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Effect of Induction on Control/Signal Cables on Shunt Capacitor Bank Protective Schemes

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by

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Abstract

Power factor correction is the main application for shunt capacitor units in the power system. The advantage of improved power factor is reduced line and transformer losses, improved voltage profile, reduced maximum demand, and improved power quality. The capacitors are installed in a distribution system on pole-mounted racks, substation banks, and high voltage (HV) or extra-high voltage (EHV) units for bulk power applications.

Capacitors have many applications in power systems: they can be used in series to compensate the inductance of transmission lines to transmit more power. They can also be used as surge capacitors, starting motors, and static VAR compensators.

Capacitor banks installed in power substations are vital in the sense that they provide the reactive power needed for the power system, which in turn improves the voltage profile in the system. There is always the option of grounding the banks or leaving them ungrounded. Each of the above configurations has its own advantages and disadvantages; to name a few, ungrounded banks are slightly more expensive compared to grounded banks as the neutral point needs to be insulated up to system basic insulation level; whilst grounded banks are prone to inject high-frequency transients (e.g., switching, ground faults) into the ground mat.

This study is intended to address the recent incident in a high-voltage substation which led to the explosion of a capacitor bank. The study goes on to suggest grounding as a method to prevent such incidents. Furthermore, the effects of grounding and induction on control/signal cables as well as protecting relays are investigated.

Keywords: Electromagnetic induction, Power system transients, Power system faults, Capacitor switching

Dedication

I dedicate this thesis to Paria, the love of my life, and my parents. Without their patience, understanding, support, and most of all love, the completion of this work would have not been possible.

Acknowledgment

This research project would not have been possible without the support of many people. I wish to express gratitude to my supervisor, Prof. Dr. Tarlochan Singh Sidhu who was abundantly helpful and offered invaluable assistance, support and guidance.

I also want to thank Messrs. Luis Marti and Andrew Yan from Hydro One as well as Messrs. Bob Beresh and Babak Jamali from Kinectrics for their help and support.

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I also wish to express my love and gratitude to my beloved family; for their understanding and endless love, through the duration of my studies.

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Chapter One

1. Introduction

Power systems play a vital role in our modern society today. As world is advancing, the demand for electricity grows rapidly as well. Basically, building blocks of a power system are sources of electricity, deliverers of electricity, and distributors of electricity. All these elements are facing new challenges with the growth of electricity market and are pushed to their operating limits. Therefore, availability of the entire power system elements definitely has extensive economic impacts. Hence, there is always an effort to enhance every element of the power system to meet with the new challenges and also provide a reliable and economical power to all consumers.

1.1. Grounding in Power System Substations

Grounding system in a substation is a vital part of the entire electrical system. Proper grounding of a substation is important as it provides a means for dissipating electric current into the ground without straining the equipment as well as it provides a safe environment for the crew to work in the vicinity of grounded facilities and protect them from electric shocks when a fault happens [1].

Grounding system includes all interconnected grounding facilities in the substation area, including the ground grid, overhead ground wires, neutral conductors, underground cables, foundations, deep well, and so on.

Grounding grids consist of horizontal interconnected bare conductors (mat) and ground rods. Grounding grid is designed to control voltage levels to safe values at an economical cost. It is often assumed that any grounded object can be safely touched. A low resistance ground is not a guarantee of safety and there is no simple relation between the resistance of the ground system and the maximum shock current a person might receive by touching a metallic object.

1.2. Capacitor Banks

The main application of capacitor banks in power systems is correction of power factor. Improving the power factor reduces the loss in lines and transformers, improves voltage profiles, reduces maximum demand, and improved power quality. The capacitors installed in the distribution level can either be pole-mounted or in banks; at higher voltages (HV or EHV), however, bulk capacitor banks are used for power factor correction.

1.2.1. Ungrounded Capacitor Banks

There is always the option of grounding the banks or leaving them ungrounded. Each of the above configurations has its own advantages and disadvantages; to name a few, ungrounded banks are slightly more expensive compared to grounded banks as the neutral point needs to be insulated up to system basic insulation level. Furthermore, a single phase fault will increase the voltage in neutral point to that of the phase voltage and this will strain the healthy phases in the system. On the other hand, inrush currents for these banks are lower than grounded banks.

1.2.2. Grounded Capacitor Banks

Another option to configure the capacitor banks is to make them grounded. This configuration is cheaper than the previous one, as there is no need for the neutral point to be insulated up to basic insulation level of the system. In case of a single phase fault, the neutral voltage still remains at ground voltage and the other phases will not experience any overvoltage. However, grounded banks are prone to inject high-frequency transients (e.g., switching, ground faults) into the ground mat. This can interfere with communication cables used for carrying measurement and/or control signals in the substation. Furthermore, touch/step voltages might occur on electrical equipment, jeopardizing the safety of the site personnel.

1.2.3. Capacitor Bank Protection

Capacitor banks installed in power substations are not only capital investments but also their continuous function is vital to the operation or the power system. Therefore, various protection schemes are in existence to protect them from different sources of hazards, e.g., faults, lightning, and switching transients. Different schemes have been investigated in this literature and their advantages and disadvantages are discussed. Some of these schemes are sensitive to the unbalance in the power system which may cause them to unnecessarily disconnect the capacitor bank from the system. Other schemes do not have this shortcoming. Most of them are already implemented in the commercial relays.

1.3. Motivation

This thesis was initially inspired from the recent incident at the HV substation. In this occasion, one of the capacitor banks has been energized, but after a short time there was a single phase to neutral fault which turned into a double and triple phase fault. On disconnecting the fault, the breaker experienced a high TRV[1] and therefore the fault was not cleared and the backup breaker on the bus tripped and cleared the fault. Although the whole duration of this event did not exceed 287ms, about 54MW of generation and 1,500MW of sensitive loads were tripped off [2].

The fact that the capacitor banks at the HV substation are ungrounded gave rise to the amount of TRV at the breaker. The objective of this thesis is to investigate the possibility of grounding the capacitor banks at this substation as well as its consequences. This change will make the transient currents such as faults, switching, and lightning to go directly into the ground mat. Also these large currents may induce voltages/currents on nearby communication cables. These transients in turn will find their way to control or protection equipment. As with any electronic apparatus the

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[1] Transient Recovery Voltage

transient might have detrimental effects on their functionality. In case of protective relays, this might affect the relay reliability and/or security.

Recently, a capacitor bank at the HV substation was energized routinely. All the capacitor banks in the mentioned substation have ungrounded double star configuration. The insulation in the branches of capacitor banks were contaminated as a result of salts being poured on freeways. This, along with capacitor element aging, caused a flashover on a unit which cascaded to all of the units in a series branch. The flashover caused a double phase-to-ground fault in 4.5 seconds after energization, which elevated the potential of the neutral point, causing the other phase to experience 1.73 times the nominal voltage. Furthermore, the insulation on the third phase could not tolerate the overvoltage and within 30 milliseconds, the fault turned into a three-phase fault. Due to the high TRV, common to this type of capacitor bank configuration, neither the main breaker nor its backup could clear the fault and both experienced re-ignition. In the end, the bus protection was able to clear the fault. This took place 287 milliseconds after fault occurrence [2].

The mentioned capacitor bank is a 249 kV, double star ungrounded, and fuseless capacitor bank. The bank is designed with six stacks as shown in Figure 1-1. One half of each stack belongs to one Wye, the other half of the stack belongs to the other Wye. Each stack contains six or seven capacitor branches for each Wye. A neutral CT is connected between the neutrals of the two Wyes.

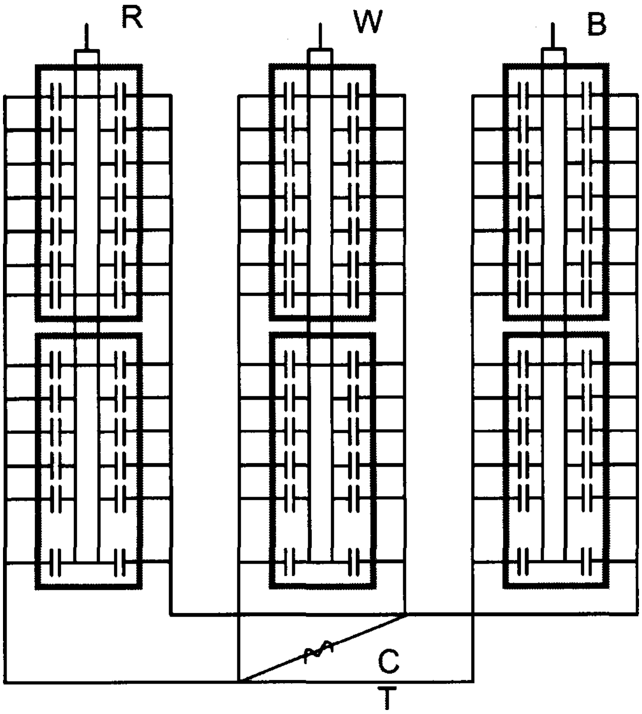

Figure 1-1: Double-star connection

Figure 1-2 shows the side view of one of the capacitor stacks. Each capacitor branch contains of eight capacitor units. Each unit contains of eleven elements in series and is exposed to a maximum of 18kV power frequency voltage during normal steady-state operation. These units are placed in four frames. All frame voltages are anchored at the voltage potentials of some particular capacitor unit terminals by frame bonding (circled connections in Figure 1-2).

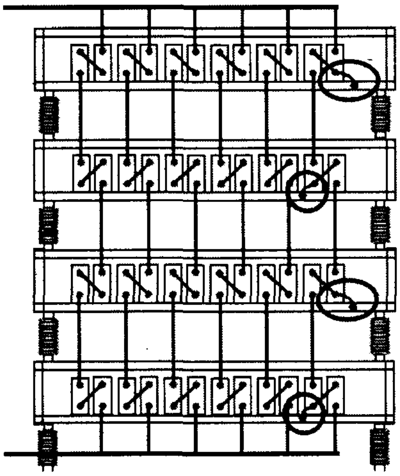

Figure 1-2: Side-view of a capacitor stack

This design ensures that the maximum power frequency stress across each capacitor unit bushing is 18kV during normal operation. The maximum power frequency voltage stress between capacitor frames is 36kV.

1.4. Research Objectives

This thesis investigates different parts of the abovementioned problems. Firstly, different configurations of capacitor banks and their relevant protection schemes are discussed. Secondly, the fault current with different configurations of capacitor banks are obtained using computer simulations. Subsequently, the induced currents and voltages on control/signal cables are acquired. In the last phase of the thesis, the above transients are fed to a commercial relay using amplifiers and the relay responses have been recorded. It is intended to find situations in which the relay's reliability and/or security are influenced due to the presence of transients induced by ground fault or switching transients.

1.5. Thesis Outline

This thesis is arranged into six chapters. In this chapter, the background for this research as well its objectives are given.

In chapter two, an introduction to capacitor banks is given, their configurations and the appropriate protection scheme for each of them is discussed. Chapter three is about the matter of grounding in power systems. In the next chapter the literature survey about previous and similar works on calculating/measuring induced transients on control/signal cables as well as the proposed method of this thesis is presented. In chapter five, the simulation results as well as the commercial relay's behaviour towards the distorted signals is given. And finally in chapter six, a summary of the research and conclusions containing the contributions of the work are given. The books, journals, and articles referred to in this thesis are brought in the final chapter.

1.6. Summary

This research intends to find out the amount of induction of transients such as fault currents and switching from ground mat into control/signal cables and their effects on relay's reliability and security. In this chapter a brief overview of the thesis organization was also presented.

Chapter Two

2. Introduction to Shunt Capacitor Banks

Shunt capacitors are used to reduce the reactive power required by inductive loads and also to assist in the regulation of system voltages. They are connected as required throughout the system, but the maximum benefit is obtained by placing the capacitors as close to reactive loads as possible. These capacitors generate reactive power, which can also be supplied by rotating machines such as synchronous condensers. Condensers provide variable control, but at a relatively higher cost. Capacitor banks are either fixed or switched. The fixed versions are connected to the system for long periods of time; whereas switched banks are added and removed as needed [3].

Capacitor banks are comprised of capacitor units (Figure 2-1). The capacitor unit itself is usually made up of individual capacitor elements, arranged in parallel and/or series-connected groups, within a steel enclosure. The internal discharge device is a resistor that reduces the unit residual voltage to 50V or less in 5 minutes according to IEC 831 standard. Capacitor units are available in a variety of voltage ratings (240V to 25kV) and sizes (2.5kvar to about 1Mvar).

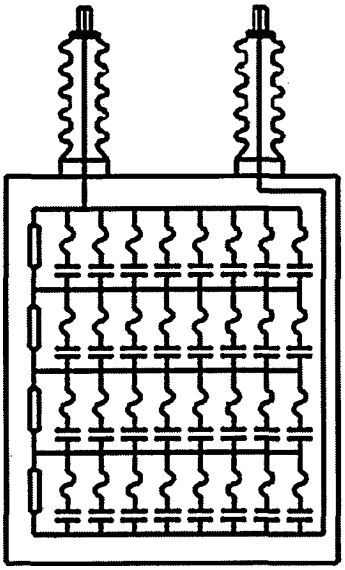

Figure 2-1: The capacitor unit

Shunt capacitors should be able to stand certain overvoltages and overcurrents experienced in a network [4]:

1. Capacitor units should be capable of continuous operation up to 110% of rated terminal rms voltage and a crest voltage not exceeding $1.2\times\sqrt{2}$ of rated rms voltage, including harmonics but excluding transients. The capacitor should also be able to carry 135% of nominal current.
2. Capacitors units should neither give less than 100% nor more than 115% of rated reactive power at rated sinusoidal voltage and frequency.
3. Capacitor units should be suitable for continuous operation at up to 135% of rated reactive power caused by the combined effects of:
    - Voltage in excess of the nameplate rating at fundamental frequency, but not over 110% of rated rms voltage.
    - Harmonic voltages superimposed on the fundamental frequency.
    - Reactive power manufacturing tolerance of up to 115% of rated reactive power.

2.1. Arrangement of Capacitor Units

Depending on the application, four connections may be used [5]:

1. Externally fused capacitor banks
2. Internally fused capacitor banks
3. Fuseless capacitor banks
4. Unfused capacitor banks

2.1.1. Externally Fused Capacitor Banks

The capacitors with external fuses are configured using one or more series-grouped of numerous parallel-connected capacitor units per phase. Each capacitor unit is typically protected by an individual fuse, externally mounted between the capacitor unit and the capacitor bank fuse bus (Figure 2-2). The capacitor unit can be designed for a relatively high voltage because the external fuse is capable of interrupting a high-voltage fault. However, the kvar rating of the individual capacitor unit may be smaller because a minimum number of parallel units are required to allow the bank to remain in service with one fuse or unit out.

A failure of a capacitor element welds the foils together and short circuits the other capacitor elements connected in parallel in the same group. The remaining capacitor elements in the unit remain in service with a higher voltage across them than before the failure and an increased in capacitor unit current. If a second element fails the process repeats itself resulting in an even higher voltage for the remaining elements. Successive failures within the same unit will make the fuse to operate, disconnecting the capacitor unit and indicating the failed one.

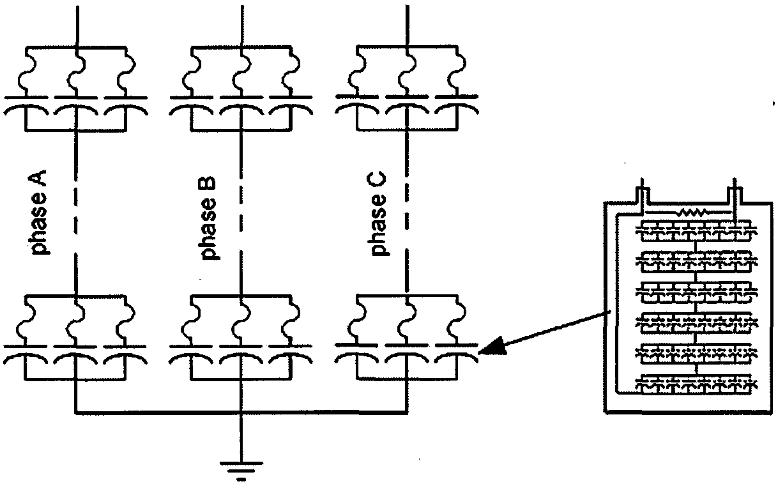

Figure 2-2: Externally fused capacitors (many parallel units)

2.1.2. Internally Fused Capacitor Banks

Figure 2-3 illustrates a capacitor utilizing internally fused capacitor units. In general, banks employing internally fused capacitor units are configured with fewer capacitor units in parallel and more series groups of units than are used in banks employing externally fused capacitor units. The capacitor units are normally large because a complete unit is not expected to fail. An internal fuse is connected in series with each capacitor element. Each internally fused capacitor unit is constructed with a large number of elements connected in parallel to form a group and with only a few groups connected in series. This construction is the opposite to that found in externally fused capacitors, which normally employ a large number of series groups made up of parallel connected elements, with correspondingly fewer elements connected in parallel per series group. Upon a capacitor element failure, the fuse removes the affected element only. The other elements, connected in parallel in the same group, remain in service but with a slightly higher voltage across them.

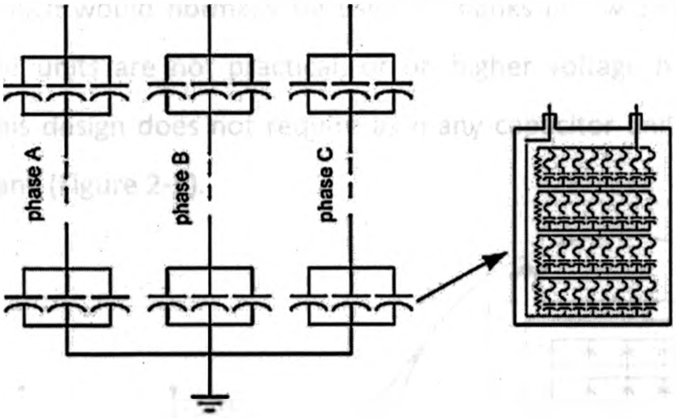

Figure 2-3: Internally fused capacitors (many series units)

2.1.3. Fuseless Capacitor Banks

These capacitor banks are identical to those for externally fused. Fuseless shunt capacitor banks are normally used for applications at or above 34.5kV. The capacitor units are normally designed with two bushings with the elements insulated from the case. The capacitor units are connected in series strings between phase and neutral (or between line terminals for delta-connected or single-phase installations). The protection is based on the capacitor element's failing in a shorted mode. The discharge energy is small because no capacitor units are connected directly in parallel. Another advantage is that the unbalance protection does not have to be delayed to coordinate with the fuses (Figure 2-4).

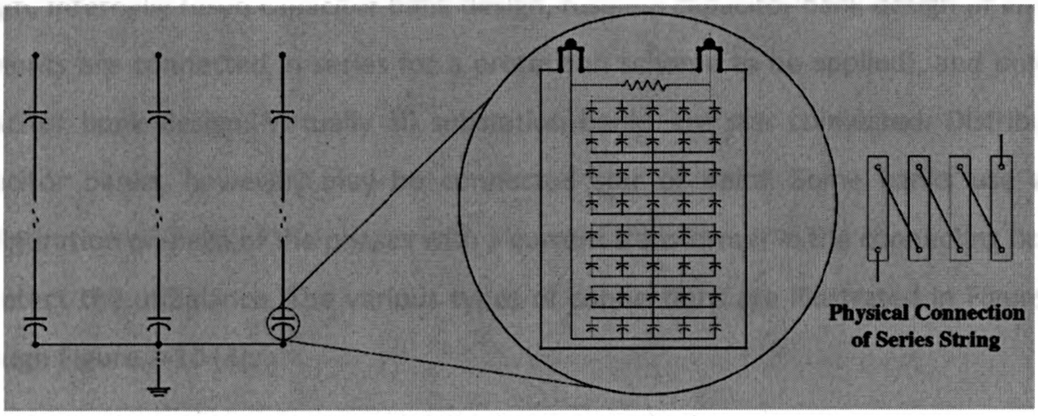

Figure 2-4: Fuseless capacitor banks

2.1.4. Unfused Capacitor Banks

Contrary to the fuseless configuration, where the units are connected in series, the unfused shunt capacitor bank uses a series/parallel connection of the capacitor units. The unfused approach would normally be used on banks below 34.5kV, where series strings of capacitor units are not practical, or on higher voltage banks with modest parallel energy. This design does not require as many capacitor units in parallel as an externally fused bank (Figure 2-5).

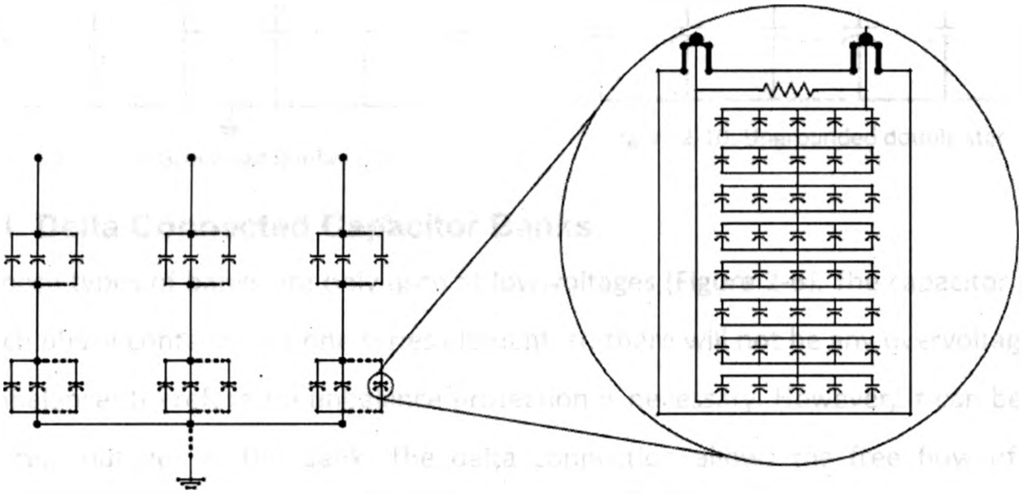

Figure 2-5: Unfused capacitor banks

2.2. Capacitor Bank Configurations

Five capacitor bank connections are common. The optimum connection depends on the best utilization of the available voltage ratings of capacitor units, fusing, and protective relaying. These connections can be used for externally fused capacitor bank design, internally fused capacitor bank design, fuseless capacitor bank design (if enough elements are connected in series for a protection scheme to be applied), and unfused capacitor bank design. Virtually all substation banks are star connected. Distribution capacitor banks, however, may be connected star or delta. Some banks use an H configuration on each of the phases with a current transformer in the connecting branch to detect the unbalance. The various types of connections are illustrated in Figure 2-6 through Figure 2-10 [4].

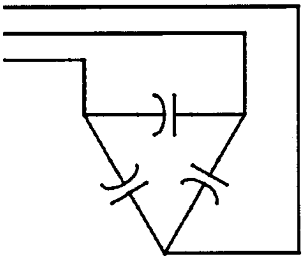

Figure 2-6: Delta

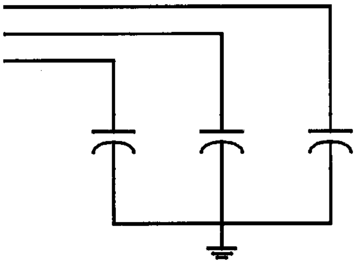

Figure 2-7: Grounded star

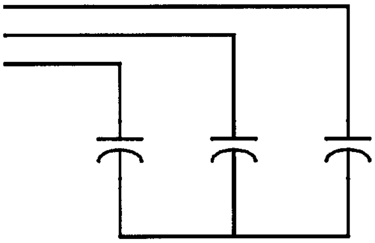

Figure 2-8: Ungrounded star

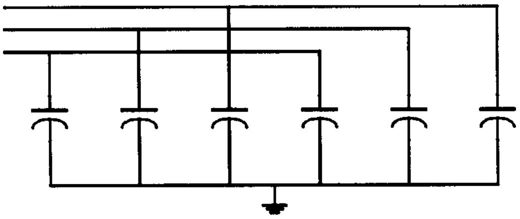

Figure 2-9: Grounded double star

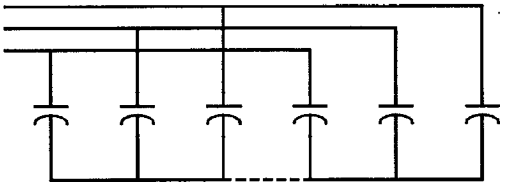

Figure 2-10: Ungrounded double star

2.2.1. Delta Connected Capacitor Banks

These types of banks are only used at low voltages (Figure 2-6). The capacitor group in each phase contains just one series element, so there will not be any overvoltage due to unbalance; therefore no unbalance protection is necessary. However, it can be used to detect outages in the bank. The delta connection allows the free flow of third harmonic and zero-sequence currents. To interrupt phase-to-phase short circuit, a current limiting fuse has to be used which is more expensive than the common expulsion fuses.

In the case that only one group of series capacitors is used for each phase, individual capacitor fuses would be able to interrupt the current for phase-to-phase fault. If the capacitor units have internal fuse, it becomes necessary to install unbalance detection schemes to detect element failure; as the blown fuse would not be visible.

2.2.2. Grounded Star

Grounded star (Figure 2-7) configuration has some advantages over ungrounded star configuration. Firstly, the initial investment would be lower, since it is not necessary to insulate the neutral point up to BIL[1] of the system; therefore, the TRV at circuit breaker would be lower. The disadvantage of this configuration compared to ungrounded star connection is the high inrush and ground currents; this may also cause interference with telephone and signal cables. Furthermore, this connection has a low impedance path for fault currents and needs a neutral relay. Still, the current limiting fuses are required to limit the phase-to-ground fault currents.

In case a single-phase fault occurs, the voltage on the faulty phase would go to zero (Figure 2-11). The neutral is grounded, so the voltage on the healthy phases would still be 1 per unit as well as their current. This means that the capacitor units in healthy phases will remain intact.

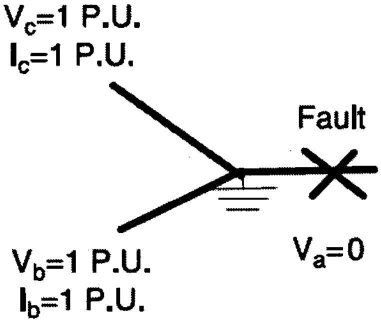

Figure 2-11: Fault in grounded star configuration

2.2.3. Ungrounded Star

The ungrounded star scheme is shown in Figure 2-8. The voltages and currents during normal operation are symmetrical. In the event of the failure of a capacitor in one phase, the neutral voltage is shifted down (Figure 2-12). This makes the voltage across healthy phases to rise to phase-to-phase voltage (1.73 times); which in turn increases the current to 1.732 times the nominal current on those phases. This may cause additional failures. The advantage of ungrounded star banks is that they do not allow the flow of third harmonic currents, zero-sequence currents, or large discharge currents during ground faults.

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[1] Basic Insulation Level

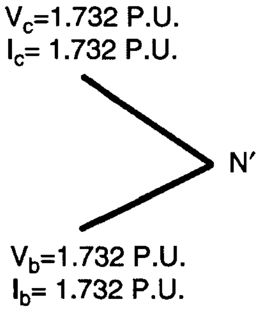


Figure 2-12: Fault in ungrounded star configuration

2.2.4. Grounded Double Star

In large capacitor banks (above 4.65Mvar), it is advisable to split the bank into two parallel groups in star connection dividing the energy between the two branches (Figure 2-9). The characteristics of these banks are similar to those of grounded single-star configuration. The two neutral points are directly connected with a single connection to ground. This configuration allows for a faster and more secure unbalance protection with a simple relay as a failed capacitor unit will immediately create an unbalance in the neutral. If the units are fused, time coordination is required; otherwise, the relay timing can be set on a shorter time.

2.2.5. Ungrounded Double Star

The configuration for an ungrounded double-star capacitor bank is shown in Figure 2-10. This scheme is basically equivalent to ungrounded single-star connection. This scheme is quite common as the unbalance in neutral is very easy to detect. Capacitor banks with grounded star, ungrounded star, or delta connection may experience ferroresonant overvoltages if they are switched together using a transformer with single-pole switching devices.

2.3. Protection Schemes for Shunt Capacitor Banks

In this section, the available schemes for shunt capacitor bank protection are introduced:

2.3.1. Overcurrent Protection

Overcurrent in capacitor bank may be caused by a capacitor unit failure or faults inside capacitor bank or system unbalances. In any case, to protect the capacitor banks from failure, measures are taken. The first line of protection in a capacitor bank against overcurrent is the fuse. These devices can protect the bank against phase-to-ground, phase-to-phase, or three-phase faults (Figure 2-13). Overcurrent relays for primary and secondary are provided here:

1. 51, 51N for overcurrent protection
2. 52, AC circuit breaker for tripping the capacitor bank

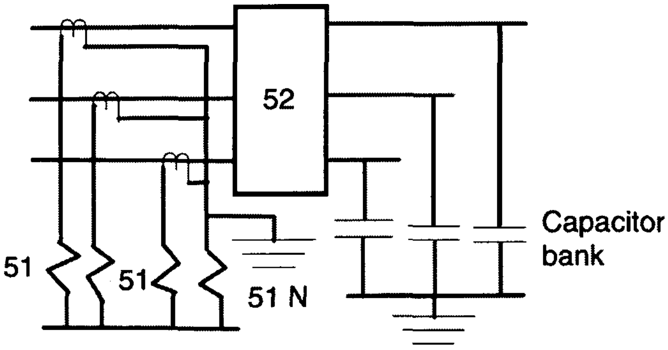


Figure 2-13: Overcurrent protection scheme

According to IEEE Std. 18-2002, capacitor banks must be able to tolerate 135% of their rated current.

2.3.2. Rack Failure Protection

Sometimes, arcs occur in the capacitor bank between series and parallel units due to animal intrusion or contamination. As an example, a rack failure between two phases is shown in Figure 2-14. If this situation is allowed to persist, more and more capacitor units on the same branch may fail due to experiencing overvoltage until the whole branch is cleared by an overcurrent relay or a fuse. The time necessary to clear such faults as mentioned can take a few seconds, resulting in more damage; therefore, overcurrent relays and/or fuses may not be the best solution against rack failures.

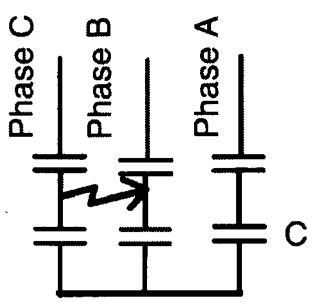


Figure 2-14: Rack failure

To deal with these failures faster and more efficiently, unbalance detection schemes are used for ungrounded capacitor banks.

2.3.3. Unbalance Protection

In unbalance protection scheme, the purpose is to remove a capacitor bank in case of a fuse operation. This will prevent overvoltages to occur on the healthy capacitor units, and prevents further failures. The capacitor connection is shown in Figure 2-15. When all four capacitors are in service, the voltage across each of them is V/2. If one of the fuses operates, 2V/3 will fall on the upper branch and the V/3 on the lower branch. This increase is unacceptable for any capacitor; therefore, such unbalance must be detected and the involved unit should be isolated before further damage is occurred.

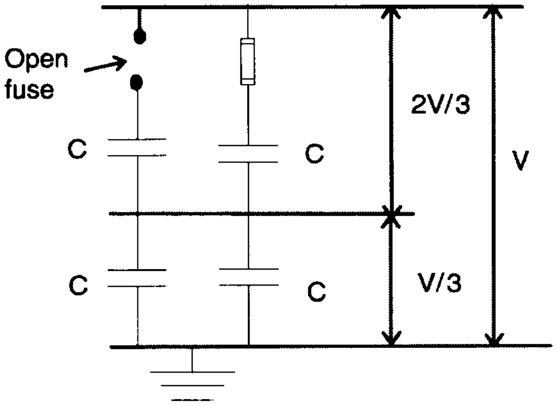


Figure 2-15: Voltage distribution due to an open fuse

Many methods exist for detecting unbalances in capacitor banks; yet no practical method is able to provide protection in all possible circumstances. The common procedure in such schemes is that an alarm is tripped after an initial failure in the bank.

If failures continue and damaging overvoltages are produced, the bank would be disconnected from the line.

2.3.3.1. Unbalance Protection of Grounded Banks using Current

A grounded capacitor arrangement is shown in Figure 2-16 with neutral current relay. A typical unbalance protective scheme consists of a current transformer with a 5A secondary using a burden of 10 to 25Ω connected to a time-delayed voltage relay through suitable filters. The advantages of this scheme are:

1. The capacitor bank contains twice as many parallel units per series group compared to the double star bank for a given kvar size which reduces the overvoltage seen by the remaining units in a group in event of a fuse operation.
2. This bank may require less substation area and connections than a double star bank.
3. Relatively inexpensive protection scheme.

The disadvantages of this scheme are:

1. Sensitive to system unbalance, a significant factor for large banks.
2. Sensitive to triple harmonics and will generally require a filter circuit.
3. Will not act when there is similar failure in all the phases.
4. It is not possible to identify the phase of the failed capacitor unit.

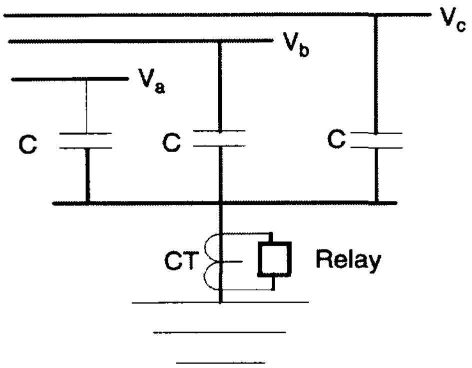


Figure 2-16: Neutral current sensing

2.3.3.2. Unbalance Protection of Grounded Banks using Voltage

Figure 2-17 shows an unbalance protection scheme for a grounded star capacitor bank provided that tap point voltages are available. Any unbalance in the capacitor units will cause an unbalance in the voltages at the tap points.

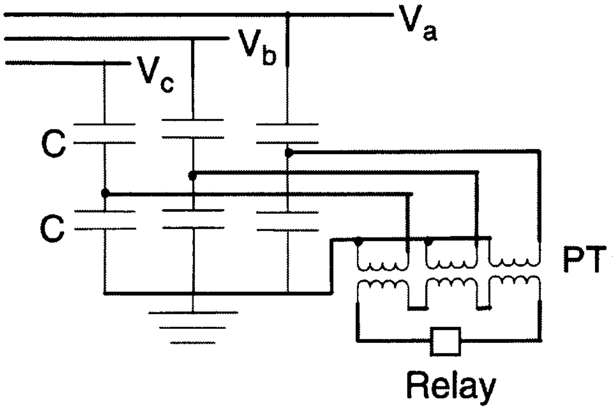


Figure 2-17: Summing intermediate tap-point voltages

2.3.3.3. Neutral Current Differential Protection for Grounded Double Star Banks

In this scheme (Figure 2-18), the neutrals of the two sections are grounded through separate current transformers. The CT secondaries are connected to an overcurrent relay, which makes it insensitive to any outside condition affecting both sections of the capacitor bank. The advantages of this scheme are:

1. The scheme is not sensitive to system unbalance and it is sensitive in detecting capacitor unit outages even on very large capacitor banks.
2. Harmonic currents do not affect this scheme.
3. For very large banks with more than one series group the amount of energy in the capacitors will decrease. This will lower the fuse interrupting duty and may reduce the cost of fuses.

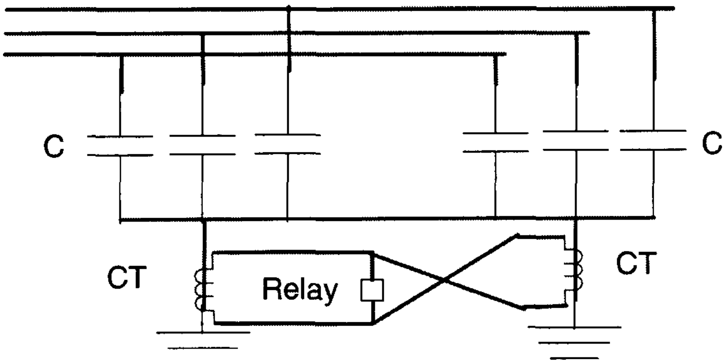


Figure 2-18: Unbalance detection for double star banks

With the star split into two section, a larger number of parallel units per series group are required which in turn increased the overvoltage on the remaining units of the series group in case a fuse operation. This type of bank requires more substation area and connections.

2.3.3.4. Voltage Differential Protection Method for Grounded Banks (ANSI 87V)

In this scheme (Figure 2-19), the outputs of two three-phase voltage transformers are compared in a differential relay. Loss of capacitor unit in each phase can be detected independently. The advantages of this scheme are:

1. The capacitor bank contains twice as many parallel units per series group compared to a split-star bank. In case of a fuse operation, the healthy units in a group will experience a lower overvoltage.
2. This scheme is less sensitive to system unbalance. It is sensitive to failure detection in the series capacitors.

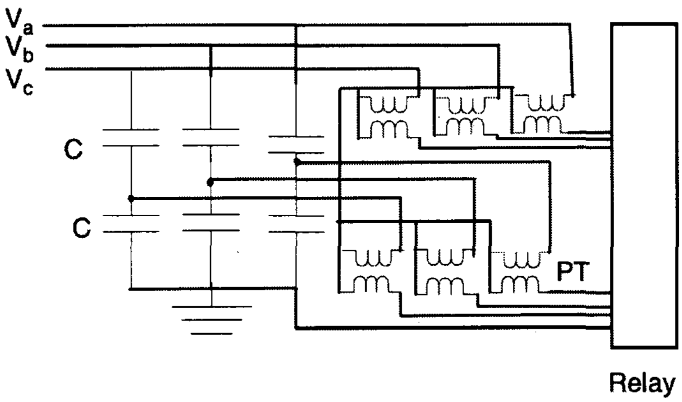


Figure 2-19: Voltage difference detection method

The main disadvantage is that six voltage transformers are required and extensive connections are also needed.

2.3.3.5. Neutral Voltage Unbalance Protection in Ungrounded Star Banks (ANSI 59NU)

Using a voltage transformer connected between the neutral and the ground, any neutral voltage shift due to the failure of a capacitor unit is sensed (Figure 2-20). The unbalance protective scheme consists of a time-delayed voltage relay with third harmonic filter connected across the secondary of the PT. The voltage transformer for this application should be rated for full system voltage because the neutral voltage can be expected to rise above the rated voltage during certain switching operations. The advantages of this scheme are:

1. The capacitor bank contains twice as many parallel units per series group compared to a split-star bank. The overvoltages seen by the remaining units in a group in the event of a fuse operation will be less.
2. This capacitor bank may require less substation area and connection in the power circuit.
3. This scheme is less sensitive to system unbalance.

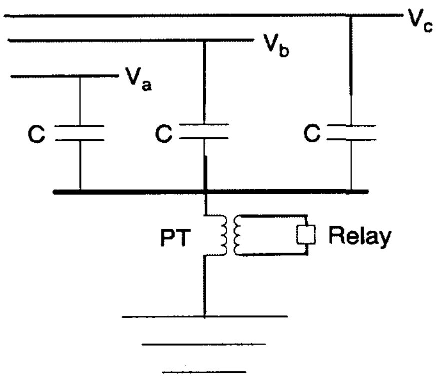


Figure 2-20: Neutral voltage unbalance detection

2.3.3.6. Neutral Voltage Unbalance Protection Method for Ungrounded Banks Using Voltage Divider

This scheme is similar to the PT scheme shown in Figure 2-21. A conventional inverse time voltage relay is connected across the grounded end capacitor. The grounded capacitor is a low voltage unit, 2.4kV or less, sized to provide the desired unbalance voltage to the relay. In the event of one phase open, the voltage in the neutral relay exceeds the short time rating and a limiter has to be used. This protection has the same advantages and disadvantages as the previous one.

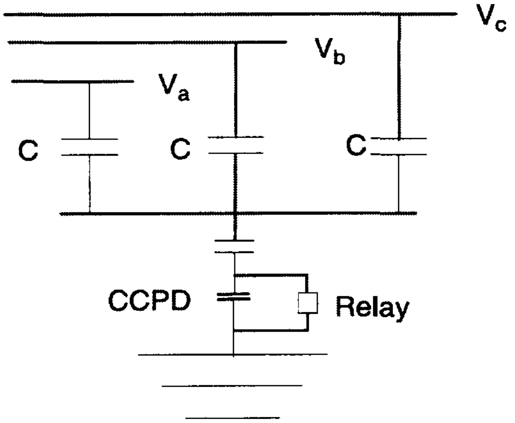


Figure 2-21: Using a capacitive voltage divider for unbalance detection

2.3.3.7. Neutral Voltage Unbalance Detection Method for Ungrounded Star Banks Using Three PTs

This protection scheme uses three lines to neutral PTs with the secondary connected in the broken delta and an overvoltage relay (Figure 2-22). This scheme has advantages similar to Scheme 5. This scheme is sensitive to triple harmonics and is expensive.

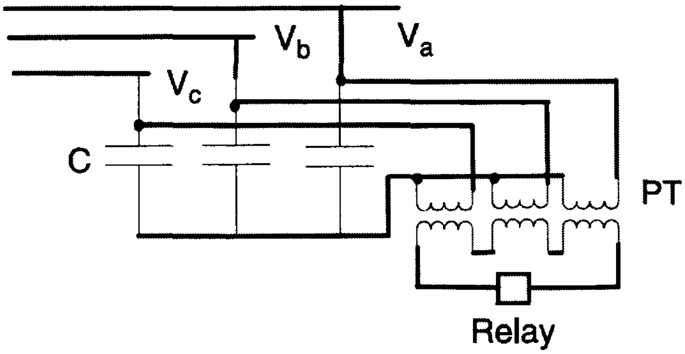


Figure 2-22: Line-to-neutral voltage summation

2.3.3.8. Neutral Current Unbalance Detection Method for Ungrounded Split-Star Banks (ANSI 60N)

In this protection scheme, a current transformer is used in the neutral circuit to identify the unbalanced current (Figure 2-23). An overcurrent relay can be used to provide an alarm or trip signal. The scheme is not sensitive to system unbalance. The scheme is sensitive to detection of capacitor unit outages and is not affected by the harmonic currents. This scheme contains only one CT and a relay. The disadvantages of this scheme are an increase in the overvoltages per unit because there are fewer parallel units per series group. The scheme requires more substation area compared to a star connected capacitor bank.

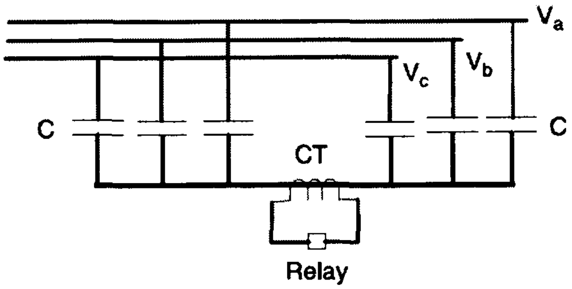


Figure 2-23: Unbalance detection method using neutral current sensing

2.3.3.9. Neutral Voltage Protection Method for Ungrounded Split-Star Banks

This scheme is similar to 2.3.3.8 (Figure 2-24) as the sensor is a PT. This scheme is not sensitive to system unbalance, but it is sensitive to unit outage and is relatively inexpensive. The split-star may require more substation area.

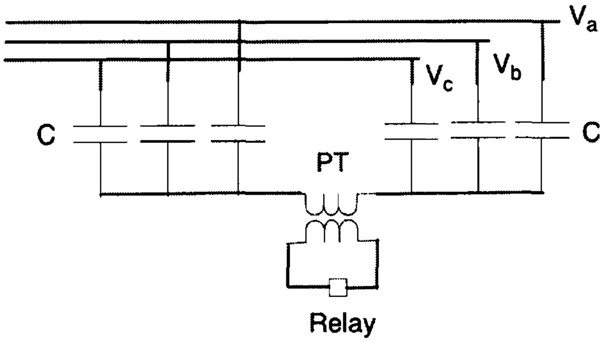


Figure 2-24: Unbalance detection method using a PT

2.3.3.10. Neutral Voltage Unbalance Protection Method for Ungrounded Split-Star Banks

This scheme (Figure 2-25) is not sensitive to system unbalance, but it is sensitive to unit outage and is relatively inexpensive.

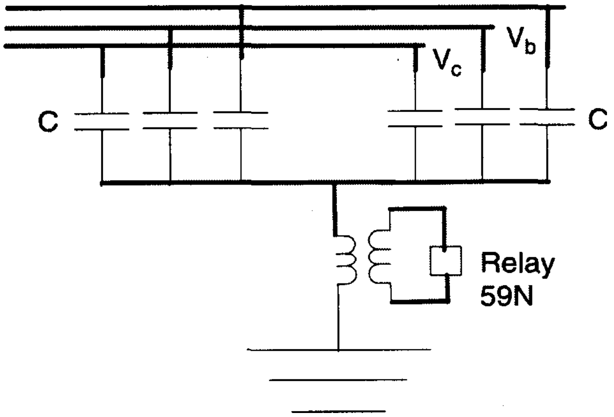


Figure 2-25: Unbalance detection using a neutral voltage sensing method

Chapter Three

3. Grounding in Power Systems

Most power system engineers at some point will face the decision about grounding an electrical system and planning or modifying the distribution. Grounding at some levels is generally recommended, although exceptions exist. There are several methods and criteria for ground the system [6].

3.1. Ground Connection in Power Systems

3.1.1. Ungrounded Systems

Ungrounded power systems have no intentional grounding. However, there is always a natural capacitance from the system to the ground. Therefore, the ground fault current level is lower and the equipment damage would be minimal. Moreover it is not necessary for the faulted section to be isolated rapidly. This is an advantage for industrial systems where a high continuity of service is important to minimize interruptions of expensive production processes. However, ungrounded systems are subject to high and destructive transient overvoltages and can pose a danger to equipment and personnel.

Single phase to neutral faults in such systems can escalate the voltage at neutral point (Figure 3-1). The small currents flowing through the series phase impedances will cause a very slight distortion of the voltage triangle, but practically, it is as shown in Figure 3-1b.

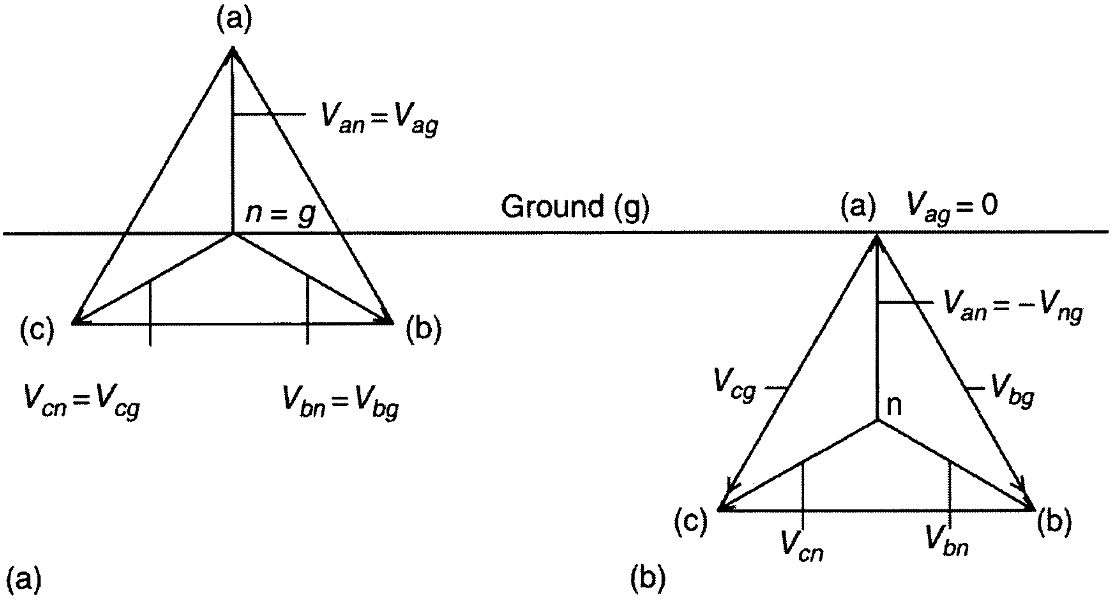


Figure 3-1: An ungrounded system (a) Normal Condition, (b) Voltage shift (fault in Phase a)

3.1.2. Resonant Grounding Systems

These systems are also known as ground-fault neutralizer or "Petersen coil" systems. In these systems, all the capacitive inductance existing between the neutral point and the ground is cancelled by an equal reactive inductance connected in the neutral point (Figure 3-2). If the neutral reactor is tuned correctly, the fault current would be zero. But practically the reactors are tap-tuned; therefore, the fault current would be very small but not zero.

In distribution systems, however, it is difficult to tune the reactor with system changes and switching regularly. Since, the circuit is a series resonant, high voltages may appear across the reactor and capacitance. The system must be able to tolerate full line-to-line voltage. A large number of line-to-line faults may occur.

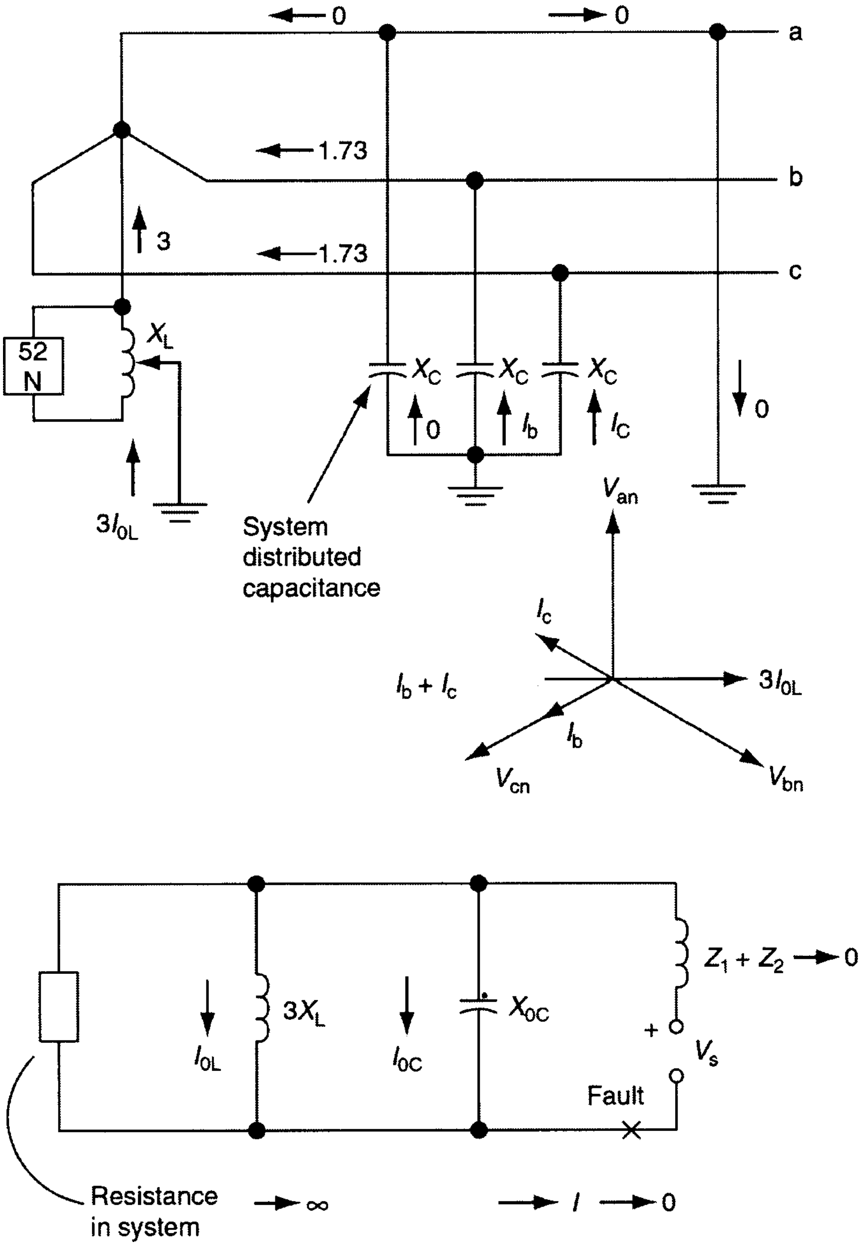


Figure 3-2: Resonant grounding

This technique is mainly used to ground unit generators, as the system capacitance has a fixed value and distances are short. This will cause the fault current to be very low and guarantees maximum continuity of operation for generators.

3.1.3. High-Resistance Grounding Systems

In this system, the power system is grounded via a resistance. Common practice to select the value of the resistor is to make it equal or slightly less than the total system capacitive inductance. The fault current and therefore the damage would be minimal; moreover, the transient overvoltages become less than 2.5 times the normal crest value to ground. The fault current range normally encountered with this method is between 1 and 25A primary, which is usually between 1 and 10A.

The grounding resistor can be connected in the neutral of a generator or a transformer (Figure 3-3). With the resistor in the neutral, a solid ground fault can produce a maximum V_0 equivalent to the phase-to-neutral voltage. Therefore a transformer with line-to-neutral voltage should be used, although line-to-line ratings have also been used.

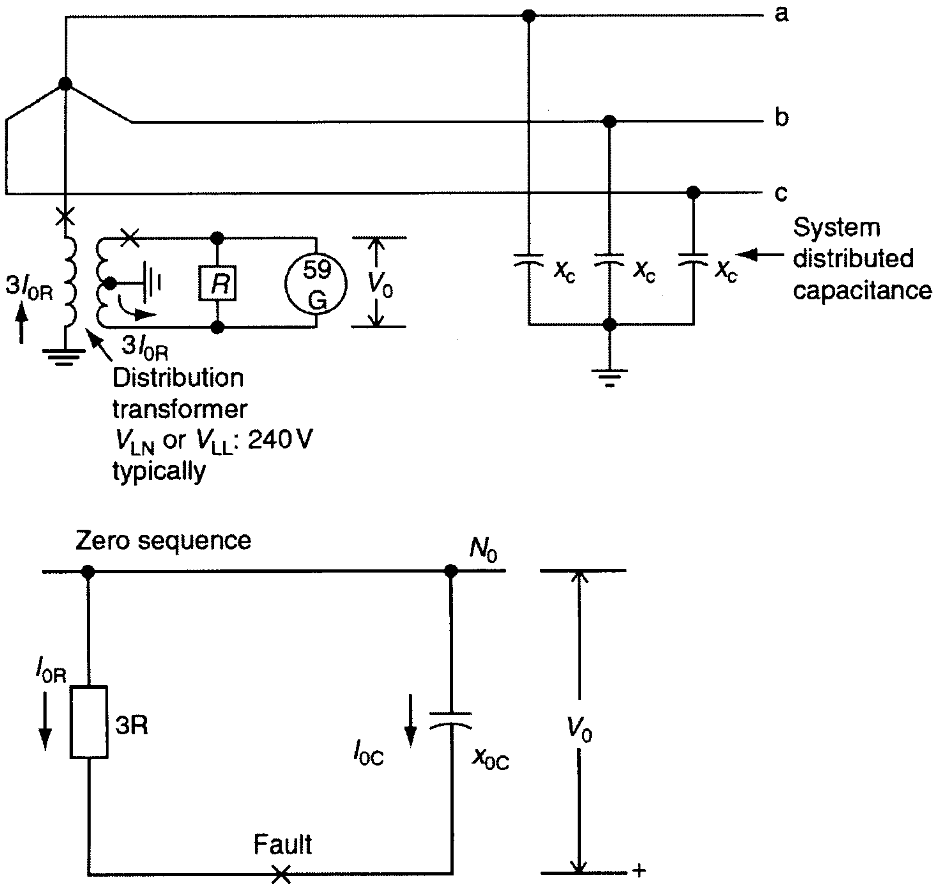


Figure 3-3: High-resistance grounding with resistor in neutral

3.1.4. Low-Impedance Grounding

This type of grounding can limit the fault current to approximately 50 to 600A primary. It is primarily used to limit the fault current, yet it permits selective relaying by magnitude differences in fault current by the power system impedances. This configuration has cost advantages due to line-to-neutral equipment insulation as the voltages on healthy phases are not increased significantly in case of a ground fault. Most typically, this type of grounding is accomplished by a reactor or resistor in the system neutral (Figure 3-4). In a distribution station it would be in the neutral of the delta-star supply transformer. Several generator units that are connected to a common bus may be grounded in this manner.

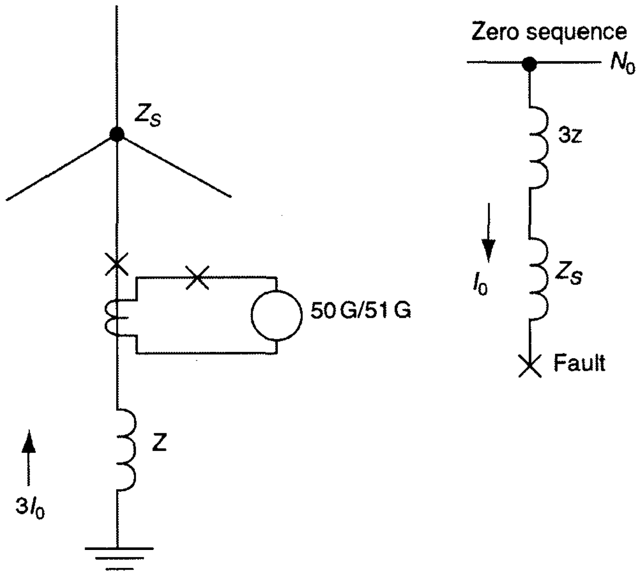


Figure 3-4: Low-impedance grounding with impedance in neutral

3.1.5. Solid (Effective) Grounding

Effective grounding is defined by ANSI/IEEE standards (IEEE 100) when the power system constants are:

$$\frac{X_0}{X_1} = 3\% \text{ and } \frac{R_0}{X_1} = 1\%$$

Where X_0 and R_0 are the zero-sequence reactance and resistance and X_1 the positive-sequence reactance of the power system. Practically, this indicates that there can be no impedance between system neutral and ground; hence, these systems are solidly grounded. Usually, this is accomplished by connecting the neutral of the star windings of the power transformer(s) to the station ground mat and ground. As a result the ground-fault currents can vary considerably, from very small currents to currents greater than the three-phase-fault value. The magnitudes depend on the power system configuration and constants, location of the fault, and the fault resistance, which may or may not be significant. Because the current level can vary with the fault location, it becomes easier to locate the fault and selectively isolate the trouble area by protective relays. The CTs are used to operate time-overcurrent relays that are set sensitively and with time to coordinate with the various lines, feeders, and so on, relays that they "over reach". Hence, this serves as backup and "last resort" protection for ground faults around the areas that are not properly cleared by their primary and associated backup protection.

3.1.6. Safety Grounding

Power stations and substations for either utilities or industrial plants are built on ground mats. These are carefully designed to provide minimum voltage drops across mat in all directions (step and touch potentials) and minimum impedance between mat and true earth or remote ground (ground potential rise). The primary aim is to reduce and minimize electric shock potentials for personnel safety. These designs are a specialized field and are beyond our scope of discussion. Standard IEEE 80 is the basic guide for this area. All equipment frames within the ground-mat area in these stations must be solidly bonded to the mat. This includes all exposed metallic parts of relays, relay switchboards, fences, secondary wiring, and so on. Thus, all secondary circuits from the CTs and PTs are grounded. There should be only one ground in the circuit, and the general practice favours grounding at the switchboard or relay house. Multiple grounds may short-out relay(s) and prevent proper clearing of a fault, and may cause secondary wiring damage. A ground in the yard and another in the switch-house place the secondary wiring in parallel with the ground mat, so that part of the heavy fault current can directly flow in the secondary winding to either damage related facilities or cause a misoperation. Only one ground in the circuit is sufficient to minimize any electrostatic potential.

If any equipment cannot be properly grounded, it should be carefully isolated from all contact with the concerned personnel. Special care must be taken for equipment that is associated with both the station and the remote ground (transfer potential). Electromagnetic induction should be minimized by design with the station. In areas involving electrical equipment where a ground mat is not possible or practical, safety must be carefully examined. Although many diverse factors are involved, it appears that the average or reasonable resistance of a human being is from 1000 to 2000Ω foot-to-foot and 500 to 1000Ω foot-to-arm, and these limits are general.

3.2. Substation Grounding

The substation grounding system is an essential part of the overall electrical system. The proper grounding of a substation is important for the following two reasons [1]:

1. It provides a means of dissipating electric current into the earth without exceeding the operating limits of the equipment.
2. It provides a safe environment to protect personnel in the vicinity of grounded facilities from the dangers of electric shock under fault conditions.

The grounding system includes all of the interconnected grounding facilities in the substation area, including the ground grid, overhead ground wires, neutral conductors, underground cables, foundations, deep well, etc. The ground grid consists of horizontal interconnected bare conductors (mat) and ground rods. The design of the ground grid to control voltage levels to safe values should consider the total grounding system to provide a safe system at an economical cost.

It is often assumed that any grounded object can be safely touched. A low substation ground resistance is not, in itself, a guarantee of safety. There is no simple relation between the resistance of the grounding system as a whole and the maximum shock current to which a person might be exposed. A substation with relatively low ground resistance might be dangerous, while another substation with very high ground resistance might be safe or could be made safe by careful design.

There are many parameters that have an effect on the voltages in and around the substation area. Since voltages are site-dependent, it is impossible to design one grounding system that is acceptable for all locations. The grid current, fault duration, soil resistivity, surface material, and the size and shape of the grid all have a substantial effect on the voltages in and around the substation area. If the geometry, location of ground electrodes, local soil characteristics, and other factors contribute to an excessive potential gradient at the earth surface, the grounding system may be inadequate from a safety aspect despite its capacity to carry the fault current in magnitudes and durations permitted by protective relays.

During typical ground fault conditions, unless proper precautions are taken in design, the maximum potential gradients along the earth surface may be of sufficient magnitude to endanger a person in the area. Moreover, hazardous voltages may develop between grounded structures or equipment frames and the nearby earth.

The circumstances that make human electric shock accidents possible are:

- Relatively high fault current to ground in relation to the area of the grounding system and its resistance to remote earth.
- Soil resistivity and distribution of ground currents such that high potential gradients may occur at points at the earth surface.
- Presence of a person at such a point, time, and position that the body is bridging two points of high potential difference.
- Absence of sufficient contact resistance or other series resistance to limit current through the body to a safe value under the above circumstances.
- Duration of the fault and body contact and, hence, of the flow of current through a human body for a sufficient time to cause harm at the given current intensity.

Relative infrequency of accidents is largely due to the low probability of coincidence of the above unfavourable conditions. To provide a safe condition for personnel within and around the substation area, the grounding system design limits the potential difference a person can come in contact with to safe levels. IEEE Std. 80, IEEE Guide for Safety in AC Substation Grounding, provides general information about substation grounding and the specific design equations necessary to design a safe substation grounding system. The following discussion is a brief description of the information presented in IEEE Std. 80. The guide's design is based on the permissible body current when a person becomes part of an accidental ground circuit. Permissible body current will not cause ventricular fibrillation, i.e., stoppage of the heart. The design methodology limits the voltages that produce the permissible body current to a safe level.

3.3. Shunt Capacitor Bank Ground Connection

Similar to any power system equipment, capacitor banks can either be grounded or ungrounded. Advantages of the grounded capacitor banks include [7,8]:

- The low-impedance path to ground provides inherent self-protection for lightning surge currents and gives some protection from surge voltages. Banks can be operated without surge arresters taking advantage of the capability of the capacitors to absorb the surge.
- They offer a low impedance path for high frequency currents and so they can be used as filters in systems with high harmonic content. However, caution shall be taken to avoid resonance between the shunt capacitor bank and the system.
- Reduced transient recovery voltages for circuit breakers and other switching equipment.
- The initial cost of the bank is lower, as the neutral does not have to be insulated from ground at full system BIL, as in the case with floating neutral arrangements.
- Capacitor switch transient recovery voltages are reduced since the neutral is grounded and the bank is switched as three single-phase sections.
- The collapse of voltage across a failed unit in ungrounded capacitor banks pulls the floating neutral to phase voltage. The neutral shift stresses the capacitors on healthy phases to 1.73 times of their rating [9].

Some drawbacks for grounded capacitor banks are:

- Increased interference on telecom circuits due to harmonic circulation.
- Circulation of inrush currents and harmonics may cause misoperations and/or over-operation on protective relays and fuses.

- Injection of high amplitude currents such as lightning, switching, and fault may cause dangerous touch/step voltages causing danger to on-site personnel and crew.
- It provides a low-impedance fault path to ground. For this reason, grounded-star banks are not applied to ungrounded systems.
- System fault current flows through a failed unit (single series group).

3.4. Summary

In this chapter, grounding in power system is discussed. Different types of grounding such as resonant, high-resistance, low-impedance, solid, and safety were introduced. Then substation grounding was explained and finally grounding configurations for shunt capacitor banks were discussed. The advantages/disadvantages for each configuration were explained. In the next chapter the works already done in this field as well as the proposed method to address the problem at hand is presented.

Chapter Four

4. Analysis Methods (Previous works as well as the proposed method)

There are many different kinds of circuits close to each other in a power substation. These include high-voltage buses, current transformers, capacitive voltage transformers, control/signal cables, and station ground grid. Any transients such as lightning, switching, or faults with high frequency oscillations can propagate through the entire high-voltage circuit and give rise to transient electromagnetic field in the substation. If another cable (control/signal cable) runs in parallel with the high-voltage bus, a significant amount of transients can be induced on the low-voltage cable. Several studies have been done dealing with different transients such as lightning, switching [10], and faults. These studies have considered generic substations not necessarily with the presence of capacitor banks.

4.1. Control/Signal Cable Grounding

An approach [10] was suggested by H. Ke, et al to calculate the induced voltage both in steady-state (single frequency) and transients (multiple frequencies). The proposed algorithm is a combination of works done by Carson [11] and the Fourier Transformation to calculate the induced voltage between parallel lines.

Four cases were simulated. In the first case, neither of the ends was grounded. In the second case both ends were grounded. In the third and fourth case only one end was grounded.

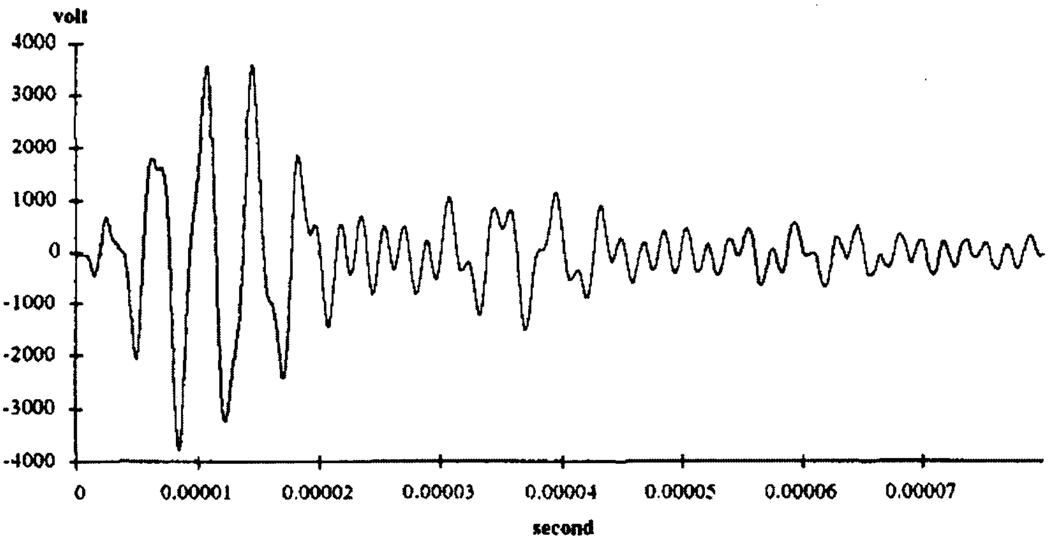


Figure 4-1: Sending voltage for first case (neither of the ends is grounded) [10]

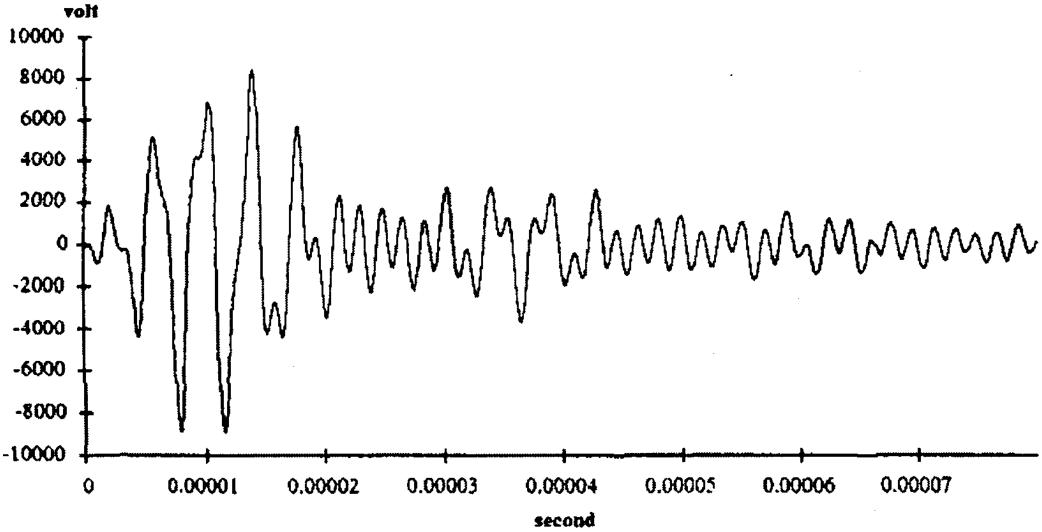


Figure 4-2: Receiving voltage for first case (neither of the ends is grounded) [10]

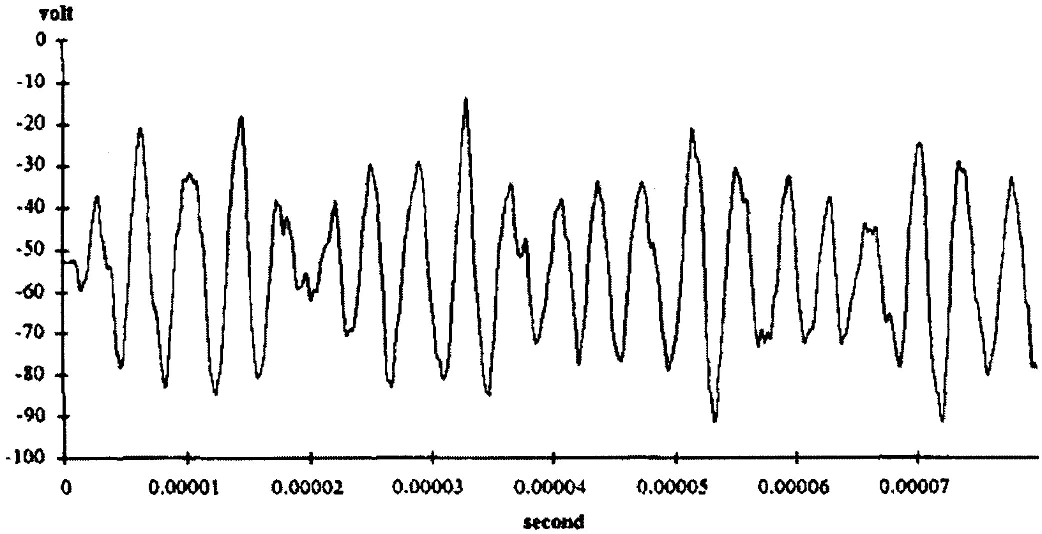


Figure 4-3: Sending voltage for second case (both ends are grounded) [10]

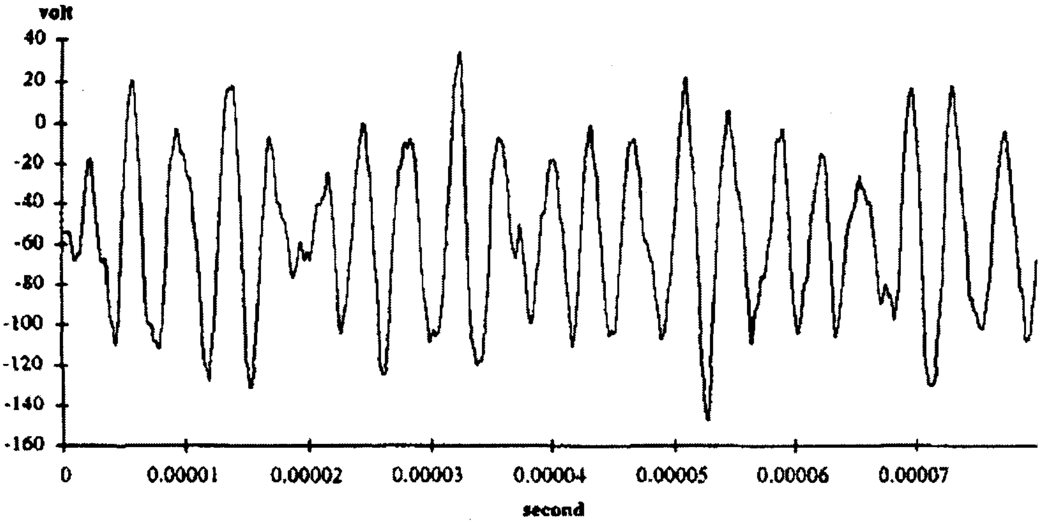


Figure 4-4: Receiving voltage for second case (both ends are grounded) [10]

Due to the complex nature of the phenomena and uncertainty of the switching arc during switching, magnitude mismatches between computer simulation and field tests were observed. When neither of the ends is grounded, the induced voltage at both ends is quite large (Figure 4-1 and Figure 4-2). If the sheath is only grounded at one end, the voltage on the grounded end is small and the voltage on the other end would still be very large. When the sheath is grounded at both ends, the induced voltage at both ends is small (Figure 4-3 and Figure 4-4). If shielded cables are used to provide voltages for relays and meters, the sheath is normally grounded at one end. However, when the presence of an electromagnetically induced voltage is a problem, one solution commonly used is to ground both ends of the cable sheath.

When the cable sheath is grounded at both ends of the cable, an alternate means must be provided for power fault currents. During a power fault involving the station ground, voltage differences will exist between different points on the ground. If an alternate ground path is not provided for the shielded cable, the cable sheath could be fused causing a loss of shielding from EMI.

4.2. Analysis Methods

Different methods are discussed here:

1. Field tests
2. Mathematical methods
3. Mutual inductance
4. Distributed parameters of a control cable

4.2.1. Field Test

H. Ke, et al [10] in 1997 did some field tests in a substation. During the test, the cables were intentionally put on the ground level and in parallel or perpendicular to the transmission lines. Furthermore, the sheaths of the cables were grounded with different methods. The induced voltages under different grounding methods were observed and recorded. There was some mismatch between the results from computer simulation and those of field testing. This has been attributed to the complex phenomena of arcs during the switching. However, the trend indicated in both studies is the same. If the sheath is only grounded at one end, the voltage on the grounded end is small and the voltage on the other end would be very large. When grounded at both ends, the sheath experiences low induced voltage. Cables carrying signals for meters and relays are normally grounded at one end only. However, in the presence of EMI voltage, a solution would be to ground the control cable at both ends (see Section 4.1).

C.S. Barrack, et al [12] in 1997 placed several antennas in a test substation to measure the EMI caused by transients such as switching. Previous similar studies have shown typical field strengths of greater than 50kV/m and up to 35 A/m in a 500kV substation with significant frequency components up to 200MHz. This study measures E and H-fields with frequency components up to 200MHz. It was established that EMC test antennas are mainly suitable for low-intensity fields with a limited instantaneous bandwidth. Optical sensors are very helpful for voltage and current measurement and can be used to measure high fields. The large bandwidth required for switching transient measurements often makes it difficult to achieve high sensitivities. Broadband sensors can provide the required frequency response and dynamic range.

4.2.2. Mathematical Methods

To predict the transients induced in control cables under the ground during transients such as lightning, A. Sowa and J. Wiater in 2004 employed a mathematical method [13]. The conductor is partitioned into small segments; therefore, the current is assumed to be linear along the segment for all frequencies. This method uses thin wire approximation. Each segment is represented as an electric dipole. Then the field of a single dipole is described as the sum of the source term, the image term, and the Sommerfeld integral. The Sommerfeld integrals are numerically calculated.

It is concluded that the direct lightning strike to the grounded components of an HV substation can cause severe interference problems in electronic equipment and systems. Furthermore, without the proper surge protection, the magnitude of lightning transients in control cables can reach values dangerous for electronic equipment.

4.2.3. Mutual Inductance

H. Ke, et al [10] used EMTP in order to do simulations and obtain the voltage induced on a typical control cable. This was done for both steady-state and transient situation. In transient situation the shape of the surge current was simulated using a current with this waveform:

$$i(t)=k\left(e^{-at}-e^{-bt}\right) \text{ whereas } a>0, b>0, a<b$$

In their paper, they conducted the simulation in different scenarios where either ends or one end of the control cable sheath was grounded and ungrounded.

Y. Gang, et al [18] investigated different configurations where none of the ends, one of the ends, or both ends of the sheath on the control cable has been grounded. The transient considered in their study is short circuit current. When the short circuit current is injected into the grounding grid of a substation, the potential distribution of the grounding grid is not uniform and there is a potential difference between the two connecting points of the control cable's metal shield to the grounding grid. The transient current will flow through the shielding sheath of secondary cables. Also, an interference current through the sheath of the cable is induced from the bus and conductors of the grounding grid buried in the earth through mutual inductance. The current through the shielding sheath of the control cable would generate an interference voltage in internal core wires of the secondary cables.

The interference potential on the core of the control cable is calculated by a two-step method. First the sheath of the control cable is considered as a parallel conductor with the conductors of the grounding grid. The current through the sheath of the control cable is then analyzed considering the equivalent model of the control cable, and the coupling potential on the core of the control cable from the sheath is obtained.

Three cases are investigated in this paper:

1. The short circuit current with 1kA magnitude is injected into the centre point of the grounding grid. The soil resistivity is 500Ωm, the mesh size of the grounding grid is 10m by 10m, and the length of the control cable is 100m. The induced current is 0.18A.
2. The fault current is injected into the grounding grid from the corner point of the grounding grid then the magnitude of the current through the sheath of the control cable is 29A.
3. The fault current is injected into the grounding grid from the corner point. The soil resistivity is 2000Ωm and the length of the control cable is 1000m. The magnitude of the induced current into the sheath is 19.4A.

This method determines the current induced on the sheath of the control cable. The radius of the core in this paper was considered to be 3.38mm, the resistivity to be

$1.84 \times 10^{-8}\,\Omega.m$, the relative dielectric constant to be 3.2, and the outer radius of the insulation is 5.07mm. The wire voltage and current induced by the shield current can be calculated using transmission line equations.

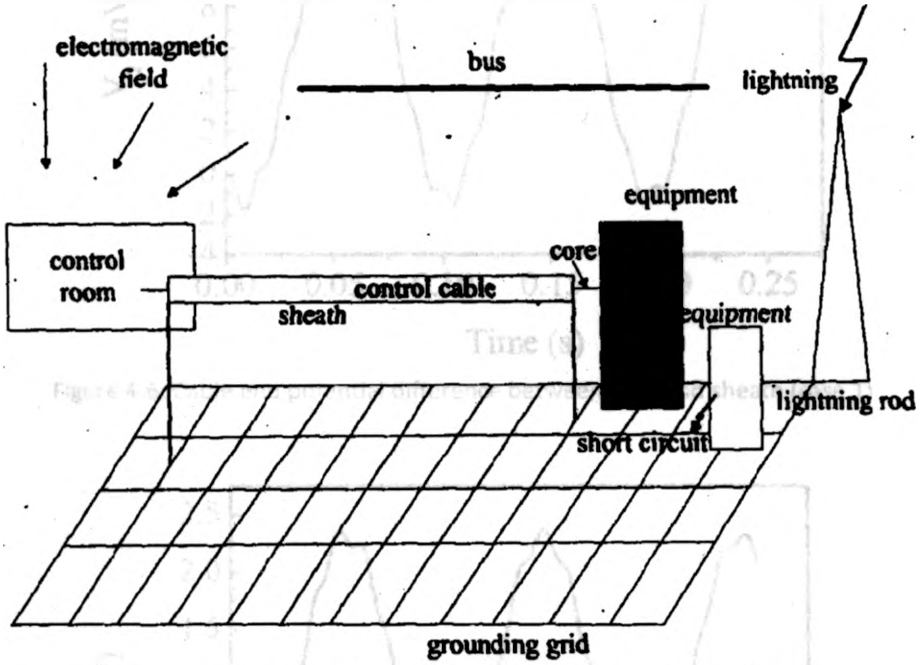


Figure 4-5: Electromagnetic interference on control cables

In the first case, the potential difference between core and sheath at the end of the control cable is shown in Figure 4-6. In case 2, the potential difference between core and sheath at the end of the control cable is shown in Figure 4-7. In case 3, the potential difference between core and sheath at the end of the control cable is shown in Figure 4-8.

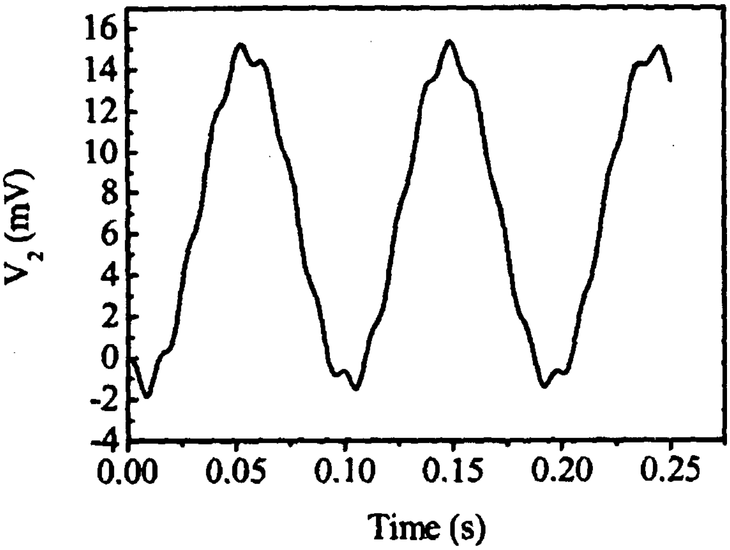


Figure 4-6: Cable end potential difference between core and sheath (case 1)

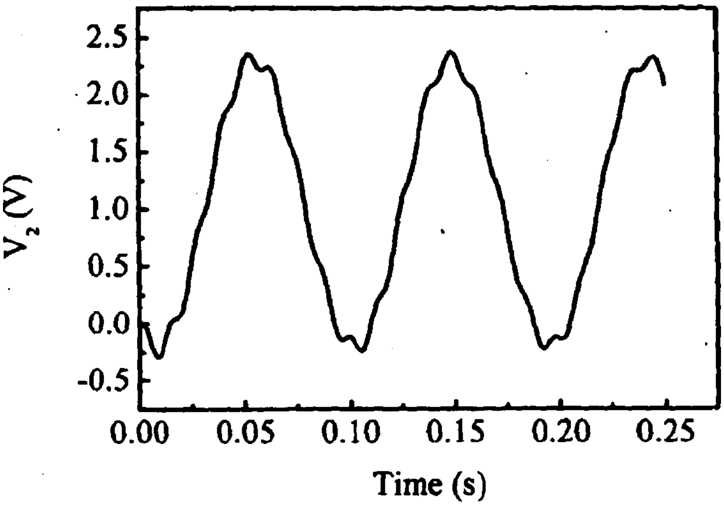


Figure 4-7: Cable end potential difference between core and sheath (case 2)

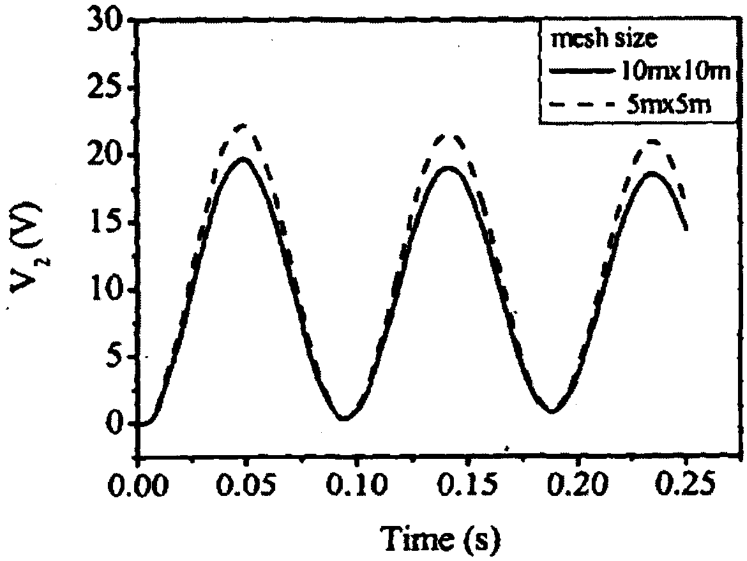


Figure 4-8: Cable end potential difference between core and sheath (case 3)

C.W. Wiggins measured and predicted cable current and voltage transients in systems ranging from 115kV to 500kV for switching transients [16]. They investigated the generation of high-frequency EMI due to switch and breaker operation. It was also established that such transients can be characterized by micro pulses and macro bursts. A micro pulse is a transient waveform resulting from a single flashover in a switch or breaker and usually lasts for several microseconds. A macro burst is a sequence of several micro pulses during the operation of a switch or breaker which can last from several milliseconds to a few seconds.

A software code was developed to calculate transients of field-induced currents on the shields of the control cables. This code uses a frequency domain admittance-based transmission line model. The code allows for multiple-segment models of secondary cables whereas each segment of the model may be driven by a unique position-dependent radiated field. The electric fields parallel to each segment are integrated to obtain source currents at the nodes of the model. At each frequency the admittance matrix for the multi-segment model (dependent on geometrical and ground parameters) is inverted to develop node voltages for all frequencies. Using these voltages, transient shield currents/voltages can be calculated anywhere along any segment. The currents predicted with the aforementioned code can be used for transfer impedance and inductive coupling to relays. It is assumed that the conductors are shallowly buried. This method was used for simulations in PSCAD® and the output COMTRADE files were used to generate signals to be fed to the relay (see next chapter).

4.2.4. Distributed Parameters of a Control Cable

The second method is called distributed parameters of a control cable in the literature [18] (see Figure 4-9). The values of capacitors in this model are 13nF, resistors are 0.0003Ω, the self inductance is 1mH, and the mutual inductance is 0.3mH for 1km length of the control/signal cable. Calculation of the model parameters is brought in Appendix B. The transient current is fed to this circuit in order to obtain the induced voltage between the sheath and the core of the control cable. This method was used for simulation in MATLAB® Simulink®. As Simulink is not able to generate output with COMTRADE format, this method was not used to generate signals to be fed to the relay.

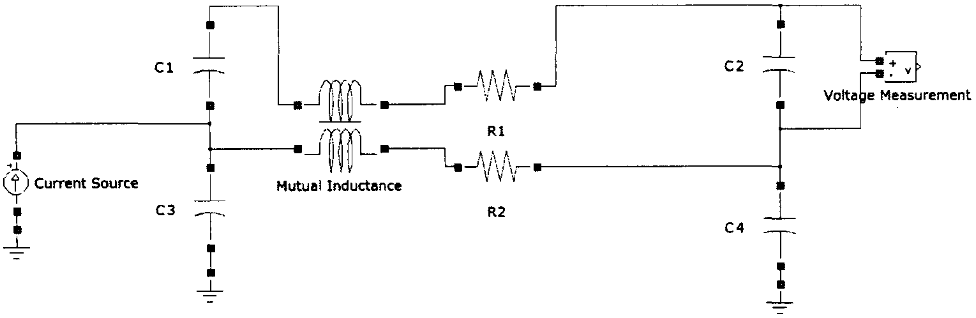


Figure 4-9: Distributed parameters of a control/signal cable

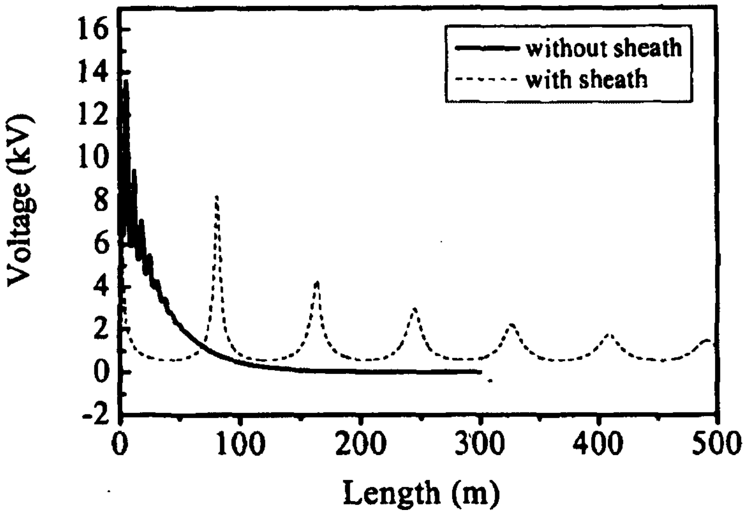


Figure 4-10: Control cable core potential with CT coupling

4.3. Proposed Method

In this section the proposed methods for the current problem are discussed. Two methods are to be considered; the first method involves mutual inductance and the second method uses the distributed parameters of a control/signal cable. As seen from the results in the next chapter, the second method has less accuracy compared to the first method.

The first method is a modified version of the method introduced in Section 4.2.3. In this method, the two steps are merged into one step thus reducing the computing burden to calculate the induced current. Furthermore, computation time is reduced. The worst case is assumed where the control cable is running in parallel with the ground conductors for a length of about 100m. The ground mat is considered to be a simple conductor and the transient current is assumed to have been injected in the vicinity of the control cable, again to assume the worst case. The grounding grid is magnetically isolated from the core of the control cable; however, the cable sheath has mutual inductance with grounding grid which in return will induce currents unto the core. The transients in the core have two major components:

1. Transients coming directly from measurement devices such as current or potential transformers. The transients in the system will propagate to the entire substation

and along the way will find their way into measurement devices. These transients depend on the frequency response of the measurement transformers.

2. Transients coming from induction of ground mat transients unto the control cable sheath and then to the core. These transients can be calculated using either of the methods introduced in the previous section.

The second method uses the distributed parameters of a control/signal cable. In this case, it is assumed that the control cable runs in parallel with the ground mat for about 1km. This causes the transients to be more significant than the previous case. Again, the signal on the control/signal cable has two components as mentioned before. The obtained signal is then fed to a commercial relay and various protection schemes are tested to verify the effect of induction on the relay's decision making.

Summary

In this chapter several methods to obtain the effect of transients on control/signal cables have been introduced.

One of those with more accurate results is selected. Furthermore, an alternative method was proposed which is used in this text. Next chapter produces the obtained results using the proposed method.

Chapter Five

5. Simulation Results and Relay Testing

The simulation part is divided into several sections, as each merits its own attention and is done using different types of simulation. The first part of this chapter deals with short circuits occurring in shunt capacitor banks in ungrounded and grounded high voltage systems. The second part of the simulations tries to show the effect(s) of the short circuit currents on control/signal cables in a substation. The transients present in the phase cables have two ways of entry into the signal cables; the first is through magnetic circuits such as CTs and CCVTs, the second part is through the induction of ground mat onto cable sheath and then the cable core itself. High voltage/current transients may be induced into these cables causing the relays and other control equipment to malfunction or worse get damaged. The third part deals with transients coming from capacitor bank switching and their effect(s) on the breakers.

The substation in question has a double bus of 230kV. There are 22 transmission lines entering the mentioned bus, which make the short circuit current of the bus to be as high as 75kA. Therefore, the bus can be split in two to reduce the short circuit current and for the breakers to be able to break that current. With the intention of investigating the worst case scenario the short circuit is put on the capacitor bank directly connected to this bus.

5.1. Short Circuit in Ungrounded Systems

The schematic of the HV substation has been implemented using PSCAD 4.1.1 Educational (Figure 5-1). This model endeavours to be a close match to reality. There are five capacitor banks present in the system, two of which are installed at 230kV level and the other three are at 345kV level. Capacitor banks are equipped with current limiting reactors to limit the discharge current as well as the inrush current. To account for losses in the capacitor banks, a resistor is put in series with each phase of the bank. The typical dielectric loss in such capacitors is about 0.1watts per kvar [14], which results in a quality factor of 10,000. However there are other losses involved in a capacitor unit; therefore, a quality factor of almost 2,000 is considered for the capacitors, making the resistance value for each branch at approximately 0.5ohm.

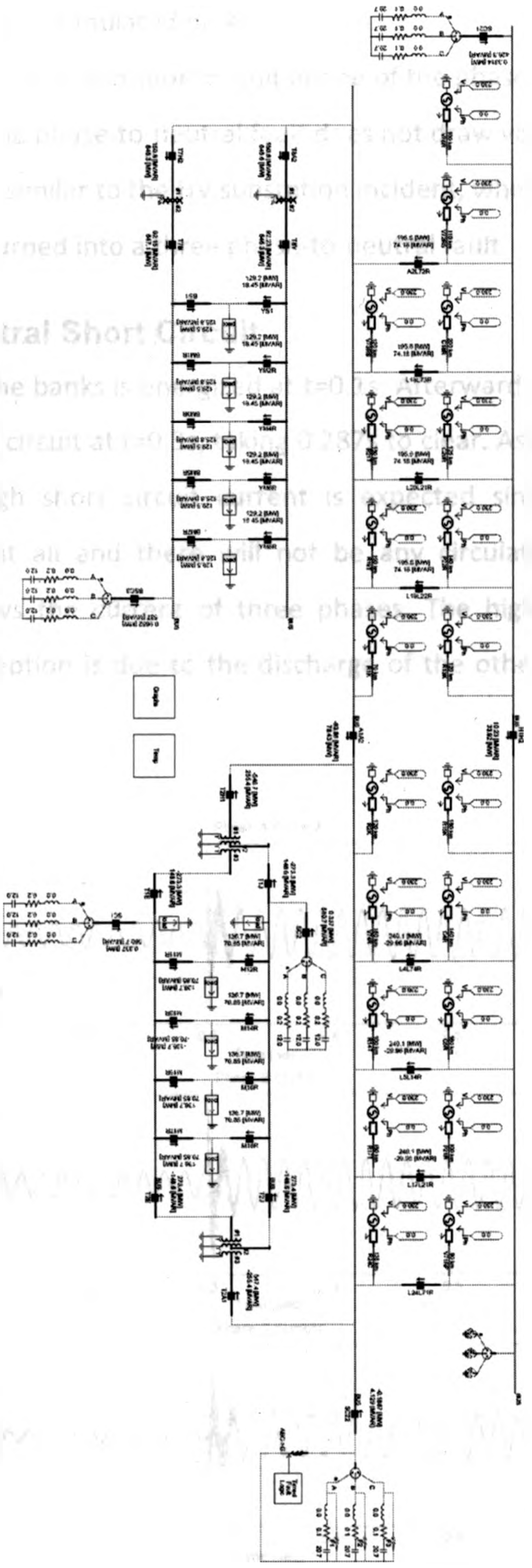


Figure 5-1: PSCAD simulation schematic

Two scenarios have been simulated here:

1. This scenario is concerned with short circuit in one of the phases and shows that in ungrounded banks, the phase-to-neutral fault does not draw very large currents.
2. This scenario is quite similar to the HV substation incident, where an initial fault (phase-to-phase) is turned into a three phase-to-neutral fault.

5.1.1. Phase-to-Neutral Short Circuit

In this case, one of the banks is energized at t=0.1s. Afterwards phase C experiences a phase-to-neutral short circuit at t=0.3s, taking 0.287s to clear. As with the ungrounded capacitor banks, no high short circuit current is expected since the bank has no connection to ground at all and there will not be any circulating current between phases. Figure 5-2 shows the current of three phases. The high-frequency transient observed after fault inception is due to the discharge of the other capacitor bank into the fault.

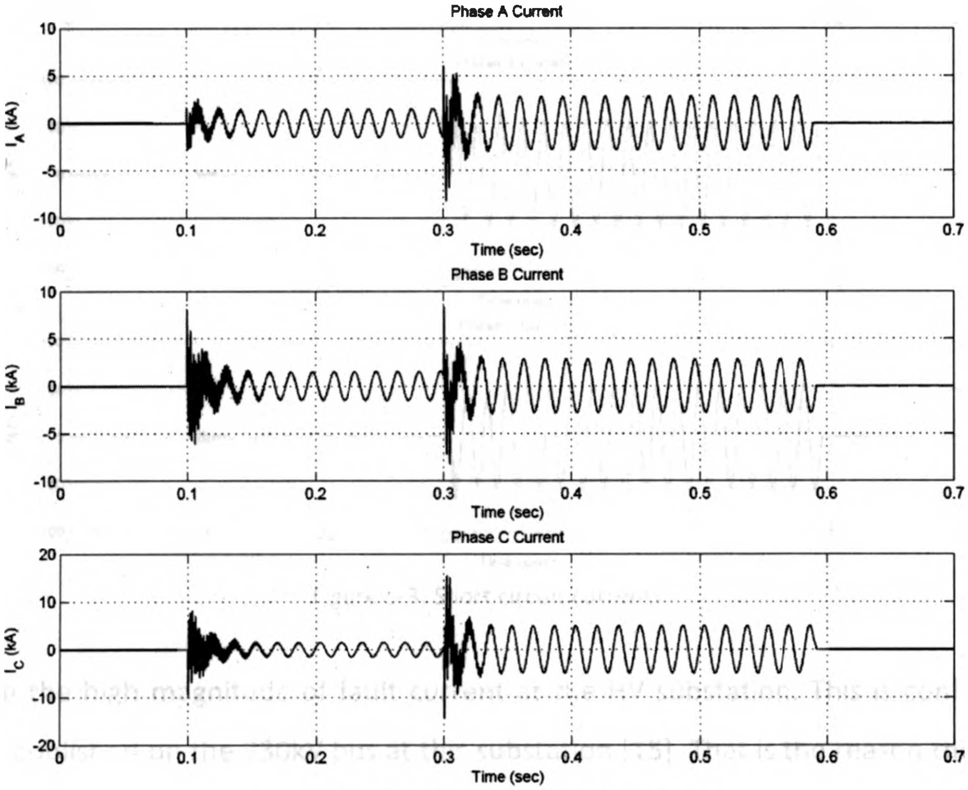


Figure 5-2: Short circuit currents

5.1.2. Phase-to-Phase Short Circuit (Similar to the Incident)

As with the incident, one of the banks is energized at t=0.1s. Afterwards, phases B and C experience the fault in t=0.3s, and after 30ms, phase A will also get shorted. After 287ms, the fault gets cleared. As a result of the short circuit in phases B and C (t=0.3s), the current in these phases starts to rise rapidly; furthermore, at t=0.33s phase A also experiences a short circuit, making the fault three-phase to neutral. Therefore, the current on phases rises until the fault is cleared at t=0.587s (Figure 5-3). Again, it is noteworthy to mention the high-frequency transient present at the beginning of each fault occurrence. In this case, where the bank is ungrounded, the mentioned high-frequency has no way of entering the ground mat and causing transient on nearby cables.

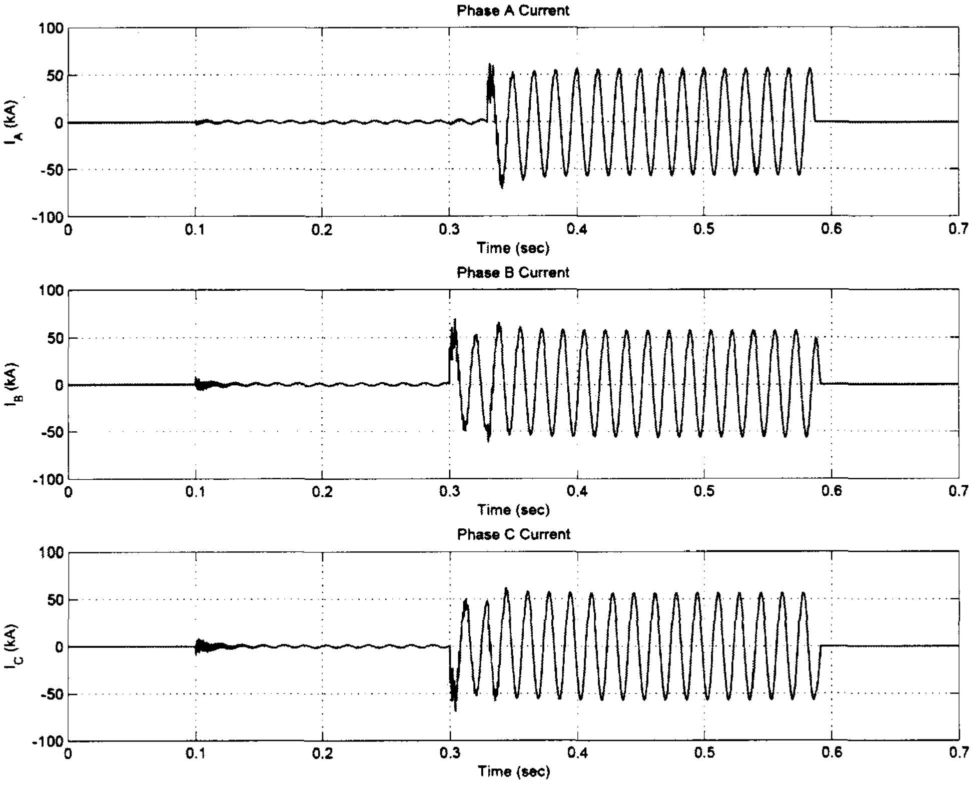


Figure 5-3: Short circuit currents

Note the high magnitude of fault current at the HV substation. This is conforms to reports published on the 230kV bus at this substation [15]. That is the reason the 230kV bus is split in two (using H1H2 and A1A2 breakers) in case of a fault. Even with the bus being split, fault currents can go as high as 63kA. The line disconnect switches have a momentary current rating of 120kA and a short duration rating of 75kA, while the breakers have a momentary current rating of 100kA and a short duration rating of 63kA.

5.2. Short Circuit in Grounded Systems

In this case, the capacitor banks are all grounded. A series of fault, similar to those of the incident, will occur. The short circuit current will be much higher than that of the ungrounded case. Also note the high-frequency content near fault inception.

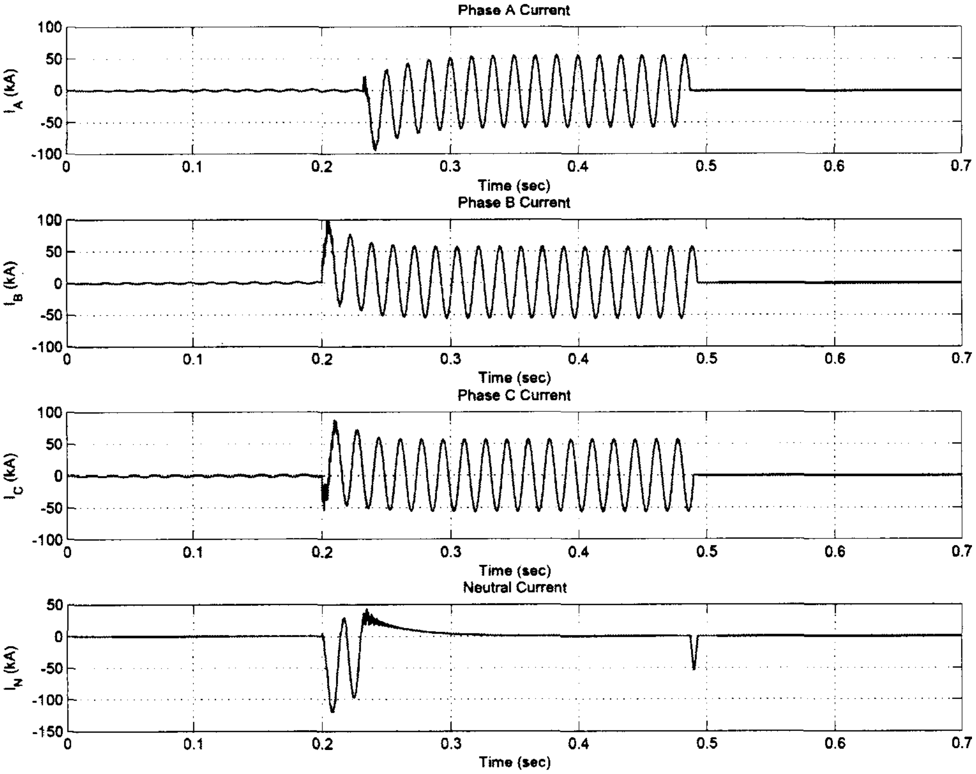


Figure 5-4: Short circuit currents injected into ground mat

5.2.1. Induced Voltages/Currents on the Control Signal Cables

Modern technology has brought us advanced control equipment and systems that nowadays are widely used in substations, but their interference withstanding capabilities have become much weaker. The control/signal cables in a substation are used for data acquisition, system control, and communication. If the control cables and their burdens are not adequately protected, transients such as short circuits and lightning can cause malfunction in the control equipment or in some cases cause damages.

The following assumptions are made:

1. The current in the power lines is available.
2. Mutual coupling capacitance between the two wires is neglected.

There are several methods available in the literature about calculating the induced voltages/currents on control cables during transients such as switching [16,17], lightning [10,13], or short circuits [18]. This thesis deals with transients resulting from short circuits.

One of the methods suggested in the literature [18] is as follows:

The induced current on the core of control/signal cable and the voltage between sheath and core is calculated in a two-step method. First, the armour of the control/signal cable is assumed to be a conductor parallel with the conductors of grounding grid. Second, the current through the armour of the control/signal cable is analyzed, and then considering the equivalent model of the control cable, the coupling potential on the core of the control cable from the armour is obtained.

This thesis tries to combine the two steps into one, thus reducing the time and effort needed to calculate the induced current on control/signal cables. In this method, the mutual inductance between the phase cable and the sheath as well as the sheath and the core is considered to be a transmission line. As can be seen from Figure 5-4, the injected current into ground mat can be as large as 100kA (SC22). This current can induce a current of about 6A on a control/signal cable (Figure 5-5). The induced current is added to the existing current on the signal cable, in this case current from CTs or voltage from CCVTs. The resistance of the lead has been assumed to be 1Ω and the resistance of the relay input is measured to be 0.62Ω. To implement this method is PSCAD the "Coupled PI Section" model is employed. The length of the signal cable parallel to the phase cable is considered to be 100 meters; this can be easily changed to accommodate different scenarios. Moreover, the induced voltage between sheath and core is shown in Figure 5-6. The spike at about 0.5s is the result of fault clearing.

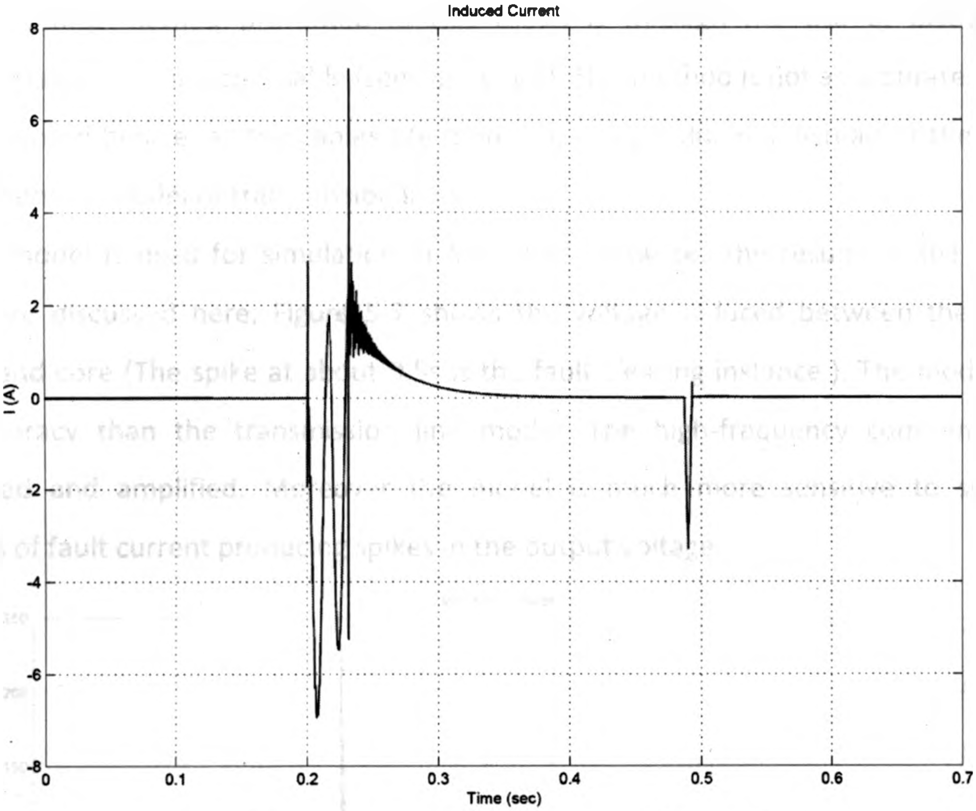


Figure 5-5: Induced current on a signal cable (first method)

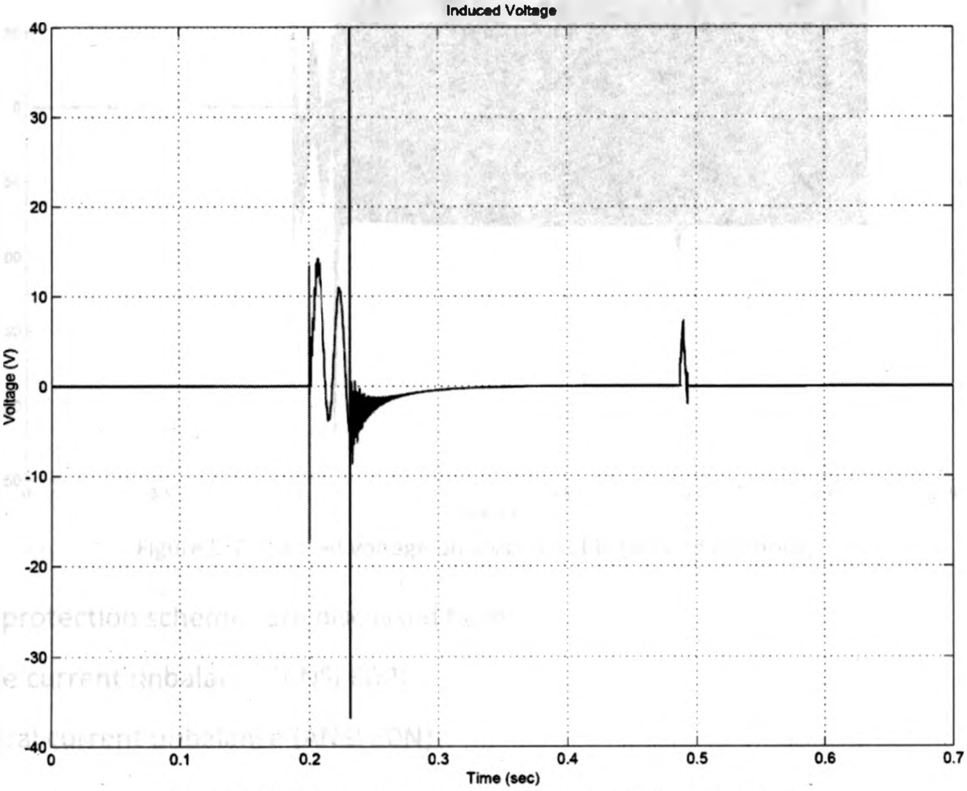


Figure 5-6: Induced voltage on a signal cable (first method)

The second method presented in this thesis is through the use of distributed parameters of control/signal cable (see Figure 4-9). This method is not as accurate as the one presented before, as the cables are modelled using inductors instead of the more comprehensive model of transmission lines.

This model is used for simulation in MATLAB® software. The results of the above model are discussed here. Figure 5-7 shows the voltage induced between the cable sheath and core (The spike at about 0.5s is the fault clearing instance.). The model has less accuracy than the transmission line model. The high-frequency component is resonated and amplified. Moreover the model is much more sensitive to sudden changes of fault current producing spikes in the output voltage.

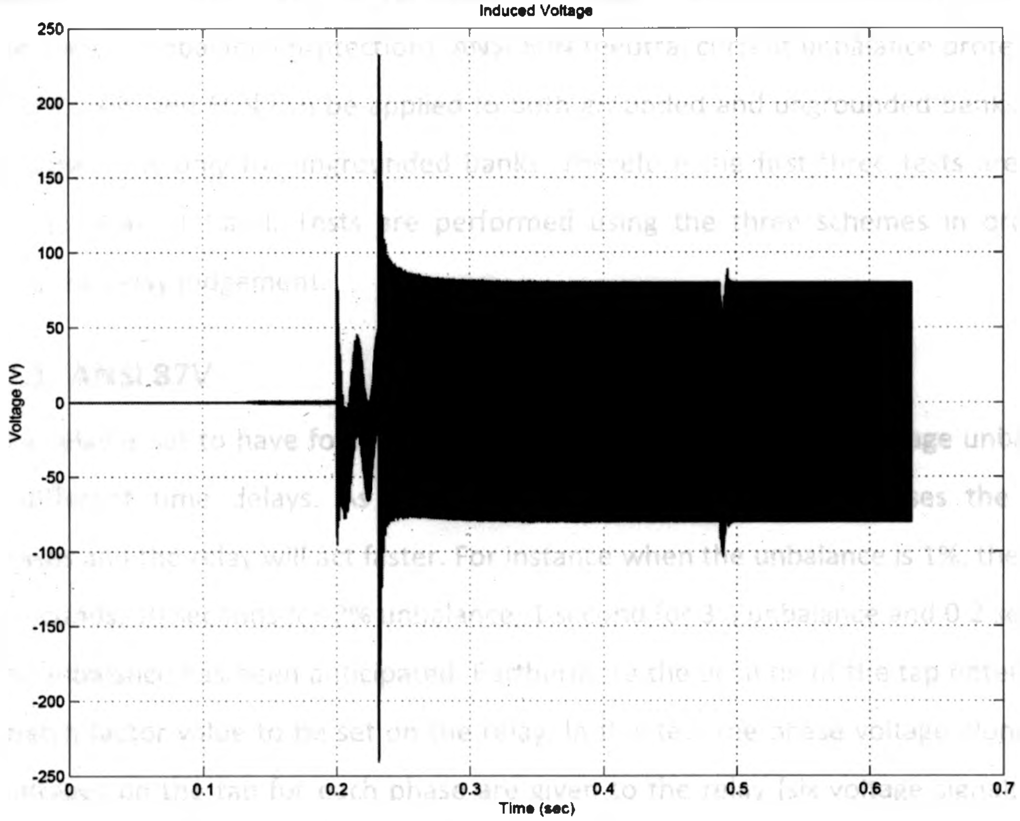


Figure 5-7: Induced voltage on a signal cable (second method)

Two protection schemes are discussed here:

- Phase current unbalance (ANSI 60P)
- Neutral current unbalance (ANSI 60N)

These schemes rely on the currents on two or more different branches to cancel out each other. Therefore, the signal of operation fed to the relay must be zero at a healthy condition, but for a small current attributable to inherent unbalance that may be present in some banks.

5.2.2. Relay Testing

In this phase, a commercial relay (see appendix) is tested using the above signals. The required signals are exported from PSCAD and using an amplifier the signals are regenerated and fed into the relay. The results are as follows:

This relay has four schemes for capacitor bank protection: ANSI 87V (voltage unbalance protection), ANSI 59NU (neutral voltage unbalance protection), ANSI 60P (phase current unbalance protection), ANSI 60N (neutral current unbalance protection). ANSI 87V, 60P, and 60N can be applied to both grounded and ungrounded banks. ANSI 59NU scheme is only for ungrounded banks. Therefore the first three tests are done using the relay at hand. Tests are performed using the three schemes in order to monitor the relay judgement.

5.2.2.1. ANSI 87V

The relay is set to have four different pickup values of the phase voltage unbalance with different time delays. As the severity of the unbalance increases the delay decreases and the relay will act faster. For instance when the unbalance is 1%, the delay is 30 seconds, 10 seconds for 2% unbalance, 1 second for 3% unbalance and 0.2 seconds for 4% unbalance has been anticipated. Furthermore the position of the tap determines the match factor value to be set on the relay. In this test the phase voltage along with the voltages on the tap for each phase are given to the relay (six voltage signals). The match factor depends on the position of the tap in the capacitor bank and should either be given to the relay or automatically acquired by the relay. During this test the relay was fed with signals from phase voltages (source 1) as well as tap voltages (source 2). One of the tap voltages was distorted using the induced signal obtained from the previous simulations. With the abovementioned typical settings the relay did not pick up anything. But when the first unbalance threshold (1%) was reduced to half its typical value, the relay picked up but as the delay in this case is 30 seconds, it was dropped out rapidly.

5.2.2.2. ANSI 60P

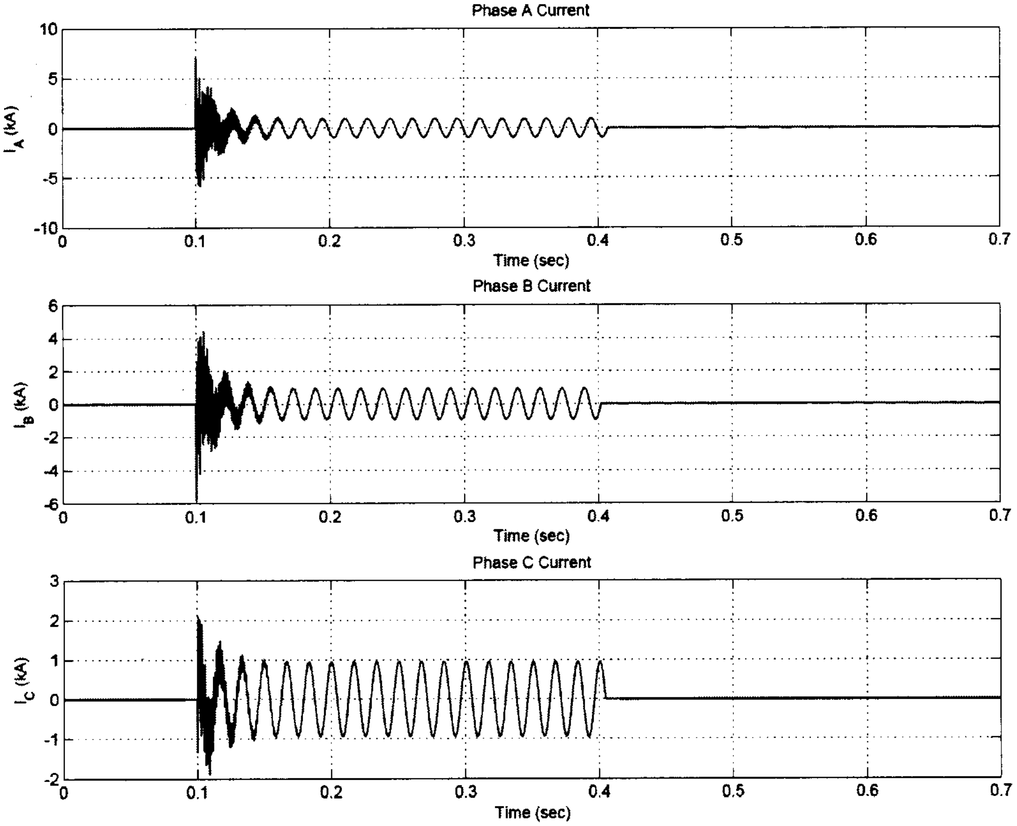
The relay is set to have four different pickup values of the phase current unbalance with different time delays. As the severity of the unbalance increases the delay decreases and the relay will act faster. For instance when the unbalance is 2%, the delay is 30 seconds, 10 seconds for 3% unbalance, 1 second for 4% unbalance and 0.2 seconds for 5% unbalance has been anticipated. During this test the relay was fed with signals from phase currents (source 1) as well as the differential currents (source 2). Initially, one of the differential currents was distorted using the induced signal obtained from the previous simulations. This scheme showed more sensitivity to the distortion on the differential current as the differential signal must be zero (or close to zero) for the balanced conditions. With the typical settings all four thresholds of the relay picked up, but the duration of the transient was not long enough for the element to operate. With increasing the element sensitivity and/or reducing the delay on a specific threshold, the relay gave the trip signal in a few cases. Distorting the phase currents did not have any effect on the relay operation at all, as it was not strong enough to trigger any of the relay's thresholds on the unbalance element. Furthermore, one of the phase currents was distorted. This caused none of the thresholds on this element to pickup.

5.2.2.3. ANSI 60N

The relay is set to have four different pickup values of the neutral current unbalance with different time delays. As the severity of the unbalance increases the delay decreases and the relay will act faster. For instance when the unbalance is 2%, the delay is 30 seconds, 10 seconds for 3% unbalance, 1 second for 4% unbalance and 0.2 seconds for 5% unbalance has been anticipated. In this case the relay was fed with four current signals, three from phase currents and one from the difference between currents of the bank's neutral points going into ground. First the unbalance signal was distorted using the acquired induced signals. In this case, the relay's four thresholds were triggered and then as the transient was not long enough the element dropped out. Reducing the threshold to half its typical value caused the relay to send a trip signal. Furthermore, reducing the delay on the threshold also caused the relay to trip. Afterwards, the distorted signal was applied to phase currents; this did not cause any of the thresholds on this element to pickup.

5.3. Switching of Grounded Capacitor Banks

The other important phenomenon to discuss is the matter of capacitor bank switching. In this section one of the capacitor banks are energized at 0.1 sec and again de-energized at 0.4 sec. Figure 5-8 shows the phase currents in this scenario.


Phase A Current

Phase B Current

Phase C Current

Figure 5-8: Phase currents for switching

The current injected to the ground mat is the sum of the neutral currents of all the banks present in the substation (see Figure 5-9). It can be gathered that the currents injected to the ground are much smaller than the case of a fault.

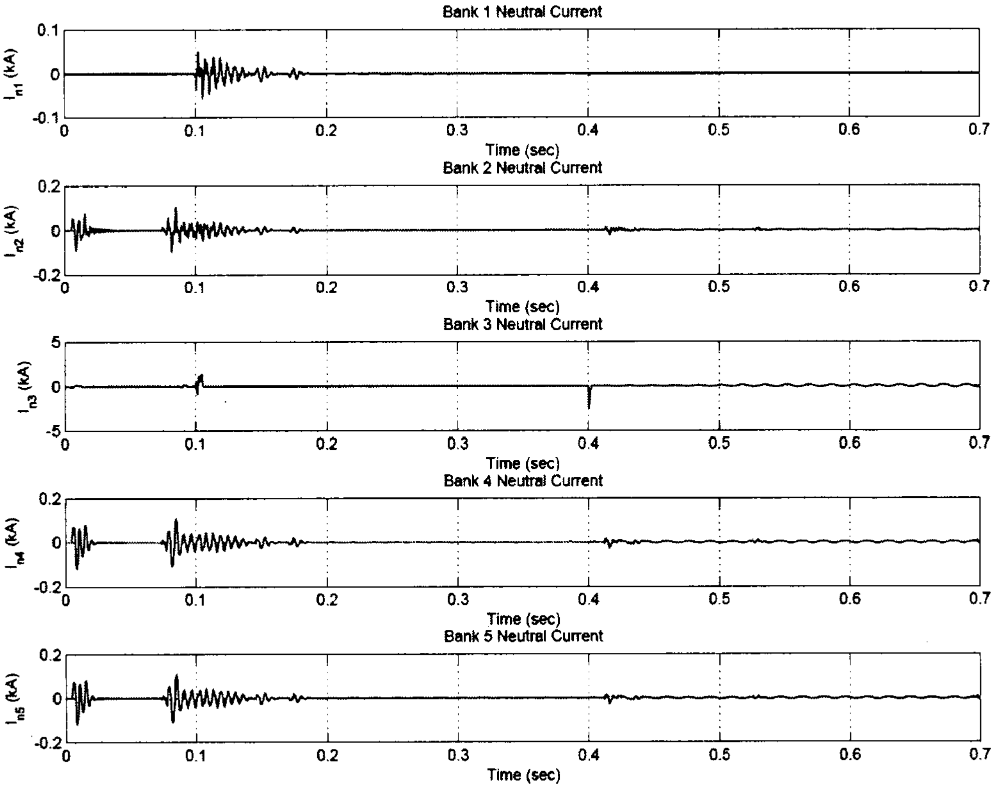


Figure 5-9: Neutral currents injected to ground mat

5.3.1. Induced Voltages/Currents on the Control Signal Cables

It was established that the currents injected to the ground grid in case of switching are much smaller than the previous case, ground faults. This will in turn reduce the amount of transients induced on the control/signal cables. Figure 5-10 shows the current induced on a typical control/signal cable which may run as long as 100m to 1km alongside a phase cable. Furthermore, Figure 5-11 shows the voltage induced between the sheath and core of the cable. It can be seen that in this case the induced transients are much smaller than the ground fault case.

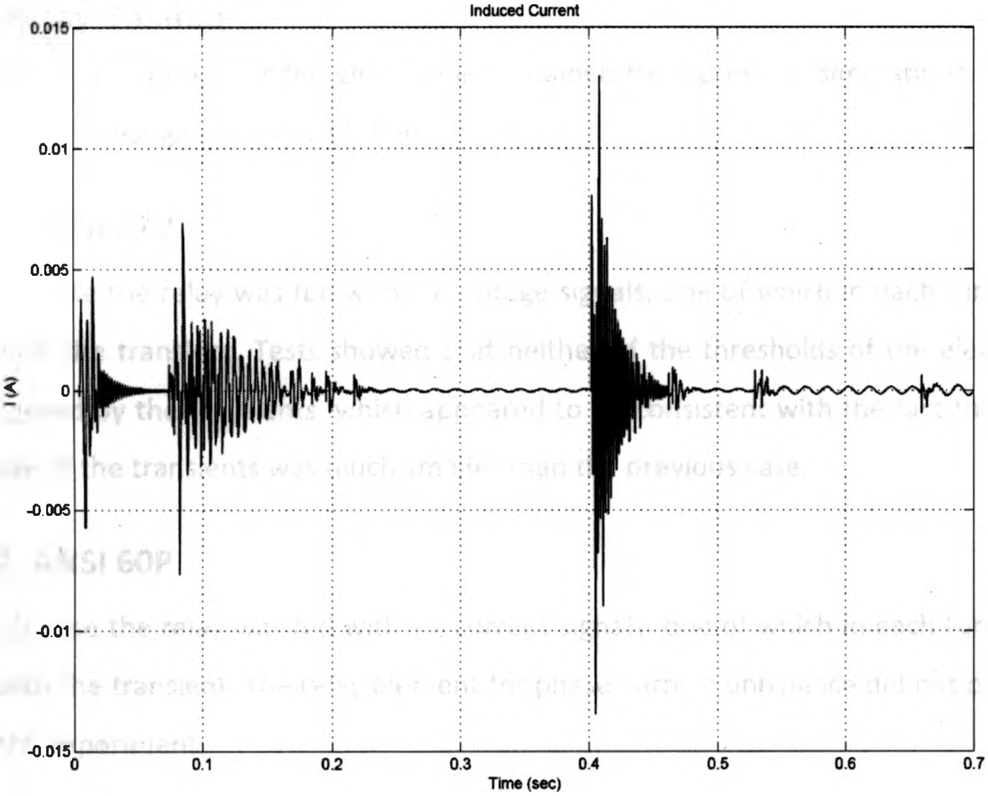


Figure 5-10: Induced current on a typical control/signal cable

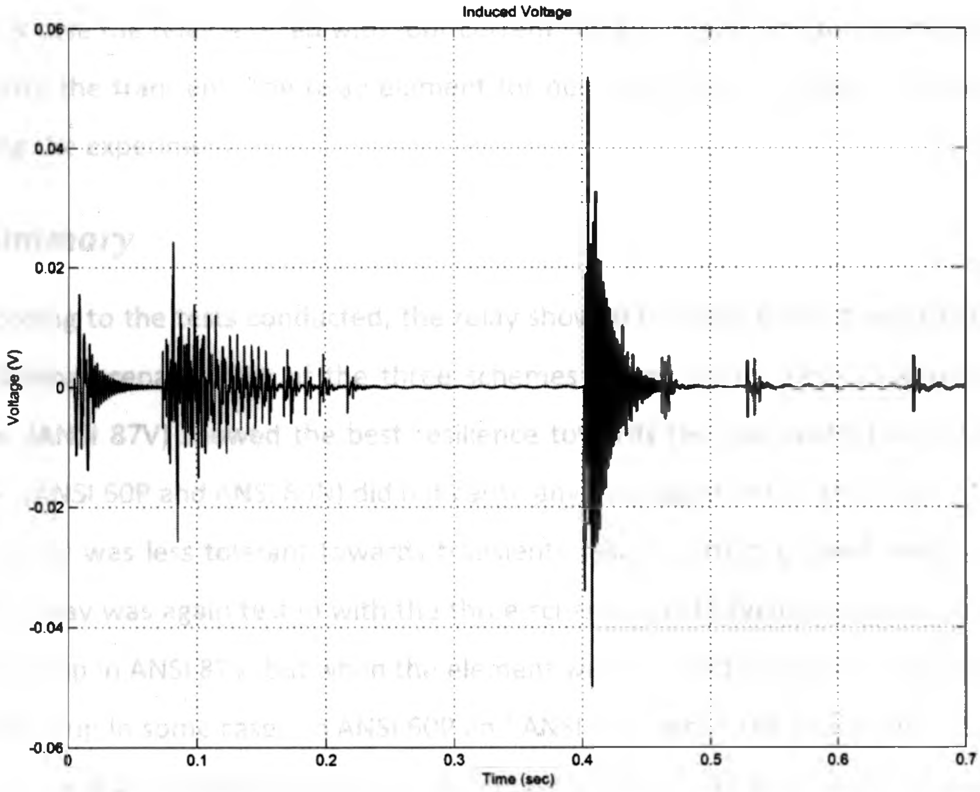


Figure 5-11: Induced voltage between sheath and core of a control/signal cable

5.3.2. Relay Testing

In this phase the relay is fed with signals obtained from previous simulations. Three schemes are investigated in this section.

5.3.2.1. ANSI 87V

In this case the relay was fed with six voltage signals, one of which in each turn was mixed with the transient. Tests showed that neither of the thresholds of the elements was triggered by the transients, which appeared to be consistent with the fact that the amplitude of the transients was much smaller than the previous case.

5.3.2.2. ANSI 60P

In this case the relay was fed with six current signals, one of which in each turn was mixed with the transient. The relay element for phase current unbalance did not pick up during the experiment.

5.3.2.3. ANSI 60N

In this case the relay was fed with four current signals, one of which in each turn was mixed with the transient. The relay element for neutral current unbalance did not pick up during the experiment.

5.4. Summary

According to the tests conducted, the relay showed the best level of security during the switching scenario. Out of the three schemes tested on the relay, voltage-based schemes (ANSI 87V) showed the best resilience towards the transients. Current-based schemes (ANSI 60P and ANSI 60N) did not cause any misjudgement on the relay.

The relay was less tolerant towards transients resulting from ground faults. In this case, the relay was again tested with the three schemes. With typical settings, the relay did not pickup in ANSI 87V, but when the element was adjusted to be more sensitive the relay picked up in some cases. In ANSI 60P and ANSI 60N, when the phase currents were distorted the relay did not pickup but when the neutral currents were distorted the relay picked up. With more sensitive settings the relay gave the false trip signal for a few cases where the neutral current was deformed. Next chapter is a summary of all the results obtained in this project.

Chapter Six

6. Conclusion

This thesis is aimed at resolving the issue of high TRV from capacitor bank switching in a high-voltage substation after an incident occurred resulting in a three-phase fault and breaker failure. To address the issue, it was suggested to investigate the possibility of grounding the capacitor banks.

In this thesis, the transients resulting from switching and ground faults for HV substations with very large capacitor banks are investigated. In case of a grounded capacitor bank, these transients have a way of entering the ground mat, causing dangerous touch and step voltages jeopardising the safety of the personnel; furthermore, these high-frequency transients can induce voltages/currents on control/signal cables.

The mentioned transients on control/signal cables can have detrimental effects on the operation of electronic control or measurement equipments such as relays. A state-of-the-art commercial relay was tested to evaluate the effects of induced transients on its operation. According to the tests conducted, the relay showed the best level of security during the switching scenario. Out of the three schemes tested on the relay, voltage-based schemes (ANSI 87V) showed the best resilience towards the transients. Current-based schemes (ANSI 60P and ANSI 60N) did not cause any misjudgement on the relay.

The relay was less tolerant towards transients resulting from ground faults. In this case, the relay was again tested with the three schemes. With typical settings, the relay did not pickup in ANSI 87V, but when the element was adjusted to be more sensitive the relay picked up in some cases. In ANSI 60P and ANSI 60N, when the phase currents were distorted the relay did not pickup but when the neutral currents were distorted the relay picked up. With more sensitive settings, the relay gave the false trip signal for a few cases where the neutral current was deformed.

6.1. Future Work

As a continuation to the work presented here, it is suggested to find remedies for the relay misoperation; these include but are not limited to:

- Better shielding for control/signal cables
- Change in the ground mat arrangement
- Designing filters for electronic control/measurement equipments

Furthermore, lightning transients can be added to this study making it more comprehensive.

Additionally, more sophisticated models can be used for control/signal cables along with considering the effect of conductivity and permittivity of the soil surrounding the area.

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Appendix A

A.1. The Commercial Relay

A commercial relay especially produced for capacitor bank protection was used in the project. The relay (Figure A-1) is an integrated protection, control and monitoring device for capacitor banks based on the well-established and proven universal relay platform (Figure A-2). This relay provides both the bank and system protection schemes for shunt capacitor protection. The current and voltage-based protection functions are designed to provide sensitive protection for grounded, ungrounded single and parallel capacitor banks and banks with taps, for a variety of capacitor bank configurations.

Figure A-1: Commercial relay front panel view

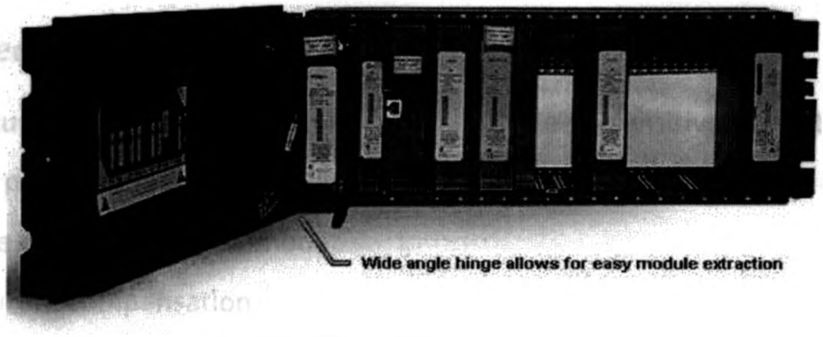


Figure A-2: Robust hinge assembly

A.2. Features and Benefits

- FlexLogic™ programmable logic
- Virtual I/O (reduce hardware cost)
- Expandable I/O
- Flash memory for field upgrades
- Optional user programmable pushbuttons
- User programmable LEDs, fault reports, display messages, and self tests
- Draw out modules for serviceability
- Common modules (reduce spare cost)
- Test mode for I/Os
- IRIG-B time synchronization and repeater

A.3. Applications

- Protect capacitor banks of variety of configurations with sensitive current and voltage balance protection functions truly compensating for the inherent bank unbalance
- Sensitive protection for grounded, ungrounded single and parallel capacitor banks and banks with taps, for a variety of capacitor bank configurations
- Protection, control, monitoring and automation of shunt capacitor banks from MV to EHV
- Shunt capacitor based AVR and capacitor control supervision

A.4. Protection

- Full featured shunt capacitor bank protection system - sensitive current and voltage balance protection functions truly compensating for the inherent bank unbalance
- Accurate compensation methods
  - Accurate compensation
  - Facilitates more sensitive and faster protection

    - Immune to severe system events
    - Immune to temperature variations
    - Mitigates impact of transients
    - Mitigates impact of constant measuring errors
    - Allows for secure relay auto-setting and/or self-tuning under any system/bank conditions
- Protection functions specific to shunt capacitor bank protection; Voltage differential protection (87V), Compensated bank neutral unbalance (59NU), Phase current unbalance (60P), Neutral current unbalance (60N)
- 512 lines of protection logic - build custom protection schemes of your choice
- Single device for protecting shunt capacitor banks for your specific configuration

A.5. Control

- Time and Date function allowing capacitor bank switching based on time of day, week and seasons.
- Automatic Voltage Regulation block (AVR) switching capacitor banks based on voltage, power factor and reactive power
- Capacitor control supervision block for processing commands from SCADA, remote communication and local control through front panel HMI
- Dependable – product from a Globally accepted platform, with performance backed up by many years of field experience
- Maintenance cost savings and simplification - Modular construction, common hardware, reduced stock of spare parts, plug & play modules

A.6. Automation

- Application flexibility – Multiple I/O options, programmable logic (FlexLogic™), modularity, customize to specific requirements
- Reduce installation space requirements through compact design - Multifunction device that integrates protection and control functions, programmable pushbuttons and status LEDS, and communication interfaces

A.7. Recording and Monitoring

- Reduce system event analyzing time and cost - Sequence of event reports, Oscillography, data logging, IRIG-B time synchronization
- Comprehensive metering functionality

A.8. Communications

- Front Panel RS232 port
- Up to two RS485 ports (up to 115 kbps)
- Ethernet port: Redundant 10BaseFL or 100BaseFX fibre optics
- Embedded Ethernet Switch for direct networking of UR devices
- Inter-relay communications interfaces, RS422, G.703, IEEE C37.94
- Direct I/O – Exchange inputs and outputs between relays with reduced wiring
- Modbus RTU and TCP/IP
- IEC61850
- DNP 3.0 RTU and TCP/IP
- IEC60870-5-104
- Ethernet Global Data (EGD)

A.9. User Interface

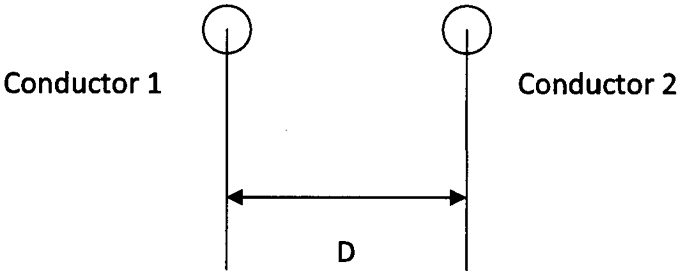
- 2 x 20 character front panel display and keypad for local access
- 48 programmable LED indicators
- User-programmable pushbuttons providing local control
- Multi-language support - French, Chinese, Russian options
- EnerVista™ UR Setup software for configuration, monitoring and troubleshooting

Appendix B

B.1. Inductance of a single-phase two-wire line

The inductance of the circuit due to current in conductor 1 is determined by [1]:

$$L_{1,ext} = 2\times10^{-7}\ln\frac{D}{r_1} \quad H/m$$



For internal flux only:

$$L_{1,\mathrm{int}} = \frac{1}{2}\times10^{-7} \quad H/m$$

The total inductance of the circuit due to the current in conductor 1 only is:

$$L_1 = \left(\frac{1}{2}+2\ln\frac{D}{r_1}\right)\times10^{-7} \quad H/m$$

The same is true for the second conductor:

$$L_2 = \left(\frac{1}{2}+2\ln\frac{D}{r_2}\right)\times10^{-7} \quad H/m$$

The distance of the conductors is taken to be 1m against a radius of 0.01m for the cables; therefore, the self-inductance of the cables for a distance of 1km would be 1mH. With coupling coefficient of 30% the mutual inductance of the two cables was established to be 0.3mH, or 300μH.

B.2. Capacitance of a two-wire line

Capacitance between the two conductors of a two-wire line was defined as the charge on the conductors per unit of potential difference between them. Therefore:

$$V_{ab} = \frac{q_a}{2\pi\varepsilon_0\varepsilon_r}\ln\frac{D}{r_a} + \frac{q_b}{2\pi\varepsilon_0\varepsilon_r}\ln\frac{r_b}{D}$$

Since $q_a = -q_b$:

$$V_{ab} = \frac{q_a}{2\pi\varepsilon_0\varepsilon_r}\left(\ln\frac{D}{r_a} - \ln\frac{r_b}{D}\right) = \frac{q_a}{2\pi k}\ln\frac{D^2}{r_a r_b}$$

So:

$$C_{ab} = \frac{q_a}{V_{ab}} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(D^2/r_a r_b\right)}$$

If we assume $r_a = r_b = r$, we will have:

$$C_{ab} = \frac{\pi\varepsilon_0\varepsilon_r}{\ln\left(D/r\right)}$$

For our case (Figure 4-9), after review of several papers [2], the relative dielectric of the soil was taken to be about 4.5 and the distance of the conductors is taken to be 1m against a radius of 0.01m for the cables. Therefore the capacitance was calculated to be 27pF per meter and 27nF for 1km was established. This capacitance is divided into two parts, each 13nF.

[1] W. D. Stevenson, Jr., "Elements of Power System Analysis", *McGraw Hill Int.*, fourth ed. 1982

[2] V. L. Mironov, S. V. Savin, "Dielectric spectroscopic model for tussock and shrub tundra soils," *Geoscience and Remote Sensing Symp., 2007. IGARSS 2007. IEEE Int.*, pp. 726-731, 23-28 July 2007