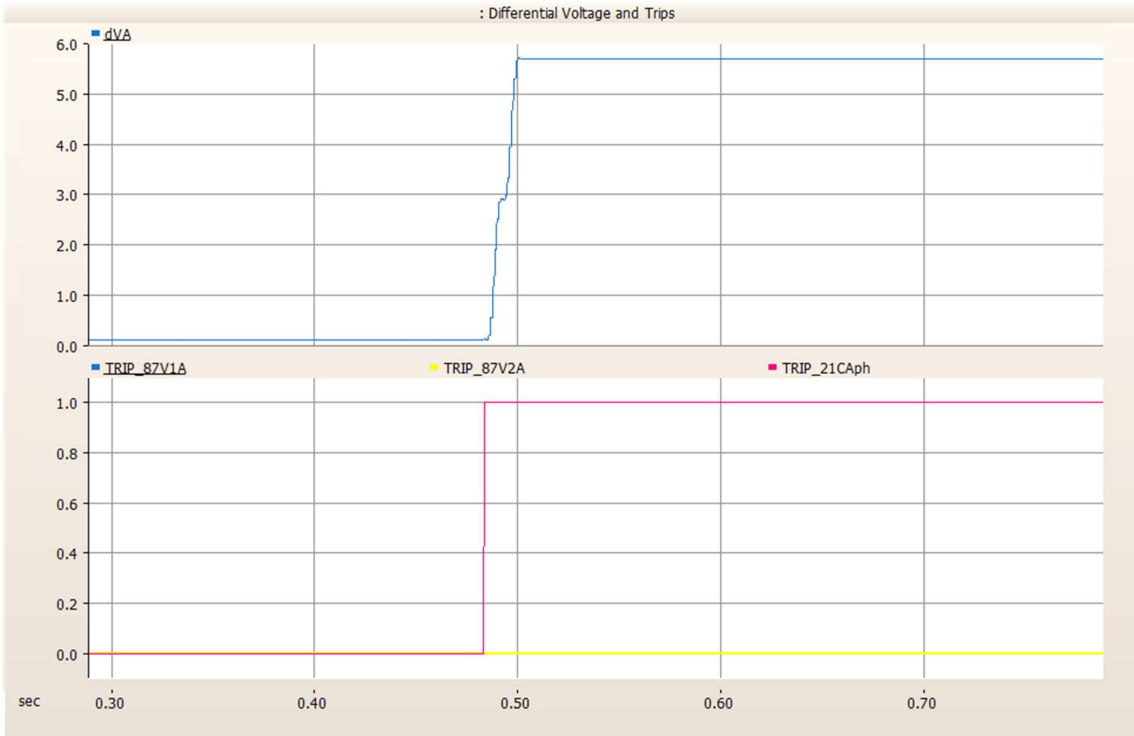


Figure 7.16: Differential voltage and trip signals versus time illustrating a phase to phase fault off each phase's midpoint

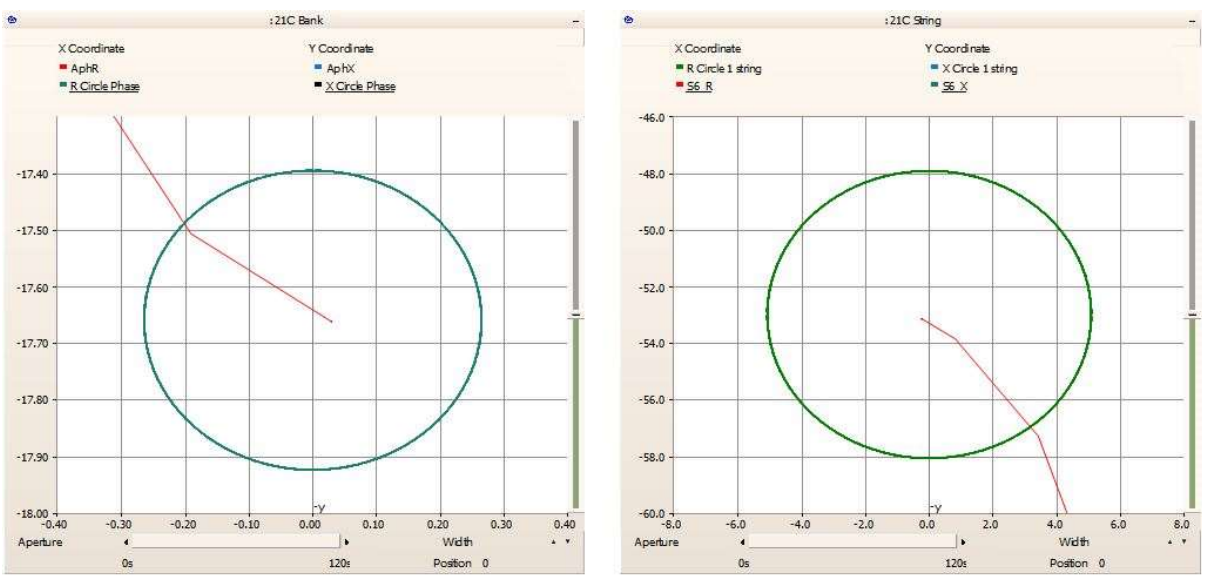


Figure 7.17: R-X diagrams of the phase element (left) and string element (right) apparent impedance trajectories due to a phase to phase fault off each phase's midpoint

7.7 Results Summary

Summarizing the results from the fault study it is concluded that the impedance based element offers advantages over the voltage differential element. When applied as a bank element the impedance element offers similar protection of the voltage differential element, with the exception being able to pick up during phase to phase and phase to ground faults. The full bank impedance element will suffer the same response of the voltage differential to distributed failures covering multiple strings. Although not shown in the simulation results, the impedance element will also allow for temperature compensation as an added benefit.

As can be seen in the results, lumping one to several strings together in sets for one CT will also adjust the sensitivity and response of the impedance based element to distributed failures. The single string based implementation offers better protection than all of the methods utilized. However one should not write off the voltage differential as ineffective. For adequate protection of large banks as suggested in [2] multiple schemes should be employed, which suggests applying both methods to protect a bank. Both schemes require similar analysis for set point calculations.

The study results did uncover a hole in current protection practices regarding string to string faults. Overvoltages were discovered that were not detected by any of the relay elements studied, however the impedance based element has potential to be modified to respond to this scenario, which will be discussed in future work.

Chapter 8: Conclusions and Future Work

8.1 Conclusions

The results presented in this thesis have demonstrated that the newer method of impedance based capacitor bank protection offers advantages over the methods currently applied as the industry norm. Depending on how this impedance based method is applied, it results in both increased sensitivity and more importantly, increased selectivity. As the grid loading continues to grow and the generation portfolio changes it has become more important for capacitor banks to remain in service. This method has proven itself to be a viable alternative to the voltage difference scheme currently used almost exclusively on grounded wye shunt capacitor banks.

The settings calculations for the impedance based method proved to be very similar to that of the voltage differential method, and do not require advanced calculations or computer software. In future situations this method could be utilized as a primary protection scheme, with redundant protection implemented using the voltage differential scheme. Utilities will also want to analyze the cost of implementation of this scheme. The cost of implementation of both methods is approximately the same if the relay is installed local to the capacitor bank. The added cost of the impedance based scheme comes from the CT wiring run from the capacitor bank to the relay house in a substation.

One other advantage the 21C impedance based elements provide that was not discussed in this thesis is the ability to monitor and report on the bank health. The measured values on the bank can be accessed remotely by grid operators to view the health of the bank. An alarm signal can be programmed to alert the operator, and information in the report indicating which string is signaling the alarm could be provided to a field crew dispatched to respond to the alarm. This would allow the field personnel to resolve the problem more quickly without needing to test the entire bank.

8.2 Future Work

Future work to further validate the results of this study and offer enhancements to the protection schemes presented in this work include the following.

I. Examine ways that the impedance elements can be applied to respond pick up for a string to string fault. The impedance based relay has potential to see these events, however a setting philosophy and logic need to be developed that will be able to correctly identify signatures for these events. Solving this issue will allow complete bank protection as identified in this study.

II. Study the effect that power system transients will have on the elements compared in this study. Coupling capacity type PTs (CCVTs) will have a transient response that the relay will see in addition to bank switching transients. These transients may have a significant effect on the proposed elements in this study and needs to be explored further.

III. Investigate other advantages of the string mounted current transformers. One application for this would be string based overcurrent elements. This addition could potentially be effective in the determination of string to string faults. Another potential application could be a bank based differential current element. Using the basic principle of current differential element, the current entering the bank will also equal the current leaving the bank. However this solution may not be of much interest other than perhaps detecting string to string faults. Faults that the differential elements would be utilized for can be seen by the impedance based elements.

IV. Examine the application of this to banks with more than 6 capacitor strings. Historically the number of strings was limited due to the resulting excessive current transformer secondary wiring. With the introduction of merging units and the substation process bus, a bank with multiple strings can be protected with one network cable with merging units connected to the CTs. The benefits of implementation of IEC 61850 sampled values to utilize additional current inputs can be examined.

V. Examine the performance impedance based protective elements as applied to other bank configurations, including split-wye, H-bridge, ungrounded type, and externally fused. The split-wye bank with a common neutral CT in the wye point would be a good candidate for a study to determine if the impedance based method offers the same benefits as seen for the bank studied in this work. Protection of harmonic filter banks where capacitor banks are rated based on the total current seen can also be examined to determine applicability as well.

VI. The use of wireless voltage and current based sensors located within capacitor banks. As wireless sensor development becomes more advanced and more cost effective, the sensors could be embedded in the bank to obtain real time measurements of the bank status. Some examples would be capacitor unit based voltage readings, or wireless current sensors allowing string measurements from the HV bus side and the grounded side. This could support string based current differential protection, which could be able to detect string to string faults.

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Appendix-A: PSCAD/EMTDC Schematic Diagram

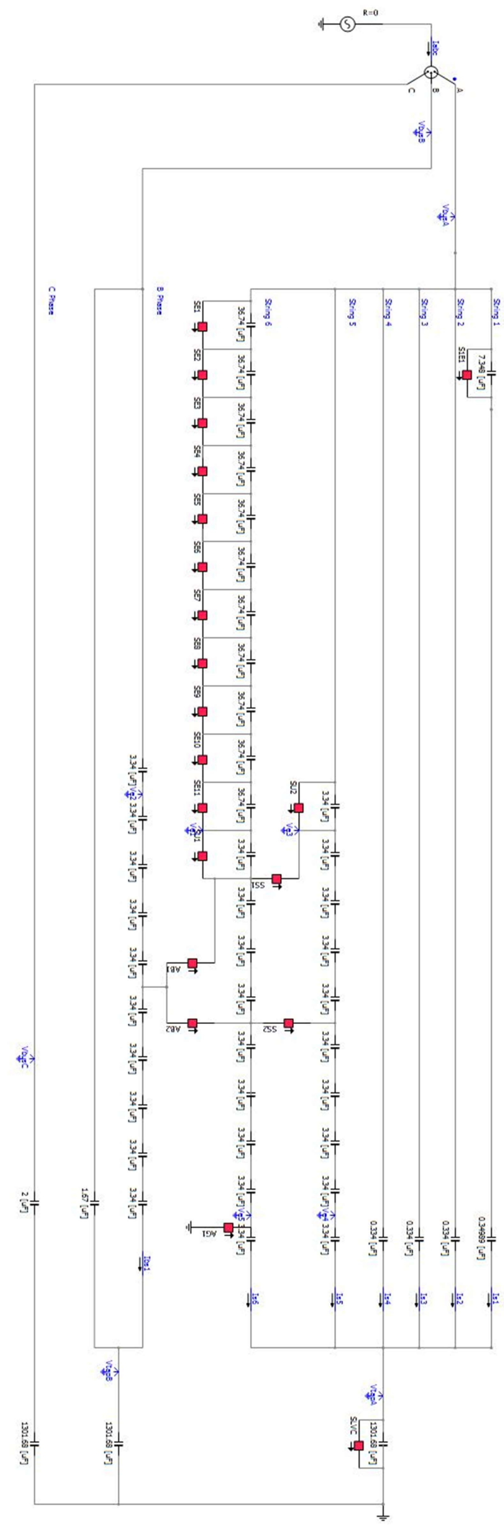

Figure A.1: PSCAD/EMTDC schematic for the capacitor bank model used to test the relay functions