CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The purpose of a power system is to transport and distribute the electrical energy generated in the power plants to the consumers in a safe and reliable way. Aluminium and copper conductors are used to carry the current, transformers are used to bring the electrical energy to the appropriate voltage level, and generators are used to take care of the conversion of mechanical energy into electrical energy. When we speak of electricity, we think of current flowing through the conductors from generator to load. This approach is valid because the physical dimensions of the power system are large compared with the wavelength of the currents and voltages; for 50-Hz signals, the wavelength is 6000 km. This enables us to apply Kirchhoff’s voltage and current laws and use lumped elements in our modelling of the power system. In fact, the transportation of the electrical energy is done by the electromagnetic fields that surround the conductors and the direction of the energy flow is given by the Pointing vector.

To ensure an uninterrupted power supply from the generation to distribution side, protective measures are being taken to ensure the safety and security of the equipment. Switching devices like circuit breakers are the most common protective devices used in power system. In high voltage ac power transfer, in case of fault conditions or any other abnormal conditions, a phenomena called “transient” is introduced.

An electrical transient occurs on a power system, each time an abrupt circuit change occurs. This circuit change is usually the result of a normal switching operation, such as breaker opening or closing or simply turning a light switch on or off. Bus transfer switching operations along with abnormal conditions, such as inception and clearing of system faults, also cause transients.

The phenomena involved in power system transients can be classified into two major categories:

- Interaction between magnetic and electrostatic energy stored in the inductance and capacitance of the circuit, respectively;
- Interaction between the mechanical energy stored in rotating machines; and
- Electrical energy stored in the inductance and capacitance of the circuit.

Basically, an electrical transient is a phenomenon that occurs due to the forcible making or braking of switching devices like circuit breakers in most cases. Most of the power system transients are oscillatory, which is caused by mainly the switching of circuit breakers. Due to this forced switching the voltage and current level at different terminals go to abnormally high levels for a very short period of time ranging from a few microseconds to a few milliseconds. These kinds of transients are known as electromagnetic transients. Secondary equipment in HV substation is highly sensitive to transient electromagnetic disturbances due to the disconnector switching operations. Opening and closing of disconnector produce electromagnetic transients with a very fast rate of rise. This kind of transient can be particularly harmful to microprocessor based electronic equipment located near the HV switching devices.

Transients in power system are harmful for the equipment for both in generation and distribution side. Due to these transients, equipment failure, temporary loss of power and even blackout can be occurred. These transients are not totally avoidable. But we can reduce the probability of occurrence of the phenomenon. Despite the fact that these transient periods are usually very short when compared with the power frequency of 50 Hz or 60 Hz, they are extremely important because at such times, the circuit components and electrical equipment are subjected to the greatest stresses resulting from abnormal transient voltages and currents. While over-voltages may result in flashovers or insulation breakdown, over-current may damage power equipment due to electromagnetic forces and excessive heat generation. Flashovers usually cause temporary power outages due to tripping of the protective devices, but insulation breakdown usually leads to permanent equipment damage.

1.2 REVIEW OF PREVIOUS WORKS

Before our work on switching transient in distribution system, there had been more works on this topic. Some of the works that are relevant to our study are discussed in this section.

A remarkable work on switching transient has been carried out by building an Artificial Neural Network (ANN)-based approach to estimate the peak over voltages resulting from the switching operations. Their goal was to establish the maximum allowable switching over voltage that power system equipment can withstand. The methodology used there was Levenberg-Marquardt method. Using this method, the accuracy of the estimated over voltage was good [1].

Electromagnetic transient simulation on a ±800 kV dc transmission line in parallel with a double circuit 500kV ac transmission line shows the interaction between ac and dc transmission system. Various serious faults on ac and dc transmission system have been simulated. The impact of switching over voltage and power frequency over voltage has been simulated to see the difference of ac and dc lines. It shows a little change in impact of these voltages on UHVDC and EHVAC transmission line when on same tower or in parallel. So the insulation scheme could be the same for the DC line running alone in a tower [2].

On a 380kV unloaded line, switching transient phenomena has been simulated using PSCAD and MathCAD software to find out the transient recovery voltage and the over currents. This simulation shows a negative impact of transient overvoltage on the power system equipment and concludes that special safety measures must be taken to reduce the transient over voltage and current [3].

MATLAB program was used to simulate the switching surge voltage on a 735kV EHVDC line to find out the worst case of switching and hence to find out the most economical and efficient insulation solution for power system. The simulated results show that re-energization (Also called sudden Reclosing) of line with high voltage breaker produces highest switching surges. Low voltage side switching produces lower voltage at open end than high voltage side switching. De-energization of line after fault gives high over voltage of sound phases [4].

Switching transient analysis for a 500kV Transmission line between Nam Theun 2 and RoiEt 2 has been conducted and simulated using PSCAD/EMTDC software to estimate the effects of switching over voltages during the line energization and de-energization in case of single line to ground fault and three phase to ground fault. Simulation result shows that, a severe transient over voltage will occur during a light load or unloaded condition [5].

A conventional study on switching transient was also carried out by using simulation software PSCAD/EMTDC/EMTP-RV to find out the characteristics of switching over voltage and to compare the simulated results in both cases. Both programs produced almost identical results. In terms of computational speed, EMTP-RV shows better performance [6].

A 400kV air insulated transmission system was designed and the switching characteristics were studied to characterize it in both the time and frequency domain. This is achieved by making use of the electromagnetic transient program. The effects of switching configurations and substation layout on the transient currents were investigated. The magnitude and dominant frequency components of the transient current at different positions were also identified. Transient currents generated during operations can have varying wave shapes, peak magnitudes and frequency components depending on each configuration [7].

Four Circuit Transmission line is an alternative solution to transfer high quality of electrical power. The study shows the switching transient of the transmission line and evaluates the electrical resonance if the transmission line connects two substations with a line reactor in one side. Based on modelling and simulation results during the switching process, the maximum transient voltage is less than the Basic switching Impulse Insulation level (BIL). On the other hand, for evaluation of electrical resonance phenomena the proposed method is able to calculate the distance of transmission line for which the resonance phenomena will occur [8].

Some techniques for switching surge transients can be derived by studying the switching transient characteristics. The study shows that, controlled switching of circuit breaker is the best technique to reduce switching over voltages than any other method [9].

Switching transient analysis on underground cable shows the huge impacts of transients on transmission cables. This study was simulated using PSCAD simulation tools. This simulations show that, switching transient can lead to a power failure although switching lasts for a few cycles. The power loss and insulations stress is high due to the transients [10].

Switching over voltage caused a huge damage to the SF_6 circuit breaker in a 400kV transmission line. For the purpose of post-mortem analysis of the circuit breaker EMTP-RV software was used. Both the breaking chambers of circuit breaker were destroyed. The report of the analysis shows the cause of failure of circuit breaker was repetitive strikes of the contacts of the circuit breaker 11].

Harmonics in switching transients are very important factor that can have a very big impact on power system equipment if they are not damped out. The characteristics of the switching transient due to harmonics are being studied and analyzed by MATLAB software. The study reveals that, the harmonics generated are of the range 250Hz-5kHz. Frequency of such low range can be matched with the transformer resonant frequency and enter the system. This may cause a high insulation stress on the transformer winding and cause an insulation break down and can be the reason of a permanent damage to the transformer [12].

Hybrid grounding of generators in different industries was used to minimize the effects of fault point burning of generator winding in conjunction with various generator grounding. Switching transients are of concern in this case. An EMTP-RV simulation was used to calculate the transient over voltage that may cause severe damage to the system of concern [13].

Switching of medium voltage capacitor banks can generate excessive transients to the electrical system. Transients following the energization and de-energization of capacitor bank was analyzed using frequency dependent model and finally a diode based transient limiter was modelled to study its effectiveness on limiting switching transients [14].

The switching transient phenomena on the power distribution network of Durgapur Steel Plant causing failures of two medium voltage distribution transformers was studied using MATLAB software. Their analysis focused on the resonance phenomena inside a transformer which lead to the failure of the transformer [15].

Switching on and off of steps of capacitor bank is associated with transient over voltages and over current. This paper mainly simulates to show the transient over voltages due to the installation of switched capacitor banks on the secondary side of primary substations using control system program VISSIM [16].

Switching of shunt capacitors can cause transient overvoltage which is traditionally evaluated with Electro-Magnetic Transients (EMT) simulation programs. This paper mainly proposes a new idea for conducting switching studies directly inside commercial power-flow/short-circuit tools such as PSS/E and compares the result with those of EMT simulations [17].

Investigates the switching transient phenomenon causing failure of some dry-type transformers that are mainly used in data centers of New York areas and also shows the effect of snubber applications for transformer protection [18].

Analyses the switching transient overvoltage due to the switching operation of vaccum circuit breakers (VCB's) during disconnection of induction motors under the starting, the full load and the light load working conditions in the power system of floating production storage and offloading vessel using ATP-EMTP [19].

This paper emphasizes the winding resonance due to switching which is the cause of transformer failure of Durgapur Steel Plant (DSP) in India and identify high frequency voltage transients across the distribution transformer winding at various switching events using Alternative Transient Program (ATP) [20].

These are the papers related to switching transients to show the consequences of high frequency, high voltage transients that may lead to the failure of smooth running of the power system. Most of the papers emphasized on the switching of transformer and capacitor banks on the utility system.

1.2 THESIS OBJECTIVES

Transient study in power system is very important because of its harmful behaviour to the equipment used in generation, transmission and distribution. Because of transient over voltages continuous flow of power is interrupted. The voltage rise during transient condition which may raise to a level beyond the rated maximum voltage level that equipment can withstand and may cause serious damage to the load side of distribution network. Transient analysis and study can help us to reduce the effects of transients that may occur due to the frequent switching of circuit breakers. Thus help us to make a power system network more reliable and efficient.

Our main objective was to analyze and show the magnitude of transients under different switching conditions that occur in a distribution network.

We also analysed a common network for both overhead line and underground cable to make a comparative study between these two transmission medium in terms of switching severity. In the last portion of analysis, we analysed the system for different types of transient short circuit fault to have a transparent idea about possible magnitude of transient over voltages that is induced in the system after the fault is cleared.

After analyses, the results were evaluated and compared together to find the worst case of switching and severity of transient overvoltage under different conditions. Finally analyzing the data and results, we tried to find some convenient way of reducing the impacts of transients on power system distribution network. After that, some necessary steps that can be taken to reduce this transient effect (or eliminate in some cases) were recommended for future study and analysis.

The main objective of this thesis work was to show the severity of switching transients for different cases and to open the future scope of study for reducing or eliminate the switching transients and hence to design a better and more efficient power system distribution network. Although it is not possible to eliminate transients from power system, but future technology may be able to reduce the effects of transients to a level where we can neglect the effects of this harmful condition.

1.3 THESIS ORGANIZATION

This thesis consists of seven chapters. Chapter 1 is the introductory chapter, where a summarized idea of transients in power system will be discussed. The objective of this thesis and a short review of previous works will be presented.

In Chapter 2, an elaborate introduction of transients, types of transients, effects of transients, sources of transients and history of accidents in power system due to transients will be discussed.

In Chapter 3, a brief overview of network modelling will be given along with transmission line modelling. A brief introduction to PSCAD simulation tool and it's scope of application will also be discussed in this chapter.

In Chapter 4, switching transient analysis of overhead lines and underground cable will be done under various switching operations like energization and de-energization of transformer, capacitor bank and switching of load. At the end of this chapter, the output results will be summarized in a table to make a comparison between different types of switching in terms of transient overvoltage for both overhead line and underground cable.

In Chapter 5, transient short circuit analysis in overhead lines will be analyzed and results will be evaluated.

Analysis of the simulated results and some recommendations to reduce the transient effects in distribution network will be given in Chapter 6.

And at last, in Chapter 7, a conclusion to the thesis will be given along with the discussion about the future scopes of study in the field of switching transients in power distribution network.

CHAPTER 2

TRANSIENTS IN POWER SYSTEM

2.1 INTRODUCTION

Power systems play a crucial role in modern society, and their operation is based on some specific principles. Since electricity cannot be stored in large quantities, the operation of the power system must achieve a permanent balance between its production in power stations and its consumption by loads in order to maintain frequency within narrow limits and ensure a reliable service. Even when the power system is running under normal operation, loads are continually connected and disconnected, and some control actions are required to maintain voltage and frequency within limits. This means that the power system is never operating in a steady state. In addition, unscheduled disturbances can alter the normal operation of the power system, force a change in its configuration, cause failure of some power equipment or cause an interruption of service that can affect a significant percentage of the system demand, such as a blackout.

For steady-state analysis of the power flow, when the power frequency is a constant 50 or 60 Hz, we can successfully make use of complex calculus and phasors to represent voltages and currents. Power system transients involve much higher frequencies up to kilo Hertz and mega-Hertz. Frequencies change rapidly, and the complex calculus and the phasor representation cannot be applied any longer. Most power system transients are oscillatory in nature and are characterized by their transient period of oscillation. Despite the fact that these transient periods are usually very short when compared with the power frequency of 50 Hz or 60 Hz, they are extremely important because at such times, the circuit components and electrical equipment are subjected to the greatest stresses resulting from abnormal transient voltages and currents. For this reason, a clear understanding of the circuit during transient periods is essential in the formulation of steps required to minimize and prevent the damaging effects of switching transients.

2.2 TRANSIENTS IN POWER SYSTEM

"Transients", a term we'll use for simplicity here, are actually "Transient Voltages". More familiar terms may be "surges" or "spikes". Transient phenomena in power systems are associated with disturbances caused by faults, switching operations, lightning strikes or load variations. These phenomena can stress and damage power equipment.

Two types of stress can be caused by transient phenomena in power systems: (1) over currents, which can damage power equipment due to excessive heat dissipation, and (2) over voltages, which can cause insulation breakdown (failure through solid or liquid insulation) or flashovers (insulation failure through air).

We get power system transients as electromagnetic, when

- It is necessary to analyze the interaction between the (electric) energy stored in capacitors and the (magnetic) energy stored in inductors, or electromechanical and
- The analysis involves the interaction between the electric energy stored in circuit elements and the mechanical energy stored in rotating machines.

Physical phenomena associated with transients make it necessary to examine the power system over a time interval as short as a few nanoseconds or as long as several minutes. Technical definition of transient is defined as a sub-cycle disturbance in the AC waveform that is evidenced by a sharp brief discontinuity of the waveform. Transients may be of either polarity and may be of additive or subtractive energy to the nominal waveform. Transients are divided into two categories. They are-

i) Impulsive transients
ii) Oscillatory transients

2.2.1 IMPULSIVE TRANSIENTS

One of the two types of transient disturbance is Impulsive Transient that may enter the power system. A sudden, non–power frequency change in the steady-state condition of voltage, current, or both that is unidirectional in polarity – either primarily positive or negative is defined as Impulsive Transient. It is normally a single, very high impulse like lightning. These are generally described by their rise and decay times. These kinds of transients can also be characterized by their spectral content. For example, a 1.3 X 40-µs 2100-V impulsive transient nominally increases from zero to its peak value of 1500 V in 1.3 µs. It decays to half its maximum value in 40 µs subsequently. The typical response of impulsive transient due to lightning is shown in Fig-2.1.

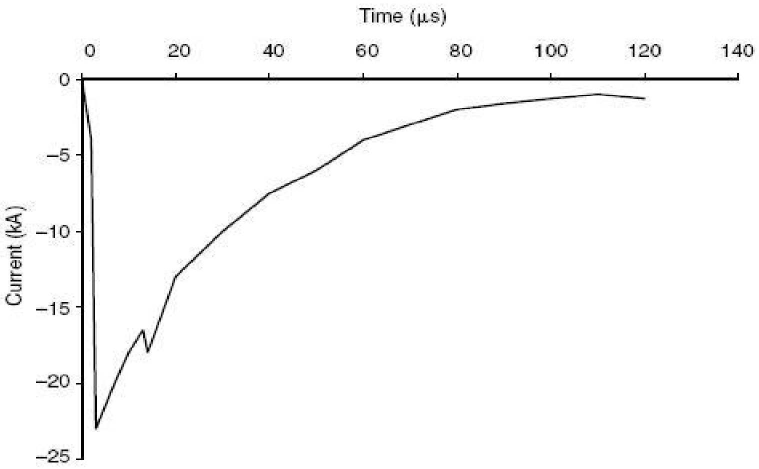


Fig-2.1: Typical current impulsive transient caused by lightning

These transients are not usually transmitted far from the source of where they enter the power system. However, they may propagate for some distance along distribution utility lines in some cases [21]. It may also considerably have different characteristics when viewed from different parts of the electrical system. Through the resistive component of the system, the high frequencies involved allow damping of the impulsive transients.allow damping of the impulsive transients through the resistive component of the system. Impulsive transients are further subdivided into three categories which are summarized in Table-2.1.

Table-2.1: Impulsive Transients Categories

Impulsive Transient	Spectral content	Typical Duration
Nanosecond	5 ns rise	Less than 50 ns
Microsecond	1 µs rise	50 ns to 1 ms
Millisecond	0.1 ms rise	More than 1 ms

Near the source of the disturbance, nanosecond transients generally exist and it rises in 5 ns with a duration of less than 50ns. Microsecond impulsive transients have much higher amplitudes but they are relatively unusual and they do not conduct as easily as the millisecond types but may cause arcing faults on the electrical system. The rising time of microsecond transient is 1µs and has a duration of 50ns to 1ms. Most common occurred transient in a power system is Millisecond impulsive transient which rises in 0.1 ms and lasts more than 1ms.

Causes

An example of an impulsive transient as mentioned is lightening where the currents produced from a lightning strike can go as high to several thousand amps in about 2-3 µs and in addition, the sudden rise has frequency components in the high MHz range. This phenomenon makes lightning similar to an intense radio frequency energy, which is an important consideration in the design of grounding and bonding systems.

Another form of an impulsive transient is Electrostatic Discharge and we can easily familiar with this, for example when touching an object (door knob) or another person after walking across a carpeted floor, we may experience such. When the charge is released suddenly, it can damage sensitive electronics. For this reason the technicians use wrist straps when servicing electronic equipment.

Effects

On a power system, the effects of transients depend on the frequency and amplitude of the transient. The amplitude of the transient is the main cause of problems in the case of impulsive transients and the damage caused by a transient can be immediate (i.e. lightning strike). But in the case of low amplitude transient, it can also be gradual, as a result electrical equipment insulation is slowly degraded making it prone to short circuit. This gradual degradation is sometimes referred to as a “slow death by a thousand cuts”.

2.2.2 OSCILLATORY TRANSIENTS

Another type of transient disturbance is Oscillatory Transient which is defined as a sudden and non–power frequency change in the steady-state condition of current, voltage, or both that has both positive and negative polarity values i.e. bidirectional. In the case of an oscillatory transient the value of instantaneous voltage or current varies its polarity quickly which is described by its spectral content or predominant frequency, magnitude and duration.

Based on selected frequency ranges, which correspond with common types of power system oscillatory transient phenomena, the oscillatory transient is subdivided into three classes which is shown in Table-2.2. It should be remembered that the frequency of the oscillation gives a trace to the origin of the disturbance [21].

. Table-2.2: Oscillatory Transients Classification

Oscillatory Transient	Spectral Content	Typical Duration	Typical Voltage Magnitude
Low frequency	< 5 kHz	0.3 to 50 ms	0-4 pu
Medium frequency	5-500 kHz	20 µs	0-8 pu
High frequency	0.5-5 MHz	5 µs	0-4 pu

2.2.2.1 Types and examples of oscillatory transient

The three types of oscillatory transients are described below in details-

Low-frequency oscillatory transient

Due to capacitor bank energization, this type could originate primarily which is normally encountered on sub-transmission and distribution systems. To improve power factor, as well as lower system losses, capacitor banks are used in the electric distribution utilities. To match with changes in the load profile, capacitor banks have to be switched in and out of the system for better results. The ranges of frequencies by which capacitor bank energizing yields an oscillatory voltage transient are between 300 and 900 Hz.

Due to transformer energizing and ferroresonance, oscillatory transients also can be observed on the distribution system with fundamental frequencies less than 300 Hz. On the other hand, this transient type may be also produced by series capacitors when i) the system resonance causes the magnification of low-frequency components in the transformer inrush current or ii) when unusual conditions lead to ferroresonance.

Medium-frequency oscillatory transient

The back-to-back capacitor switching is the example of medium-frequency oscillatory transient that occurs when a capacitor bank is switch in close electrical proximity to another capacitor bank which is already energized, that sees the de-energized bank as a low impedance path.

The response of oscillatory transients due to back-to-back switching is shown in Fig-2.2.

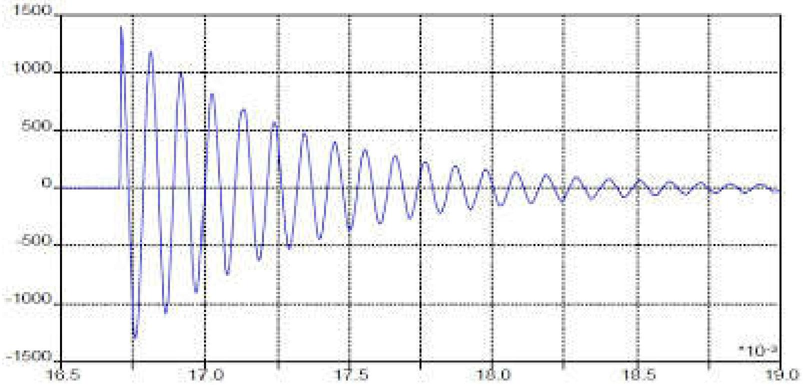


Fig-2.2: Oscillatory Transient Due to Back-to-Back Capacitor Switching

Other causes of medium-frequency oscillatory transient include cable switching and as a system response to an impulsive transient.

High-frequency oscillatory transient

Power electronics and switching events (i.e. in the case of line or cable energization) are linked with high-frequency oscillatory transient. For example power electronics, such as the switching power supply in computers generates oscillatory voltage transients that repeat several times per 60 Hz cycle. Usually, local system responses to an impulsive transient are also the result due to this type of transient.

2.3 OSCILLATORY TRANSIENTS FROM SWITCHING

When load break switches, circuit breakers, disconnectors, or fuses operate, a switching action takes place in the network and parts of the power system are separated from or connected to each other. The switching action can be either a closing or an opening operation in the case of a switching device. Fuses can perform opening operations only. After a closing operation, transient currents will flow through the system, and after an opening operation, when a power-frequency current is interrupted, a transient recovery voltage or TRV will appear across the terminals of the interrupting device. We can determine amplitude, frequency, and shape of the current and voltage oscillations from the terminals of the switching device.

When capacitor banks for voltage regulation are placed in a substation, the switching devices interrupt a mainly capacitive load when operating under normal load conditions. The current and voltage are approximately 90^0 out of phase and the current is leading the voltage. When a large transformer is disconnected in a normal load situation, current and voltage are also approximately 90^0 out of phase but now the current is lagging. In a dominantly capacitive or inductive network if we close a switch or a circuit breaker then there will be an inrush current, which can cause problems for the protection system [23].

2.3.1 SHUNT CAPACITOR BANK SWITCHING

In a power system, capacitor banks for load factor improvement or for filtering out higher harmonics have to be switched in and out of service regularly. The interruption of a capacitive current can cause dielectric problems for the switching device, but when a capacitor bank is taken into service, large inrush currents can flow through the substation.

The single line diagram of the power system shown in Fig-2.3 will be used to analyze transient characteristics due to shunt capacitor switching.

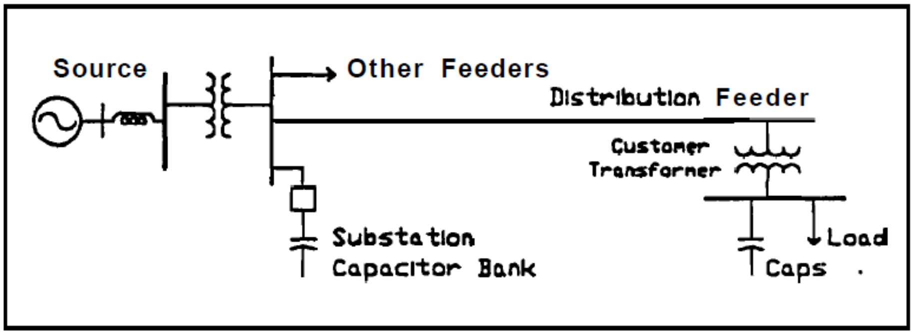


Fig-2.3: Single line diagram of a simple network

To simplify the ideas, the system is divided into two parts of different LC circuits as shown in Fig- 2.4. The circuit in part one consists of Ll and C1, which can be viewed as system inductance (from source and step-up transformer) and switched shunt capacitance, respectively. Likewise, the circuit in part two consists of L2 and C2, which represents step down transformer inductance (inductance in distribution lines may also be included) and capacitance appearing at the low voltage bus. The source of the capacitance C2 founded in customer systems can be power factor correction capacitors or capacitors used as a filter in adjustable speed drives.

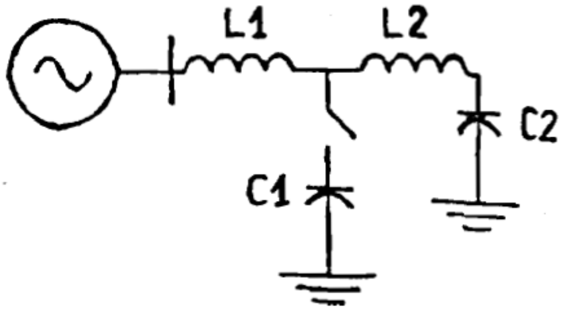


Fig-2.4: Simplified equivalent circuit of the simple network

Energizing a shunt capacitor bank from a predominately inductive source can cause an oscillatory transient voltage which can be as high as 2.0 pu at the shunt capacitor location with a resonant frequency of f = $1/2\pi\sqrt{L1C1}$. Using simplified equivalent circuit as shown in Fig-2.5 for the case where shunt capacitor bank is connected in ungrounded-wye. In this equivalent circuit, CA , CB, and Cc represent the shunt capacitor for each phase, **A** B C respectively, while ***CN*** represents the effective capacitance to ground of the bank neutral.

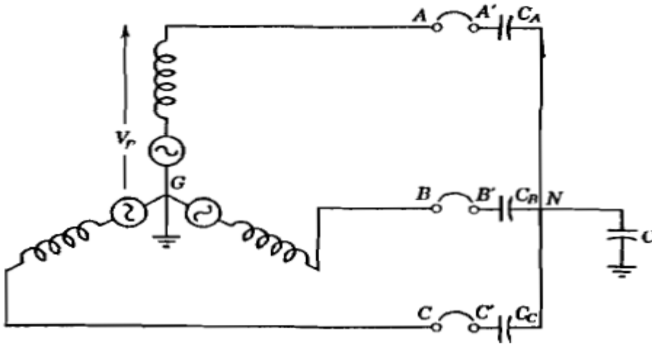


Fig. 2.5: Simple equivalent circuit for three-phase shunt capacitor switching.

Condition set in this analysis is that at the moment when the switched is opened, phase **A** interrupts first, causing the rest of the system to be a single phase circuit composed of phases B and C, and then, phases B and C interrupt at the next current zero passing through switching contacts B and C.

Transients due to shunt capacitor switching in the LC circuit in part one (L1 and C 1) can excite an LC circuit in part two (L2 and C2), resulting in transient magnification at the low voltage bus where C2 is connected. This happens when the resonant frequencies of these two LC circuits are in the same range [22]. The worst case magnification occurs when the following conditions are satisfied-

1. The resonant frequencies of these two LC circuits are equal

2. The switched shunt capacitor C1 is much larger than the low voltage capacitor C2

3. The connected loads at the low voltage bus provide little damping for the system.

2.3.2 SWITCHING OF TRANSFORMER

Power transformers bring in the transmission system the electrical energy to higher voltage levels to reduce losses when transporting electrical energy over long distances, and at the distribution level they transform the voltage down to the required level for the consumer. A switching operation carried out in a substation always involves transformer switching. When switching off a transformer under load, the load determines the power factor and the switching device interrupts the load current, which is normally not a problem for the switch or circuit breaker, creating no overvoltage in the system. When a part of the system is energized by connecting it to the rest of the system by a closing operation of a switch or breaker, the transformer can cause high inrush currents [23].

2.3.2.1 Causes and factors affecting transformer inrush current

The nonlinear behaviour of the transformer core is the cause of this. An air-core reactor switched on to compensate for cable charging current does not cause inrush currents. When a power transformer is energized under no-load condition, the magnetizing current necessary to maintain the magnetic flux in the core is in general only a few percent of the nominal rated load current. Fig-2.6 shows the magnetizing curve and the hysteresis loop.

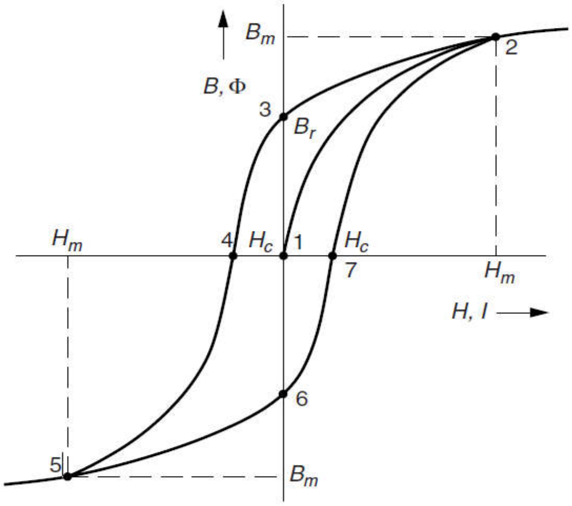


Fig-2.6: Magnetizing curve and hysteresis loop of a transformer core

When a power transformer has been switched off from the system, the transformer core is left with residual flux Br. When the power transformer is connected to the network again at such an instant that the polarity of the system voltage is the same as the polarity of the residual flux Br, then at maximum voltage, the total flux density in the core would have increased to Bm + Br. The core is forced into saturation and the transformer draws a large current from the supplying network. When the voltage reverses its polarity in the next half cycle, then the maximum flux in the core is less than the maximum flux density Bm in the no-load situation. The transformer inrush current is therefore asymmetrical and also contains a DC component, which takes seconds to disappear.

Beside these, there are many factors that affect the transformer inrush current such as the Point of Time when the Transformer is energized relative to the Voltage Source, the magnitude of the Voltage Source etc. Residual flux in the transformer core especially the magnitude and sign also affect the transformer inrush current. The transformer construction, tertiary winding, source impedance and winding resistance are also responsible for this phenomenon.

2.4 SOURCES OF TRANSIENTS

There are two types of sources of transients. They are-

i. External Sources
ii. Internal Sources

2.4.1 EXTERNAL SOURCES

The external sources are the least common source of transients. Some external sources of transient activity are described below:

The most common of the externally generated transients is lightning. These are most often induced onto conductors as lightning strikes near the power line.

Transient can be induced due to the large electric fields those are generated during a discharge can couple into the power system.

i) Other externally generated transients may also be imposed on power lines through normal utility operations. Closing and opening of disconnects on energized lines, switching of capacitor banks, switching of facility loads, tap changing and re-closure operations on transformers can all cause transients.
ii) Poor or loose connections in the distribution system can also generate transients. They may be caused where high wind can blow one power line into another or blow tree limbs into the lines causing arcing then.
iii) Some externally generated transients cause due to accidents and human error since most power lines are run above-ground. Otherwise, animals and weather can also produce conditions which generate transients.
iv) If we share a transformer with other users, any transient activity generated on his premises will be seen at our electrical main, which is known as neighboring business. It is also its an another common source.

The external sources that causes transient activity is shown in Table-2.3 in summarized form-

Table-2.3: External sources of transient activity

External Sources	
Lightning	Capacitor switching
Line/cable switching	Transformer switching
Current-limiting fuse operation.	Poor or loose connections

2.4.2 INTERNAL SOURCES:

The majority of transients are produced within our own facility. The main culprits are device switching, static discharge, and arcing. The internal sources are shown in Table-2.4.

Table-2.4: Common internal sources of transient activity

Internal Sources			
Photocopiers PC	Power Supplies	Laser Printers	Electronic Ballasts
Welders	Power Factor Correction Equipment	Power Supplies	Temperature Controllers
Motor Controllers	Pumps	Inverters	Compressors
Generators	Variable Speed Motors	Standard Electric Motors	High-Frequency Lighting Power Supplies

2.5 EFFECTS OF TRANSIENTS IN POWER SYSTEM

Engineers can use several factors to characterize voltage transients, including crest (or peak) value, area, energy, maximum rate of rise, duration, and the frequency of the transient. The effect of a transient overvoltage event on a specific load depends on the level of susceptibility of that load to one or more of these factors. The influence of transients on electronic equipments are described below-

2.5.1 ELECTRONIC EQUIPMENT

Electronic devices may operate erratically and at decreased efficiencies. As a result lock up and garbled results are produced in this type of equipment. It may be difficult to diagnose these types of disruptions because improper specification and installation of transient voltage surge suppression equipment can actually increase the incidents of failure.

On the other hand, damage in electronic equipment is not readily seen and can result in early failure of affected devices. The most common symptoms are unusually high frequencies of failures in electronic power supplies.

Again electronic chips also called integrated circuits may fail immediately or fail prematurely. The age of the equipment also effects to the failure of it at most of time and that is why modern electronic devices provided clean, filtered power should outlast the mechanical devices by which they control.

2.5.2 MOTORS

When transient voltages are present then motors will run at higher temperatures. The normal timing of the motor can be interrupted due to transients and these transients result in "micro-jogging". Excessive heat, motor vibration, and noise are the results of this type of disruption. Winding insulation of motor is degraded and eventually fails. As a result, transient activity to the point that they produce transients continually can cause degradation of motors and can accelerate the failure of other equipment that is commonly connected in the facility's electrical distribution system. Hysteresis losses are produced by transients in motors that increase the amount of current necessary to operate the motor. Transient also affect electronic motor drives and controls and can cause early failures of these.

2.5.3 LIGHTING

Early failures of all types of lights are caused by transient activity such as early bulbs failures, early failure of ballasts and reduced operating efficiencies are placed in Fluorescent systems. The premature appearance of black "rings" at the ends of the tubes is one of the most common indicators of transient activity. If transients are of sufficient magnitude then a sputtering of the anodes will be caused and these sputters deposited on the insides of the tube result the black "ends" that are commonly seen. Because of the failure of premature filament, incandescent lights fail. The hysteresis losses that produced in motors will be reproduced in transformers. The losses obtained from the results causes increased current draws and hotter operating temperatures. Those rings will be eliminated by the suppression of effective transients and bulbs are lasted for 4 to 6 times longer.

2.5.4 ELECTRICAL DISTRIBUTION EQUIPMENTS

The equipments of electrical distribution systems are also affected by transient activity such as the contacting surfaces of switches, disconnects, and circuit breakers are degraded by it. Nuisance tripping of breaker which is a result of heating of breaker and fooling it into reacting to non-existent current demand can be produced by intense transient activity. Because of the hysteresis losses produced by transients, electrical transformers are forced to operate inefficiently and can run hotter than normal.

2.5.5 PROTECTIVE EQUIPMENTS

Transformer inrush current could potentially affect several things on the power system. One of these is the tripping of the protective relays due to the energization of a transformer and not a fault on the system. This could occur because as the inrush current reaches its peak value, there could be a momentary dip of the voltage that could cause a differential relay to trip out.

2.6 ACCIDENTS DUE TO TRANSIENTS

The number of transformer failure due to primary switching of vaccum circuit breaker is increasing day by day. Table-2.5 details a history of transformers related to primary switching vaccum circuit breakers occurring in the recent past years.

In case-1, at a hydro dam, the transformer was "value engineered" with a 13.8 kV primary winding BIL of 50 kV BIL. The BIL should have been 95 kV BIL for the 13.8 kV class. The user chose to energize the transformer before conducting a switching transient analysis and failed the transformer primary winding. The post mortem analysis revealed that no surge protection was there.

Table-2.5: History of Transformer failure related to primary winding vaccum breaker switching

Case	Facility	Voltage (kV)	Cable feet	BIL (kV)	Type	Arrester	Failure mode	Vendor	Switching
1*	Hydro Dam	13.80	20	50	Dry (VPI)	No	1st turn	A	Close
2	Hospital	13.80	27	95	Dry (VPI)	No	1st turn	A	Close
3	Railroad	26.40	37	150	Liquid(layer wound)	N/A	middle	A	Open
4	Data centre	26.40	40 80	150 150	Dry (VPI)	Yes Yes	1st turn None	B B	Close/open Close
5	Oil Field	33.00	7		Dry (VPI)	No	1st turn	C	Close
6**	Oil Drill Ship	11.00	<30	75	Dry	Yes	1st turn	C	Close

Notes: * = 40-50 yrs. Old with new breaker. ** = 2 yrs. Old. All others new.

In Case 2 at a hospital, the vacuum breaker was close- coupled through 27 feet of cable to a 2500 kVA dry type transformer with 95 kV BIL primary winding. The vacuum breakers were supplied with no surge protection because the particular vacuum breaker installed had a very low value of current chop. During vacuum breaker switching off the transformer, the transformer failed. The transformer was rewound and surge protection/snubbers were installed.

In Case 3 at a railroad substation, vacuum breakers applied at 26.4 kV were used to switch a liquid filled rectifier transformer with 150 kV BIL primary winding. The switching transient overvoltage failed the middle of the primary winding. Forensic analysis determined a rectifier with DC link capacitors and the transformer inductance formed an internal resonance and that was excited by the switching. Such an LC series resonance typically fails the middle of the transformer primary winding.

In Case 4 at a data center, vacuum breakers applied at 26.4 kV were used to switch six dry type transformers with 150 kV BIL primary windings under light load. Two transformers failed, one on breaker closing and the other on opening. The failed transformers were connected by 40 feet of cable to the vacuum breaker, while the other transformers had either 80 feet or 100 feet of cable. Arresters were in place at the time of failure, but there were no snubbers.

In Case 5 in an oil field, a dry type transformer for a VSD had multiple windings to achieve a 36-pulse effective “harmonic free” VSD.A vacuum breaker at 33 kV was separated from the transformer by only 7 feet of cable. Arresters were applied in the primary winding. However, upon closing the breaker, the transformer failed.

Finally, in Case 6 on an oil drilling ship, vacuum breakers designed to IEC standards were applied at 11 kV and connected by 30 feet of cable to a dry type cast-coil propulsion transformer rated 7500 kVA. The transformer was also designed to IEC standards and the primary winding had a BIL of 75 kV. The IEC transformer BIL is much lower than ANSI BIL for the same voltage class winding. The transformer failed on opening the breaker [25].

During commissioning of a large data centre, while switching medium-voltage circuit breakers without any appreciable load, several potential transformers (PT) failed catastrophically which is shown in Fig-2.7. A detailed investigation, including a computer simulation, was performed. Ferro-resonance produced by switching transients associated with opening and closing the vacuum breakers was determined to be the cause [24].

Fig- 2.7: Damage of PT but fuses remained intact

A case study on New Data Center with a 26 kV double-ended loop-through feed to six dry-type transformers each rated as 3000 kVA, 26/0.48 kV ,delta-wye solidly grounded. The study reveals that when four electricians simultaneously opened four 26 kV vaccum breakers, all systems transferred to standby generation but a “loud pop” was heard in substation room and the relay for the vaccum circuit breaker feeding the transformer signalled a trip. After few minutes, when two electricians simultaneously closed two vaccum breakers, then another transformer failed. The damaged transformers are shown in Fig-2.8 [25].

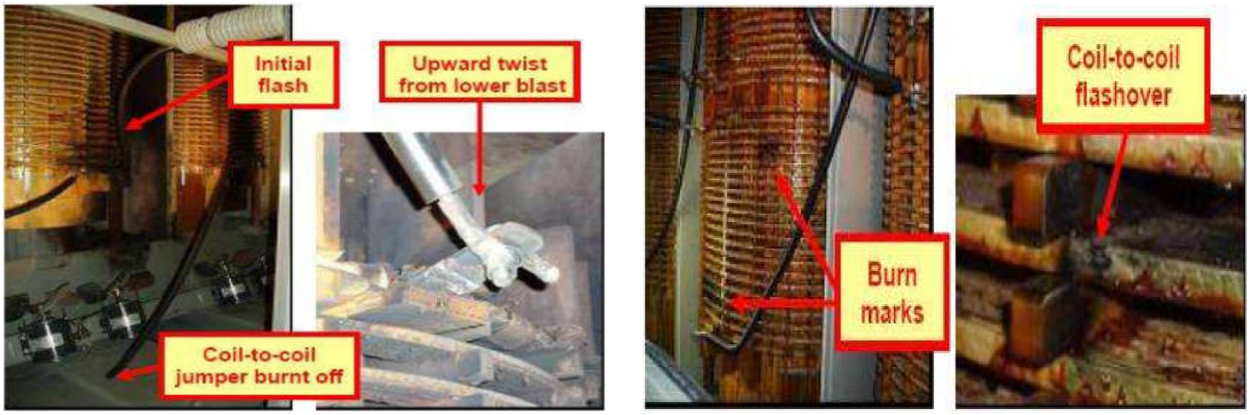


Fig-2.8: Failure of transformer during energization and de-energization

CHAPTER 3

NETWORK MODELLING AND SIMULATION

3.1 INTRODUCTION

The analysis and simulation of electromagnetic transients has become a fundamental methodology for understanding the performance of power systems, determining power component ratings, explaining equipment failures or testing protection devices. The study of transients is a mature field that can be used in the design of modern power systems. Since the first steps in this field, a significant effort has been dedicated to the development of new techniques and more powerful software tools. Sophisticated models, complex solution techniques and powerful simulation tools have been developed to perform studies that are of paramount importance in the design of modern power systems. The first developments of transient tools were mostly aimed at calculating over-voltages. Presently, these tools are applied in a myriad of studies (e.g. FACTS and custom power applications, protective relay performance, power quality studies) for which detailed models and accurate solutions can be extremely important.

3.2 TRANSMISSION LINE MODELLING

Transmission line modelling for short transmission line (about 15 km) uses the nominal PI model. Here the travelling time is less than the solution time steps. But such models are unsuitable for transmission distances. Instead, travelling wave theory is used to generate more realistic models.

A simple and more convenient travelling wave model for a lossless transmission line can be designed using a dual Norton equivalent circuit. The model is equally applicable for overhead lines and underground cables. The main differences arise from the procedures used in the calculation of the electrical parameters from their respective geometries.

The modelling of transmission lines can be done for two cases.

i) Overhead lines
ii) Underground cables.

These two will be discussed separately in two sections.

Overhead transmission line and underground cable segments (or right-of-ways) are represented in two parts: The definition of the transmission segment itself, which can include the admittance/impedance data or the conductor and insulation properties, ground impedance data, and geometric position of all towers and conductors; and the interface to the rest of the electrical system, through electrical interface components (one at each end). If the transmission line is configured in Direct Connection mode, the interface components are not required.

Transmission segments considered to be electrically short in length (i.e. less than 15km for a 50μs time step), may also be represented using an equivalent π-section representation. This is accomplished by either: Using the π-section component in the master library, where only the admittance and impedance data of the line segment is required, or by using the π-section equivalent component creator feature in the Line Constants Program (LCP). π-sections are essentially a network of passive elements, and hence do not represent propagation delay.

Using the data provided by the cross-sectional definition of the segment, the transmission lines and cables are modeled using one of two distributed (travelling wave) models:

i) Bergeon's model (Single frequency)
ii) Frequency dependent (phase) model (Multiple frequencies)

The most accurate of these models are frequency dependent model, which represents all frequency dependent effects of transmission line. When using the Bergeron model, impedance/admittance data can also be entered directly to define the transmission segment.

We will be using the Frequency dependent model for modelling transmission line in the network considered for analysis. For now, a short description for both the models is given below.

The Bergeon's model

Bergeon's model is a simple, constant frequency method, based on travelling wave theory. Here the line is treated as lossless but it's distributed series resistance is added in lumped form. Although the lumped resistances can be inserted throughout the line by dividing its total length into several sections, it makes little difference to do so and the use of just two sections at the ends is perfectly adequate. This lumped resistance model, shown in the Figure below, gives reasonable answers provided that *R*/4 _ *ZC*, where *ZC* is the characteristic (or surge) impedance. However, for high frequency studies (e.g. power line carrier) this lumped resistance model may not be adequate. The two port network for the line with lumped losses is shown in Fig-3.1.

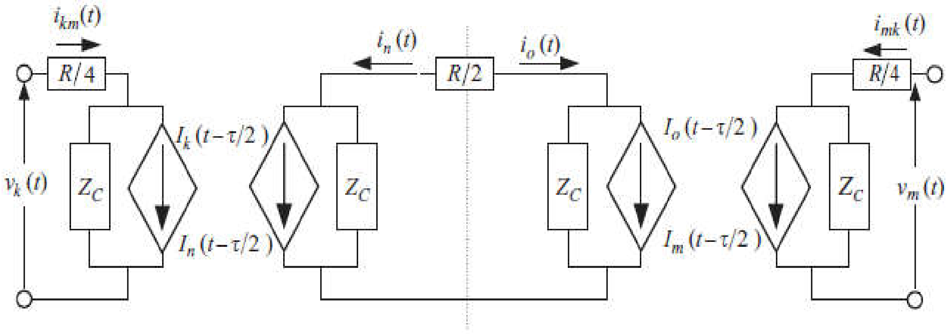


Fig-3.1: Equivalent two port network for line with lumped losses

The frequency dependent (Phase) model

The Frequency Dependent (Phase) model is basically a distributed RLC traveling wave model, which incorporates the frequency dependence of all parameters. This model represents the frequency dependence of internal transformation matrices.

The line frequency-dependent surge impedance (or admittance) and line propagation matrix are first calculated from the physical line geometry. To obtain the time domain response, a convolution must be performed as this is equivalent to a multiplication in the frequency domain. It can be achieved efficiently using recursive convolutions (which can be shown to be a form of root-matching, even though this is not generally recognized). This is performed by fitting a rational function in the frequency domain to both the frequency-dependent surge impedance and propagation constant. As the line parameters are functions of frequency, the relevant equations should first be viewed in the frequency domain, making extensive use of curve fitting to incorporate the frequency-dependent parameters into the model. Two important frequency-dependent parameters influencing wave propagation are the characteristic impedance *ZC* and propagation constant *γ*. Rather than looking at *ZC* and *γ* in the frequency domain and considering each frequency independently, they are expressed by continuous functions of frequency that need to be approximated by a fitted rational function. The characteristic impedance is given by the equation-(3.1) and the propagation constant is given by equation-(3.2) as-

$$Z=\sqrt{\frac{R'(\omega)+j\omega L'(\omega)}{G'(\omega)+j\omega C'(\omega)}}=\sqrt{\frac{Z'(\omega)}{Y'(\omega)}} \tag{3.1}$$

While the propagation constant is:

$$\gamma\,(\omega)=\sqrt{(R'(\omega)+j\omega L'(\omega))(G'(\omega)+j\omega C'(\omega))} \tag{3.2}$$

3.2.1 OVERHEAD LINE

For our analysis, the frequency dependent (phase) model has been used. The frequency (phase) dependent model uses curve fitting to duplicate the frequency response of a line or cable. It is the most advanced time domain model available as it represents the full frequency dependence of all line parameters (including the effect of a frequency dependent transform). It is useful for uses wherever the transient or harmonic behavior of the line or cable is important. The specifications used for designing of transmission line are shown in Table-3.1 and Table-3.2.

Table 3.1: Frequency dependent (phase) model specifications

Frequency Dependent (phase) Model Options	
Travel time interruption	On
Curve fitting starting frequency	0.5 Hz
Curve fitting end frequency	1.0E6[Hz]
Total number of frequency increments	100
Maximum order of fitting for Yc	20
Maximum fitting error for Yc	0.2[%]
Max. order per delay Grp. for prop. Func.	20
Max. fitting error for prop. Func.	0.2[%]
Dc correction	Disabled
Passivity checking	Disabled

Table 3.2: Frequency dependent (mode) model specifications

Frequency Dependent (mode) Model Options	
Travel time interruption	On
Curve fitting starting frequency	0.5 Hz
Curve fitting end frequency	1.0E6[Hz]
Maximum order of fitting for Z Surge	20
Maximum order of fitting for prop. Func.	20
Maximum fitting error for Z Surge	2[%]
Maximum fitting error for Prop. Func.	2[%]

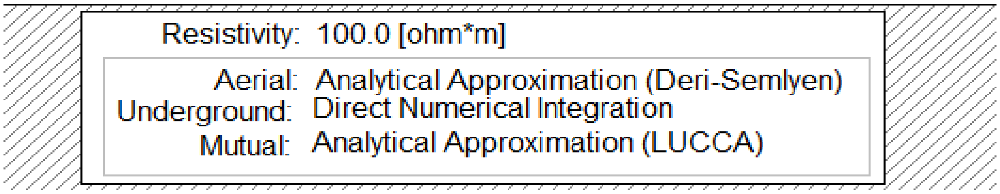
Other specifications of transmission lines are shown in Table-3.3 and Table-3.4 and the resistivity in Fig-3.2.

Table 3.3: Definition Canvas (TLine_1)

Definition Canvas (TLine_1)	
Segment name	Tline_1
Steady state frequency	50.0 [Hz]
Length of line	30.0 [km]
Number of conductors	3

Table 3.4: Definition Canvas (TLine_2)

Definition Canvas (TLine_2)	
Segment name	Tline_2
Steady state frequency	50.0 [Hz]
Length of line	10.0 [km]
Number of conductors	3



Resistivity: 100.0 [ohm*m]

Aerial: Analytical Approximation (Deri-Semlyen)
Underground: Direct Numerical Integration
Mutual: Analytical Approximation (LUCCA)

Fig-3.2: Resistivity of overhead lines

The tower model and the specifications used for tower designs are shown in Fig-3.3 and Table-3.5

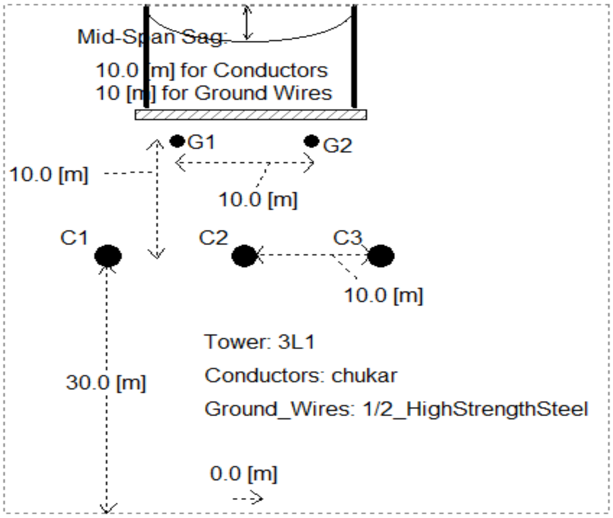


Fig-3.3: Tower model

Table-3.5: Relevant parameters used in overhead line tower design

3 conductor flat tower configuration	
GENERAL	**Value**
Graphic of conductor sag is	Visible
Ideal transposition of this circuit is	Enabled
Shunt conductance	1.0e-11[mho/m]
Tower name	3L1
TOWER/CONDUCTOR/GROUND WIRE PLACEMENT	
Relative x-position of tower centre	0.0[m]
Height of all conductors	30.0[m]
Horizontal spacing between conductor	10.0[m]
Height of ground wire over lowest conductor	10.0[m]
Spacing between ground wire	10.0[m]

3.2.2 UNDERGROUND CABLE

For designing underground cable, we used the same model as the overhead transmission line. The typical cross section of a cable is shown in Fig-3.4.

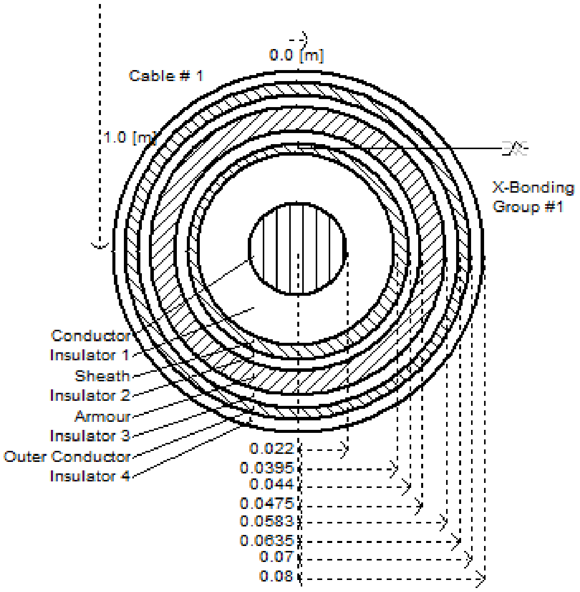


Fig-3.4: Typical cross section of a single core underground cable

For our analysis, we used three single core cables. The related specifications and cable models are illustrated in Fig-3.5.

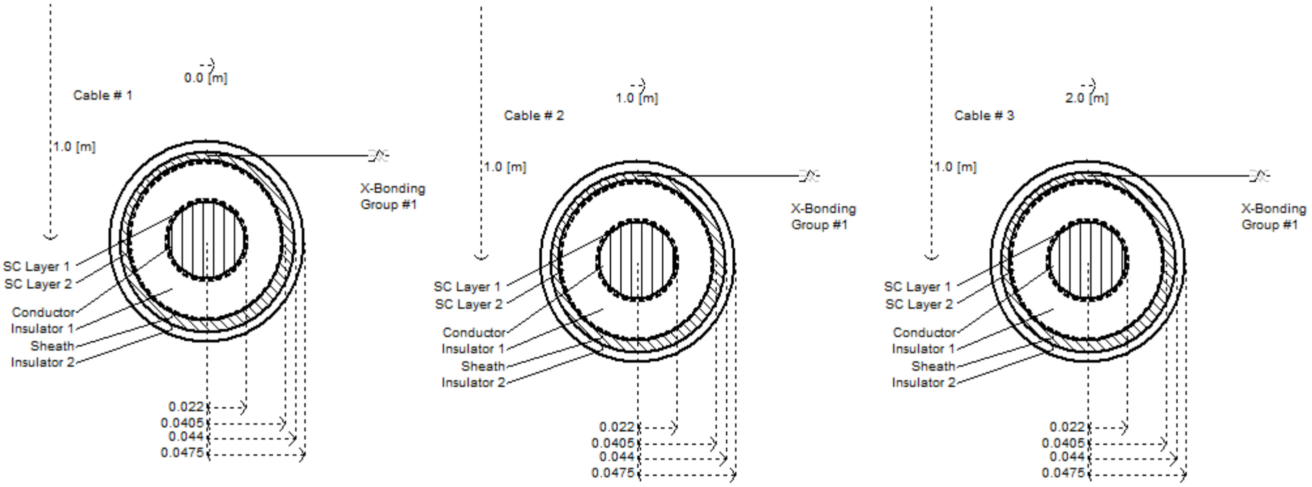


Fig-3.5: Cross section of three single core cable used for analysis

3.3 FAULT MODULE

For transient short circuit fault analysis in chapter-05, we used a fault module from the master library of simulation tool-PSCAD. Both symmetrical and unsymmetrical fault analysis can be done using this fault module. The figure and specifications of fault module is given in Fig-3.6 and Fig-3.7.

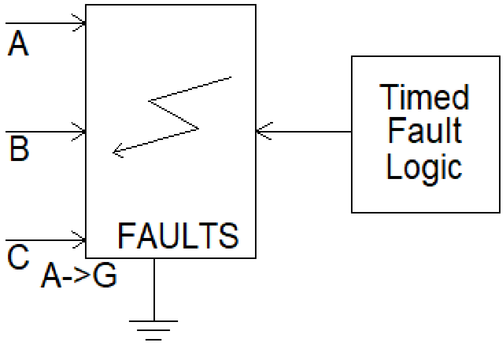


Fig-3.6: Three phase view of fault module

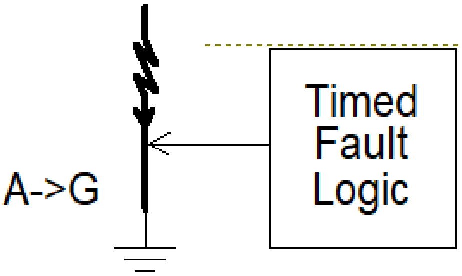


Fig-3.7: Single line view of fault module

3.4 EVALUATION OF DISTRIBUTION NETWORK

The primary purpose of an electricity distribution system is to meet the customer’s demands for energy after receiving the bulk electrical energy from transmission or sub transmission substation. There are basically two major types of distribution substations: primary substation and customer substation. The primary substation serves as a load centre and the customer substation interfaces to the low voltage (LV) network. Customer substation is referred to a distribution room normally provided by the customer. The distribution room can accommodate a number of HV switchgear panel and the transformer to enable LV connection to the customer incoming switchboard. Depending on the geographical location, the distribution network can be in the form of overhead lines or underground cables [26].

Cables are commonly used in urban areas and overhead lines are adopted for rural areas. Different network configurations are possible in order to meet the required supply reliability. Protection, control and monitoring equipment are provided to enable effective operation of the distribution network.

The distribution system is commonly broken down into three components: distribution substation, distribution primary and secondary. At the substation level, the voltage is reduced and the power is distributed in smaller amounts to the customers. Consequently, one substation will supply many customers with power. Thus, the number of transmission lines in the distribution systems is many times that of the transmission systems. Furthermore, most customers are connected to only one of the three phases in the distribution system. Therefore, the power flow on each of the lines is different and the system is typically ‘unbalanced’. This characteristic needs to be accounted for load flow studies and transient analysis related to distribution networks.

Distribution Substations

The distribution system is fed through distribution substations. These substations have an almost infinite number of designs based on consideration such as load density, high side and low side voltage, land availability, reliability requirements, load growth, voltage drop, cost and losses, etc. For a typical substation, the voltage of the high side bus can be anywhere from 33 kV all the way up to 345 kV. The average high side voltage level is approximately 115 to 138 kV. Two or more feeders are normally connected to the low voltage bus through a feeder breaker.

Distribution Feeders

On a primary distribution feeder, various equipments can be distinguished such as fuses, distribution transformers, reclosers, switches. Much of these equipments, such as reclosers, are used only at the distribution level. Other equipment such as capacitors, transformers, and arresters are also used at the transmission levels but with considerably different rules of application.

Most distribution feeders are three-phase and four-wire. The fourth wire is the neutral wire which is connected to the pole, usually below the phase wires, and grounded periodically. A three-phase feeder main can be fairly short, on the order of a mile or two, or it can be as long as 30 miles. Actually, the length of feeders is closely linked with load density at location. For instance, for an area where the customer load density is strong, primary network will end very close of consumers and secondary feeders will be short. For a weak load density area, primary and secondary feeders will be longer. Distance separating substation from customers will be covered both by primary and secondary feeders in order to provide the best quality supply. These differences explain why a distinction is made between country distribution networks, where customers are spread, and urban distribution networks, where large urban agglomerations must be taken into consideration. Some characteristics of the secondary spot network are going to be given because it is frequently used in the United States. Secondary spot network is characterized by a maximum service reliability and an operating flexibility. It includes two or more 'transformer / protector' units in parallel. The low voltage bus is continuously energized by all units, and automatic disconnection of any unit is obtained by sensitive reverse power relays in the protector. Maintenance switching of primary feeders can be done without customer interruption or involvement. This system represents the most compact and reliable arrangement of components and is the most reliable for all classes of loads.

Secondaries

The purpose of the distribution transformer is to reduce the primary voltage to a level where it can be used by the customer. Single-phase transformers range in size from 10 kVA to about 300 kVA with units in the 25 and 37.5 kVA size being the most popular for residential areas. The secondary voltage level in the United States for residential service is 120/240 Volts. Lower wattage devices, such as lights, are connected line-to-neutral across both sides of the 7 transformer secondary. Higher wattage devices, such as ovens, clothes dryers, etc., are usually connected across the 240 volt circuit since this has the effect of reducing voltage drop and losses [27].

3.5 SIMULATION TOOL - PSCAD

PSCAD (Power Systems Computer Aided Design) is a powerful and flexible graphical user interface to the world-renowned, EMTDC electromagnetic transient simulation engine. PSCAD enables the user to schematically construct a circuit, run a simulation, analyze the results, and manage the data in a completely integrated, graphical environment. Online plotting functions, controls and meters are also included, enabling the user to alter system parameters during a simulation run, and thereby view the effects while the simulation is in progress.

PSCAD comes complete with a library of pre-programmed and tested simulation models, ranging from simple passive elements and control functions, to more complex models, such as electric machines, full-on FACTS devices, transmission lines and cables. If a required model does not exist, PSCAD provides avenues for building custom models. For example, custom models may be constructed by piecing together existing models to form a module, or by constructing rudimentary models from scratch in a flexible design environment.

The following are some common models found in the PSCAD master library:

i) Resistors, inductors, capacitors

ii) Mutually coupled windings, such as transformers

iii) Frequency dependent transmission lines and cables (including the most accurate time domain line model in the world)

iv) Current and voltage sources

v) Switches and breakers

vi) Protection and relaying

vii) Diodes, thyristors and GTOs

viii) Wind source, turbines and governors

ix) AC and DC machines, exciters, governors, stabilizers and inertial models

x) Meters and measuring functions

xi) Generic DC and AC controls

xii) HVDC, SVC, and other FACTS controllers

xiii) Wind source, turbines and governors

3.5.1 CONTENTS/SCOPE OF PSCAD

The following is a general overview (not exhaustive) of new and enhanced features to be aware of:

i) Multiple Instance Modules (MIM)

ii) **EMTDC Runtime Configuration:** Runtime configuration is a term used to describe a collection of changes to both the EMTDC system dynamics structure and methods in the design of components, in order to ensure support for MIM.

iii) **#BEGIN/#ENDBEGIN Directive Block:** This directive provides access to the BEGIN outer process in EMTDC, and is required for supporting MIM in custom components.

iv) **#STORAGE Arrays:** New storage arrays have been added to EMTDC specifically for the transfer of data from the new BEGIN section to the DSDYN/DSOUT sections in the EMTDC system dynamics.

v) **High Performance Computing:** Two unique parallel computing functions were incorporated that both utilize multiple processor cores: A parallel solution of transmission lines and cables, and a ability to launch multiple EMTDC simulation runs simultaneously.

vi) **Electric Network Interface (ENI):** Multiple case projects representing multiple parts of a complete electric network, may be run simultaneously as a single simulation. A single electric network may be split so that each electric subsystem is represented by a separate case project, and thereby run using a separate EMTDC process. Each EMTDC process is linked together via an Electric Network Interface (ENI) to form a cohesive simulation that is run from within a single workspace.

vii) **Multiple Workspaces:** PSCAD now supports multiple workspaces: What this means from the user's perspective is that entire workspaces may be loaded, saved and unloaded without having to close the application. A single workspace may house multiple projects, including both libraries and cases, as well as possessing its own unique setting options.

viii) **Workspace-Level Control:** Workspace-level, multi-project, multiple-run control support has been added to the application. Communicating inter-project signal values via Radio Link components to and from a common value table in the workspace, a master project can control a number of slave projects to simultaneously perform necessary calculations and report them back to the master.

ix) **Black boxing Modules:** With a simple click, this feature will convert any page module containing purely control-based systems into an equivalent, non-module component, complete with generated source files and/or compiled binary files. Black boxing allows users to design their systems graphically, and then quickly black box the system, thereby protecting their intellectual property when distributing their models to clients.

x) **Simulation Sets/Multiple EMTDC:** It is now possible to simultaneously launch and run multiple, simultaneous EMTDC simulations. Both sequential and parallel simulation runs are possible via the defining of what are referred to as 'simulation sets' in the workspace.

xi) **Enhanced Searching:** The searching facilities have been enhanced. The background search engine is now based on X Path, a query language for selecting nodes in an XML document.

xii) **Fortran Compiler Support:** A new free Fortran 95 compiler called GFortran now accompanies PSCAD X4.

xiii) **Mutual Coupling:** This feature enables users to mutually couple individual line or cable segments with identical lengths. Multiple segments can be merged into a single Right-Of-Way (ROW) without affecting the individuality of the each segment.

xiv) **Oscilloscope:** A new meter utility has been added as yet another avenue for viewing data online.

xv) **Comparator Tool:** The schematic comparator tool allows for quick and convenient visual differentiation between module component definitions.

xvi) **Parameter Grid Pane:** The component parameter grid pane provides a convenient means to display the parameters for all instances of a given component or module definition. More importantly, it enables the ability to modify multiple parameter values in multiple component instances simultaneously.

xvii) **Bird's Eye View Pane:** The Bird’s Eye View navigation pane provides an overview of the entire Schematic or Graphic canvas and indicates what is currently in view with a blue box.

xviii) **Layers Pane:** The layers pane is the interface to the schematic canvas drawing layers feature. Drawing layers provide the ability to efficiently enable or disable components on the canvas, or to toggle the visibility of any objects that appear on the canvas.

xix) **Display Voltage on Buses:** This option allows for the dynamic display of RMS voltage directly on Bus components.

xx) **Saving Graphics to File:** Graphic objects used in the Graphics section of the component design environment can now be stored in and imported from files.

These are the most recent features of PSCAD simulation tool. More and more research is going on for the future development of PSCAD. Further research and development programs can be conducted faster and better performance of the software. In future, PSCAD may add more extensive features that can be used to:

i) Model and analyze smart grid.
ii) Switchgear protection system design.
iii) Circuit breaker modeling.
iv) Nuclear power plant design and protection system analysis.
v) More accuracy in system analysis results.
vi) More realistic and convenient system design.
vii) Customization of generator and transformer model.
viii) Harmonic analysis of a system
ix) FACTS technology analysis
x) HVDC system analysis

CHAPTER 4

TRANSIENT ANALYSIS OF OVERHEAD LINE AND UNDERGROUND CABLE

4.1 INTRODUCTION

An overhead power line is a structure used in electric power transmission and distribution to transmit electrical energy along large distances. It consists of one or more conductors (commonly multiples of three) suspended by towers or poles. Since most of the insulation is provided by air, overhead power lines are generally the lowest-cost method of power transmission for large quantities of electric energy [28].

Fig- 4.1: Overhead Line

Today, transmission-level voltages are usually considered to be 110 kV and above. Lower voltages, such as 66 kV and 33 kV, are usually considered sub-transmission voltages, but are occasionally used on long lines with light loads. The overhead lines are shown in Fig-4.1. Voltages less than 33 kV are usually used for distribution. Voltages above 765 kV are considered extra high voltage and require different designs compared to equipment used at lower voltages [30].

4.2 FAMILIARIZATION TO THE ANALYSED NETWORK

During transmission of power from the generation side upto the customer end, we require different types of switching like transformer energization and de-energization, capacitor bank switching and switching of load etc. During performing these switching operations, transients are developed across the circuit breaker which travels along the transmission line as a travelling wave. These high voltage, high frequency transients may be severe enough to cause the equipment and hence system failure. In these chapters, we mainly analysed a distribution network where transmission was done through overhead lines under different switching conditions. The single line diagram of the considered network for analysis of overhead line is shown in Fig-4.2.

Fig-4.2 shows a single line diagram of the considered distribution network for our analysis. The network is fed from a 132kV external grid which has been shown in the figure as the symbol of generator. The network consists of 10 buses where bus-3, bus-4, bus7 and bus-8 represent four feeders. There are two power transformers named as T1 (132kV/33kV) and T2 (33kV/11kV) and one distribution transformer T3 (11kV/0.4kV).The power ratings of T1, T2 and T3 are 100MVA, 50MVA and 20MVA respectively. At the end of the transmission line, a load is connected of 10MVA with power factor of 0.8.

The length of the transmission line, Tline_1 is 30km and Tline_2 is 10km. The line parameter has been chosen as default case and is modelled using frequency dependent phase model. Two capacitor banks of ratings 2.0MVAR and 1.0MVAR are installed at bus-5 and bus-9 for the improvement of the power factor.

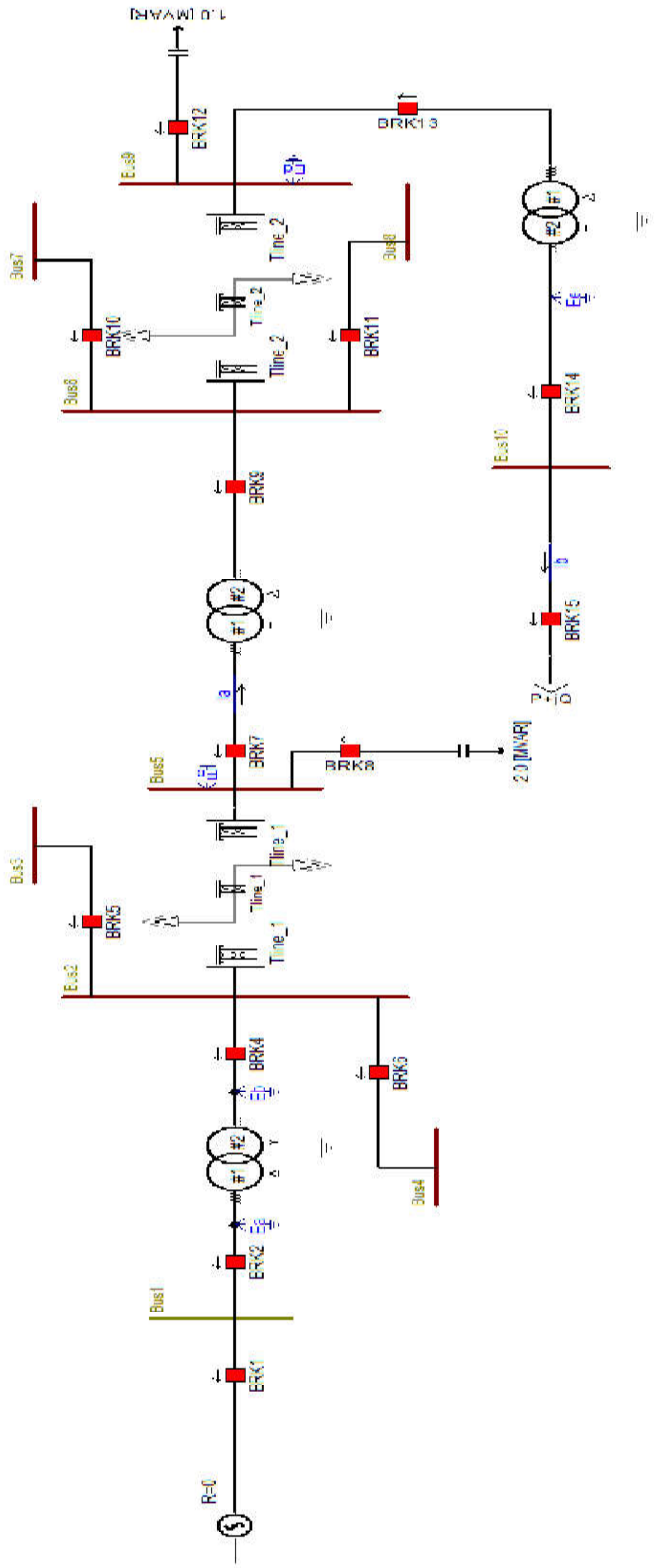


Fig-4.2: Considered network for switching transient analysis of overhead lines

4.3 SWITCHING EVENTS OF THE NETWORK

Transient over-voltages are developed during switching operation in the transmission line. In this section, we mainly analysed the system for three switching events. The switching events include-

i) Energization and de-energization of the transformer
ii) Energization and de-energization of capacitor bank
iii) Switching of load at the distribution side.

4.3.1 ENERGIZATION AND DE-ENERGIZATION OF TRANSFORMER

When the transformer is energized and de-energized, high frequency oscillatory transients are developed which travels along the transmission line. In the given network of fig-4.2, when simulation was done for transformer, T1 energization, then the voltage at different buses were measured. The outputs of the voltage profile at bus-1 and bus-2 are shown in Fig-4.3 and Fig-4.4.

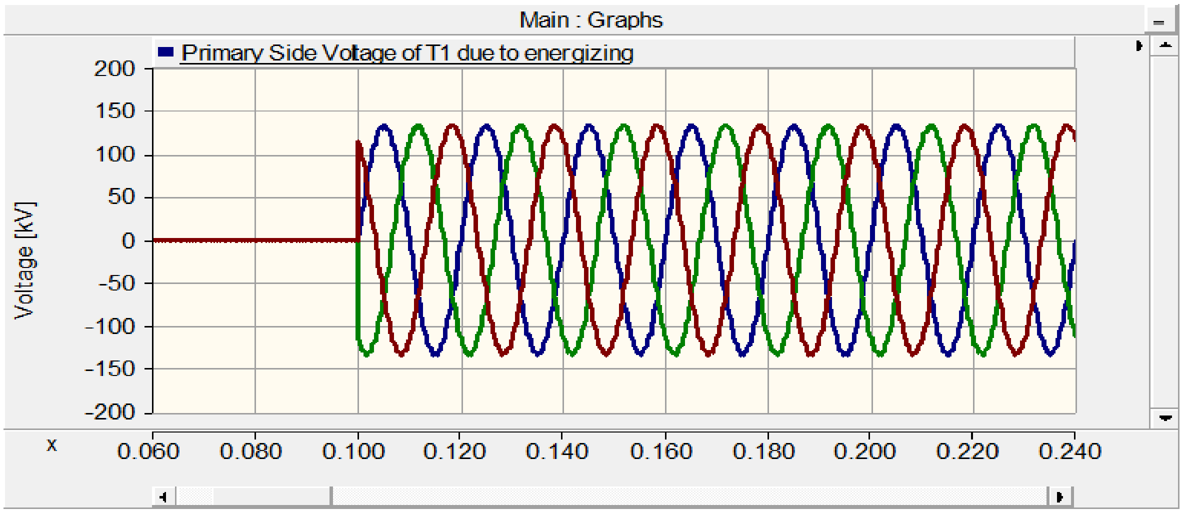


Fig-4.3: Primary side voltage of T1 (i.e.bus-1) due to energization

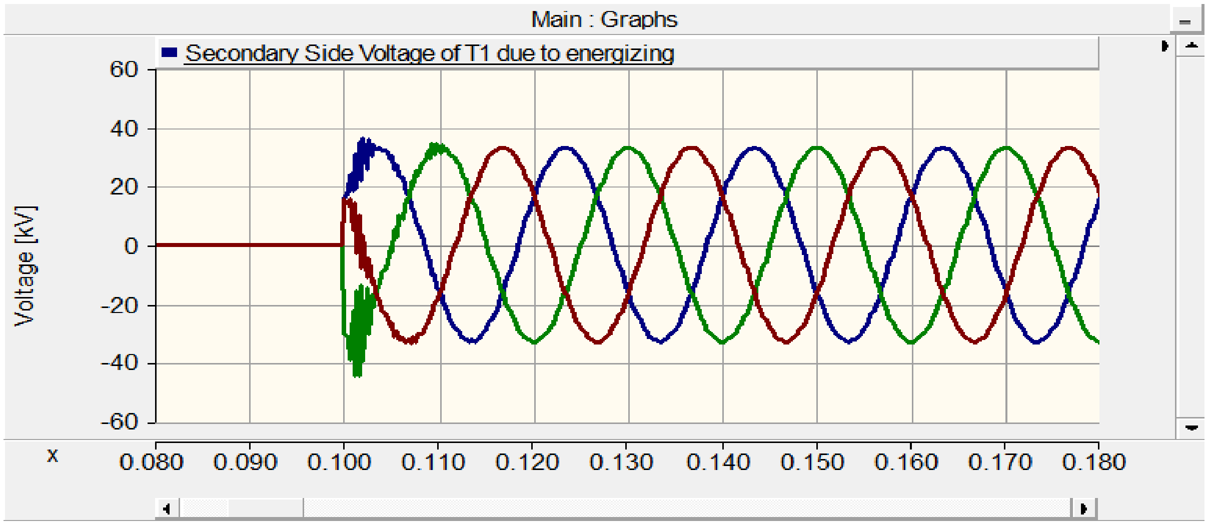


Fig-4.4: Secondary side voltage of T1 (i.e. bus-2) due to energization

The energization of transformer at the upstream side also affects the downstream side. The effect of the energization of T1 on the distribution side had been measured. These are shown through the outputs waveforms in Fig-4.5.

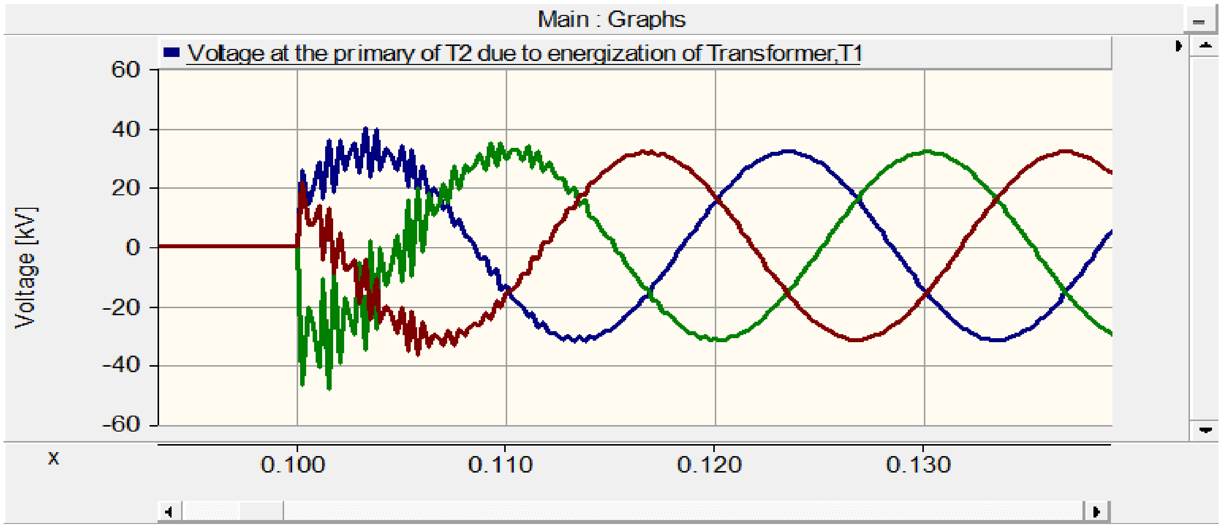


Fig-4.5: Voltage at the primary side of T2 (i.e. bus-5) due to energization of transformer, T1

Under the condition that the transformer ,T1 is ON and the capacitor banks are OFF, the network had been simulated for the energization of transformer, T2. The output waveform is shown in Fig-4.6.

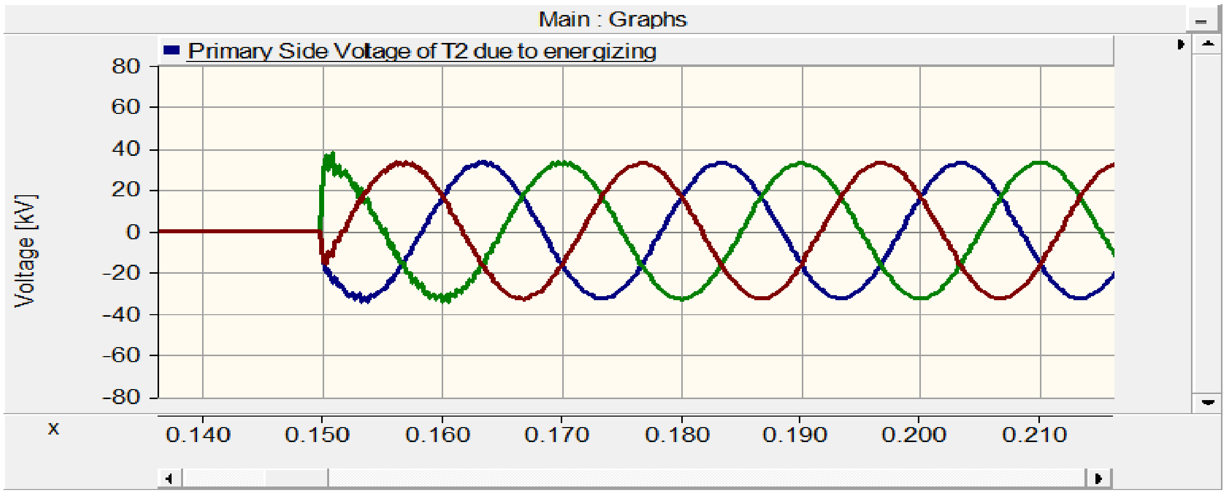


Fig-4.6: Primary side voltage of T2 (i.e.bus-5) during energization of T2

Transient condition also appears at the secondary side of the transformer, T2. The magnitude in per unit was higher than the primary side voltage of the transformer, T2. This is shown in Fig-4.7.

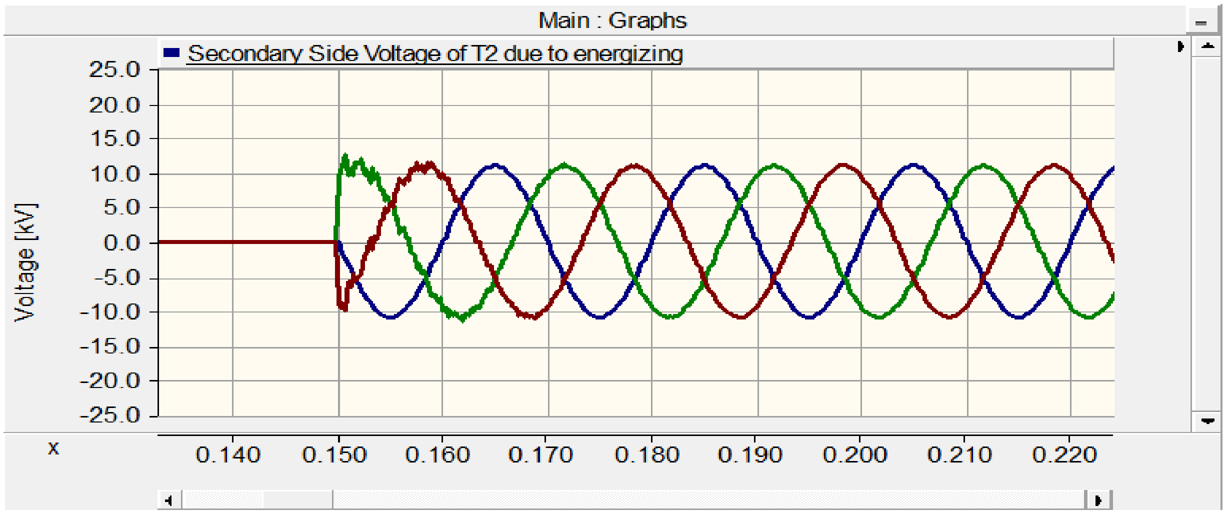


Fig-4.7: Secondary side voltage of T2 (i.e. bus-6) due to energization of T2

De-energization of transformer can also produce huge transient overvoltage. The response of voltage of bus-5 is shown in Fig-4.8. Although , the figure below doesn't show any overvoltage during de-energization.

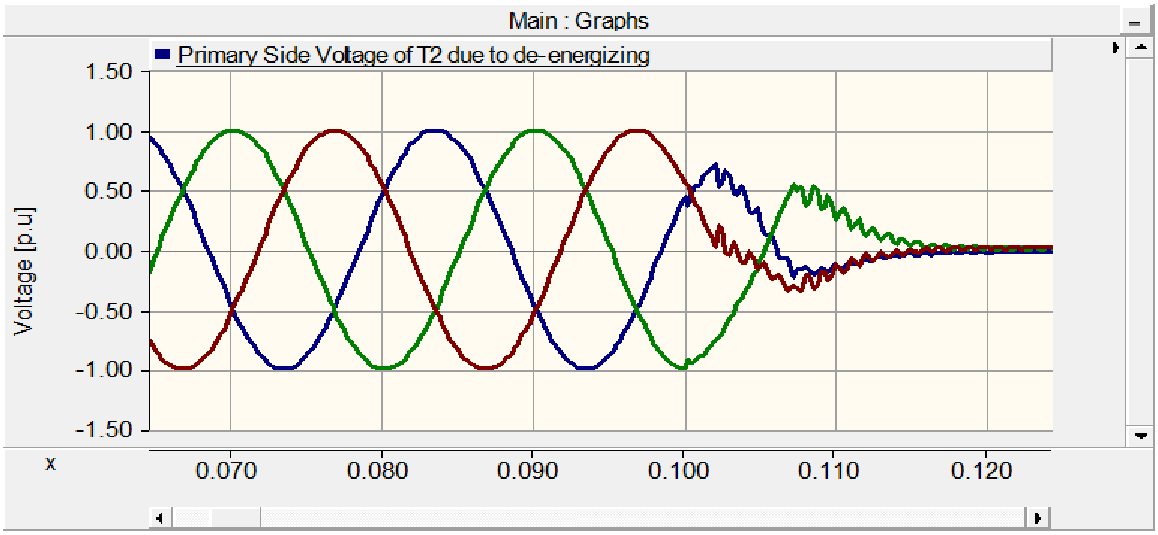


Fig-4.8: Primary side voltage of T2 (i.e. bus-5) due to de-energization

4.3.2 ENERGIZATION AND DE-ENERGIZATION OF CAPACITOR BANK

The electrical energy is almost exclusively generated, transmitted and distributed in the form of alternating current. Therefore, the question of power factor immediately comes into picture. Most of the loads are inductive in nature and hence have lagging power factor. The low power factor is highly undesirable as it causes an increase in current, resulting in additional losses of active power in all the elements of power system from power station generator down to the utilisation devices. In order to ensure most favourable conditions for a supply system from engineering and economical standpoint, it is important to have power factor as close to unity as possible. Improved power factor increase efficiency, voltage regulation and decreases line losses [29]. Hence capacitor banks are installed in the power system for the improvement of power factor. PFI panels are widely used in industry which is shown in Fig-4.9.

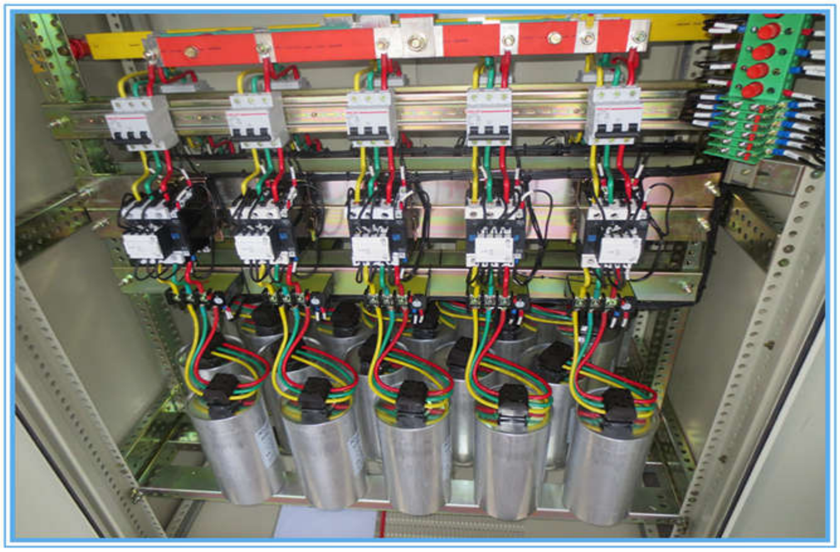


Fig-4.9: Power factor improvement (PFI) panel

During switching of these capacitor banks, high voltage transients are induced in the system which may lead to the system failure. When an uncharged capacitor banks are switched, inrush charging current flows through the capacitor bank and the magnitude of the inrush current depends on the size of the capacitor bank. Larger the size of the bank, higher will be the value of the inrush current. The output waveform of the charging is shown in Fig-4.10 and Fig-4.11 for 2.0MVAR capacitor bank and also 10MVAR capacitor bank for comparative study.

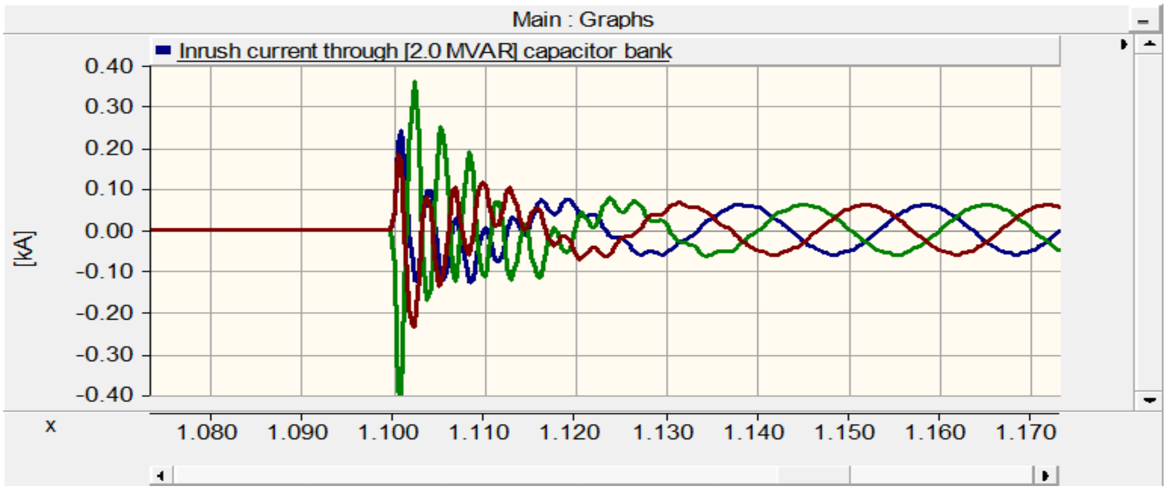


Fig-4.10: Inrush charging current through the 2.0MVAR capacitor bank

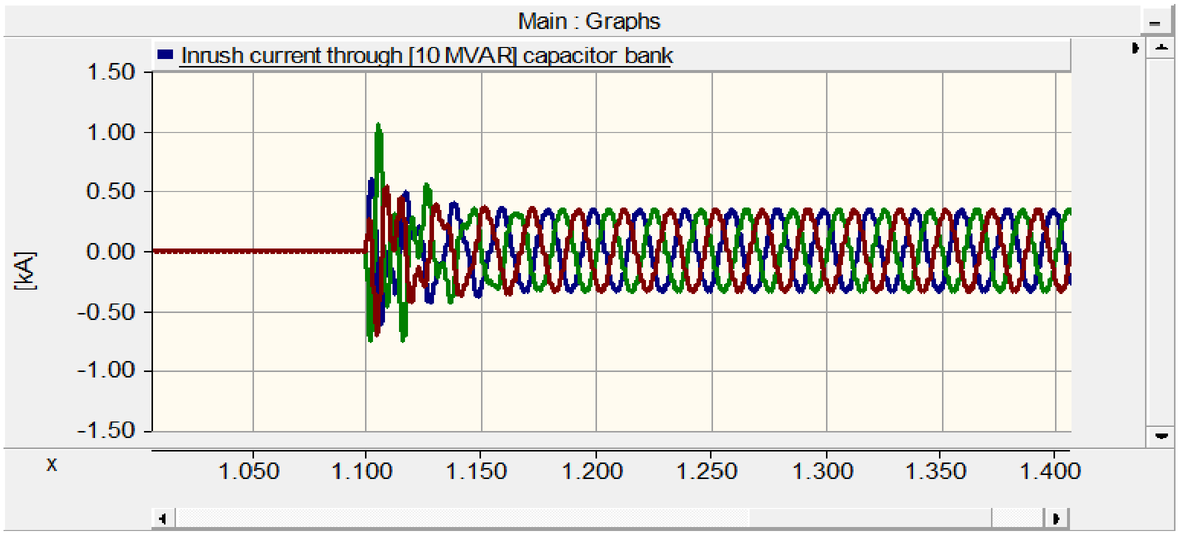


Fig-4.11: Inrush charging current through the 10MVAR capacitor bank

Switching of 2.0MVAR capacitor bank

The capacitor bank (2.0MVAR) was installed at bus-5. The network was simulated at the instance of the switching of this capacitor bank and the voltage profiles of the buses were recorded during this switching operation. The voltage waveform of bus-5 is given in Fig-4.12.

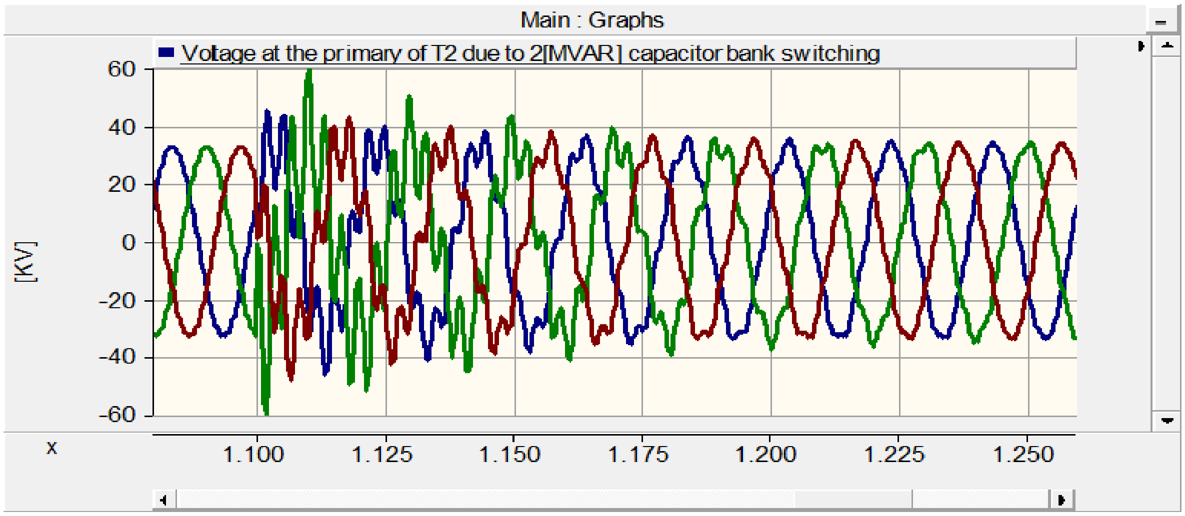


Fig-4.12: Voltage at the primary side of T2 due to 2.0MVAR capacitor bank switching

In Fig-4.12, the voltage of bus-5 reaches much higher than the nominal value. Apparently the voltage crosses 60kV. The output waveform of each phases are shown separately in Fig-4.13, Fig-4.14 and Fig-4.15 for analysis purposes-

Phase-A

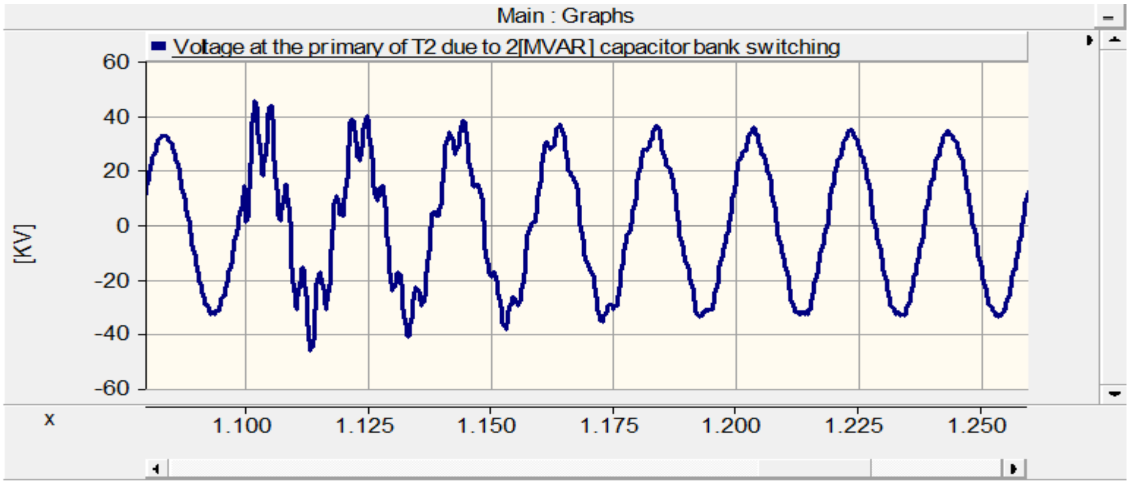


Fig-4.13: Phase-A voltage of bus-5 due to capacitor bank switching

Fig-4.13 shows that the voltage of phase-A experiences a transient condition due to switching of the capacitor bank. The switching was done during the rising edge of phase-A i.e. at time t =1.10 sec. The voltage of phase-B is shown in Fig-4.14.

Phase-B

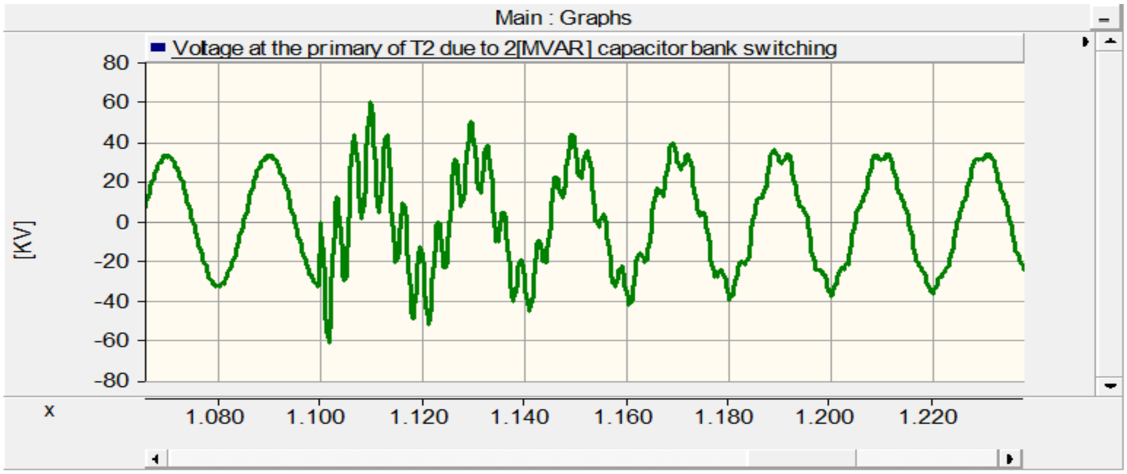


Fig-4.14: Phase-B voltage of bus-5 due to capacitor bank switching

The voltage peak of phase-B is greater than that of phase-A. The switching operation was done at the peak of phase-B and the voltage appears across the contacts of phase-B of the circuit breaker was maximum. The response of phase-C has also been analysed separately and is shown in Fig-4.15.

Phase-C

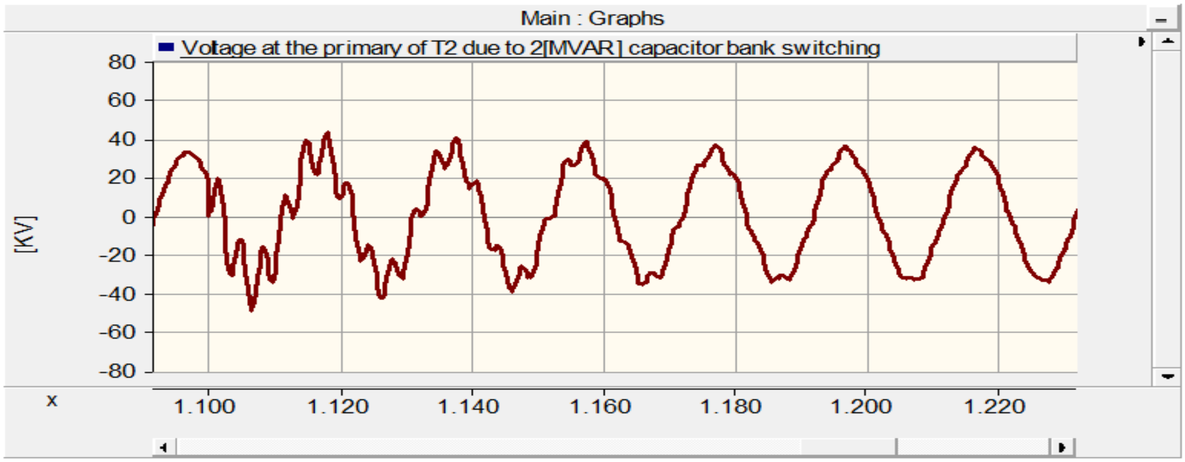


Fig-4.15: Phase-C voltage of bus-5 due to capacitor bank switching

From Fig-4.15, we can see that the switching was done at the falling edge of voltage at time t = 1.1 sec and the voltage appears at the two contacts of the circuit breaker of phase-C is minimum at this time. The primary side voltage of T3 i.e. bus-9 due to the switching of 2.0 MVAR capacitor bank is shown in Fig-4.16.

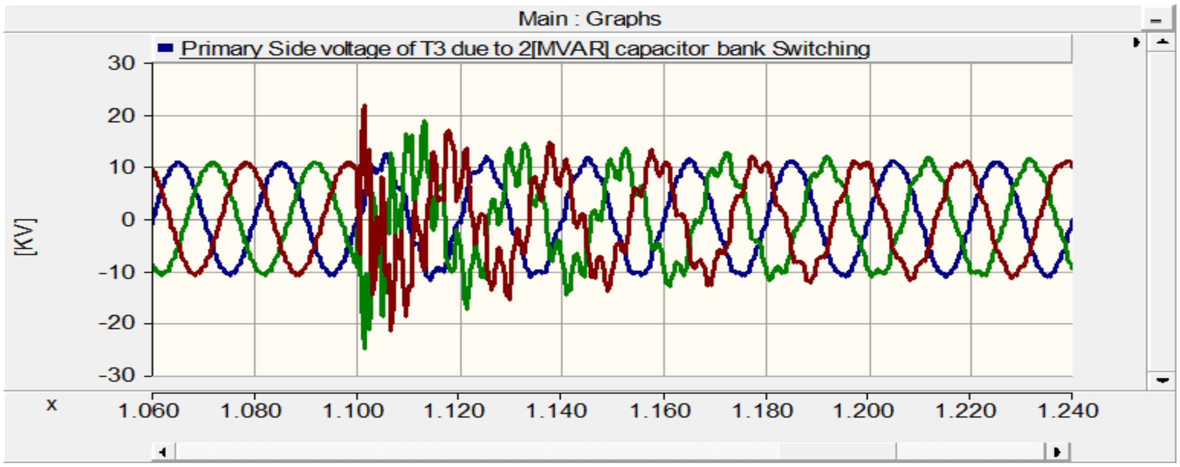


Fig-4.16: Primary side voltage of T3 (i.e. bus-9) due to 2.0 MVAR capacitor bank switching

Due to the switching of capacitor bank, current also affected by transient. The current profile due to the switching of capacitor bank at the primary side of T2 is shown in Fig-4.17.

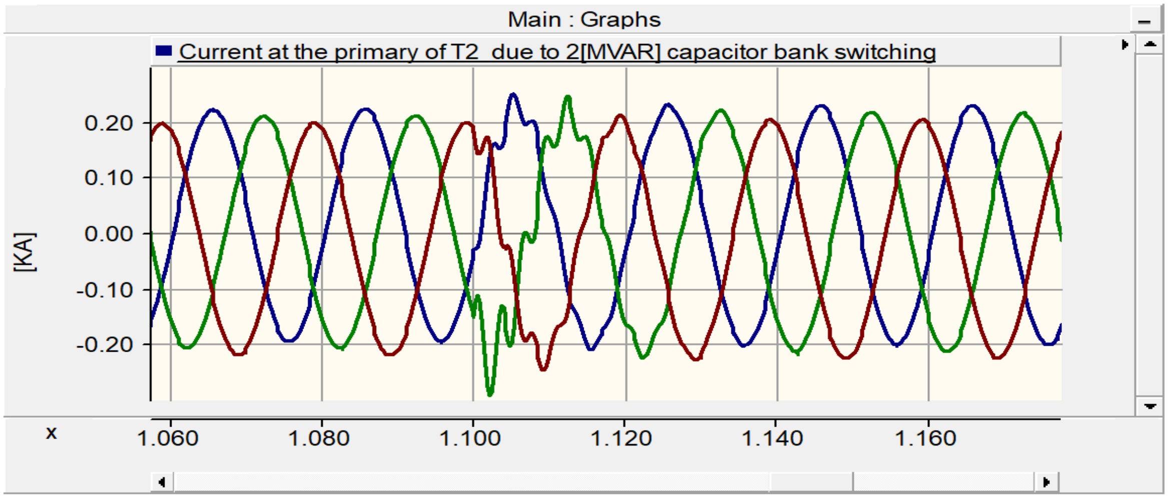


Fig-4.17: Current at the primary side of T2 due to 2.0MVAR capacitor bank switching

De-energization of the capacitor bank also involves transient overvoltage. The de-energization was not too much severe as in case of energization. The output waveform is given in Fig-4.18.

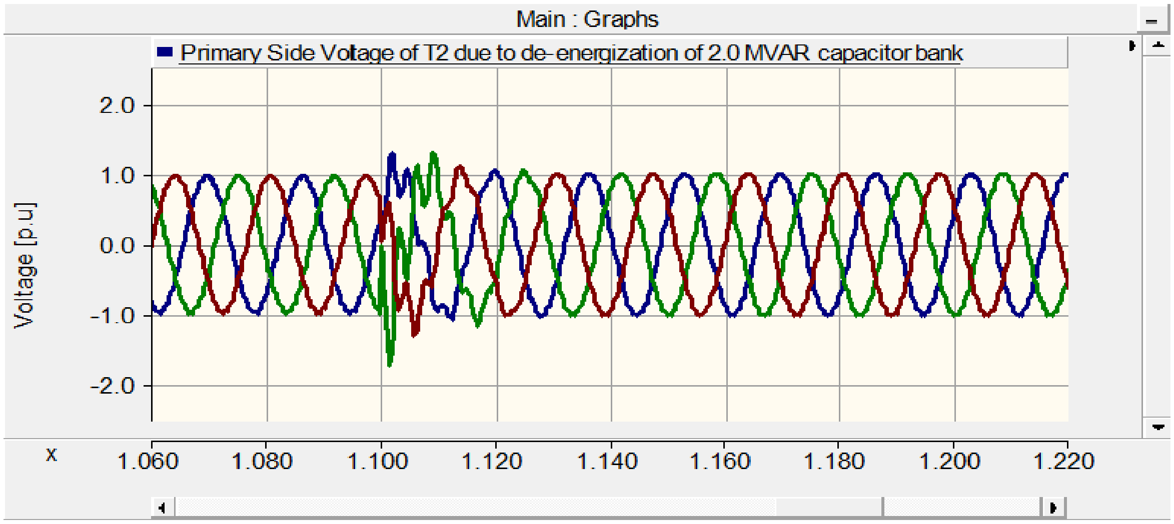


Fig-4.18: Primary side voltage of T2 (i.e. bus-5) during de-energization of capacitor bank

Switching of 1.0MVAR capacitor bank:

The capacitor bank (1.0MVAR) was installed at bus-9. The network was simulated at the instance of the switching of this capacitor bank provided that the capacitor bank at bus-5 was switched off. The voltage profiles of the buses were recorded during this switching operation. The output waveform is shown in Fig-4.19.

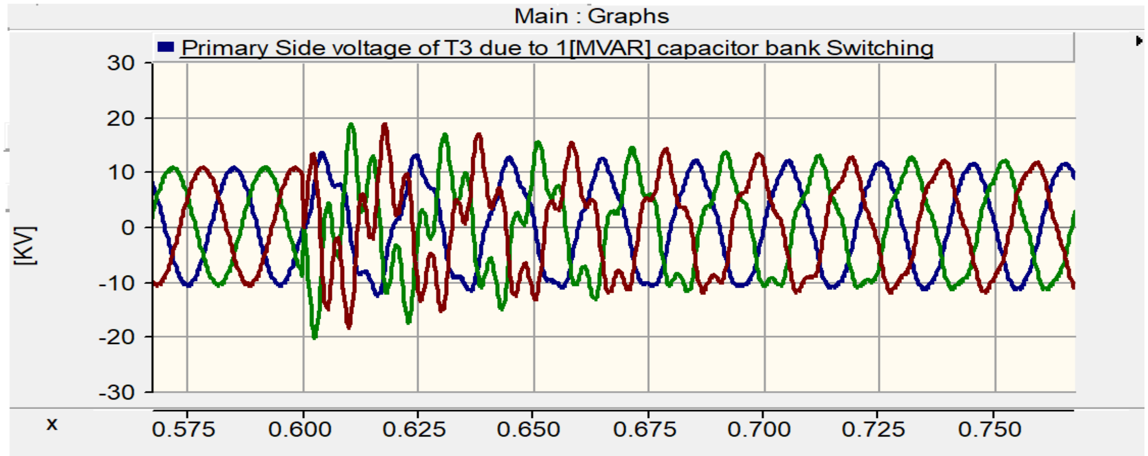


Fig-4.19: Primary side voltage of T3 (i.e. bus-9) due to 1.0MVAR capacitor bank switching

For post mortem analysis of the transient overvoltage that occurs at bus-9 due to the 1.0MVAR capacitor bank was done. The output waveform of each phases are shown separately for analysis purposes. The response of phase-A voltage is shown in Fig-4.20.

Phase-A

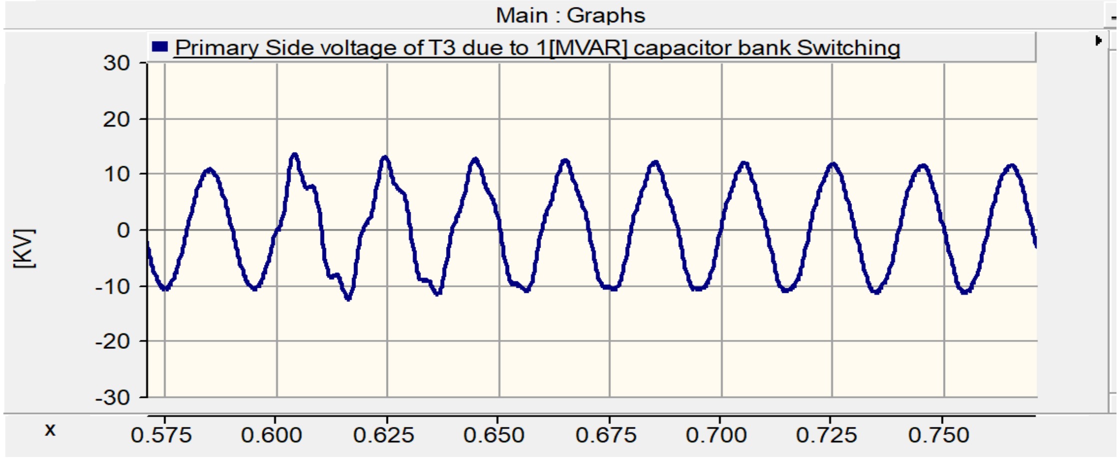


Fig-4.20: Phase-A voltage of bus-9 due to 1.0MVAR capacitor bank energization

For phase-A, the switching was done at the voltage zero point and hence the transient developed is negligible. The switching was done at time, t=0.6 sec. The output response of phase-B is shown in Fig-4.21

Phase-B

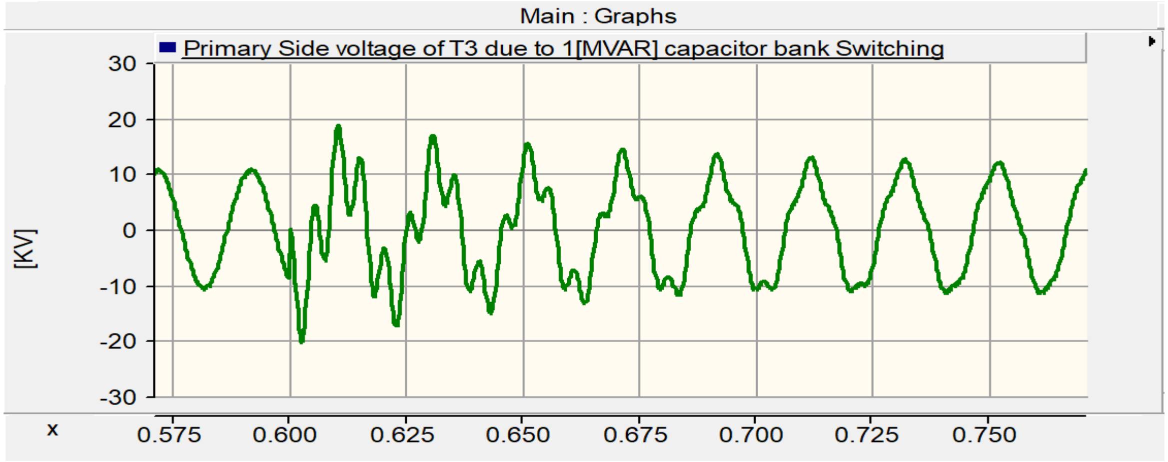


Fig-4.21: Phase-B voltage of bus-9 due to 1.0MVAR capacitor bank energization

For phase-B, the switching was done at the rising edge and the maximum voltage appeared at bus-9 for phase-B was much higher than the nominal value. For phase-C, the switching was done at the peak of its waveform at time, t=0.6 sec and the output is shown in Fig-4.22.

Phase-C

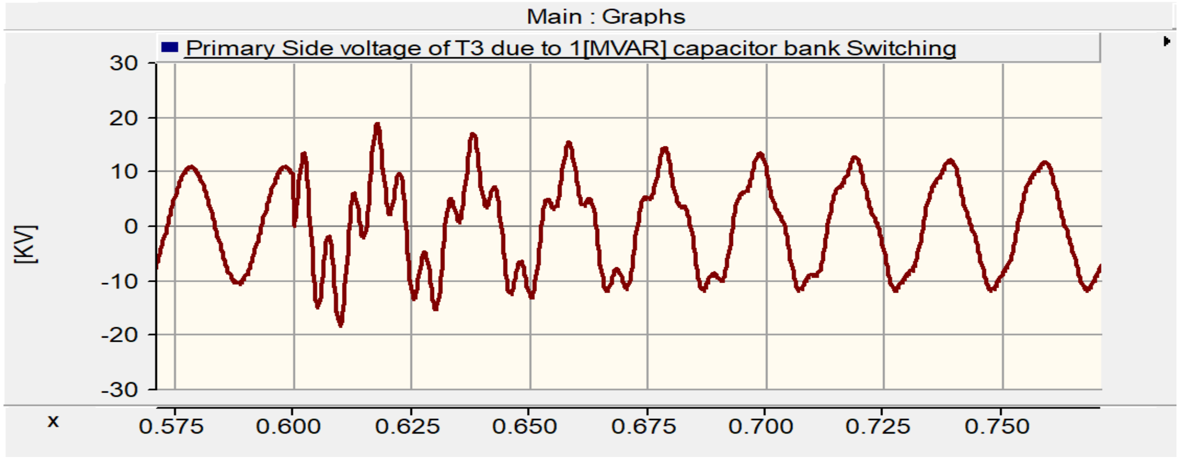


Fig-4.22: Phase-C voltage of bus-9 due to 1.0MVAR capacitor bank energization

The de-energization of 1.0MVAR capacitor bank also produces transient condition which was of negligible amount. The output waveform is shown in Fig-4.23.

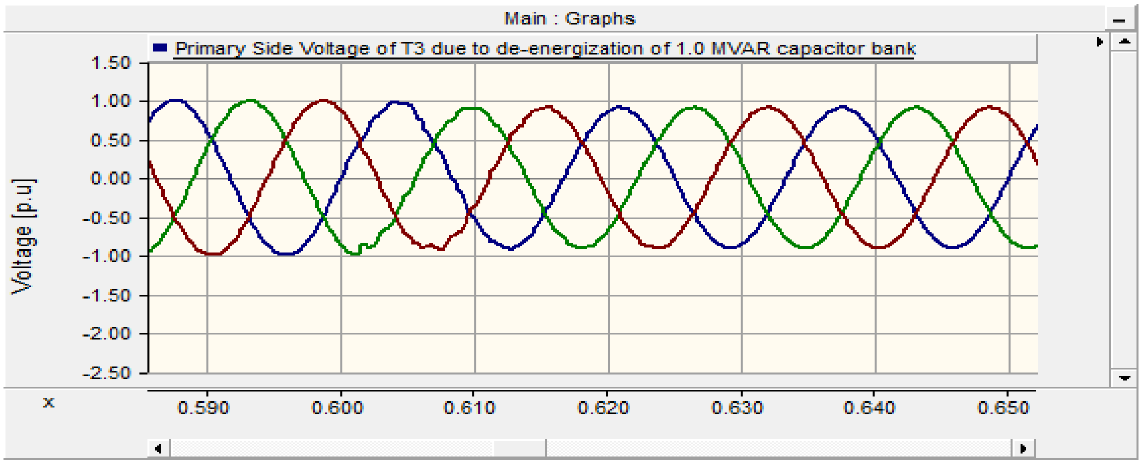


Fig-4.23: Primary side voltage of T3 due to de-energization of 1.0MVAR capacitor bank

4.3.3 SWITCHING OF LOAD AT THE DISTRIBUTION SIDE

When load was suddenly switched ON, then inrush current flows into the load and the voltage at the terminal falls down suddenly. The relevant output waveforms are given in Fig-4.24 and Fig-4.25.

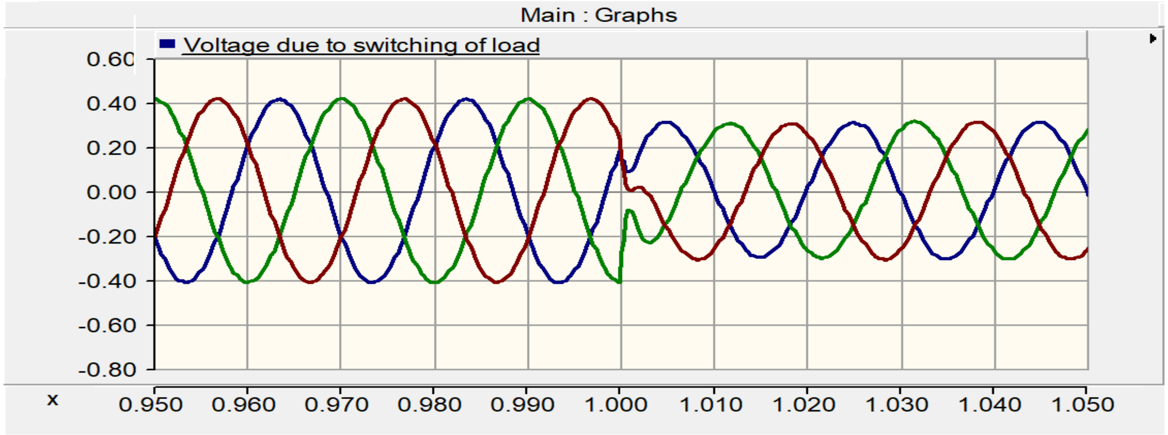


Fig-4.24: Voltage of bus-10 due to switching of load

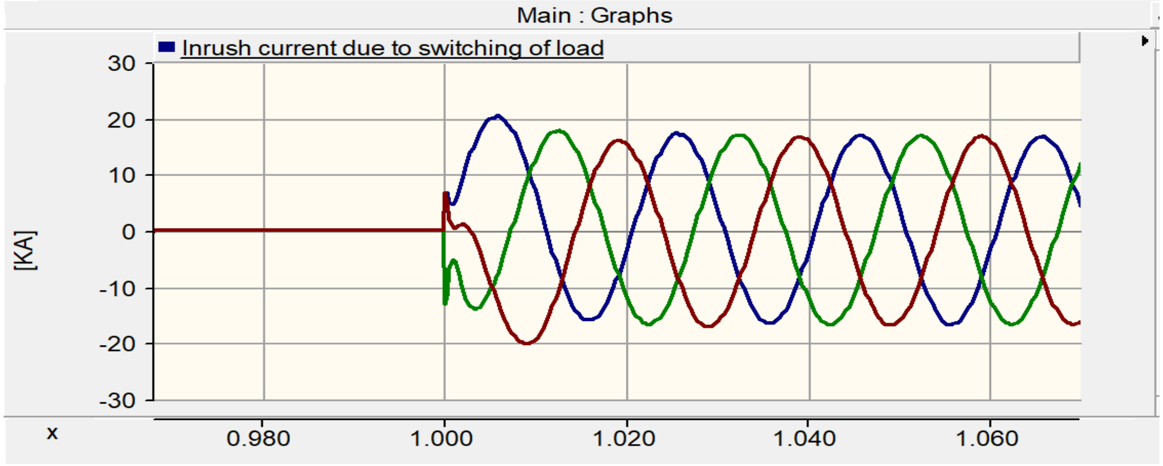


Fig-4.25: Inrush current due to switching of load

4.4 TRANSIENT RECOVERY VOLTAGE (TRV)

A transient recovery voltage (or TRV) for high-voltage circuit breakers is the voltage that appears across the terminals after current interruption. It is a critical parameter for fault interruption by a high-voltage circuit breaker, its characteristics (amplitude, rate of rise voltage) can lead either to a successful current interruption or to a failure (called re-ignition or re-strike). TRV can also be defined as a point by point difference of voltage at the incoming side and at the outgoing side of a circuit breaker. When a circuit breaker interrupts, incoming side or the side to bus or supply is connected tries to return to power frequency voltage level and the outgoing side depending on what is connected also oscillates [33]. The difference between these voltages is recovery voltage which is shown in Fig-4.26.

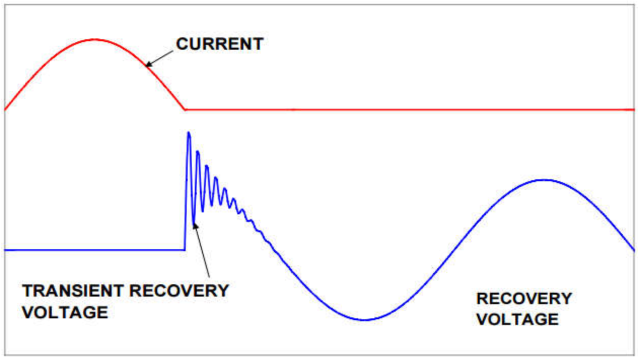


Fig-4.26: Figure showing current, transient recovery voltage (TRV) and recovery voltage

Transient recovery voltage is affected by various parameters of the system. Prominent among them are listed below:-

1) Inductance and capacitance in the system

2. Fault current level of the system at point of study of TRV.

3. Bushing capacitance of circuit breakers, voltage transformers etc

4. Number of transmission lines terminating at a bus and their characteristics impedance.

5. Internal factors of the circuit breaker like the first pole to clear a fault etc.

6. System grounding [31].

Fig-4.27 shows the transient recovery voltage (TRV) across the contacts of the circuit breaker.

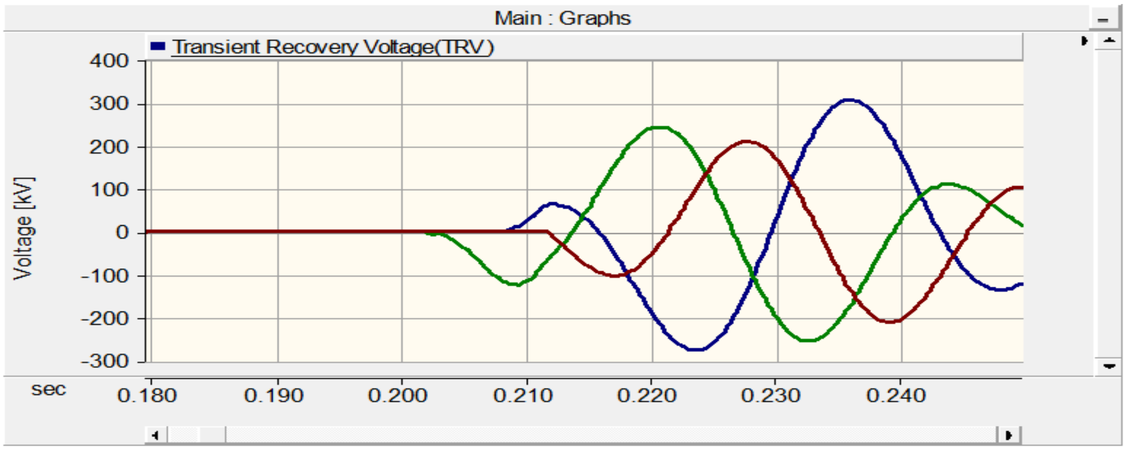


Fig-4.27: Transient recovery voltage (TRV) across the circuit breaker

4.5 RESULT AND DISCUSSIONS

Table 4.1 shows the result obtained during our analysis for ease of understanding. During energization of the transformer, the maximum voltage reached was 1.205 p.u and the time required for mitigation of the transient condition was 25ms i.e. 1.25 cycles. At the distribution side i.e. at the primary side of transformer,T2 the maximum voltage was 1.455 p.u during energization of transformer,T1.

Table-4.1: Output results for different switching events in overhead transmission line

Serial Number	Types of switching	Bus Number	Nominal Value (kV or kA)	Recorded maximum value during switching (kV or kA)	Recorded maximum value in per unit (p.u)	Time or cycles required for mitigation
1.	Energization of Transformer(T1)	Bus-1 (Voltage)	132 kV	132.63 kV	1.004	5ms
		Bus-2 (Voltage)	33 kV for all phases	Ph-A: 35.47 kV	1.075	10ms or 0.5 cycles
				Ph-B: 39.76 kV	1.205	
				Ph-C: 35.33 kV	1.070	
		Bus-5 (Voltage)	33 kV	48.018 kV	1.455	15ms or 0.75 cycle
2.	Energization of Transformer(T2)	Bus-5 (Voltage)	33 kV	37.468 kV	1.135	10ms or 0.5 cycle
		Bus-6 (Voltage)	11 kV	12.5 kV	1.136	5ms
3.	Capacitor Bank [2.0 MVAR]	Bus-5 (Voltage)	33 kV for all phases	Ph-A: 45.95 kV	1.392	150ms or 7.5 cycles
				Ph-B: 60.53 kV	1.834	
				Ph-C: 47.98 kV	1.454	
		Bus-9 (Voltage)	11 kV	24.822 kV	2.256	100ms or 5 cycles
		Bus-5 (Current)	Ph-A:0.226 kA	Ph-A: 0.249 kA	1.101	25ms or 1.25 cycles
			Ph-B: 0.214 kA	Ph-B: 0.294 kA	1.373	
			Ph-C: 0.202 kA	Ph-C: 0.249 kA	1.232	
4.	De-energization of capacitor bank	Bus-5 (Voltage)	33 kV	56.43 kV	1.71	20ms or 1 cycle
5.	Capacitor Bank [1.0 MVAR]	Bus-9 (Voltage)	11 kV for all phases	Ph-A: 13.34 kV	1.212	140ms or 7 cycles
				Ph-B: 20.26 kV	1.842	
				Ph-C: 18.58 kV	1.689	
6.	Switching of Load (10MVA)	Bus-10 (Current)	16.87 kA	20.53 kA	1.217	10ms or Half cycle

When transformer,T2 is energized, the maximum voltage recorded at bus-5 was 1.135 p.u and the required time was only 10ms or half cycle.

For 2.0[MVAR] capacitor bank switching, the maximum voltage recorded at Bus-5 was 1.834 p.u and time taken for mitigation of the transient condition was 150ms i.e. 7.5 cycles. At the same time, the voltage of Bus-9 was recorded as 2.256 p.u and time taken was 100ms i.e. 5 cycles. The maximum current at Bus-5 was monitored as 1.373 p.u and mitigation time was 25ms i.e. 1.25 cycles.

Similarly, due to switching of 1.0[MVAR] capacitor bank, the maximum voltage at Bus-9 was recorded as 1.842 p.u and time taken for mitigation of the transient condition was 140ms i.e. 7 cycles. During switching of load, the maximum inrush current was recorded as 1.217 p.u and the transient condition was mitigated within 10ms i.e. half cycle.

Hence, from the above analysis, we can come to a conclusion that, capacitor bank switching is the worst case of switching for our system due to its high transient overvoltage and higher time required for mitigation of the transient condition in case of overhead transmission lines.

4.6 UNDERGROUND CABLE

Electric power can be transmitted or distributed either by overhead system or by underground cables. The underground cables have several advantages such as less liable to damage through storms or lightning, low maintenance cost, less chance of faults, smaller voltage drop and better general appearance. However, their major drawback is that they have greater installation cost and introduce insulation problems at high voltages compared with the equivalent overhead system. For these reason, underground cables are employed where it is impracticable to use overhead lines. Such locations may be thickly populated areas where municipal authorities prohibit overhead lines for reasons of safety, or around plants and substations or where maintenance conditions do not permit the use of overhead construction.

The chief use of underground cables for many years has been for distribution of electric power in congested urban areas at comparatively low or moderate voltages. However, recent improvements in the design and manufacture have lead to the development of cables suitable for use at a high voltage. This has made it possible to employ underground cables for transmission of electric power for short or moderate distances [29].

Fig-4.28: BRB underground cable structure

4.7 FAMILIARIZATION TO THE ANALYSED NETWORK

In this section, we will analyse the same network of Fig-4.2 discussed in chapter-04 by replacing the overhead transmission lines by underground cables. For a comparative study between overhead line and underground cable in the context of switching operations, we analysed the system for various switching events. The single line diagram of the considered network is shown in Fig-4.29.

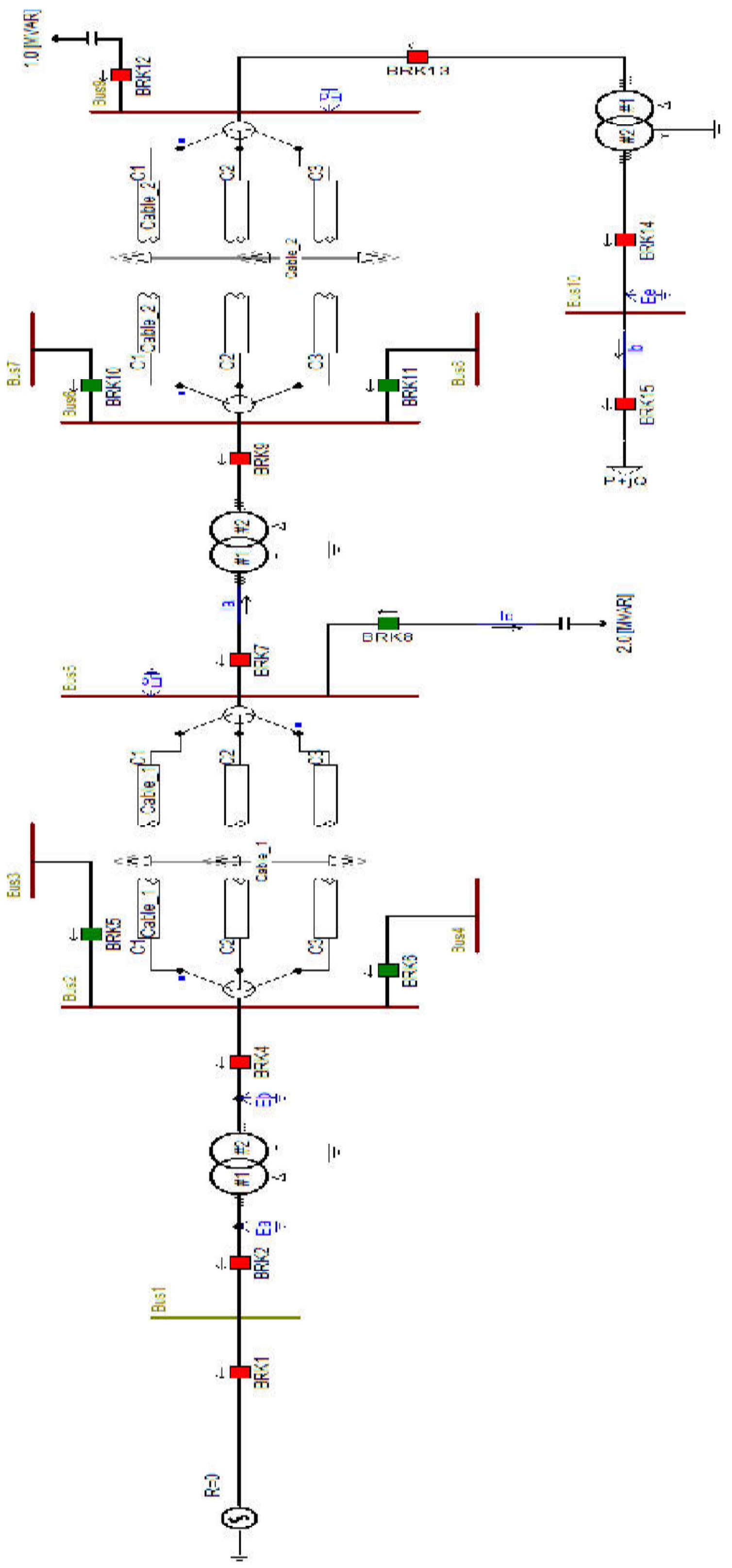


Fig-4.29: Considered network for transient analysis of underground cable

The two underground cable named as Cable_1 and Cable_2 are implemented having length 30km and 10km respectively for our analysis. The cable was designed considering some parameters which have been illustrated in chapter-03.

4.8 SWITCHING EVENTS OF THE NETWORK

Transient over-voltages are developed during switching operation in underground cable. In this section, we will mainly analyse the system for two switching events. The switching events include-

i) Energization and de-energization of the transformer

ii) Energization and de-energization of capacitor bank

4.8.1 ENERGIZATION AND DE-ENERGIZATION OF TRANSFORMER

When the transformer is energized and de-energized, high frequency oscillatory transients are developed which travels along the underground cable. In the given network of Fig-4.29, when simulation was done for transformer, T1 energization and then the voltage at different buses were measured. The outputs of the voltage profile at different buses are shown in Fig-4.30, Fig-4.31, Fig-4.32 and Fig-4.35.

Energization of transformer, T1

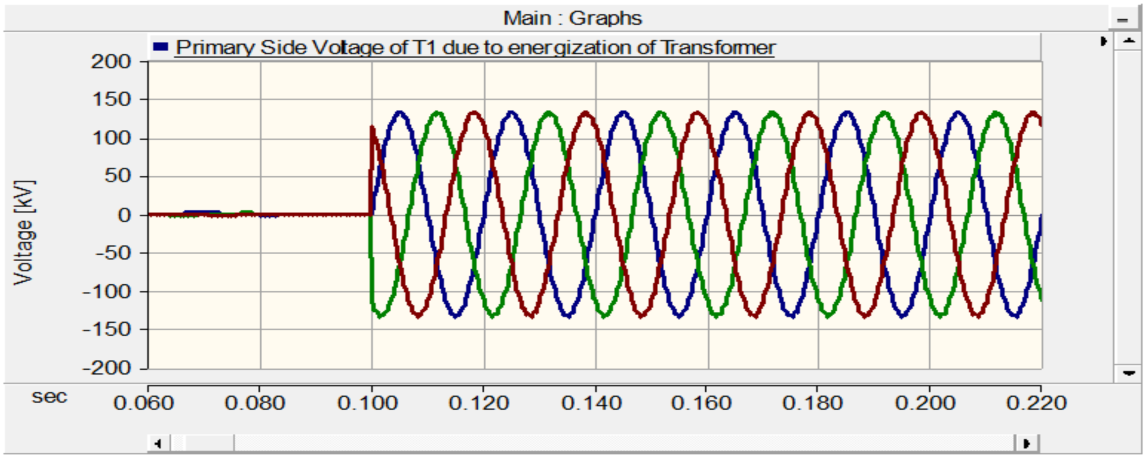


Fig-4.30: Primary side voltage of T1 (i.e. bus-1) due to energization of transformer

For underground cable, the energization of transformer also causes transient overvoltage which is shown in Fig-4.31. The voltage of the secondary winding of transformer, T1 i.e. bus-2 reaches to a maximum greater than the nominal value. The switching operation was done at time, t=0.1 sec under unloaded condition.

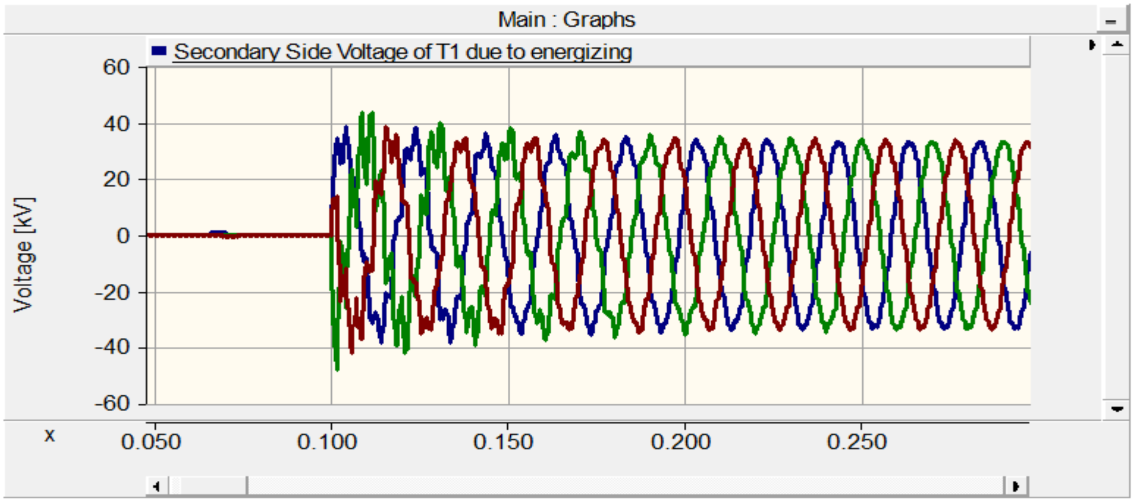


Fig-4.31: Secondary side voltage of T1 (i.e. bus-2) due to energization

The effect of the energization of transformer, T1 to the low voltage side were also measured which is shown in Fig-4.32.

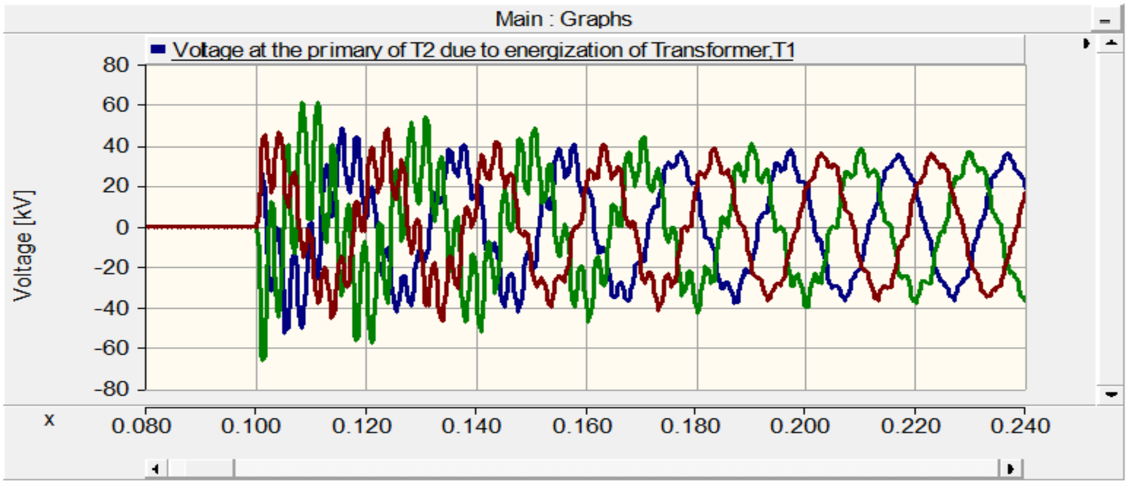


Fig-4.32: Voltage at the primary of T2 due to energization of transformer, T1

For underground cable, due to the higher capacitance effect than the overhead transmission line, charging current flows through the cable during unloaded condition. This leads to a considerable amount of losses which is a major disadvantage of underground cable. The waveform of charging current through the cable is shown in Fig-4.33.

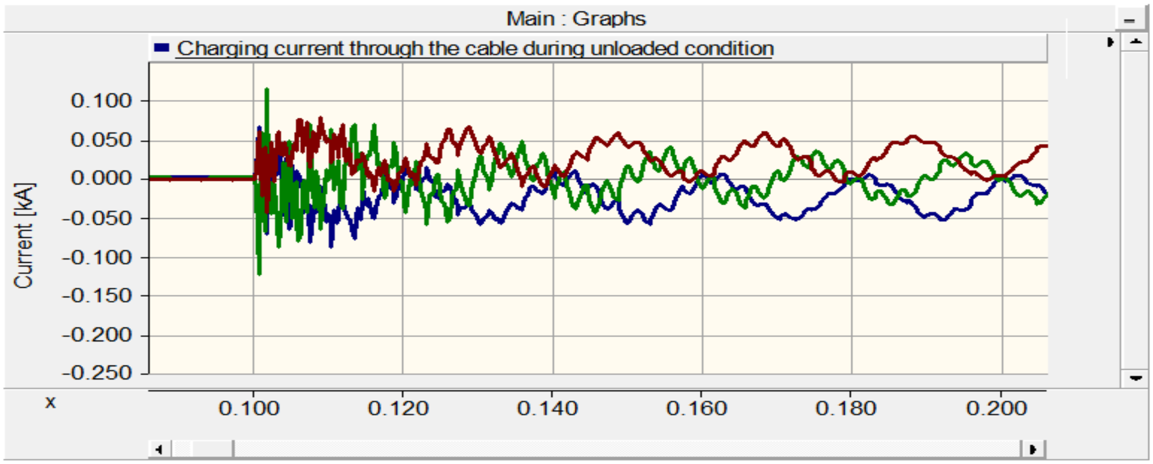


Fig-4.33: Charging current through the cable during unloaded condition

The transient condition developed during switching of transformer also affects the distribution side. The voltage appeared at the primary winding of transformer, T3 is shown in Fig-4.34. The voltage is greater than 2 times of the nominal value. The higher capacitance of underground cable tends to increase the voltage.

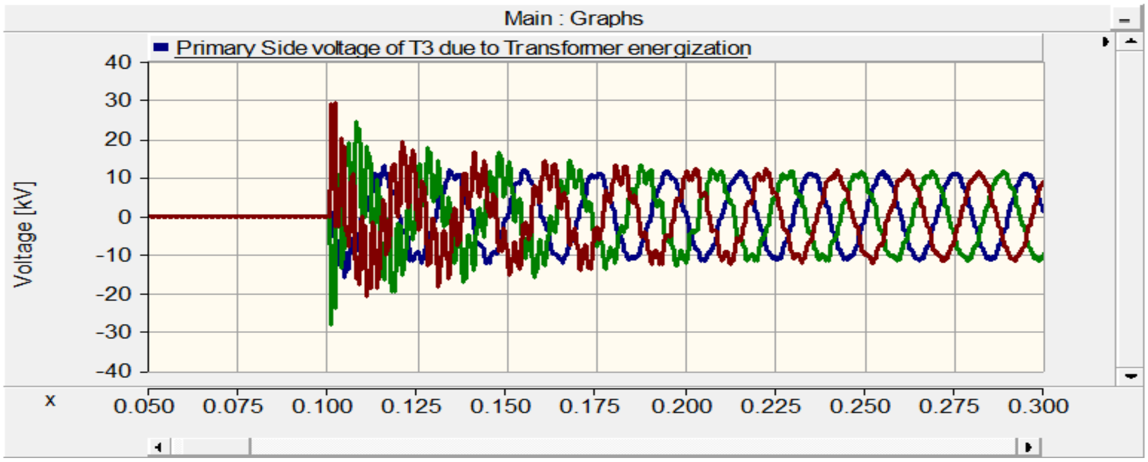


Fig-4.34: Primary side voltage of T3 (i.e. bus-9) due to transformer energization

The effect of the transformer energization was also noted at the load side for better understanding. At the load side, the maximum voltage reached was more than 1.25 p.u and hence may cause damage to our equipments. The voltage at the load side is shown in Fig-4.35.

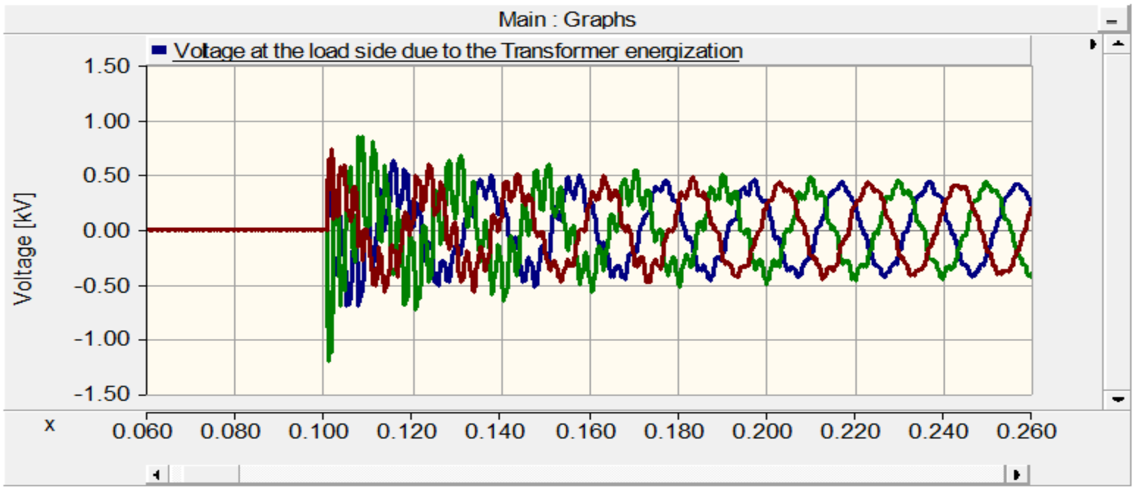


Fig-4.35: Voltage at the load side due to the transformer energization

Energization of transformer, T2

Under the condition that the transformer, T1 is ON, we analysed the system for the energization of transformer, T2 and hence the voltage profile at different buses were recorded. The output is given in Fig-4.36.

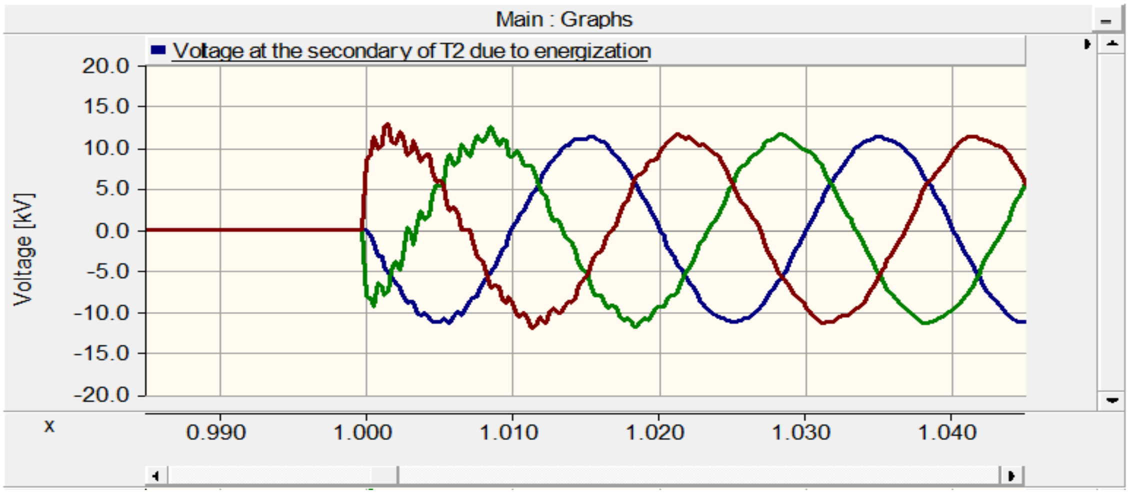


Fig-4.36: Voltage at the secondary of T2 (i.e. bus-6) due to energization

The switching was done at the peak of phase-B and at time, t=1.0 sec. The voltage magnitude is amplified after going through the cable due to high capacitance. The voltage of bus-9 due to energization of transformer, T2 is shown in Fig-4.37.

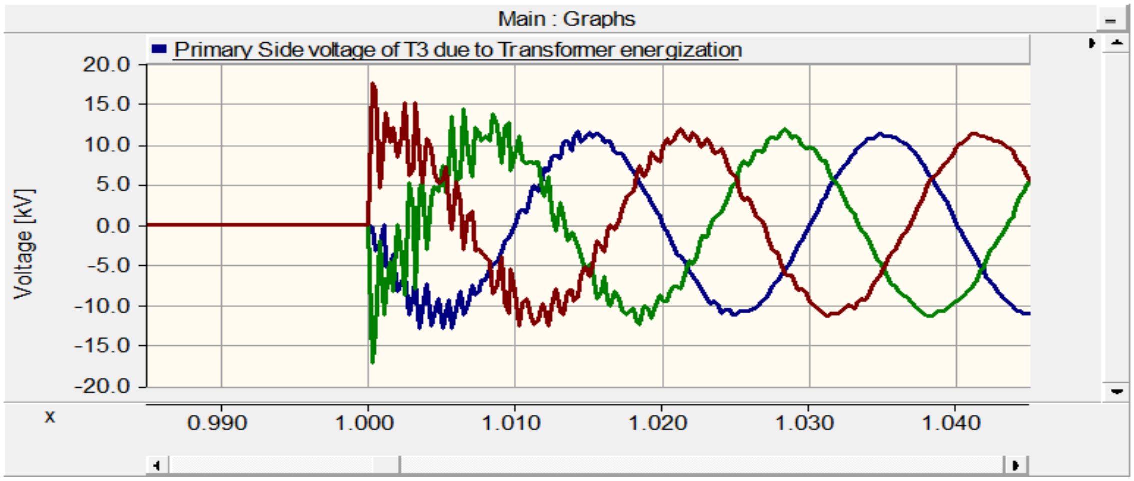


Fig-4.37: Primary side voltage of T3 (i.e. bus-9) due to transformer energization

De-energization of the transformer,T1:

De-energization of transformer induces high voltage transient at the bus voltage and then it took almost 3.0 seconds to reach the voltage zero. The peak of the transient overvoltage reaches almost upto a maximum of 200kV where the nominal voltage was only 132kV. The output is shown in Fig-4.38.

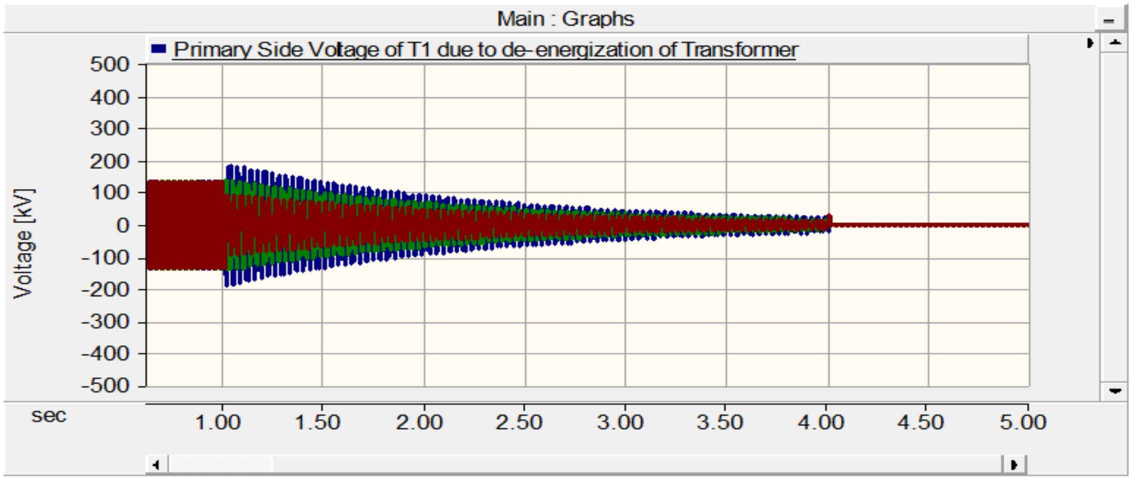


Fig-4.38: Primary side voltage of T1 (i.e.bus-1) due to de-energization of transformer

The response of the voltage at bus-2 was also measured and high voltages were seen during de-energization of the transformer. The peak voltage recorded was almost 45kV, which is much more than that of nominal voltage, 33kV. This is shown in Fig-4.39.

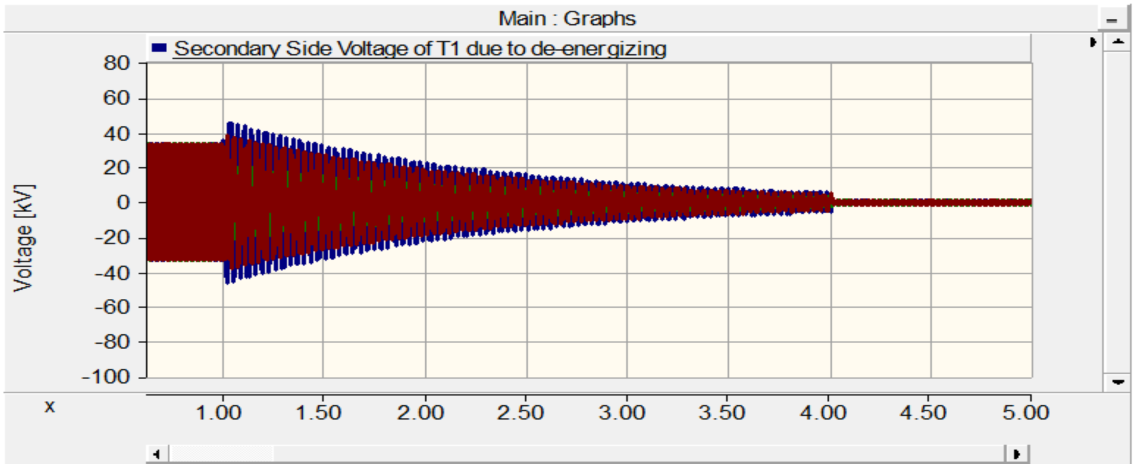


Fig-4.39: Secondary side voltage of T1 (i.e. bus-2) due to de-energization of transformer

The impact of this overvoltage was also measured at the primary side of transformer T3. The peak was recorded as almost 16kV where the nominal voltage was 11kV. So if the voltage becomes greater than BIL of transformer, then the insulation of transformer will damage. The response of voltage at bus-9 is shown in Fig-4.40.

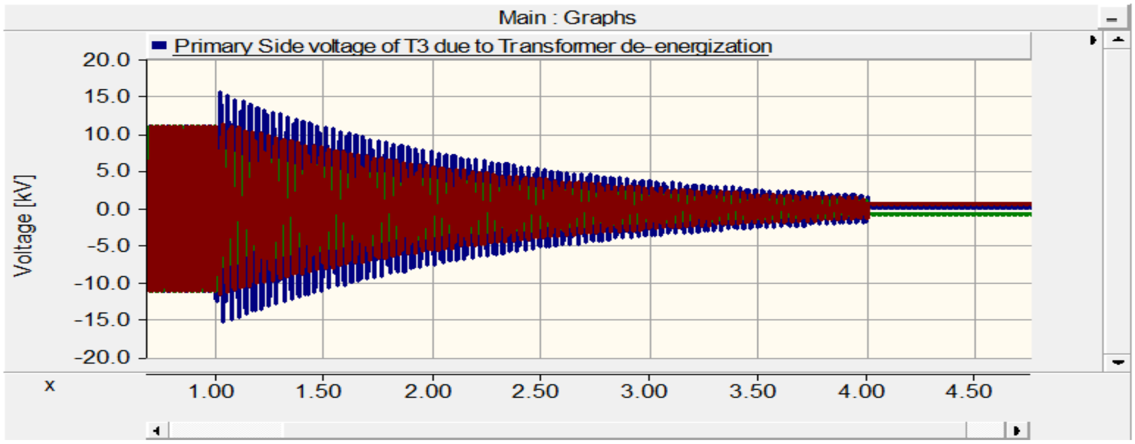


Fig-4.40: Primary side voltage of T3 (i.e. bus-9) due to transformer de-energization

4.8.2 ENERGIZATION AND DE-ENERGIZATION OF CAPACITOR BANK

When capacitor banks are installed in the network, considerable amount of transients are developed which may be amplified while going along the cable due to the higher capacitance effect of the cable which is shown in Fig-4.41 and Fig-4.42.

Switching of 2.0MVAR capacitor bank:

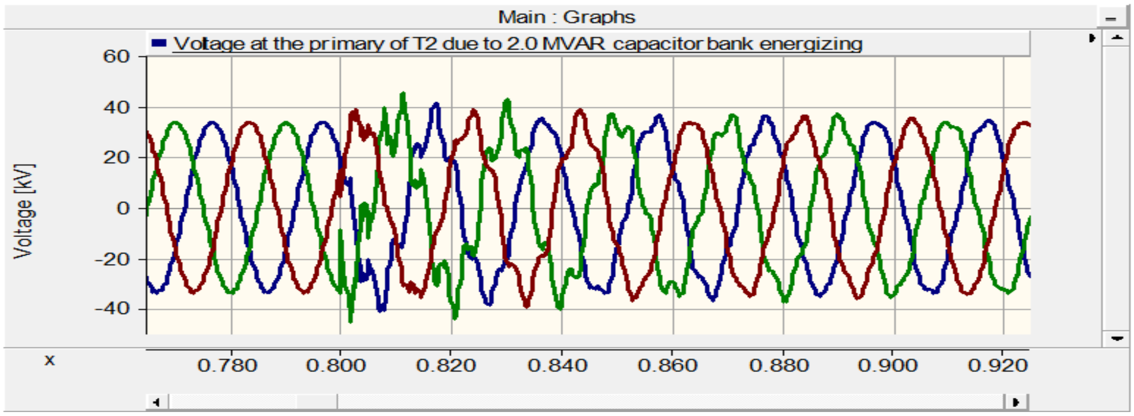


Fig-4.41: Voltage at the primary side of T2 (i.e. bus-5) due to capacitor bank switching

The switching operation was done at time, t=0.8 sec at the peak of phase-A and hence the transient overvoltage experienced by phase-A is maximum than other phases which is shown in Fig-4.42. Due to capacitance of underground cable, the voltage increases after going through the cable.

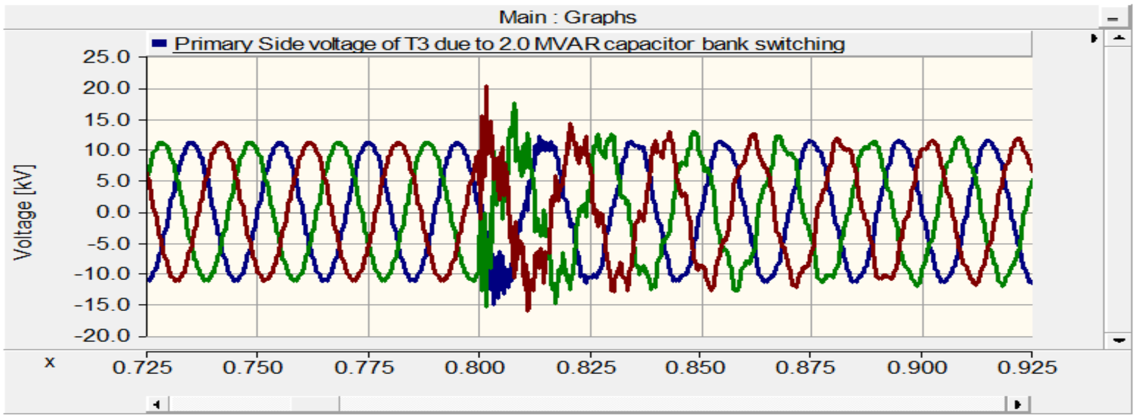


Fig-4.42: Primary side voltage of T3 (i.e.bus-9) due to capacitor bank switching

When an uncharged capacitor bank was installed in the network, charging current flowed into the bank. Initially inrush current flows through it. The charging current through the 2.0MVAR capacitor bank is shown in Fig-4.43.

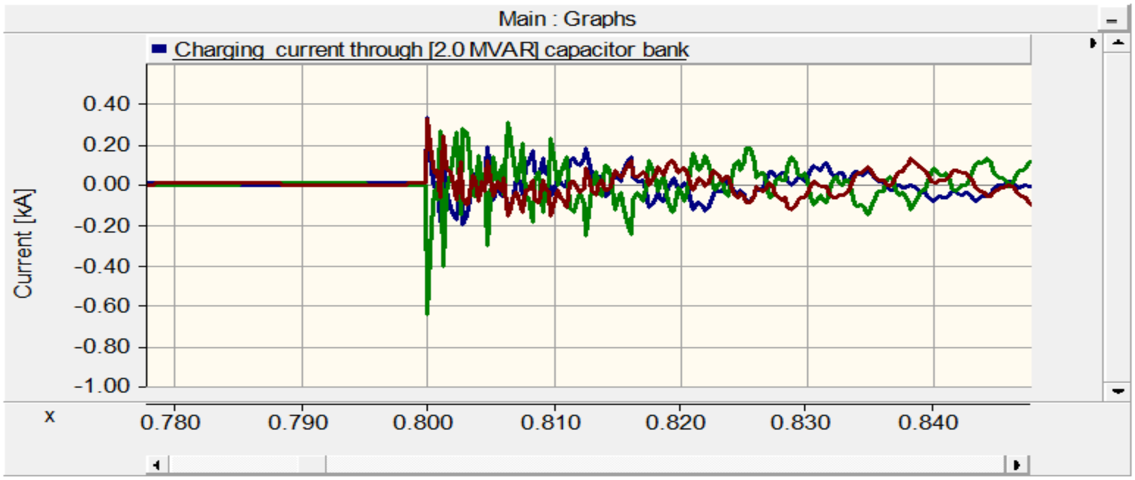


Fig-4.43: Charging current through [2.0MVAR] capacitor bank during switching

De-energization of the capacitor bank:

The de-energization of capacitor bank also induces transient overvoltage. Fig-4.44 shows the voltage at bus-6 during de-energization. This seems to be transient free which was due to the fully charged condition of capacitor bank.

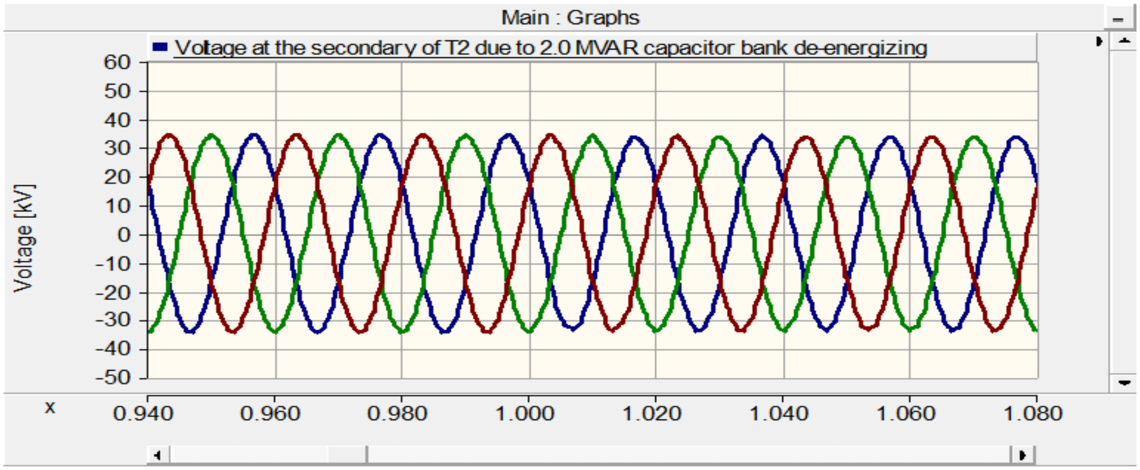


Fig-4.44: Voltage at the secondary of T2 due to de-energization of the capacitor bank

Energization of 1.0MVAR capacitor bank:

We also analysed the system for the installation of 1.0MVAR capacitor bank. It also causes the formation of transient overvoltage which is shown in Fig-4.45.

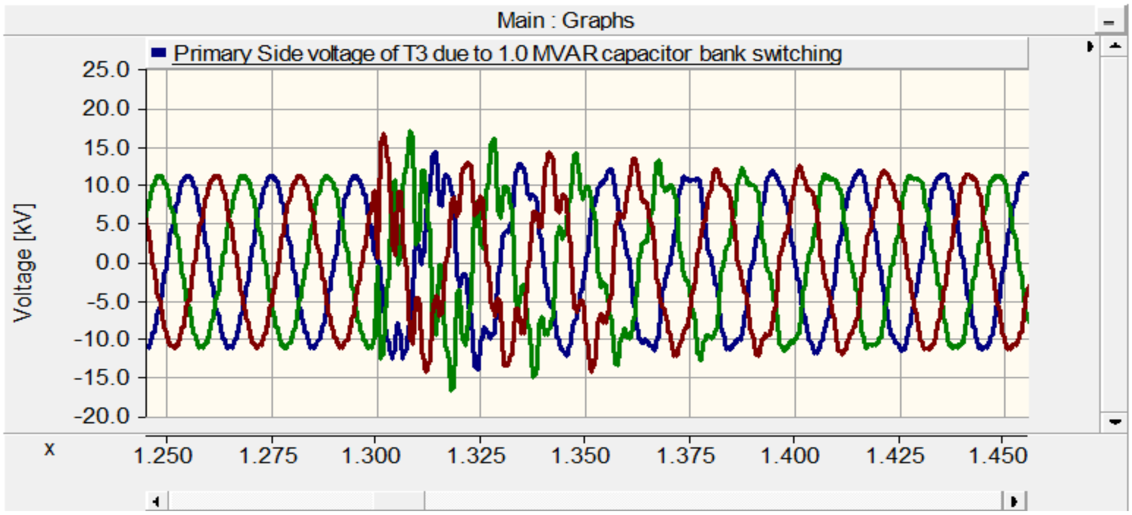


Fig-4.45: Primary side voltage of T3 (i.e.bus-9) due to capacitor bank switching

Transient developed due to installation of capacitor bank at bus-9 also affects the voltage at load side i.e. bus-10. The switching was done at time, t=1.3 sec at the peak of phase-B. At that time the voltage appeared at the two contacts of circuit breaker for phase-B was maximum. This is shown in Fig-4.46.

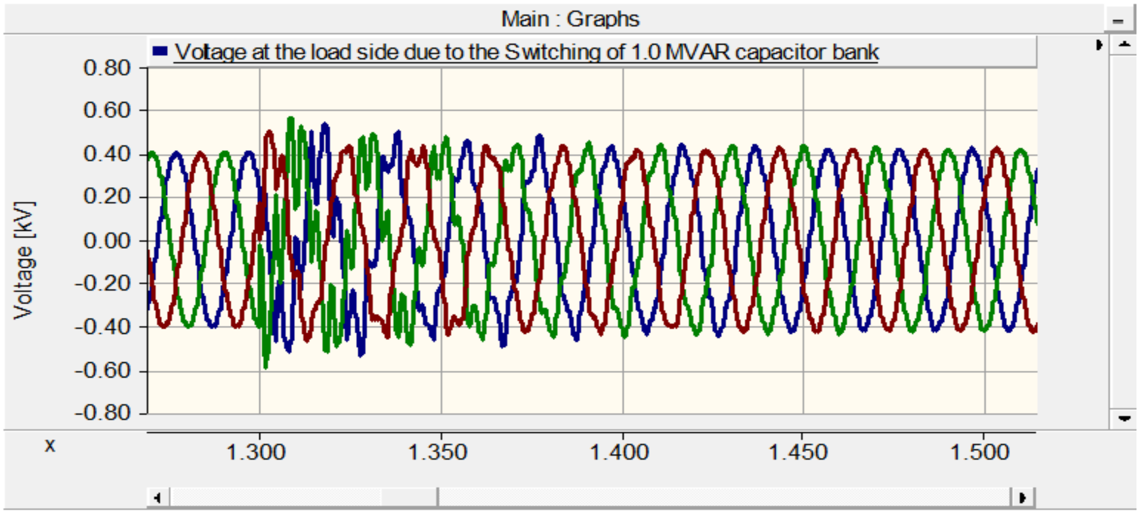


Fig-4.46: Voltage at the load side (i.e.bus-10) due to the switching of capacitor bank

4.9 RESULT EVALUATION AND DISCUSSION

The above analyses are summarized in Table-4.2. From the above analysis of underground cable, it is clear that the switching case becomes severe especially for transformer energization than the overhead lines. This is due to the higher capacitance effect of the underground cable as they are very close to the earth. The voltage is amplified after going through the underground cable as it is clear from the Table-4.2.

The maximum voltage attained at bus-1, bus-2, bus-5, bus-9 and bus-10 are 1.004 p.u for phase-A, 1.447 p.u for phase-B ,2.008 p.u for phase-B, 2.656 p.u for phase-C and 2.9775 p.u for phase-B respectively. Hence the maximum voltage reached in per unit (p.u) is increasing from the upstream to the downstream.

For capacitor bank, the maximum voltage of bus-5, bus-9 and bus-10 were monitored as 1.346 p.u , 1.841 p.u and 1.445 p.u respectively. It took more cycles to be mitigated after transient condition occured. The time required for mitigation depends on the damping factor of the system. This damping is mainly provided by the resistance of the line. Higher the resistance, larger is the damping provided by the system and lower will be the mitigation time.

Table 4.2: Output results for transient analysis of underground cable

Serial Number	Types of switching	Bus Number	Nominal Value (kV or kA)	Recorded maximum value during switching (kV or kA)	Recorded maximum value in per unit (p.u)	Time or cycles required for mitigation
1.	Energization of Transformer[T1]	Bus-1 (Voltage)	132 kV	132.63 kV	1.004	5ms
		Bus-2 (Voltage)	33 kV for all phases	Ph-A: 38.36 kV	1.162	125ms or 6.25 cycles
				Ph-B: 47.75 kV	1.447	
				Ph-C: 41.57 kV	1.259	
		Bus-5 (Voltage)	33 kV for all phases	Ph-A: 52.27 kV	1.584	160ms or 8 cycles
				Ph-B: 66.28 kV	2.008	
				Ph-C: 46.81 kV	1.418	
		Bus-9 (Voltage)	11 kV for all phases	Ph-A: 15.7 kV	1.427	125ms or 6.25 cycles
				Ph-B: 27.66 kV	2.514	
				Ph-C: 29.217 kV	2.656	
		Bus-10 (Voltage)	0.4 kV for all phases	Ph-A: 0.689 kV	1.7225	150ms or 7.5 cycles
				Ph-B: 1.191 kV	2.9775	
				Ph-C: 0.727 kV	1.8175	
2.	Energization of Transformer[T2]	Bus-6 (Voltage)	11 kV for all phases	Ph-A: 11.36 kV	1.032	22ms or 1.1 cycles
				Ph-B: 12.52 kV	1.138	
				Ph-C: 12.82 kV	1.165	
		Bus-9 (Voltage)	11 kV for all phases	Ph-A: 12.90 kV	1.172	42ms or 2.1 cycles
				Ph-B: 17.20 kV	1.563	
				Ph-C: 17.58 kV	1.598	
3.	Capacitor Bank [2.0 MVAR]	Bus-5 (Voltage)	33 kV	Ph-A: 41.369 kV	1.253	115ms or 5.75 cycles
				Ph-B: 44.428 kV	1.346	
				Ph-C: 39.03 kV	1.182	
		Bus-9 (Voltage)	11 kV	Ph-A: 15.0 kV	1.363	125ms or 6.25 cycles
				Ph-B: 17.36 kV	1.578	
				Ph-C: 20.26 kV	1.841	
4.	De-energization of Transformer[T1]	Bus-1 (Voltage)	132 kV	193.67 kV	1.467	3000ms or 150 cycles
		Bus-2 (Voltage)	33 kV	48.19 kV	1.46	3000ms or 150 cycles
		Bus-9 (Voltage)	11 kV	16 kV	1.454	3000ms or 150 cycles
5.	Capacitor Bank [1.0 MVAR]	Bus-9 (Voltage)	11 kV for all phases	Ph-A: 14.15 kV	1.286	115ms or 5.75 cycles
				Ph-B: 16.89 kV	1.535	
				Ph-C: 16.50 kV	1.5	
		Bus-10 (Voltage)	0.4 kV for all phases	Ph-A: 0.5388 kV	1.347	125ms or 6.25 cycles
				Ph-B: 0.578 kV	1.445	
				Ph-C: 0.5 kV	1.25	

4.10 COMPARISON BETWEEN CABLE AND OVERHEAD LINE

Electric power needs to be transmitted over long distances from the point of generation upto the point of consumption. This transmission can be done by using either overhead transmission lines or underground cables. Each of these two methods of transmission has it's own advantages or disadvantages.

Overhead lines are cheaper as the insulation cost is lesser and conductor material cost is lesser too. They also have better heat dissipation capability. But they have more chances of being subjected to lightning strikes and they interfaces with communication system. Overhead line uses bare conductors and can cause damage if they break. Underground cables are free from lightning strikes and don't interfere with communication channel. There is very less chance of accidents and hence widely used in the distribution network. But the insulation and installation cost of underground cable much higher compared to overhead lines. Maintenance cost is higher and it is very difficult to locate any fault if occurred in the cable.

From the view point of above analysis of underground cable and the analysis of overhead lines, a more specific comparison can be made in the context of transients developed during switching operations. Comparing Table-4.1 and Table-4.2, it is clear that the energization of transformer,T1 is more severe for underground cable than the overhead line. The maximum recorded voltage of bus-2 was 1.447 p.u for underground cable and 1.205 p.u for overhead transmission line. The time required for mitigation of the transient condition was recorded as 6.25 cycles for underground cable and only 1.25 cycles for overhead lines. Similarly, the maximum voltage of bus-5 was 2.008 p.u for underground cable and mitigation time was 8 cycles. But for overhead lines, the maximum value recorded was only 1.510 p.u and mitigation time required was 0.75 cycle.

Similarly, during the energization of transformer, T2 the maximum voltage reached at bus-6 was 1.165 p.u and mitigation time was 22ms for underground cable and for overhead lines, this value was 1.136 p.u and mitigation time was only 5ms. De-energization of the transformer for overhead lines didn't impose much voltage but for underground cable, it reached to a peak value of 1.467 p.u and the time required for dropping the voltage to zero was 3000ms or 150 cycles.

Now when the capacitor bank [2.0 MVAR] was switched to the system, then the maximum voltage recorded at bus-5 was 1.346 p.u and mitigation time required was 5.75 cycles for underground cable and 1.903 p.u for overhead line with mitigation time of 7.5 cycles. At bus-9, the peak voltage reached during switching was 1.841 p.u and mitigation time was 6.25 cycles for underground cable and 2.256 p.u for overhead line and mitigated within 5 cycles.

For the capacitor bank [1.0 MVAR], the maximum voltage recorded at bus-9 was 1.535 p.u with mitigation time of 5.75 cycles for cable and for overhead line, the maximum transient voltage was 1.842 p.u with mitigation time of 7 cycles. Hence, for capacitor bank switching, overhead lines become more severe than that of underground cable.

CHAPTER 5

TRANSIENT SHORT CIRCUIT FAULT ANALYSIS

5.1 INTRODUCTION

A fault in an electric power system can be defined as, any abnormal condition of the system that involves the electrical failure of the equipment, such as, transformers, generators, busbars, etc. The fault inception also involves in insulation failures and conducting path failures which results short circuit and open circuit of conductors. Under normal or safe operating conditions, the electric equipments in a power system network operate at normal voltage and current ratings. Once the fault takes place in a circuit or device, voltage and current values deviates from their nominal ranges. The faults in power system causes over current, under voltage, unbalance of the phases, reversed power and high voltage surges. This results in the interruption of the normal operation of the network, failure of equipments, electrical fires, etc. Usually power system networks are protected with switchgear protection equipments such as circuit breakers and relays in order to limit the loss of service due to the electrical failures [33].

Fig-5.1: Short circuit fault in a tower

A transient fault is a fault that is no longer present if power is disconnected for a short time and then restored; or an insulation fault which only temporarily affects a device's dielectric properties which are restored after a short time. Many faults in overhead power lines are transient in nature. When a fault occurs, equipment used for power system protection operates to isolate the area of the fault. A transient fault will then clear and the power-line can be returned to service. Typical examples of transient faults include:

- momentary tree contact
- bird or other animal contact
- lightning strike
- conductor clashing

Transmission and distribution systems use an automatic re-close function which is commonly used on overhead lines to attempt to restore power in the event of a transient fault. This functionality is not as common on underground systems as faults there are typically of a persistent nature. Transient faults may still cause damage both at the site of the original fault or elsewhere in the network as fault current is generated [34].

In this chapter, we will perform some analysis considering a transient short circuit fault which was considered to be cleared after 7.5 cycles or 150ms under different conditions. We consider the same distribution network of chapter-04 for our analysis. The single line diagram of the considered network setting a fault module at the very beginning of transmission line, Tline_1 or bus-2 is shown below-

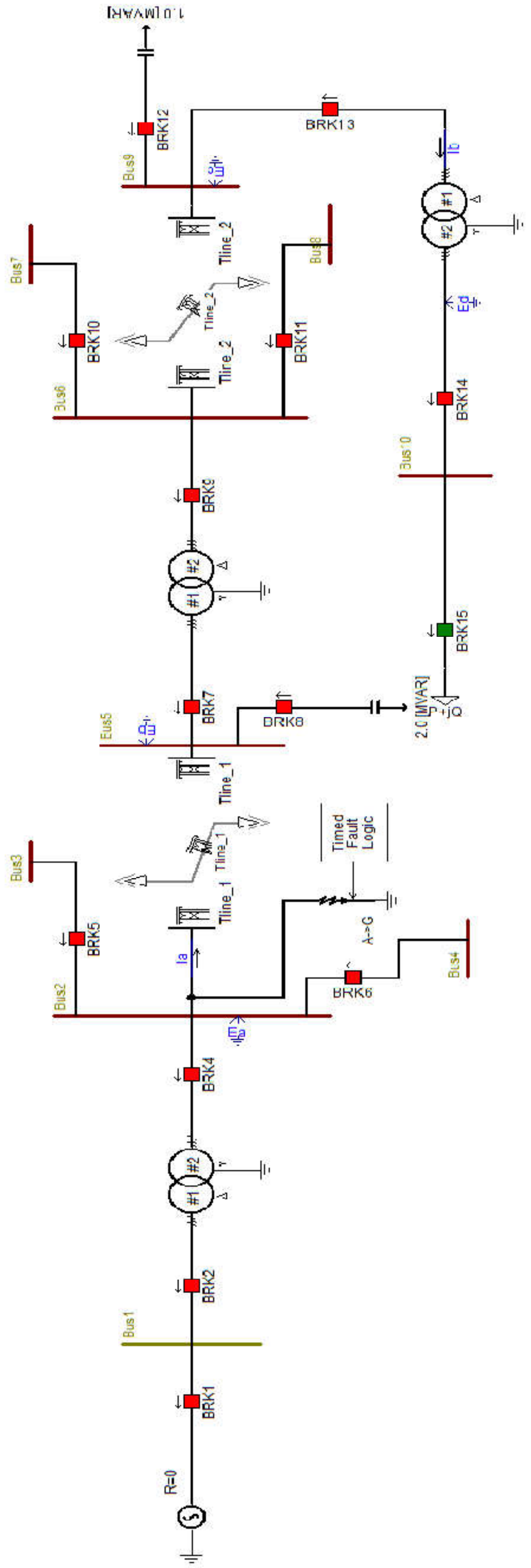


Fig-5.2: Considered network for transient short circuit fault analysis

5.2 SHORT CIRCUIT FAULT

The short circuit fault can be classified into two categories. They are-

i) Symmetrical fault
ii) Unsymmetrical fault

That fault on the power system which gives rise to symmetrical fault currents (i.e. equal fault currents in the lines with 120^0 displacement) is called a symmetrical fault. The symmetrical fault is the most severe and imposes more heavy duty on the circuit breaker. When a short circuit occurs at any point in a system, the short-circuit current is limited by the impedance of the system upto the point of fault. Hence the short circuit current will be maximum if the fault occurs at the beginning of a transmission line or at the bus [29].

The great majority of faults on the power system are of unsymmetrical nature; the most common type being a short circuit from one line to ground. When such a fault occurs, it gives rise to unsymmetrical currents i.e. the magnitude of fault currents in the three lines are different having unequal phase displacement.

In this chapter we will mainly analyse the network for three cases. These are:

i) Single line to ground fault (Unsymmetrical)
ii) Double line to ground fault (Unsymmetrical)
iii) Three phase to ground fault (Symmetrical)

The fault was applied at time 0.2 seconds and is cleared after 150ms. It was assumed that the line is shorted with the ground through zero resistance. The fault ON resistance was set to 0 [ohm] and the fault OFF resistance was set to a value of 1×10^6 [ohm].

5.2.1 SINGLE LINE TO GROUND FAULT ANALYSIS

The fault module was set for the single-line-ground fault making phase-A short with the ground. The voltage of the shorted line will be zero which is shown in Fig-5.3. The fault was considered at the beginning of the overhead line.

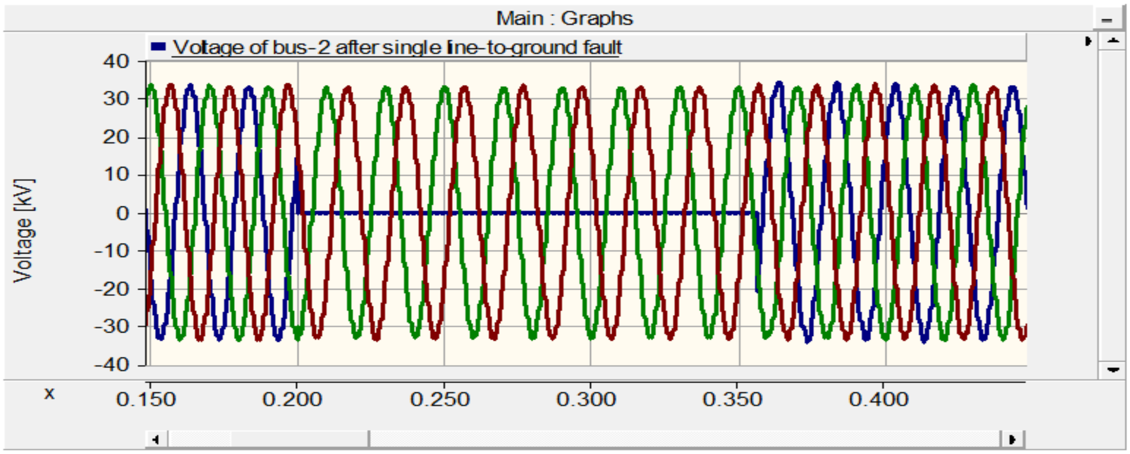


Fig-5.3: Voltage of bus-2 after single-line-ground fault

Since the fault was transient fault, hence it was cleared after 7.5 cycles. At the time of clearing of fault, transient conditions occured during that transition. The voltage recorded at bus-5 is shown in Fig-5.4. The fault occured at time, t=0.2 sec and it was cleared at time, t=0.35 sec.

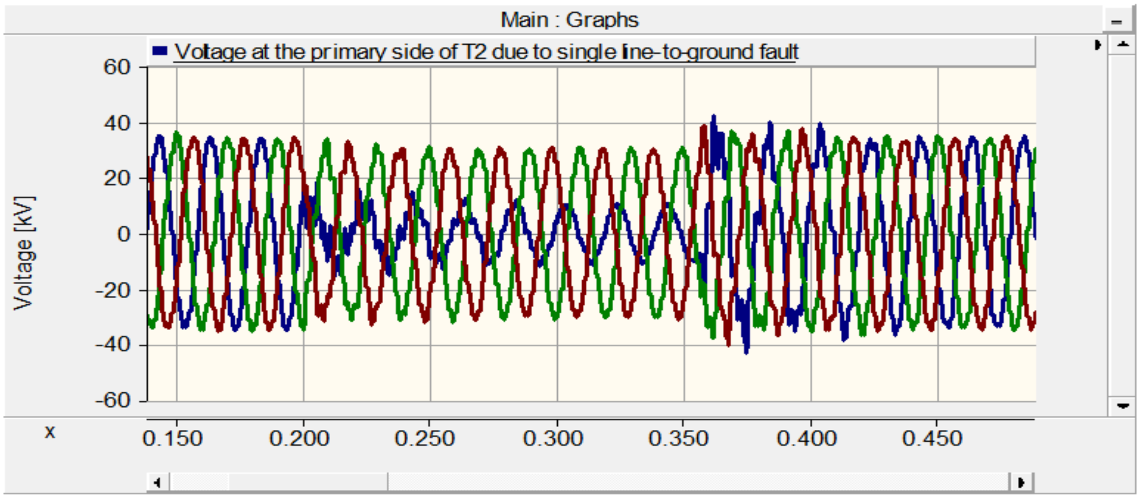


Fig-5.4: Voltage at the primary side of T2 (i.e. bus-5) due to single-line-ground fault

During single line to ground fault, the voltage recorded at bus-10 i.e. at the load side is shown in Fig-5.5. The maximum voltage appeared at bus-10 was almost 0.647kV where the nominal voltage was only 0.4kV.

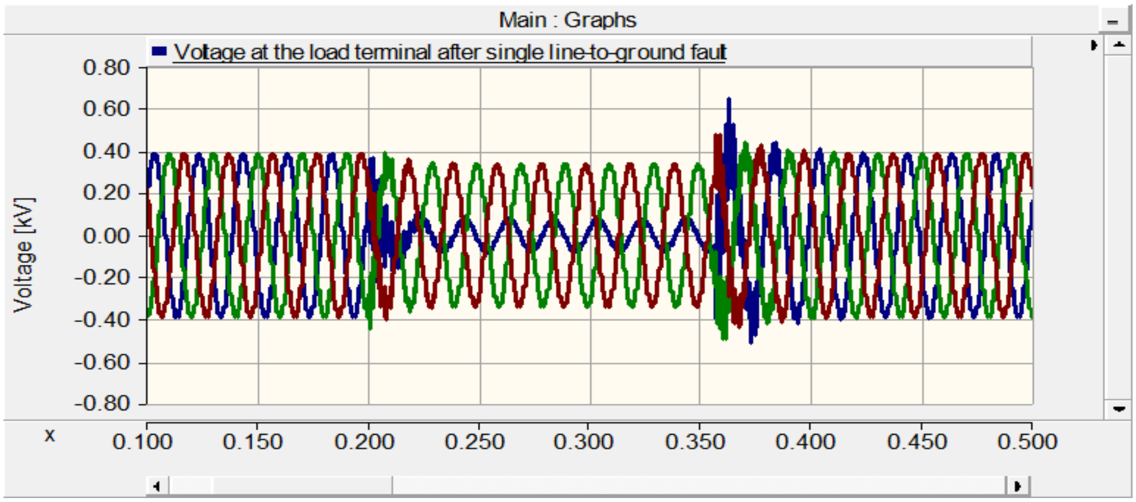


Fig-5.5: Voltage at the load terminal (i.e. bus-10) after single-line-ground fault

During this type of unsymmetrical fault, unbalance current flows with unbalance in magnitude and also the phase. The fault current is many a time greater than that of nominal current due to the short circuit. The short circuit fault current is shown in Fig-5.6.

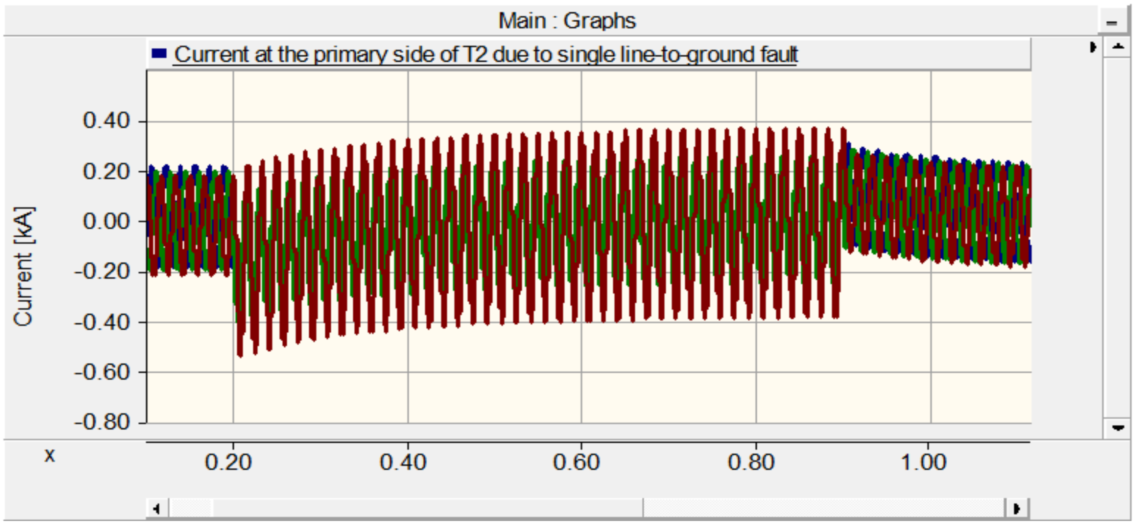


Fig-5.6: Current at the primary side of T2 (i.e. bus-5) due to single-line-ground fault

5.2.2 DOUBLE LINE TO GROUND FAULT ANALYSIS

The fault module was set for the double-line-ground fault making phase-A and phase-B short with the ground. The voltage of phase-A and phase-B will drop to zero due to this fault. The fault was applied at time, t=0.2 sec. The voltage waveform of bus-2 is shown in Fig-5.7.

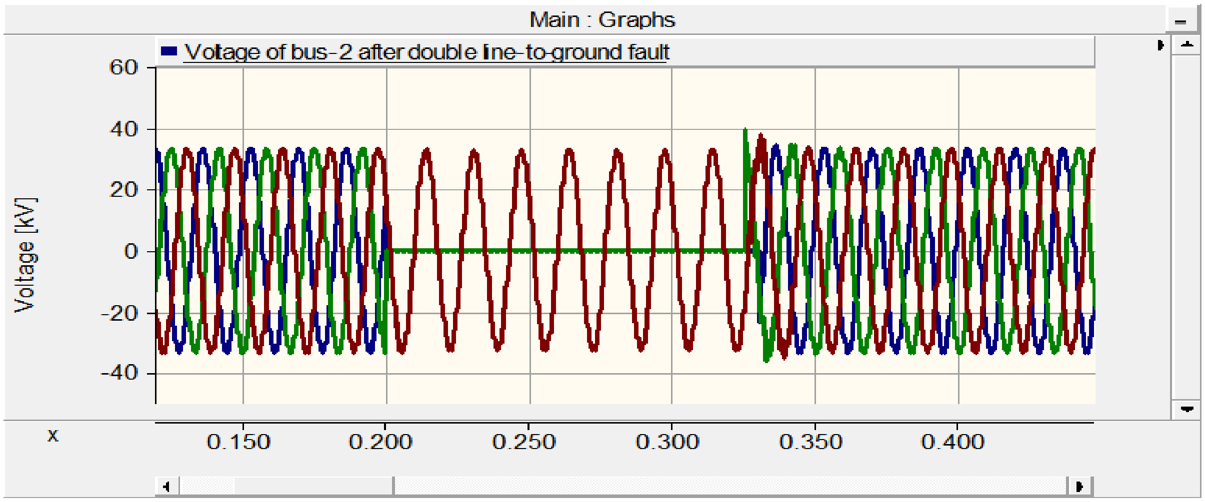


Fig-5.7: Voltage of bus-2 after double-line-ground fault

The double-line-ground fault when cleared also causes much transient overvoltage which may reach upto 1.5-1.8 p.u as shown in Fig-5.8. For unsymmetrical fault, the voltages are unbalanced in both magnitude and phase.

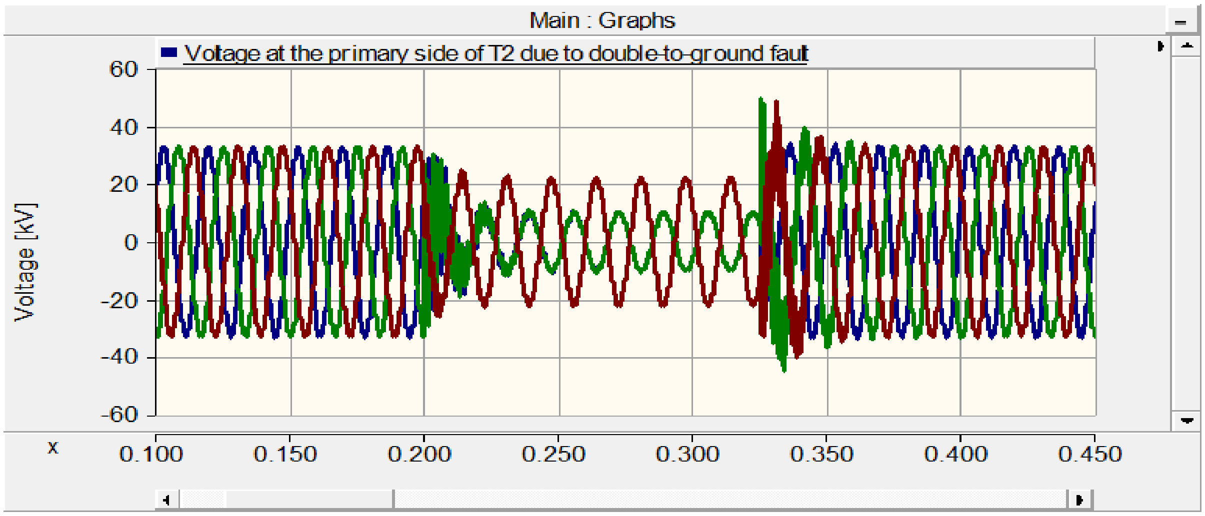


Fig-5.8: Voltage at the primary side of T2 (i.e. bus-5) due to double-line-ground fault

The voltage recorded at the load terminal i.e. bus-10, reaches to a value much more than the nominal voltage. The maximum voltage was recorded as almost more than 2.0 p.u. The voltage of phase-B was maximum. The voltage profile at bus-10 is shown in Fig-5.9.

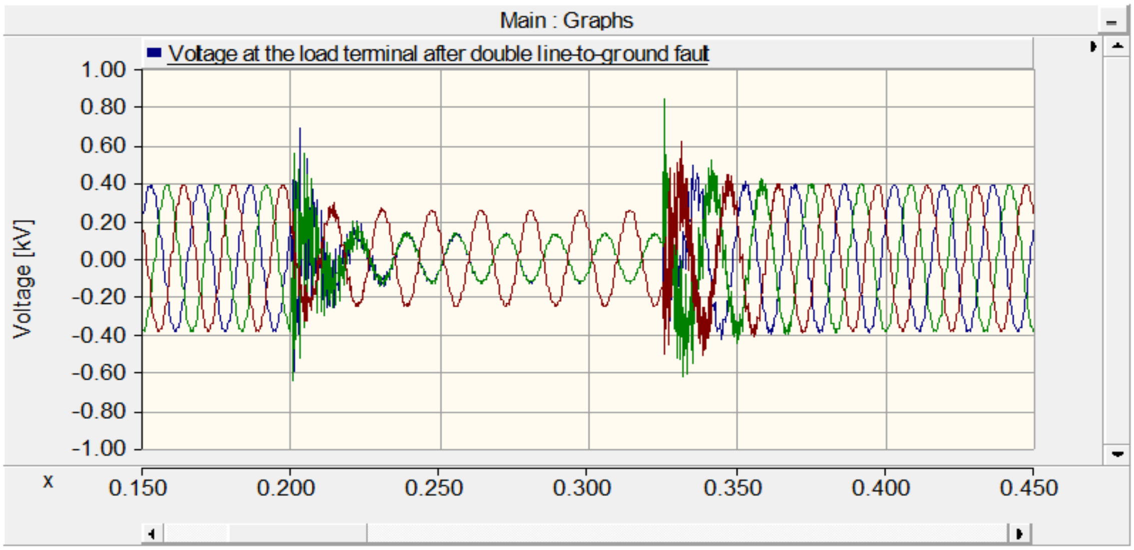


Fig-5.9: Voltage at the load terminal (i.e. bus-10) after double-line-ground fault

The fault current associated with the double-line-ground fault is given in Fig-5.10. It was seen from the response that the fault current was many a time greater than the nominal current which may cause over heating of transformer. The fault occurs at time, t=0.2 sec and was cleared at time, t=0.7 sec.

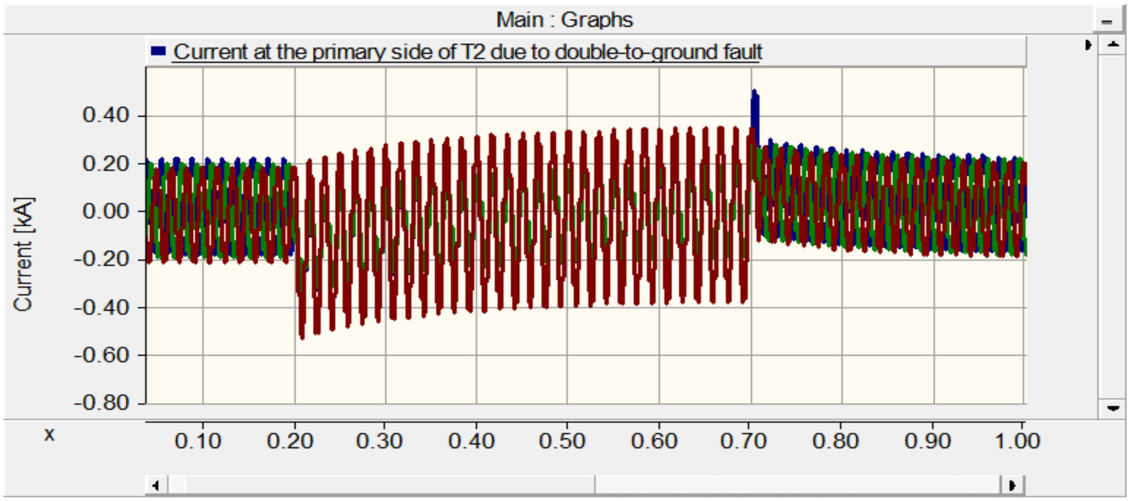


Fig-5.10: Fault current at the primary side of T2 due to double-line-ground fault

5.2.3 THREE PHASE TO GROUND FAULT ANALYSIS

The fault module was set for the three phase to ground fault making phase-A, phase-B and phase-C short with the ground. The voltages of all the three lines were zero which is shown in Fig-5.11.

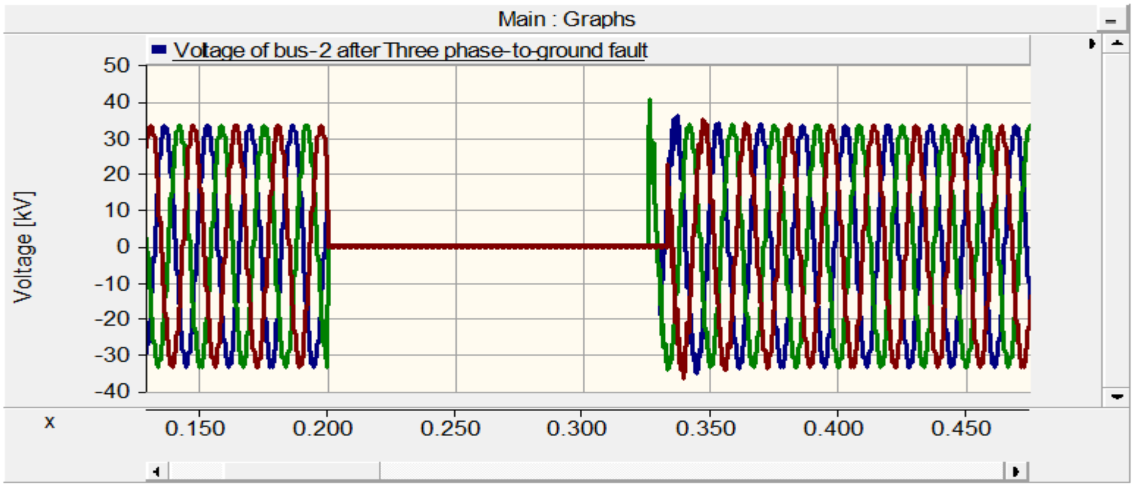


Fig-5.11: Voltage of bus-2 after three phase to ground fault

Three phase to ground fault is a symmetrical and the worst type of fault that rarely occur in the system which was also simulated for our analysis. The voltage at bus-5 that appeared during this fault is shown in Fig-5.12.

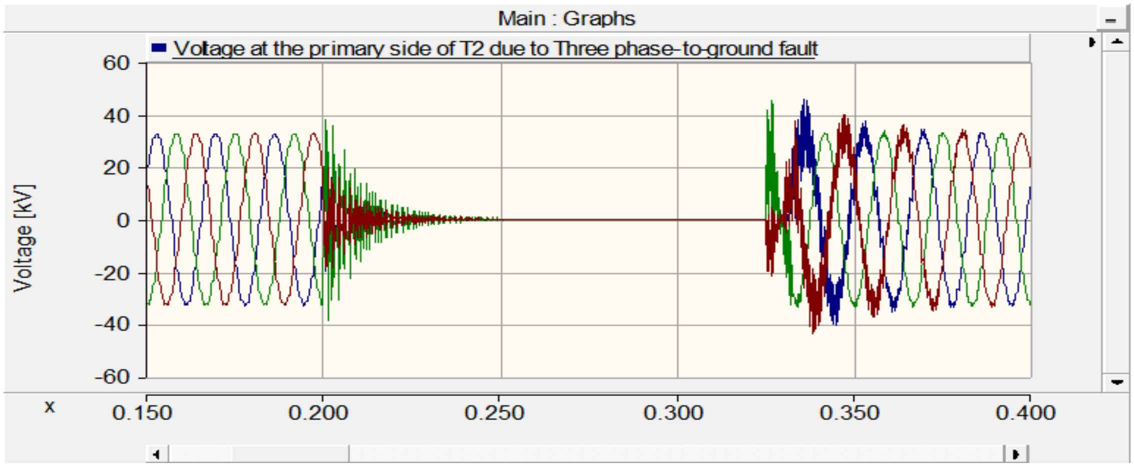


Fig-5.12: Voltage at the primary side of T2 (i.e. bus-5) due to three phase to ground fault

The voltage at the load terminal i.e. at bus-10 was also recorded and the maximum voltage attained was more than two times than the nominal voltage. This is shown in Fig-5.13.

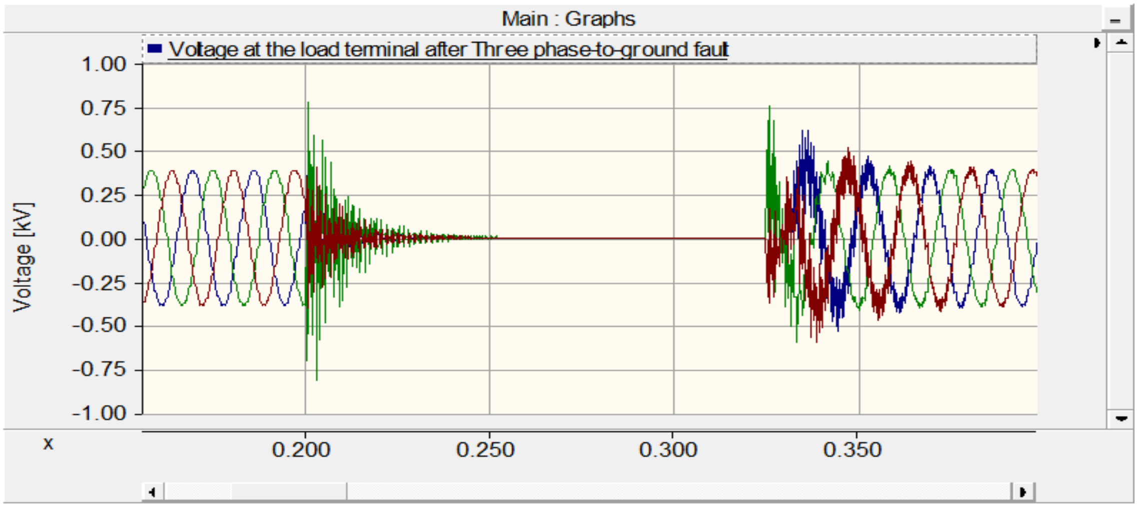


Fig-5.13: Voltage at the load terminal (i.e. bus-10) after three phase to ground fault

For three phase fault, no current flows through the line which is shown in Fig-5.14. The fault current reaches to a peak during clearing of the fault as shown in figure.

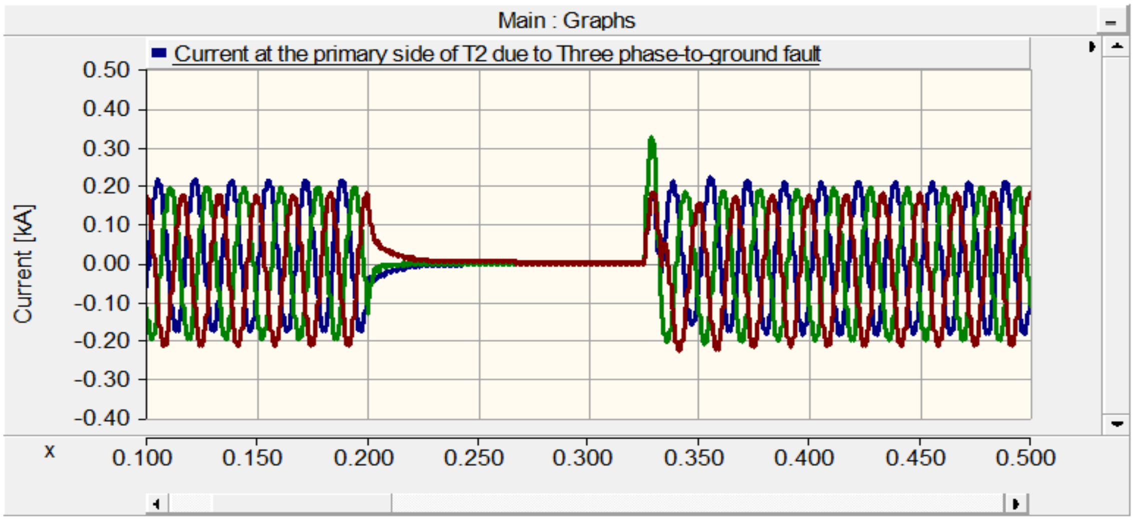


Fig-5.14: Current at the primary side of T2 due to three phase to ground fault

5.3 RESULT AND DISCUSSION ON FAULT ANALYSIS

During single-line-ground fault and double-line-ground fault, it gives rise to unsymmetrical currents of unequal magnitudes and phase displacements which are shown in figures given above. It is seen from the above analysis that during a transient short circuit fault, when the fault is cleared, a high voltage, high frequency transient is developed which may be severe enough to cause the system failure.

Table-5.1 shows the summary of transient short circuit analysis of overhead transmission line. For single line to ground fault, the maximum recorded voltage at bus- 5 was 42.57kV or 1.290 p.u and mitigation time was 5 cycles. At the load side, the maximum voltage at bus-10 was 1.617 p.u and time taken for mitigation was 2.5 cycles.

For double line to ground fault, the maximum voltages attained at bus-2, bus-5 and bus-10 were 1.192 p.u, 1.508 p.u and 2.100 p.u respectively. For three phase to ground fault, the maximum voltage attained at bus-2, bus-5 and bus-10 were 1.219 p.u, 1.383 p.u and 2.00 p.u respectively.

Hence, this situation should be taken under consideration during protective equipments design and transmission line design. The protective equipments must withstand this transient overvoltage for proper functioning of the system. It must be designed after transient analysis of the network and it should be designed considering the maximum voltage that can be attained during a transient fault.

Table-5.1: Recorded data for transient short circuit analysis

Serial number	**Type of fault**	**Bus number**	**Nominal voltage (kV)**	**Maximum recorded voltage (kV)**	**Maximum recorded voltage (p.u)**	**Mitigation time or cycles**
01.	Single-line-ground fault	Bus-2 (Voltage)	33 kV	33.7	1.021	4ms
		Bus-5 (Voltage)	33 kV for all phases	Ph-A: 42.57	1.290	100ms or 5 cycles
				Ph-B: 37.21	1.127	
				Ph-C: 39.51	1.197	
		Bus-10 (Voltage)	0.4 kV for all phases	Ph-A: 0.647	1.617	50ms or 2.5 cycles
				Ph-B: 0.49	1.225	
				Ph-C: 0.477	1.192	
02.	Double-line-ground fault	Bus-2 (Voltage)	33 kV for all phases	Ph-A: 33.8	1.024	20ms or 1 cycle
				Ph-B: 39.36	1.192	
				Ph-C: 37.67	1.141	
		Bus-5 (Voltage)	33 kV for all phases	Ph-A: 34.1	1.033	35ms or 1.75 cycles
				Ph-B: 49.78	1.508	
				Ph-C: 48.60	1.473	
		Bus-10 (Voltage)	0.4 kV for all phases	Ph-A: 0.50	1.250	45ms or 2.25 cycles
				Ph-B: 0.84	2.100	
				Ph-C: 0.61	1.525	
03.	Three phase-ground fault	Bus-2 (Voltage)	33 kV for all phases	Ph-A: 35.71	1.082	50 ms or 2.5 cycles
				Ph-B: 40.24	1.219	
				Ph-C: 34.62	1.049	
		Bus-5 (Voltage)	33 kV for all phases	Ph-A: 45.64	1.383	70ms or 3.5 cycles
				Ph-B: 45.25	1.371	
				Ph-C: 43.17	1.308	
		Bus-10 (Voltage)	0.4 kV for all phases	Ph-A: 0.685	1.712	75ms or 3.75 cycles
				Ph-B: 0.80	2.00	
				Ph-C: 0.60	1.50	

CHAPTER 6

ANALYSIS OF THE RESULTS AND RECOMMENDATIONS

6.1 FORMATION OF TRANSIENTS IN CIRCUIT BREAKER

During closing of circuit breaker, the electric field between the contacts increases as the contacts come closer together. An arc is formed once the dielectric strength of the air gap is less than the contact voltage and the gap breaks down with the formation of voltage spikes as shown in Fig-6.1.

For instance, when a short circuit occurs, a heavy current flows through the contacts of the circuit breaker before they opened by the protective system. At the instant when the contacts begin to separate, the contact area decreases rapidly and large fault current causes increased current density and hence rise in temperature. The heat produced in the medium between contacts (usually the medium is oil or air) is sufficient to ionise the air or vaporise and ionise the oil. The ionised air or oil acts as a conducting medium sufficient to maintain arc. The arc provides a low resistance path and consequently the current in the circuit remains uninterrupted so long as the arc persists [29]. The arc will be extinguished at the first current zero but if the voltage across the contacts exceeds the dielectric capability of the contact gap, the arc will reignite making transient conditions.

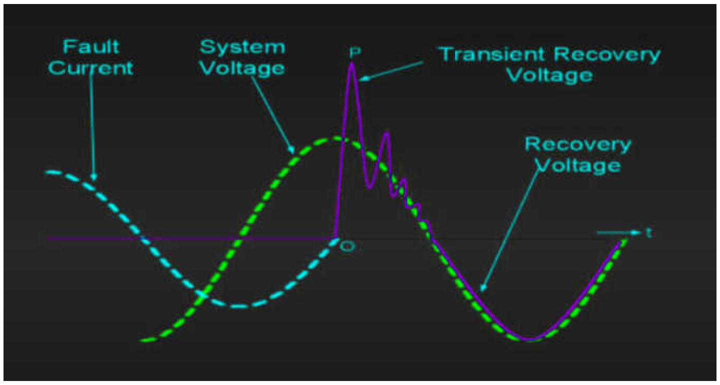


Fig-6.1: Transients developed across the circuit breaker

6.2 DOUBLING EFFECT

When transformers are energised (or when a transformer primary is switched on to the supply source), a transient inrush current up to 10-50 times the rated transformer current can flow and may last for several cycles. The worst condition exists when the transformer is switched on at or around the zero crossing of the current wave form. This inrush current can cause malfunctioning or unwanted tripping of the primary protective devices. The magnitude and duration of inrush current depends on the following factors:

i) Size of the transformer bank

ii) Size of the power system as well as the magnitude and the ratio of inductance to resistance of the system from the source of the transformer bank

iii) Type of iron used in the core

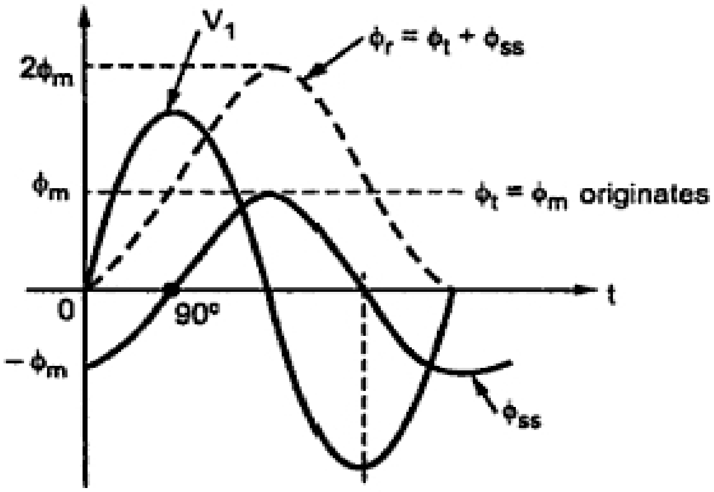


Fig-6.2: Doubling effect of transformer

When the primary side of a transformer is switched, the core flux and the exciting current undergo a transient before achieving the steady state. They pass through a transient period. The effect of transient is severe when current wave pass through origin. In the inductive circuit flux can start with zero value. But the steady state value of flux at start is $-\Phi_m$, as shown in the Fig-6.2, at t = 0. Thus during transients a transient flux called off-set flux, $\Phi_t = \Phi_m$ originates such that at t = 0, $\Phi_t + \Phi_{ss}$ is zero at the instant of switching. This transient flux Φ_t then decays according to circuit constants i.e. ratio L/R. This ratio is generally very small for transformers.

Thus during transients, the total flux goes through a maximum value of $2\Phi_m$. Such effect is called doubling effect. Due to the doubling effect, core flux achieves a value of $2\Phi_m$ due to which transformer draws a large exciting current. This is due to the fact that core goes into deep saturation region of magnetisation. Such a large exiting current can be as large as 100 times the normal exciting current. To withstand electromagnetic forces developed due to large current, the windings of transformer must be strongly braced. This large current drawn during transient is called inrush phenomenon.

Practically initial core flux can't be zero due to the residual flux Φ'_r present, due to retentively property of core. The transient resultant flux goes through $\Phi_r = \Phi'_r + 2\Phi_m$ and there is heavy inrush current in practice. The effect of transient is even severe in practice. Such high transient current gradually decreases and finally acquires a steady state. It can last for several seconds. The transient flux Φ_t and exciting current both are unidirectional during transients. In steady state, exciting current becomes sinusoidal [35].

Hence due to doubling effect, the transient voltage can also be doubled at the transformer terminal. This doubling effect has been observed for transformer energization in case of underground cable of Chapter 4.

6.3 EFFECT OF TIME OF SWITCHING ON TRANSIENTS

The magnitude of transient overvoltage largely depends on the time at which the switching operation is done. If the switching is done at that time when the voltage between the two contacts of the circuit breaker is maximum, then the transient voltage appeared will be maximum. So, if the switching operation can be done at voltage zero point, the severity of the transient overvoltage can be minimized.

If we carefully observe the output result data of different bus voltages in case of overhead transmission line, then it will be seen that the voltage of phase-B for bus-2 during transformer energization was recorded as 1.205 p.u. This is the maximum voltage attained at that bus. Similarly, for bus-5, the maximum voltage was recorded as 1.903 p.u for phase-B during 2.0MVAR capacitor bank. Also the maximum voltage reached at bus-9 was 1.842 p.u for phase-B during 1.0 MVAR capacitor bank switching. Hence, in all cases, the maximum voltage attained was for phase-B. The reason for this is that, the switching operation for all cases were done at the peak of phase-B and as a result the voltage of that phase was maximum.

6.4 EFFECT OF THE SIZE OF CAPACITOR BANK

The magnitude of transient overvoltage is also affected by the size of the capacitor bank. The inrush current is inversely proportional to the surge impedance of the load circuit. Capacitor banks have small surge impedance, far smaller than cables and lines. Due to their distributed nature, cables and lines have surge impedance from several tens to several hundred of ohms. Energization of capacitor banks, however having surge impedances of just few ohms, may lead to very large inrush currents if no current limiting measures have been taken.

The inrush current through the capacitor bank is given by the equation-6.1 below-

$$i(t) = \frac{V(0)}{Z_0} \sin \omega_0 t$$

(6.1)

Where,

$V(0) = V_s - V_c$

Z_0 = Surge impedance = $\sqrt{\frac{L}{C}}$

V_s = Bus voltage

V_c = Initial capacitor bank voltage

Hence, larger the size of the capacitor bank, larger will be the capacitance, lower will be the surge impedance and hence higher will be the magnitude of inrush current. Hence, transients associated with large sized capacitor bank will be of higher magnitude than for smaller size.

6.5 RECOMMENDATIONS TO MINIMIZE TRANSIENTS

The main criterion of switching transients that occurs can be seen as the shunt capacitor bank switching and Transformer switching as the previous study shows. Protective measures must be taken to reduce the effects of these transients. Among these two types of switching, the shunt capacitor bank switching transient is the most dangerous and harmful case of switching transient. The steps that can be taken to minimize the effects of these switching transients are discussed in the section below.

6.5.1 Minimization of transients due to shunt capacitor bank

In power transmission and distribution it is necessary to improve the reactive power content. To achieve this, shunt capacitor banks are used. Because of it’s low cost and flexibility of insulation and operation it is a widely used device to improve the reactive power of the transmission and distribution.

However, energizing these shunt capacitors introduces a transient oscillation in power systems. Due to the fact that the operation of switching shunt capacitors happens frequently, shunt capacitor switching is regarded as the main source of generating transient voltages on many utility systems. These transients can cause damages on both utility systems and customer systems, depending on the system parameters such as switched shunt capacitor- size, transformer size, and the type of customer loads connected to the system.

Pre-strikes during capacitor energizing can occur when there is an arc forming across switching contacts and contracting before the contacts are completely closed. This arc is extinguished by the switch being able to clear the current zeroes and causing the contacts to close completely.

Re-strike during de-energizing capacitor can occur when the switch is unable to handle the voltages across the contacts when the switch is opened and therefore, causes the contacts to reclose momentarily. It is essential for utility system suppliers that they use switching devices which have mechanism to minimize the occurrence of both pre-strikes and re-strikes [22].

The necessary steps that can be taken to reduce the effect of capacitor bank switching are:

i) Synchronous closing control
ii) Optimum closing/ Opening resistors
iii) Metal oxide Varistor (MOV)
iv) Harmonic filters
v) Surge arresters
vi) Snubber circuit

6.5.1.1 Synchronous closing control

This method is to control closing instants of the capacitor switching device so that each phase of the capacitor bank is energized at the time when the voltage across switching contacts is zero. In practice, a vacuum breaker is the only switching device that can be implemented with this concept. It has been proven that synchronous closing control is efficient for large substation banks and transmission system capacitors. This method has not typically been employed for feeder capacitors.

6.5.1.2 Optimum closing/Opening resistors

Opening and/or closing of the capacitor banks can be another way of minimizing the capacitor switching transients. The capacitor switching device may be equipped with closing and/or opening resistors to accomplish this process. These resistors can be set up to an optimum size for this purpose. The main advantage of this method is that, it is possible to reduce transient effects due to capacitor bank switching and to prevent both the restrikes and prestrikes of switching. The only lacking of the process is the optimum size of the resistors is not available for the distribution network. Nonetheless this method is considered as an effective way to reduce transient effects due to capacitor bank switching in power system.

6.5.1.3 Metal Oxide Varistor (MOV)

Metal oxide varistor is basically an electronic device. The resistance of varistor varies with the applied voltage. For these reasons it is also known as voltage dependent resistors. It has a non-linear, non-ohmic current voltage characteristic that is similar to that of a diode.

When used in electronic circuits, varistors are used as compensators, but in power systems, it is used as a protective device against transient over voltages. When the voltage across the varistor is low, it's resistance is very high to flow current through it. But when a very high voltage is applied it's resistance becomes much lower and it allows the excessive current to pass through it caused by the transient over voltage [22].

A basic cross sectional figure of MOV is given in Fig-6.3.

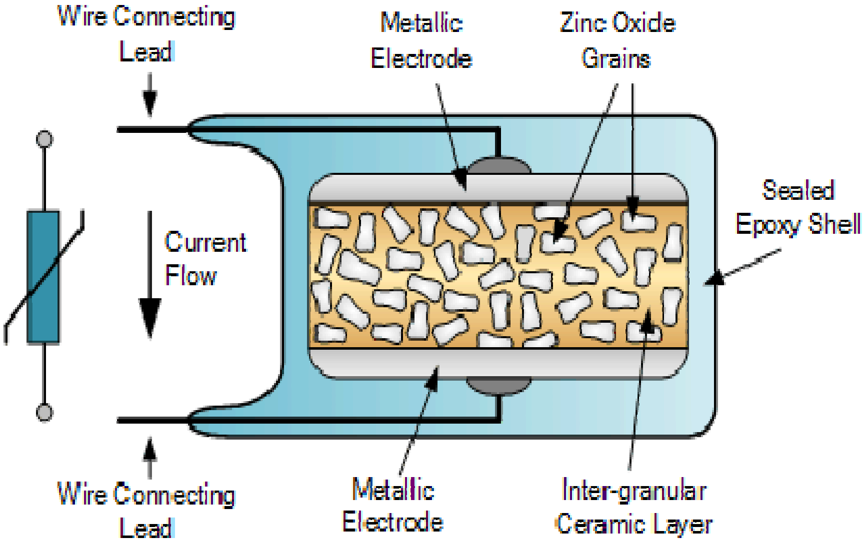


Fig-6.3: Cross sectional view of Metal Oxide Varistor (MOV)

MOV arresters are extensively used in both utility systems and customer systems to reduce transient over-voltages and to protect power electronic equipment. The coordination among these MOVs in the system has to be done properly.

6.5.1.4 Harmonic filters

The idea of this method is to eliminate transient magnification by detuning the LC circuit in part two so that its resonant frequency is out of range of the resonant frequency of LC circuit in part one, and hence, not being easily excited by shunt capacitor switching.

Harmonic filters are also known as the power conditioner. In some cases of transient switching, harmonics due to capacitor bank may enter the transformer system and lead to a resonance that may not be damped and lead to a severe damage to the equipment of concerned. Thus to remove these harmonics we need a filter to filter out the harmonics.

The main purpose of the harmonic filters is to smoothing the AC power supplied. A distortion in voltage level is eliminated through these filters. Although it is not possible to eliminate all the harmonic components, the higher order harmonic components must be eliminated using filter of a rated level. Specially, the harmonic components that are harmful to the system components.

6.5.1.5 Surge arresters

Surge arresters are also known as Surge Protection Device (SPD) or Transient Voltage Surge Suppressor (TVSS). This is a device that can bypass the excessive surge voltage and current to the ground through it. The energy criterion for various insulation materials can be compared by impulse ratio. The surge arrester should have low impulse ratio.

The surge arrester is connected in the conjunction between the cable and the equipment (Just before the cable enters an equipment). It is also connected to the ground. Because of it’s low impulse ratio, when a surge voltage or transient over voltage is generated, it bypasses the excessive current through it’s ground conductor to the ground. Thus saves the equipment and components used in both the customer side and utility side.

Surge arresters are usually used in the transmission and distribution side mainly for user protection. A simple cross sectional diagram of surge arresters are given in Fig-6.4.

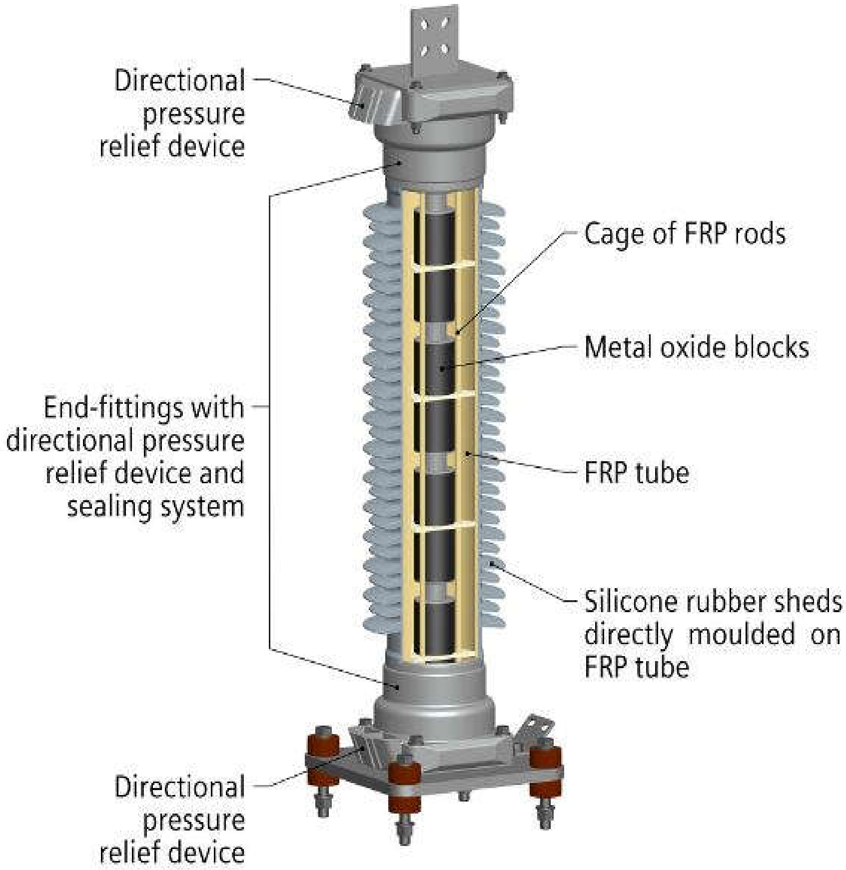


Fig-6.4: Surge arrester cross sectional view

6.5.1.6 Snubber Circuit

Snubber circuit in power system is a phenomenon that is used usually to snub or suppress the electrical power surge (e.g. Transient over voltage) in transmission and distribution of power. Snubbers are more frequently used in electrical systems with an inductive load. It is device that creates a short path for the excessive current to pass through the circuit instead of flowing through the equipment of interest or the equipment that is to be protected.

Snubber circuits can be very useful to suppress the transient over voltage due to capacitor bank switching. A conventional RC snubber circuit is shown below:

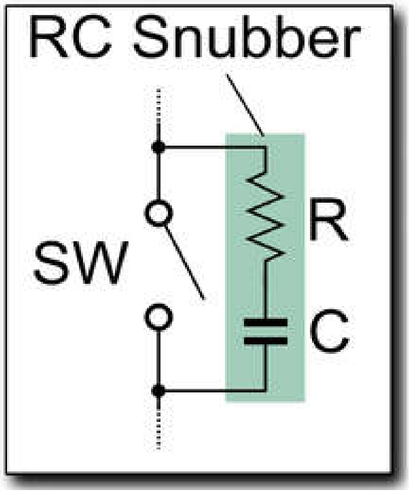


Fig-6.5: RC Snubber circuits

6.5.2 Minimization of transients due to transformer switching

The Factors that causes transient over voltage due to transformer switching are:

i) Point in time when the transformer is energized relative to the voltage source.
ii) The magnitude of the voltage source.
iii) Magnetization curve of the transformer.
iv) The magnitude of the residual flux in transformer.
v) The sign of residual flux in transformer.
vi) The presence of tertiary winding.
vii) The load on the secondary side of the transformer.
viii) The source impedance and the winding resistance of the transformer.
ix) Transformer construction type (i.e. single phase, three-phase bank, three-phase three limb core type, etc.)

The relative measures that can be taken against the causes that are responsible for transformer transient switching over current or inrush current are as below:

i) Energize the transformer at the same point that it was de-energized. This causes the time interval between energization and de-energization zero and inrush current can be eliminated.

ii) There is no effective measure that can be taken to minimize the effect of inrush current due to the magnitude of voltage source as it is not a variable quantity.

iii) Some design considerations can be taken to minimize the effect of transient due to the magnetization curve of transformer.

iv) In case of magnitude of the residual flux in transformer, the transformer can be de-energized when the flux content is zero.

v) Keeping track of the sign of the residual flux in transformer can reduce the inrush current caused by the sign of the residual flux.

vi) When a tertiary winding is present in transformer and a transient occurs due to this, no effective measures are there which can be taken to reduce the inrush current.

vii) Using load balancing capacitors that produce a back EMF proportional to the magnetizing flux during the saturation of the transformer at the point of energization can reduce the transient effect due to the load on the secondary side of the transformer.

viii) Setting the level of source impedance and transformer winding resistance to a convenient value in the design of transformer can reduce the inrush current.

ix) For a given application, a single phase or three phase type would be required, but the use of a core, or three single phase transformers in a bank is a choice that canbe made to minimize the inrush current [22].

Thus we can reduce the effect of transient switching of transformer taking the actions stated above.

6.6 DISCUSSION

Hence from the above analyses of the results, it is clear that, the time of switching is a major issue for transient analysis of a network. Beside these, doubling effect has been seen during the switching of transformer which may lead to the failure of transformer. The worst case occurs when the transient frequency of the over-voltages matches the resonance frequency of the transformer. It leads to the voltage or current or both voltage and current amplifications and in some cases it may be higher than the Basic Insulation Level (BIL) of transformer and hence causes the failure of transformer winding insulation.

So the transformer winding should be designed considering the maximum voltage stress during switching so that the transformer can withstand this high voltage. The protection equipments like potential transformer, current transformer, circuit breaker, auto-recloser and protective relays etc. should be designed carefully after transient study so that they don’t go for false tripping. They must have the withstand capability and keep smooth running of the system.

Transients can’t be completely eliminated but by adopting the recommendations given above, it is possible to minimize the severity of over-voltages. Now-a-days, most of the utility system uses surge protector to protect their transformers and other costly equipments from switching surges. For capacitor bank switching, snubber RC suppressors are mostly used. Recently invented diode based transient limiter is also very effective in decreasing the effect of transients.

CHAPTER 7

FURTHER RESEARCH AND CONCLUSION

7.1 INTRODUCTION

In the last chapters, we had analysed a common network under different cases like overhead lines, underground cable and transient short circuit fault for different switching events. In this chapter, we will mainly discuss the difficulties we faced during accomplishing the thesis works especially regarding software.

The main objectives of our thesis work was to show the effects of switching and to make a comparative study between overhead lines and underground cables so that different necessary protective actions can be taken to minimize that transients. And hence at the later part, we will be discussing the limitations that we had during our study and analysis.

At the end, some directions will be given to the researchers so that they can make further research in this field for finding new and improved methods of lowering or eliminating switching transient overvoltage.

7.2 DIFFICULTIES FACED DURING ACCOMPLISHING THESIS

Electromagnetic transients are real and disruptive events in power systems. Yet, they are often difficult to study. The simulation tool that we used for our thesis work was Power System Computer Aided Design (PSCAD). The first problem that we faced was with software. Firstly, we used the demo version of this software with lots of limitations. The maximum allowable simulation that can be done using that version was limited.

Then we installed the crack version of PSCAD with little bit of flexibility than the demo version. But since that was not authorized, hence we had some difficulties regarding model of transmission line, circuit breaker etc.

Moreover, PSCAD requires lots of data and parameters. Hence we faced some problems regarding collection of accurate data for our analysis. Then the problem that we faced was with the output curves. The per unit (p.u) representation of the output curve was little bit difficult and the value could not be shown in the graph. There was no option to show the value of the transient overvoltage in the graph and hence we faced a lot of problems in accumulation of output data.

For designing of overhead transmission line and underground cable, we had to select the transmission line model, tower model and solve constants, which was too much difficult as a beginner. Lastly, the problem that we had related to software was with the error command. If any error occurs in the system design or if any wrong parameters are given in the system, the PSCAD only shows error signal without detailed information of error. Hence it was very difficult for us to find out the errors during performing analysis.

These are the main problems that we faced during accomplishing the analysis and thesis. It took much time to overcome these problems.

7.3 LIMITATIONS OF STUDY AND ANALYSIS

We tried to make our analysis more accurate and applicable to any system. But we have some limitations regarding our analysis. These are shortly listed below-

i) We had the plan to work on an actual distribution network in Bangladesh; but due to the unavailability of necessary data and parameters, we couldn't do that. Hence we had taken an arbitrary distribution network for switching transient study and analysis.

ii) Due to the software limitations, we couldn't model the transformers used according to our requirements and hence we used the default model of transformers.

iii) Since we worked upon the distribution network, hence the system must be fed from the external grid. But due to the unavailability of external grid module, we used generator as the external grid.

iv) Since we used the crack version of the software, we had some limitations regarding modelling and hence we used the default model of circuit breaker. If we could do that, we also had the plan to show the performance of different types of circuit breaker.

v) During our analysis, we neglected the action of Automatic Voltage Regulator (AVR) and hence the output voltage at different buses decreases than the nominal value due to the load connected at the distribution side. Hence we did the analysis under unloaded condition.

vi) We did the analysis of switching transients during unloaded condition to show the extreme cases but switching of capacitor bank during unloaded condition is totally impractical. Hence, practically the magnitude of transient overvoltage at different buses will be less than the evaluated value.

vii) We used different parameters like line resistance, reactance and capacitance, tower parameters, Transformer parameters, Circuit breaker parameters etc. arbitrarily and hence the evaluated result is not applicable to any particular system. The output response will vary according to the data given during simulation.

viii) Since distribution networks remain interconnected with other utility system, hence practically the transient response can be affected by other systems, which has been neglected during our study.

ix) Due to software authorization problem, we just mentioned the protective measures that can be taken to reduce transient overvoltage during switching. We could not simulate the system by using that protective equipment to show the response.

x) Due to the limitation of time, we could not analyse the system for other effects like harmonics on the transient response.

These are the limitations that we had during our analysis. But though we have some limitations, the analysed output can help anyone to get a better and clear idea about the consequences of switching transients.

7.4 FUTURE WORKS

The purpose of this thesis was to show the transient overvoltage occurs during switching operations for overhead lines and underground cable and also during transient short circuit fault. The future directions for the researcher will be to overcome the limitations that we have. They can have a more specific and clear idea about the transients under different switching conditions and it's severity for different transmission system. These ideas will enable them to work and have their research in this field in a better way. Now-a-days, due to the recent failure of some costly equipments like transformer, circuit breaker etc in the history of power system, it has drawn attention to the researches to work on it. So, this thesis paper will help them to think and analyse any system in a more convenient way and find more and more protective actions.

Due to software limitations, we could not simulate the transient response after installation of protective equipments as suggested in the previous chapter. Hence, more research can be done for analyzing the performance of these protective equipments for the mitigation of transient overvoltage.

7.5 CONCLUSION

Switching of predominantly reactive equipment represents the greatest potential for creating excessive transient duties. Principal offending situations are switching capacitor banks with inadequate or malfunctioning switching devices and energizing and de-energizing transformers with same switching deficiencies. Capacitors can store, trap and suddenly release relatively large quantities of energy. Similarly, highly inductive equipment possesses an energy storage capability that can also release large quantities of electromagnetic energy during a rapid current decay. Since, transient voltages and currents arise in conjunction with energy redistribution following a switching event, the greater the energy storage in associated system elements, the greater the transient magnitude.

The overall switching transient studies in this thesis paper will provided many important criteria to enable system designers to avoid excessive transients in most common circumstances. The criteria for proper system grounding to avoid transient over-voltages during a ground fault are also clear from the analysis.

These analyses also show the importance of system design (i.e. Transformer, transmission line, cable, circuit breaker, protective relays etc.) so that it can withstand the transient overvoltage. Cables joints and terminations should be done using good materials and following instructions to increase their ability to withstand transient overvoltage. Hence for designing any new utility system, transient analysis must be done to chose the equipments rating which enable a more reliable and efficient system.

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