Study and Analysis of Switching Transients in High Voltage Transmission Line

A Thesis
Submitted to the Dept. of EEE, BRAC University
In Partial Fulfillment of the Requirements for the Bachelor of Science Degree in Electrical & Electronics Engineering

By

Prottasha Ahmed	14121023
Alif Fatin Faiyaz	14221017
Anik Das Gupta	14321040
Hisham -Al- Rashid	14321041

Supervised by

Abdul Hasib Chowdhury, PhD

Professor, Dept. of EEE, BUET

BRAC UNIVERSITY
Inspiring Excellence

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DECLARATION

This is to declare that this thesis titled ''Study and Analysis of Switching Transients in High Voltage Transmission Line'' is submitted to the department of Electrical and Electronics Engineering of BRAC University for the partial fulfillment of the degree of Bachelor of Science in Electrical and Electronics Engineering. We hereby affirm that the simulation based research and result was conducted solely by us and has not been presented previously elsewhere for assessment. Materials of the study and work found by other researchers have been properly referred and acknowledged.

Submission Date: 17th April, 2018

PROTTASHA

Prottasha Ahmed

Student ID: 14121023

Anik Das Gupta

Student ID: 14321040

Alif Fatin Faiyaz

Student ID: 14221017

Hisham-Al-Rashid

Student ID: 14321041

Thesis Supervisor

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ABSTRACT

A switching transient over-voltage is created and travels along the line following switching to energize or de-energize a transmission line. This switching transient over-voltage will reach its highest levels at the transition points connecting an underground cable to an overhead line. The transient over-voltage will exceed the normal operating voltage and will be transmitted to the lower voltage level system. The magnitude of the transient over-voltage has to be limited to avoid exceeding substation equipment surge ratings. Without the limitation, the overvoltage may cause damage to the system protective devices. This study will investigate transient over-voltages associated with closing a breaker to energize or de-energize a high voltage transmission line.

ACKNOWLEDGEMENTS

First and foremost we are thankful to our God for providing us with the patience and strength to go on and complete this thesis.

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Lastly we offer our regards and gratitude towards all of those who supported in any aspect, especially Power Grid Company of Bangladesh Limited (PGCB), during the completion of this thesis.

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List of Abbreviations

AC	Alternating Current
ACCC	Aluminium Conductor Composite Core
ACSR	Aluminium conductor steel-reinforced cable
Bibi_1	Bibiyana Line 1
Boro_1	Boropukuria Line 1
Bogura_1	Bogura Line 1
Bpuk_2	Boropukuria Line 2
CB	Circuit Breaker
EMTP	Electromagnetic Transients Program
EMTDC	Electromagnetic Transient including DC
EHV	Extra High Voltage
ETL	Extract, Transform, Load
FACTS	Flexible Alternating Current Transmission System
FFT	Fast Fourier Transform
GPS	Global Positioning System
GT	Gas Turbine
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
kalia1	Kaliakair Line 1
KV	Kilo Voltage
km	kilo meter
MVA	Mega VA
NEA	Numerical Electromagnetic Analysis

NLDC	National Load Dispatch Centre
OHL	Over Head Line
OGW	Overhead Ground Wires
PGCB	Power Grid Company Bangladesh
PU	per unit
ST	Steam Turbine
TEM	Transverse Electromagnetic mode
TNA	Transient Network Analyzer
TRV	Transient Recovery Voltage
UHV	Ultra High Voltage
UPS	Uninterruptable Power Supply

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Chapter 1

Introduction

1.1 Switching Transient

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 three major categories:

1. Interaction between magnetic and electrostatic energy stored in the inductance and capacitance of the circuit, respectively;

2. Interaction between the mechanical energy stored in rotating machines;

3. Electrical energy stored in the inductance and capacitance of the circuit.

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. While over-voltages may result in flashovers or insulation breakdown, overcurrent 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.

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.

1.2 Literature Review

The first work related to the power system transient, specifically wave propagation on a distributed-parameter line, is so called "Kelvin arrival curve" derived by Lord Kelvin to investigate signal distortion on the planned Trans-Atlantic telephone cable in 1854 **[1-2]**. Theoretically the solution was confirmed by Heaviside"s transform which had become the most powerful and promised approach to deal with a transient in an electric circuit until 1960s **[3-5]**. In 1926, a transformer breakdown occurred due to lightning to a 220 kV transmission line in Pennsylvania **[6-8]**. This was an origin of applying a transient analysis to a high-voltage power system. A traveling wave theory, theoretical transient analysis methods etc. were established in 1930s **[9-10]**. Also in this time period, accurate formulas of a conductor internal impedance, an earth-return impedance and admittance of an overhead line were derived for studying telephone line interferences from a power line **[11-14]**. In 1960s, a digital computer became available, and an enormous number of engineering researches were carried out all over the world. In 1970, CIGRE WG 13.05 started to investigate various transient simulation methods and carried out a comparison with field test results of switching surges **[15-17]** and the WG reached a conclusion that the EMTP was most powerful and useful **[18-20]**. Recent advancement of ICT technologies, measuring technologies so on has made clear the application limit of a circuit-theory based approach such as the EMTP. Thus, a new approach to deal with such phenomena is required, and a numerical electromagnetic analysis (NEA) is becoming a powerful approach to deal with a transient involving non-TEM mode propagation etc. **[21-24]**.

Electrical transients associated with a wave propagation characteristic are mathematically represented by a hyperbolic partial differential equation. The earliest solution of the partial differential equation was given by D" Alembert for the case of a vibrating string in 1750 **[25]**. At the same time Bernoulli found a solution which was of quite different form from the D" Alembert solution. Bernoulli"s solution is based on the Eigen function, and is comparable with the Fourier series. The first work related to a power system transient seems Lord Kelvin"s investigation of wave propagation characteristic on the planned Trans-Atlantic telecommunication cable in 1854 **[1-2]**.He derived well-known "Kelvin arrival curve", which expressed a signal distortion along the cable in the form of $\exp(-\alpha x)$ with time delay $\tau = x/v$, v: velocity. The solution is very similar to that of heat-transfer along a heat conducting material. In the same generation, Heaviside developed so-called "Heaviside transform", which was the same as Laplace transform, and gave a number of solutions/formulas between time (t) and frequency (ω or s = jω) functions **[3-5]**. The Heaviside transform was widely used to obtain a transient (dynamic) response in a lumped-parameter circuit, not only for electrical phenomena but also for acoustic, mechanical vibration, heat transfer etc. until 1960s.It is noteworthy to mention that Heaviside derived Maxwell‟s equation by applying double integral Heaviside transform **[3]**. In 1926, the Walenpaupack-Siegfried 220 kV line in northwestern Pennsylvania was put into operation with no overhead grounding wire and no arrester at the terminals. A cooperative lightning investigation was begun. In 1928, the coordination of transmission line and apparatus insulation was discussed in the AIEE meeting **[6-8]**. When arresters and overhead ground wires became common and the insulation of transmission lines and substation apparatuses were coordinated, a switching surge was focused as a cause of troubles in a power system. To analyze the switching surge and also a fault surge, it is necessary to deal with a three-phase circuit. As a consequence, a symmetrical component theory developed in 1918 **[26]** was applied to analyze the switching surge **[27-30]**. In late 1950s, a digital computer became available, and an enormous number of computer applied researches were carried out all over the world. All the tedious theoretical and hand calculations were replaced with computer simulations. Many computer programs to deal with electrical transients were developed. Among various approaches of solving a transient, a traveling wave technique became one of the most powerful approaches because of the distributed nature of a transmission line. The concepts and the theory of traveling waves have been well developed since D‟Alembert‟s solution. Allievi first applied the theory to the field of hydraulic engineering and established the general theory and the idea of a graphical method which was a direct application of the traveling-wave concept to engineering fields **[31]**. The method developed by Allievi has been applied to the analysis of a water hammer by Schnyder **[32]**, Bergeron **[33]** and Angus **[34]**. This is originally called Schnyder-Bergeron method in the electrical engineering field. The detail and application of the graphical method is well described by Parmakian in his book **[35]**. The graphical method corresponds to the method of characteristic to solve Maxwell‟s equation mathematically **[36]**. The graphical method and Bewley‟s lattice diagram were implemented on a digital computer for calculating electrical transients **[18]**, **[37-40]**. These techniques are generally called the traveling-wave technique, or a time-domain method.

Numerical Fourier transform appeared in the electrical engineering field only very recently **[41-44]**. Gibbs‟ phenomena and instability in a transform process, which are the inherent nature of the discrete Fourier transform, are greatly reduced by developing the modified

Fourier transform **[42-43]**. At a later stage, the modified Fourier or Laplace transform was applied to transient calculations by various authors **[45-48]**. Since the modified Fourier or Laplace transform provides a high accuracy for obtaining a time solution on a frequency-dependent line, and implementation of Fast Fourier Transform (FFT) procedure into the modified Fourier or Laplace transform greatly improves the computational efficiency **[46]**, the method has become one of the most accurate and efficient computer techniques for transient calculations. CIGRE WG 13.05 started to investigate various transient simulation methods and carried out a comparison with field test results of switching surges **[16-17]**. In 1975, most of the WG members including H. Dommel reached a conclusion that the EMTP developed in Bonneville Power Administration was most powerful and useful **[18-20]**. Thus, many scientists or engineers started to contribute the further development of the EMTP and also to use the EMTP for a power system transient analysis. Since the EMTP has become a kind of a world standard simulation tool to solve a power system transient, a number of papers have been published. Those are, for example, accuracy improvement and increasing numerical stability which are closely related to the advancement of ICT technology.

A case study **[49]** was done on SF_6 circuit breaker failure during switching-off an unloaded and relative long 400 kV transmission line. Both breaking chambers of the circuit breaker were destroyed. Due to the specific place and type of fault the relay protection system did not operate during circuit breaker failure and transients have been recorded only by a power quality monitoring system installed in the nearby line bay. Recorded events were used for circuit breaker post-mortem analysis. The post-mortem analysis of SF6 CB during switching-off an unloaded 400 kV transmission line showed that the CB failure was initiated by the repetitive restrikes occurrence between the contacts. Due to the specific place and the absence of phase-to-ground fault and voltage breakdown, the relay protection system did not operate during the CB failure. Additional analysis of regular switching-off operation shows pretty unequal voltage distribution between breaking chambers, which in real conditions of this particular case with relatively high TRV, can lead to restrike occurrence.

Another study **[49]** was conducted on 735 KV transmission line to find out switching surge transients. A three-phase, 50 Hz, 735 KV power system transmitting power from a power plant consisting of six 350 MVA generators to an equivalent network through a 300 km transmission line was considered for this study. Observations showed that re-energization of line with high side breaker produces highest switching surges which is also called sudden reclosing. There is some effect of tertiary is also observed, de-energization of line after fault give high overvoltage of sound phases. In single phase reclosing due to mutual coupling from other phases C.B reenergizes the faulted phase from stored charges and presence of series compensation up to 40-50% line reactance does not affect surge magnitude and wave shape.

A comparative analysis of control switching transient techniques in transmission lines **[50]** made in an actual 500 kV AC transmission system considering two alternatives in order to limit switching surge over voltages during line energization: the use of metal oxide surge arresters at both line ends and along the line and the use of synchronized closing of circuit breakers. Switching overvoltage limitation at the energization maneuver of a 500 kV transmission trunk was achieved through the use of line surge arresters and controlled circuit breaker closing. These techniques can replace the use of circuit breaker with pre-insertion resistor and its associated problems. The high-energy dissipation capability of modern metal oxide surge arresters copes with lines switching requirements. It was observed that the energy absorption capacity of the arresters has not been exceeded in any simulation, but the maximum operating voltage of the system and the temporary overvoltage needs to be carefully considered for the arrester specification **[51]**.

1.3 Thesis Objective

A switching transient over-voltage is created and travels along the line following switching to energize or de-energize a transmission line. This switching transient over-voltage will reach its highest levels at the transition points connecting an underground cable to an overhead line. The transient over-voltage will exceed the normal operating voltage and will be transmitted to the lower voltage level system. The magnitude of the transient over-voltage has to be limited to avoid exceeding substation equipment surge ratings. Without the limitation, the overvoltage may cause damage to the system protective devices. The objective our thesis is to investigate transient over-voltages associated with closing a breaker to energize or de-energize a high voltage transmission line.

1.4 Simulation Tool

The study was performed in an actual 400 kV power system. The PSCAD (Power System Computer Aided Design) has been used for the simulations. PSCAD is the professional's simulation tool for analyzing power systems transients. It is also known as PSCAD/EMTDC. EMTDC is the simulation engine, which is now the integral part of PSCAD. PSCAD is most suitable for simulating the time domain instantaneous responses, also popularly known as electromagnetic transients of electrical systems.

1.5: Thesis Organization

Chapter 1

This introductory circuit provides the background information of the switching transient and it also includes present analysis on switching, describes the objective, simulation tool and outline of the thesis.

Chapter 2

This second chapter gives an overview of significance of switching transient, various types of overvoltage, and effects of overvoltage and energizes or de-energize of high voltage transmission line.

Chapter 3

In this chapter focuses on simulation performed on single line model of the real 400KV transmission line for switching and fault analysis. Also, 400KV and 230KV double circuit transmission line, how the adverse effects of transient can be reduced to protect the line equipment.

Chapter 4

In the last chapter summarizes the switching transients analysis that has been studied in the earlier chapters and also describes further research topics and developments are stated.

Chapter 2

Significance of Studying Switching Transient

2.1 Introduction

In circuit analysis we study the circuit completely also we study its behavior during different states such as Steady and Transient. In steady state a system behaves normally everything is fine with the circuit but if any fault occurs or any input is given to the circuit suddenly or if any input is removed from the circuit then for a very small time the circuit goes in transient state. Basically if any change occurs in the circuit then it goes in transient mode. Generally transients last for very short duration but it is very important to study that small duration of time. In that small instant of time current or voltage may rise or drop to a certain value if that happens then our circuit must sustain those conditions also. So, we perform transient analysis on the system.

2.2 Transmission Line Overvoltage

Transmission systems are subject to overvoltage surges produced by transmission line switching operations. This overvoltage appears as traveling waves on the transmission network, occurring in a millisecond time frame, usually as a result of circuit breaker operation. The magnitude and shape of the switching overvoltage vary with the system parameters and network configuration. Even with the same system parameters and network configuration, the switching overvoltage is highly dependent on the characteristics of the circuit breaker operation and the point-on-wave where the switching operation takes place. The worst-case initiating events occur when a circuit breaker pole closes into a line with pre-existing trapped charge at a time when the source voltage is of the opposite polarity of a trapped charge. This condition causes a collapse of approximately a 2.0pu. overvoltage across the circuit breaker pole. The highest overvoltage result when a traveling voltage wave reaches an open breaker, causing it to tend to double in magnitude, stressing the circuit breaker insulation (across the bushing), the insulation across the open breaker contacts, and the transmission line insulation. The transient voltages generated from switching transmission lines can have an impact on the equipment design and protection. Over voltages are caused on power systems due to external and internal influencing factors. The voltage stress caused by over voltage can damage the lines and equipment‟s connected to the system **[52-53]**. Over voltages arising on a system can be generally classified into two main categories as below:

i) External Over voltages &

ii) Internal Over voltages

2.2.1 External Over voltages

This type of over voltages originates from atmospheric disturbances, mainly due to lightning. This takes the form of a surge and has no direct relationship with the operating voltage of the line. It may be due to any of the following causes:

a) Direct lightning stroke

b) Electromagnetically induced over voltages due to lightning discharge taking place near the line, called 'side stroke'.

c) Voltages induced due to atmospheric changes along the length of the line.

d) Electrostatically induced voltages due to presence of charged clouds nearby.

e) Electrostatically induced over voltages due to the frictional effects of small particles like dust or dry snow in the atmosphere or due to change in the altitude of the line.

2.2.2 Internal Over voltages

These over voltages are caused by changes in the operating conditions of the power system. These can be divided into two groups as below:

1. **Switching over voltages or Transient over operation voltages of high frequency**

There is a great variety of events that would initiate a switching surge in a power network. The switching operations of greatest relevance to insulation design can be classified as follows:

i. Energization of transmission lines and cables

The following specific switching operations are some of the most common in this category:

a. Energization of a line that is open circuited at the far end

b. Energization of a line that is terminated by an unloaded transformer

c. Energization of a line through the low-voltage side of a transformer

ii. Re-energization of a line

This means the energization of transmission line carrying charges trapped by previous line interruptions when high-speed reclosers are used.

iii. Load rejection

This is affected by a circuit breaker opening at the far end of the line. This may also be followed by opening the line at the sending end in what is called a line dropping operation.

iv. Switching on and off of equipment

All switching operations involving an element of the transmission network will produce a switching surge.

- Switching of high-voltage reactors
- Switching of transformers that are loaded by a reactor on their tertiary winding
- Switching of a transformer at no load.

v. Fault initiation and clearing

Some important switching operations which can lead to switching overvoltage:

- Line energization
- Reclosing (energization of a line with trapped charges)
- Low voltage side Energization of a line
- Energization a line terminated by an unloaded transformer
- Load rejection at the receiving end of a line
- Load rejection at the receiving end of a line followed by line dropping at the sending end
- Interrupting lines at no-load (line dropping)
- Switching of transformers at no-load
- Switching reactor loaded transformers
- Switching high voltage reactors
- Switching at intermediate substations

Initiation of a single-phase to earth fault without a switching operation [53].

2. **Temporary over voltages**

Temporary overvoltage (sustained overvoltage) differ from transient switching overvoltage in that they last for longer durations, typically from a few cycles to a few seconds. They take the form of undamped or slightly damped oscillations at a frequency equal or close to the power frequency. The classification of temporary overvoltage as distinct from transient switching overvoltage is due mainly to the fact that the responses of power network insulation and surge arresters to their wave shapes are different.

Events leading to the generation of temporary overvoltage:

i. **Load Rejection**

When a transmission line or a large inductive load that is fed from a power station is suddenly switched off, the generator will speed up and the bus bar voltage will rise.

ii. **Ferranti Effect**

The Ferranti effect on an uncompensated transmission line is

Given by: $\frac{Vr}{Vs} = \frac{1}{\cos(\beta 0 * l)}$

Where Vr and Vs are the receiving end and sending end voltages, respectively, and ℓ is the line length (km). β_0 is the phase shift constant of the line per unit length. It is equal to the imaginary part of $\sqrt{ZY}$, where Z and Y are the impedance and admittance of the line per unit length. For a lossless line $\beta_0 = \omega\sqrt{lC}$ where L and C are the inductance and capacitance of the line per unit length. β_0 has a value of about 6° per 100 km at normal power.

iii. **Ground Fault**

A single line-to-ground fault will cause the voltages to ground of the healthy phases to rise. In the case of a line-to-ground fault, systems with neutrals isolated or grounded through high impedance may develop overvoltage on healthy phases higher than normal line-toline voltages. Solidly grounded systems will only permit phase-to-ground overvoltage well below the line-to-line value. An earth fault factor is defined as the ratio of the higher of the two sound phase voltages to the line-to-neutral voltage at the same point in the system with the fault removed **[53]**.

2.3 Causes of Switching Transient Overvoltage

The operation of circuit breakers produces a transient overvoltage. However, the concept of switching should not be limited only to the intentional actions of opening and closing circuit breakers and switches but may also include the arcing faults and even lightning **[60-62]**. The causes of switching transient overvoltage can be summarized as follows:

i. normal line energizing or de-energizing
ii. high-speed line reclosing
iii. switching cable circuits, capacitor banks, and shunt reactors
iv. load rejection
v. out-of-phase switching
vi. circuit breaker re-striking
vii. current chopping
viii. reinsertion of series capacitors

When 50Hz voltages are caused by an abnormal condition then few more examples of this condition are:

i. voltages on the non-faulted phases during a phase-to-ground fault
ii. load rejection
iii. open end of a long energized line (Ferranti effect)
iv. Ferro resonance.

2.4 Effects of Switching Transient Overvoltage on Power System

Over voltage tends to stress the insulation of the electrical equipment"s and likely to cause damage to them when it frequently occurs. Over voltage caused by surges can result in spark over and flash over between phase and ground at the weakest point in the network, breakdown of gaseous/solid/ liquid insulation, failure of transformers and rotating machines.

Electronic Equipment

Electronic devices may operate erratically. Equipment could lock up or produced garbled results. These types of disruptions may be difficult to diagnose because improper specification and installation of transient voltage surge suppression equipment can actually INCREASE the incidents of failure as described above. Electronic devices may operate at decreased efficiencies. Damage is not readily seen and can result in early failure of affected devices. Unusually high frequency of failures in electronic power supplies is the most common symptom. Integrated circuits (sometimes called "electronic chips") may fail immediately or fail prematurely. Most of the time, the failure is attributed to "age of the equipment". Modern electronic devices provided clean, filtered power should outlast the mechanical devices they control.

Motors

Motors will run at higher temperatures when transient voltages are present. Transients can interrupt the normal timing of the motor and result in "micro-jogging". This type of disruption produces motor vibration, noise, and excessive heat. Motor winding insulation is degraded and eventually fails. Motors can become degraded by transient activity to the point that they produce transients continually which accelerates the failure of other equipment that is commonly connected in the facility's electrical distribution system. Transients produce hysteresis losses in motors that increase the amount of current necessary to operate the motor. Transients can cause early failures of electronic motor drives and controls.

Lighting

Transient activity causes early failure of all types of lights. Fluorescent systems suffer early failure of ballasts, reduced operating efficiencies, and early bulb failures. One of the most common indicators of transient activity is the premature appearance of black "rings" at the ends of the tubes. Transients that are of sufficient magnitude will cause a sputtering of the anodes--when these sputters deposit on the insides of the tube, the result is the black "ends" commonly seen. Incandescent lights fail because of premature filament failures. The same hysteresis losses produced in motors are reproduced in transformers. The results of these losses include hotter operating temperatures, and increased current draws.

Electrical Distribution Equipment

The facility's electrical distribution system is also affected by transient activity. Transient degrade the contacting surfaces of switches, disconnects, and circuit breakers. Intense transient activity can produce "nuisance tripping" of breakers by heating the breaker and "fooling" it into reacting to a non-existent current demand. Electrical transformers are forced to operate inefficiently because of the hysteresis losses produced by transients and can run hotter than normal **[54]**.

2.5 Energize or De-energize High Voltage Transmission Line

An electrical system is energized when connected to any power source including any of the following; utility power, local generator power (including renewable energy such as wind and solar) or a UPS system. An electrical system is de-energized when disconnected from any and all power sources, properly locked out, and in many cases safety grounding instruments applied. All electrical systems are assumed to be energized until proven to be in a zero energy state.

The transmission line energization is a typical maneuver, whose transient magnitude is influenced by the system configuration as well as by the equipment characteristics. Consequently, overvoltage control measures have to be adopted providing suitable protection for the network. Transmission line switching transient and its severity depend on the difference between the supply and the line voltages at the instant of energization. If energization occurs at an instant when the difference between supply voltage and the line voltage is high, a large traveling wave would be injected on the transmission line. At the time, this wave reaches the open far end of the line, it gets reflected and a high transient overvoltage is experienced.

2.6 Switching Transient in RLC Circuit

The entire basic network is the series connection of an inductance and a capacitance; this is the fact the simplest representation of a high voltage CB switching capacitor bank or a cable network. A cable or a short transmission line can be described as a lumped pi model with arrangement of resistance, capacitance and inductance parameters of the mutually coupled phases calculated at the steady state frequency. R and L represents the series impedances where shunt loses are ignored and total admittance is divided into sections lumped at the sending and receiving ends. Such a model can be used to perform accurate steady state system calculations and suitable for studies. Cascading many RLC circuit represents the long transmission line **[62]**

2.6.1 PSCAD Simulation of Simple RLC circuit

Firstly, we observed the switching transient in a simple RLC circuit in the PSCAD 4.5 version. A medium transmission line can be described as a lumped pi model with the arrangement of inductance, resistance and Capacitance (RLC) parameters of the mutually coupled phases calculated at the steady state frequency. Here, the injected to the system is 230KV AC, 50Hz and the load is set to be 10MW and the components values are R_1=1Ω, R_2=19.02284304Ω, C_1=C_2= 38.973μF and L_1= 0.02447 H.

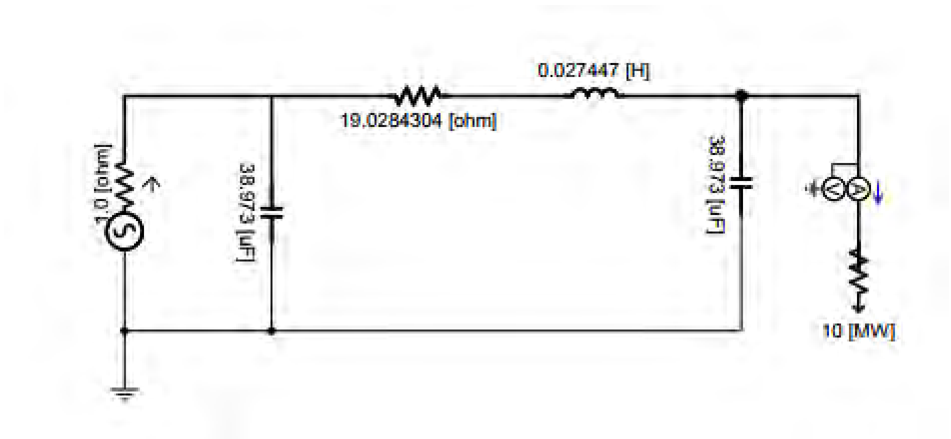


Figure 2.1: A simple RLC circuit without breakers

After the simulation of simple RLC circuit (Fig.2.1) in PSCAD, we got a 3-phase breaker current and 3-phase voltage curve which is given below:

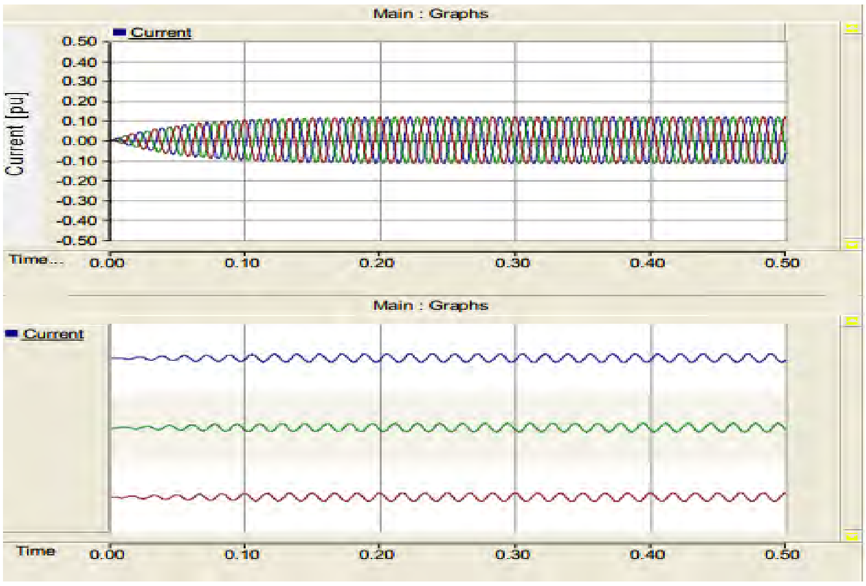


Figure 2.2: Without breaker Observation of 3-phase current

The simulated value of the 3-phase current is 0.10pu in continuous sine wave shape and the three single phases current showed with different color (Fig.2.2).

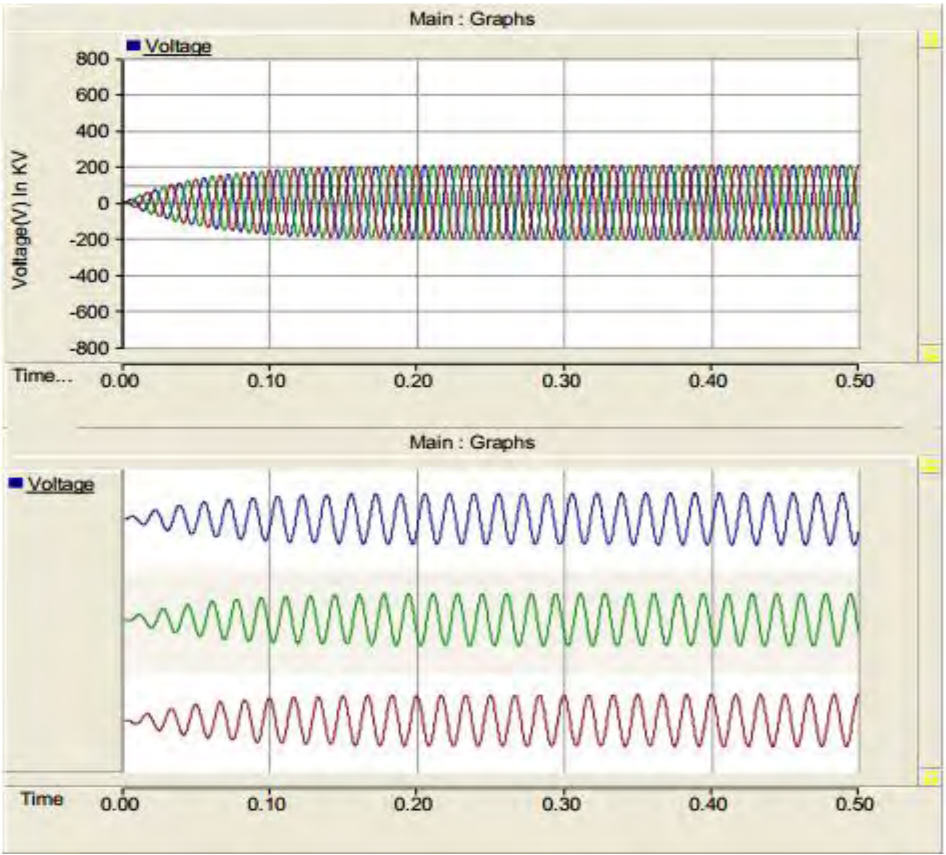


Figure 2.3: Without breaker Observation of 3-phase Voltage

The simulated value of the 3-phase voltage is 210KV where given value was in 230K and the three single phases voltages showed with different color (Fig.2.3).

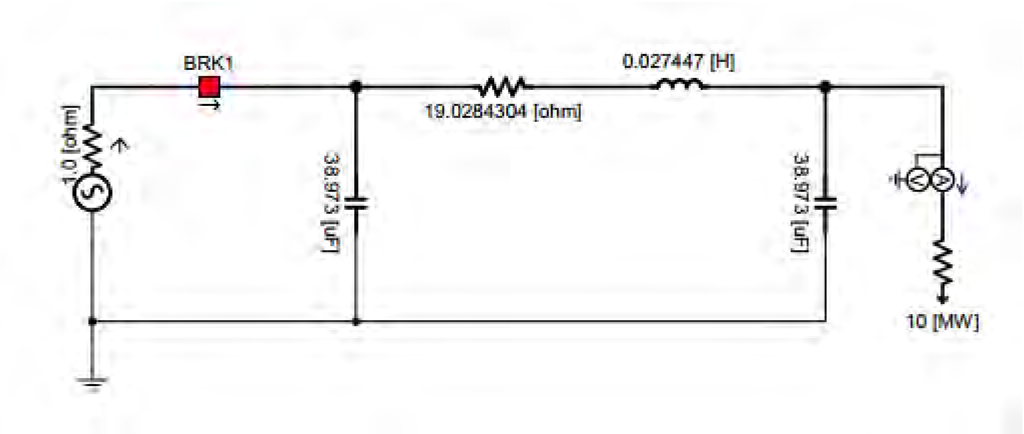


Figure 2.4: Simple RLC circuit with breakers

In the above RLC circuit (Fig.2.4) with 3-phase breaker which will close at t =0.10s and open at t = 0.20s. This setting is done to breaker to imitate the switching process in power system.

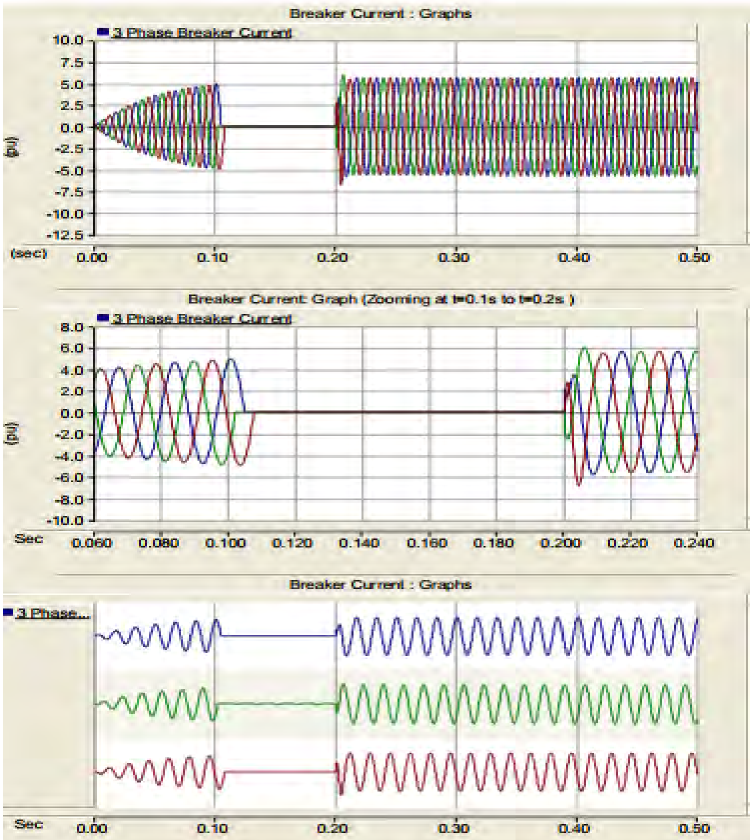


Figure 2.5: Observation of 3-phase breaker current

After the simulation of RLC circuit with breakers (Fig.2.4) got the current graph (Fig.2.5) corresponding to the settings and the current was in up to 5pu when t = 0.10s and after the breaker tripping current becomes 6.0pu at t = 0.20s.

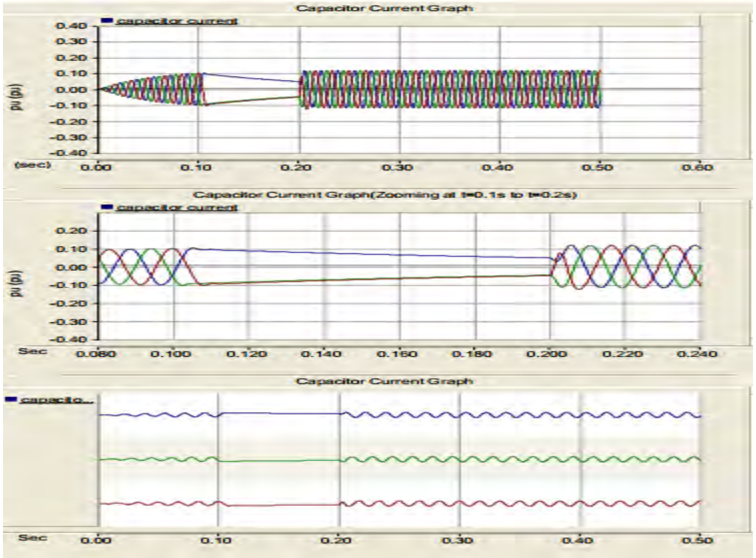


Figure 2.6: Observation of Capacitor current

Initially both capacitors C_1 and C_2 were being charged and when the breaker is set to open the capacitor started discharging. As seen from the result the current decaying until the circuit is close at t = 0.2s. At t = 0.2s when the circuit breaker is set to close a slight increment of current is observed (Fig.2.6).

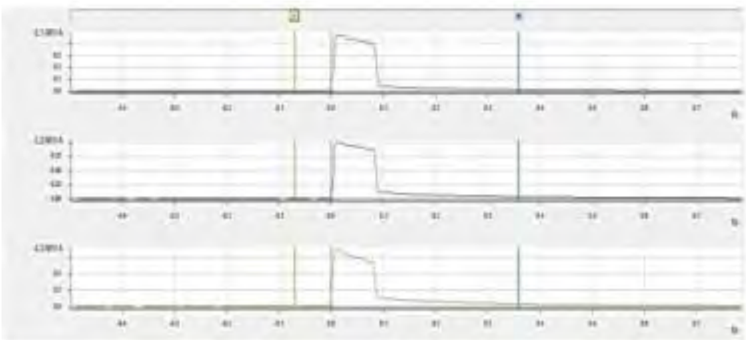


Figure 2.7: Switching transient from recorder

The graph (Fig.2.7) shows a recording of inrush current and also shows the increment of current during switching and the system trips due to current inrush condition. To measure this we used a disturbance recorder which use in TNB high voltage substations. The device also helps the control engineers in NLDC to analyze a faulted line fast and energizes it in case of emergency and another most useful use in analysis **[62]**.

Chapter 3

Transient Analysis of 400KV and 400KV-230KV Double Circuit Overhead Transmission Line

3.1 Introduction

The switching transient in a transmission system cannot be prevented as well as its total suppression is extremely difficult. However, its magnitudes have to be limited to become compatible with insulation level of the system equipment. The transmission line energization is a typical maneuver, whose transient magnitude is influenced by the system configuration as well as by the equipment characteristics. Consequently, overvoltage control measures have to be adopted providing suitable protection for the network.

3.2 Design of a 400KV and 400KV-230KV transmission line

In the entire analysis need to work on the 400KV and 400KV-230KV transmission line so beginning of the analysis need to design the transmission line. In transmission line designing have to have few components like conductor types and tower geometry, line length, CB configuration, transformer configuration, generator configuration and 3-phase fault configuration. The data require configuring the transmission line components is given below.

3.2.1 Tower Modeling and Conductors Types

The tower is represented by impedance model (R/L) in EMTP model. This value can be obtained by experimental evaluations.

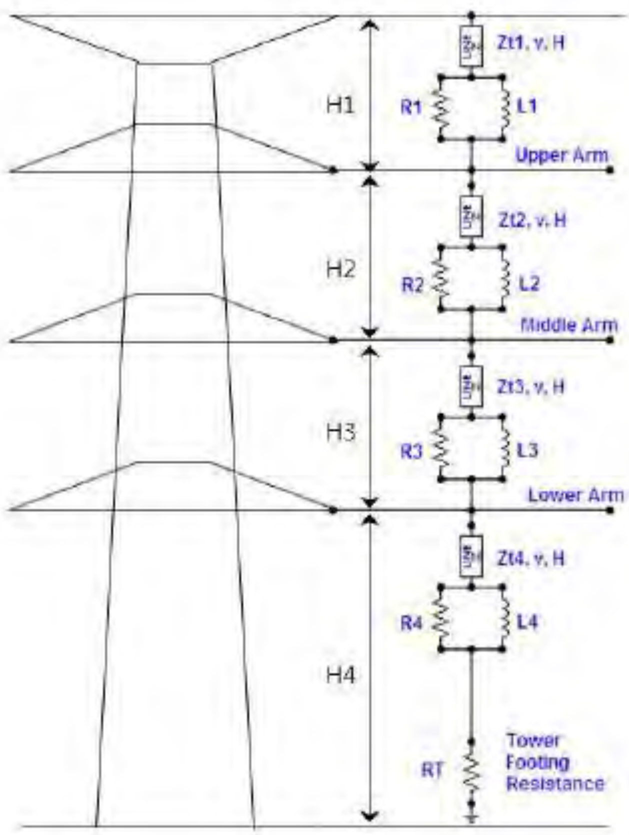


Figure 3.1: Tower structure for EMTP **[56]**

Model Name: Tower (Four-secondtion tower model), R/L

$$\gamma = \sqrt{0.8} = 0.8944$$

$$\tau = L/R = 2 * H_{total}/V$$

$$r_1 = r_2 = r_3 = -2 * Zt_1 * \ln\gamma / (H_1+H_2+H_3)$$

$$r_4 = -2*Zt_4* \ln\gamma/(H_4)$$

$$R_1, R_2, R_3, R_4, L_1, L_2, L_3, L_4$$

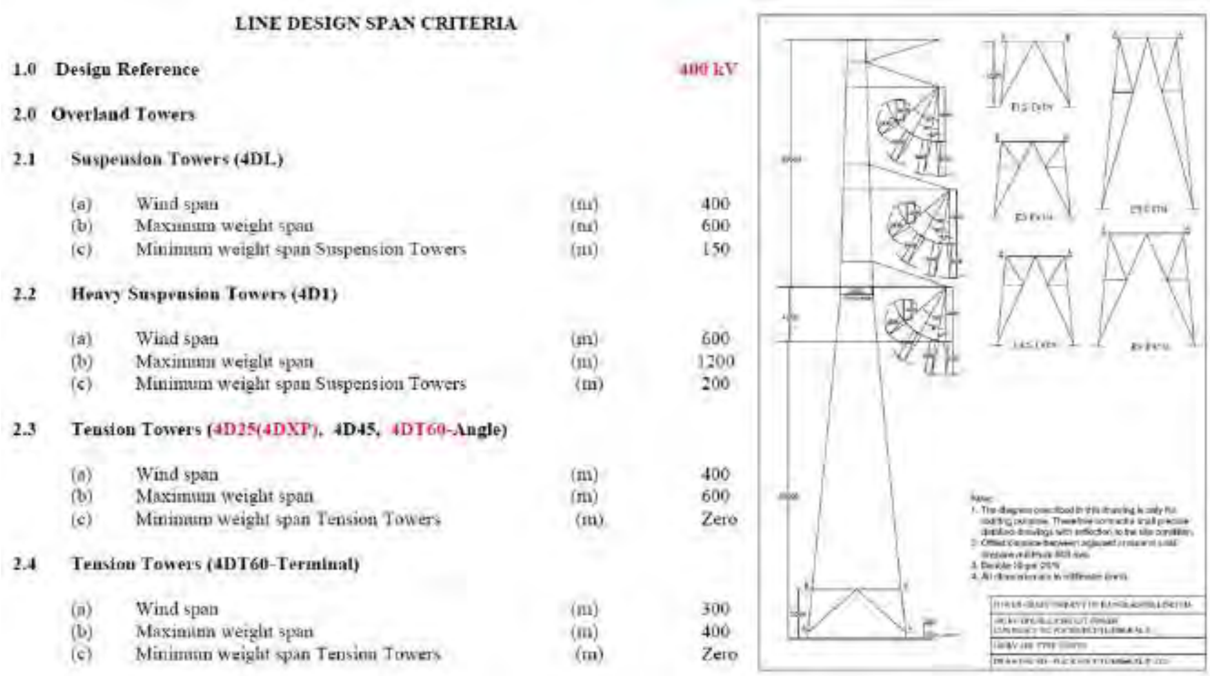
$R_1 = r_1 * H_1$	$L_1 = R_1 * \gamma$
$R_2 = r_2 * H_2$	$L_2 = R_2 * \gamma$
$R_3 = r_3 * H_3$	$L_3 = R_3 * \gamma$
$R_4 = r_4 * H_4$	$L_4 = R_4 * \gamma$

Tower structure (Fig.3.1) shows the resistance and inductance combination of a tower.

Table 3.1: Tower Model (four secondtion tower model)

Tower [m]		Resistor [Ω]		Inductor [mH]	
H1	3.70	R1	8.860	L1	0.002971
H2	8.65	R2	20.7 14	L2	0.006946
H3	8.15	R3	19.5 17	L3	0.006545
H4	29.80	R4	33.472	L4	0.011224

Standard value of the tower height (H), resistor and inductance value in (Table 3.1).


LINE DESIGN SPAN CRITERIA

1.0 Design Reference 400 kV

2.0 Overland Towers

2.1 Suspension Towers (4DL)

(a)	Wind span	(m)	400
(b)	Maximum weight span	(m)	600
(c)	Minimum weight span Suspension Towers	(m)	150

2.2 Heavy Suspension Towers (4D1)

(a)	Wind span	(m)	600
(b)	Maximum weight span	(m)	1200
(c)	Minimum weight span Suspension Towers	(m)	200

2.3 Tension Towers (4D25(4DXP), 4D45, 4DT60-Angle)

(a)	Wind span	(m)	400
(b)	Maximum weight span	(m)	600
(c)	Minimum weight span Tension Towers	(m)	Zero

2.4 Tension Towers (4DT60-Terminal)

(a)	Wind span	(m)	300
(b)	Maximum weight span	(m)	400
(c)	Minimum weight span Tension Towers	(m)	Zero

Figure 3.2: Line design span criteria **[56]**

Standard line design span criteria of the transmission tower (Fig.3.2) which is followed in 400KV and 230KV designing.

The transmission lines and cables are modeled using one of two distributed (travelling wave) models:

i. Bergeron‟s Model

ii. Frequency dependent (phase) model

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

In this paper, we used frequency dependent model for modeling transmission line in our network. The frequency dependent is basically a distributed RLC travelling wave model, which incorporates the frequency dependence of all parameters. This model represents the frequency dependence of internal transformation matrices. 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 users whenever the transient or harmonic behavior of the line or cable is important. We used frequency-dependent (phase) model for designing our overhead plans and the specifications for this model as shown in the below table:

Table 3.2: frequency dependent (phase) model specifications in PSCAD

Parameter	Value
Travel Time Interpolation	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 [%]
Maximum Order per Delay Group for Proper Function	20
Maximum Fitting Error for Proper Function	0.2 [%]
DC Correction	Disabled
Passivity Checking	Disabled

The parameter shown in (Table 3.2) and the respective value is given in the PSCAD tower modeling designing.

The tower model we used for designing 230KV and 400KV overhead lines tower is shown below:

Table 3.3: 400KV conductor type data from PGCB

ID	Conductor Name	KV LEVEL	R_0 [p.u.]	X_0 [p.u.]	B_0 [p.u.]	Loading Limit [A]	Emergency Loading Limit [A]
Bibi_kalia1	QUAD FINCH 1113 MCM	400	0	0.01751	0.08675	1738	1738
Bibi_kalia2	QUAD FINCH 1113 MCM	400	0	0.01751	0.08675	1738	1738
Bogura_Kalia 1	QUAD FINCH ACCC	400	0	0.01254	0.06212	8452	8452
Bogura_Kalia 2	QUAD FINCH ACCC	400	0	0.01254	0.06212	8452	8452
Bpuk_Bog1	QUAD FINCH ACCC	400	0	0.01131	0.05605	8452	8452
Bpuk_Bog2	QUAD FINCH ACCC	400	0	0.01131	0.05605	8452	8452

According to the data of PGCB (Table 3.3) 400KV conductor type will be like that and that is the estimated value of the any 400KV line conductor. This data (Table 3.3) is used in the entire analysis.

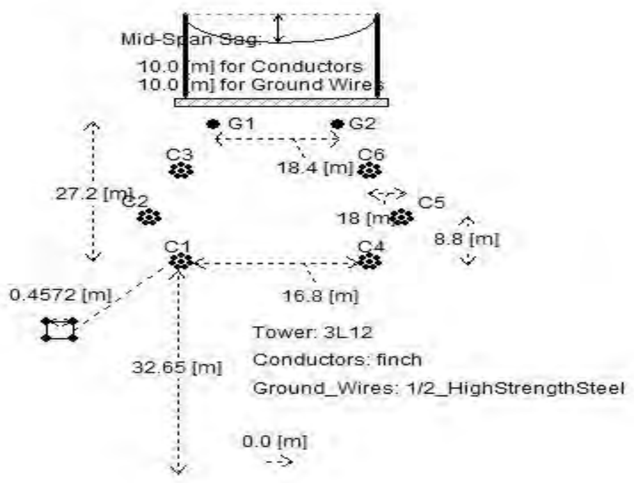


Figure 3.3: Tower model in PSCAD

In PSCAD the designed tower model is like that (Fig.3.3). As the conductor is quad finch so need to work with that configure. Here, (Fig.3.3) mid span sag for the ground wire G_1 to G_2 is 10m and for conductors is also 10m.

Table 3.4: 230KV conductor type data from PGCB

ID	Conductor Name	KV LEVEL
Ashugonj_CumillaSouth	QUAD FINCH 1113 MCM	230
Srepur_Ashugonj	QUAD FINCH 1113 MCM	230
Bogura_Shirajgonj	QUAD FINCH ACCC	230
Shirajgonj_Srepur	QUAD FINCH ACCC	230
Bpuk_Bog1	QUAD FINCH ACCC	230
Bpuk_Bog2	QUAD FINCH ACCC	230
CumillaSouth_Bibi	QUAD FINCH ACCC	230

This (Table 3.4) is the collected data from the PGCB which is used for the 230KV transmission line based on the bus bar or area location. Same conductor type is used like 400KV conductor.

There also need some relevant data for overhead line tower design in PSCAD. There are few more parameters which actually need to define in the designing software which is given below.

Table 3.5: Settings for finch type conductors in PSCAD

Relative x-position of tower centre	0.0 [m]
Height of lowest conductors	32.65 [m]
Horizontal spacing between lowest conductors	16.8 [m]
Horizontal offset of centre conductors	18 [m]
Vertical spacing between phase conductors	8.8 [m]
Height of ground wires over lowest conductors	27.2 [m]
Spacing between ground wires	18.4 [m]
Shunt conductance	1.0E-11 [S/m]
Outer radius	0.0164211 [m]
Inner radius	0.0 [m]
Total number of strands	54
Total number of outer strands	24
Strand radius	0.00365 [m]
DC resistance (entire conductor)	0.050567 [ohm/km]
Sag (all conductors)	10.0 [m]

In the above table (Table 3.5) is given all the necessary parameters and the respective values set in PSCAD while designing the finch type conductor for the purpose of our simulation in duplicating the real life scenario.

Table 3.6: 400KV transmission line data from PGCB

ID	**KV LEVEL**	**Length [km]**	**R_0 [p.u.]**	**X_0 [p.u.]**	**B_0 [p.u.]**	**Loading Limit [A]**	**Emergency Loading Limit [A]**
Bibi_kalia1	400	**168.64**	0.01751	0.08675	0.6286	1738	1738
Bibi_kalia2	400	**168.64**	0.01751	0.08675	0.6286	1738	1738
Bogura_Kalia1	400	**133**	0.01254	0.06212	0.6105	8452	8452
Bogura_Kalia2	400	**133**	0.01254	0.06212	0.6105	8452	8452
Bpuk_Bog1	400	**120**	0.01131	0.05605	0.5508	8452	8452
Bpuk_Bog2	400	**120**	0.01131	0.05605	0.5508	8452	8452

Table 3.7: 400KV Line length data from PGCB

ID	**KV LEVEL**	**Length, km**
Bibi_kalia1	400	**168.64**
Bibi_kalia2	400	**168.64**
Bogura_Kalia1	400	**133**
Bogura_Kalia2	400	**133**
Bpuk_Bog1	400	**120**
Bpuk_Bog2	400	**120**

In the above tables (Table 3.6 and Table 3.7) are given all the necessary parameters and the respective values set in PSCAD while designing the 400KV transmission line for the purpose of our simulation in duplicating the real life scenario.

Table 3.8: 230KV Line length data from PGCB

ID	KV LEVEL	Length, km
Ashugonj_CumillaSouth	230	**79**
Sripur_Ashugonj	230	**60**
Bogura_Shirajgonj	230	**79.50**
Shirajgonj_Sripur	230	**90**
Bpuk_Bog1	230	**120**
Bpuk_Bog2	230	**120**
CumillaSouth_Bibi	230	**154**

In the above table (Table 3.8) is given all the sensible parameters and the respective values set in PSCAD while designing the 230KV transmission line for the purpose of our simulation in duplicating the real life scenario.

3.2.2 Circuit Beaker Configuration

The circuit breakers are represented by the switch in EMTP model to calculate the overvoltage in substation and transmission line. In this book, we used PSCAD built in CB and two color indication. Red color denotes the CB which is used in switching purpose and green one denotes the CB used for the fault clearing purpose and after the fault clearing it will be back its previous state.

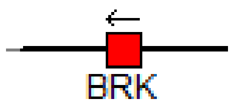


Figure 3.4: Circuit Breaker symbol in PSCAD

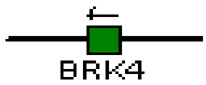


Figure 3.5: Circuit Breaker symbol in PSCAD

Model name: 3Phase Circuit Breaker

T_{cl} = 1.1 second

T_{op} = 1 second

This configuration is for the green breaker which is responsible for the fault clearing.

T_{cl} = 0.2 second but it is initially its open.

This configuration is for the breaker which is responsible for the switching of the transformer.

The configuration of the breaker is same for the all bus bar, transformer and generator in Boropukuria, Bogura, Kaliakair and Bibiyana for both 400KV and 230KV transmission line.

3.2.3 Transformer Configuration

In our analysis we used 3-phase delta (Δ)-wye(Y), 3/5 limb transformer and is based on the UMEC modeling approach.

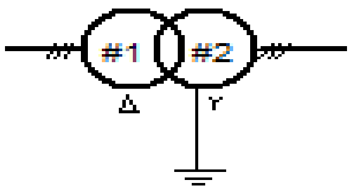


Figure 3.6: 3-phase, Δ-Y transformer symbol in PSCAD

Options are provided so that the user may model the core saturation characteristic directly as an I-V curve. If desired, the magnetizing branch can be eliminated altogether, leaving the transformer in 'ideal' mode, where all that remains is a series leakage reactance. Some elements of core geometry (i.e. core type, yoke and winding limb dimensions, etc.) are required for data input as well. Inter-phase coupling is represented in this model.

We gave different types of input in the transformer based on the location of the bus bar for both 400KV and multi circuit which is combination of 400KV and 230KV

In Boropukuria site, we used two transformers; one is for to rise up the voltage from 13.8KV bus bar to 230KV bus bar and then another transformer from Boropukuria230KV to Bogura 400KV bus bar. The configuration of the transformer is same in the Bibiyana site bus bar. In Bibiyana generation site, we used two transformers to raise the voltage level from 13.8KV to 230KV because there are six generators. Then, another transformer raise up the voltage from 230KV Bibiyana to 400KV Kaliakair and in the middle of the transmission line we connect another transformer in Bogura 400KV to Bogura 230 KV. All the transformer in delta- wye connection expect the Boropukuria 13.8 KV to 230KV transformer we used wye-wye connection. [PGCB]

The transformer data collected from PGCB for the analysis is given below.

Table 3.9: 400KV transformer data from PGCB

DATABASE ID	Rated S [MVA]	Primary [kV]	Secondary [kV]	Primary Winding	Secondary Winding	Phase Shift
BIBIYANA 400/230	520	400	230	YG	YG	0
BOROPUKURIA SS 400/230 2X750	750	400	230	YG	YG	0
BARAPUKURIA 275MW U3 ST 1X375	375	13.8	230	D	YG	-30
BIBIYANA 365 CCPP GT 1X380	380	13.8	230	D	YG	30
BIBIYANA CCPP 365 ST 1X200	200	13.8	230	D	YG	30

Table 3.10: 400KV transformer data with impedance and reactance from PGCB

DATABASE ID	Z0 [p.u.]	X/R Zero	Type	Loading Limit [MVA]	Emergency Loading Limit [MVA]
BIBIYANA 400/230	0.058	42	Shell type	520	520
BOROPUKURIA SS 400/230 2X750	0.058	42	Shell type	750	750
BARAPUKURIA 275MW U3 ST 1X375	0.058	42	Shell type	375	375
BIBIYANA 365 CCPP GT 1X380	0.058	42	Shell type	380	380
BIBIYANA CCPP 365 ST 1X200	0.058	42	Shell type	200	200

In the above table (Table 3.9 and Table 3.10) is given all the sensible parameters and the respective values set in PSCAD while designing all the transformers for the purpose of our simulation in duplicating the real life scenario. Along with the information from the tables, some additional information required in PSCAD on transformers is shown in (Fig. 3.7).

Name	Caption	Type	Unit	Minimum	Maximum	Data	Value
Name	Transformer Name	String				T1	T1
Tmva	3 Phase Transformer MVA	Real	MVA	1e-006		100.0 [MVA]	100.0
f	Base operation frequency	Real	Hz	0.0001		50.0 [Hz]	50.0
YD1	Winding #1 Type	Choice				1	1
YD2	Winding #2 Type	Choice				0	0
Lead	Delta Lags or Leads Y	Choice				1	1
Xl	Positive sequence leakag...	Real	pu	1e-307	1	0.1 [pu]	0.1
Ideal	Ideal Transformer Model	Choice				0	0
NLL	No load losses	Real	pu	0	1	0.0 [pu]	0.0
CuL	Copper losses	Real	pu	0	1	0.0 [pu]	0.0
Tap	Tap changer on winding	Choice				0	0
View	Graphics Display	Choice				1	1
Dtls	Display Details?	Choice				0	0
V1	Winding 1 Line to Line v...	Real	kV	0.0001		13.80 [kV]	13.8
V2	Winding 2 Line to Line v...	Real	kV	0.0001		230.0 [kV]	230.0
Enab	Saturation Enabled	Choice				0	0
Sat	Saturation Placed on Win...	Choice				1	1
Xair	Air core reactance	Real	pu	0.001	10	0.2 [pu]	0.2
Tdc	In rush decay time const...	Real	s	0.0		0.0 [s]	0.0
Xknee	Knee voltage	Real	pu	1e-307		1.17 [pu]	1.17

Figure 3.7: Transformer settings in PSCAD

3.2.4 Generator Configuration

In our analysis, we used two steam turbine (ST) generator in Boropukuria site and six generators in the Bibiyana site. Among six generators three generators are steam turbine and three are gas turbine (GT) generators. The generation voltage of all the generators is 13.8KV except one GT in Bibiyana which generates 15KV.

In PSCAD the component models a 3-phase AC voltage source, where source impedance may be specified as ideal (infinite bus). This source may be controlled through either fixed, internal parameters or variable external signals. The external inputs are described as follows:

- V**:** Line-to-Ground, Peak Voltage Magnitude [kV]
- f**:** Frequency [Hz]

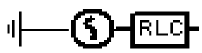


Figure 3.8: 3-phase Generator symbol in PSCAD

Name	Caption	Type	Unit	Minimum	Maximum	Data	Value
Name	Source Name	String				Source 1	Source 1
Type	Source Impedance Type	Choice				3	3
Grnd	Is the star point grounde...	Choice				1	1
View	Graphics Display	Choice				1	1
Spec	Specified Parameters	Choice				0	0
VCtrl	External Control of Volta...	Choice				0	0
FCtrl	External Control of Frequ...	Choice				0	0
Vm	Magnitude (AC:L-L,RMS)	Real	kV	0		13.80 [kV]	13.8
Tc	Voltage ramp up time	Real	s	0		0.05 [s]	0.05
f	Frequency	Real	Hz	0		50.0 [Hz]	50.0
Ph	Phase Shift	Real	deg	-360	360	0.0 [deg]	0.0
Vbase	Base Voltage (L-L,RMS)	Real	kV	0		230.0 [kV]	230.0
Sbase	Base MVA	Real	MVA	0		100.0 [MVA]	100.0
Vpu	Terminal voltage	Real	pu			1.0 [pu]	1.0
PhT	Phase angle	Real	deg	-360	360	0.0 [deg]	0.0
Pinit	Real power	Real	pu			0.0 [pu]	0.0
Qinit	Reactive power	Real	pu			0.0 [pu]	0.0
R	Resistance	Real	ohm	0		1.0 [ohm]	1.0
Rs	Resistance (series)	Real	ohm	0		1.0 [ohm]	1.0
Rp	Resistance (parallel)	Real	ohm	0.001		1.0 [ohm]	1.0

Figure 3.9: Generator settings in PSCAD

The generator configuration data taken from PGCB is given below.

Table 3.11: Generator Capacity Data from PGCB

DATABASE ID	KV Nominal	Rated S [MVA]	P Gen [MW]	Power Factor [p.u.]	Pole No.	Winding Connection
BARAPUKURIA 275MW ST	13.8	344	220	0.8	2	YG
BARAPUKURIA 275MW ST	13.8	344	220	0.8	2	YG
BIBIYANA SUMMIT CCPP341 GT	15	331	70	0.8	2	YG
BIBIYANA SUMMIT CCPP341 ST	13.8	168.75	20	0.8	2	YG
BIBIYANA SOUTH 383 CCPP GT	13.8	315	70	0.8	2	YG
BIBIYANA SOUTH 383 CCPP ST	13.8	163.75	30	0.8	2	YG
BIBIYANA U3 CCPP 400 GT	13.8	342.5	70	0.8	2	YG
BIBIYANA U3 CCPP 400 ST	13.8	157.5	30	0.8	2	YG

Table 3.12: Generator resistance and reactance Data from PGCB

DATABASE ID	Internal R [p.u.]	Internal X [p.u.]	R0 [p.u.]	X0 [p.u.]	Rground [p.u.]	Xground [p.u.]
BARAPUKURIA 275MW ST	0.02692	1.935	0	0.082	18061.625	18061.625
BARAPUKURIA 275MW ST	0.02692	1.935	0	0.082	18061.625	18061.625
BIBIYANA SUMMIT CCPP341 GT	0.0592	2.07	0	0.097	14709.64	14709.64
BIBIYANA SUMMIT CCPP341 ST	0.0592	2.2	0	0.072	8860.172	8860.172
BIBIYANA SOUTH 383 CCPP GT	0.0592	2.07	0	0.097	16538.988	16538.988
BIBIYANA SOUTH 383 CCPP ST	0.0592	2.2	0	0.072	8597.648	8597.648
BIBIYANA U3 CCPP 400 GT	0.0592	2.07	0	0.097	17982.867	17982.867
BIBIYANA U3 CCPP 400 ST	0.0592	2.2	0	0.072	8269.494	8269.494

In the above table (Table 3.11 and Table 3.12) is given all the necessary parameters and the respective values set in PSCAD while designing the generators for the purpose of our simulation in duplicating the real life scenario. Along with the information from the tables, some additional information required in PSCAD on generators is shown in Fig. 3.9.

3.2.5 Fault analysis

The short circuit fault can be classified into two categories:

i. Symmetrical fault

ii. Unsymmetrical fault

That fault of the power system which gives rise to the symmetrical fault currents that is equal fault current in the lines with 120 degree 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 up to the point of fault. Hence, the short circuit current will be a maximum if the fault occurs at the beginning of a transmission line or at the bus in this section we will perform some analysis considering a transient short circuit fault which was considered to be cleared after 0.1 second on the different conditions. We through a 3-Phase fault in the 400KV transmission line in between of Bogura 400KV bus to Kaliakair 400KV bus. In the double circuit network, 230KV and 400KV, we through another fault in between of Boropukuria 400KV and Bogura 400 and 230KV.

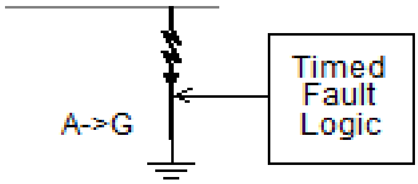


Figure 3.10: 3-Phase Fault symbol in PSCAD

3.3 Factors affecting Line Design

The function of the overhead three-phase electric power transmission line is to transmit bulk amount of power to the designated load centers and large industrial consumers which lies beyond the primary distribution lines. A transmission system comprises all conversion structures, land and equipment at a primary source of supply including lines, switching and conversion stations between a receiving point or generating point and a load center or wholesale point. It includes all lines and equipment whose main function is to integrate, increase or synchronize together power supply sources.

The decision to build a transmission system results from system planning studies to determining and mitigating the best to meet up to all the marks of the system requirements. At this stage, the following factors need to be considered and established **[55]:**

- Voltage level
- Conductor type and size
- Line regulation and voltage control
- Corona and losses
- Proper load flow and system stability
- System protection
- Grounding

- Insulation Coordination
- Mechanical Design
    i. Sag and stress calculations
    ii. Conductor composition
    iii. Conductor Spacing
    iv. Insulator and Conductor hardware spacing
    v. Insulator and conductor hardware selection
- Structural design:
    i. Structure types
    ii. Stress calculations.

The basic configuration selection depends on many performance criteria, economics, company policies, esthetic considerations, interrelated factors, preferred materials, construction techniques, line profile and practice. [1]

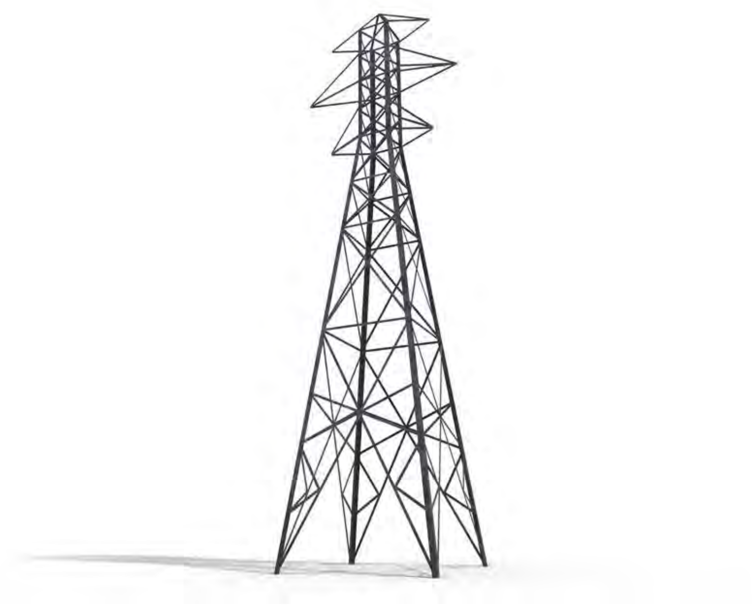


Figure 3.11: typical structure of 400KV and 230 KV Transmission double line circuit with steel tower **[56]**

3.4 Simulation of BPS 400KV Single Transmission Line

From the data of BPS 400KV, we designed a transmission line. After designing the transmission line we have analyzed the switching transient and then we have created a fault at different location and examined it sequentially based on the fault type.

3.4.1 Transformer Switching of 400KV Single Line

In this simulation, there are seven bus bars in a single, stretched out, long transmission line starting from Boropukuria to Bibiyana via Bogura and Kaliakair. The total distance of the transmission lines is 421.64 km and electricity is transmitted at 400KV. Two steam generators are connected in Boropukuria end with a 13.8 KV bus bar. With the help of a transformer, the voltage gets step up to 400 KV and is connected to 400KV bus bar as shown in the Fig (3.12) below. From Boropukuria, electricity is first transmitted to Bogura 400KV bus bar and then onwards to Kaliakair and Bibiyana 400KV bus bars. Three steam generators are connected to Bibiyana 400KV bus bar via two step-up transformers: first stage is 13.8KV to 230KV and second is 230KV to 400KV.

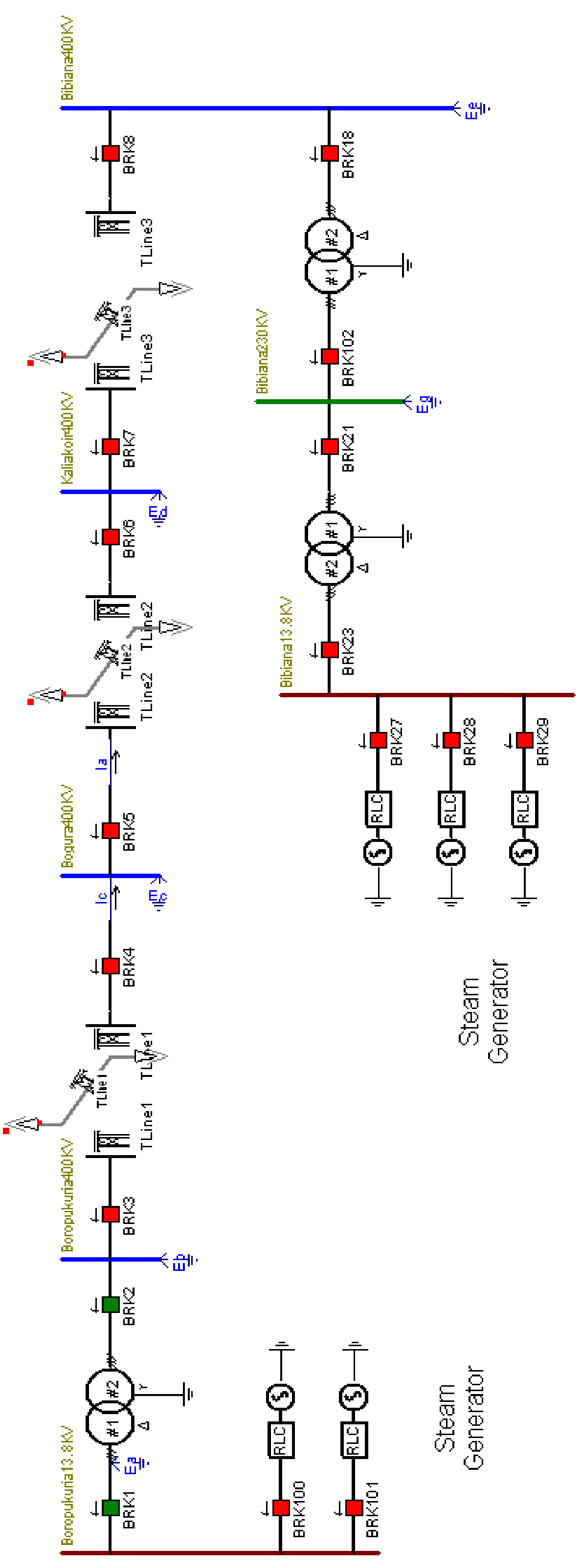


Figure 3.12: 400KV single transmission line from Boropukuria to Bibiyana

For transformer switching, Boropukuria 400KV bus bar is switched on at a time of 0.2 second with the help of breaker 1 and breaker 2.

The energization of transformer at Boropukuria side will impose its effect to the other side of the line. The effects of energization of Boropukuria 400KV bus bar had been measured. These are shown through output waveform in Fig(3.13).

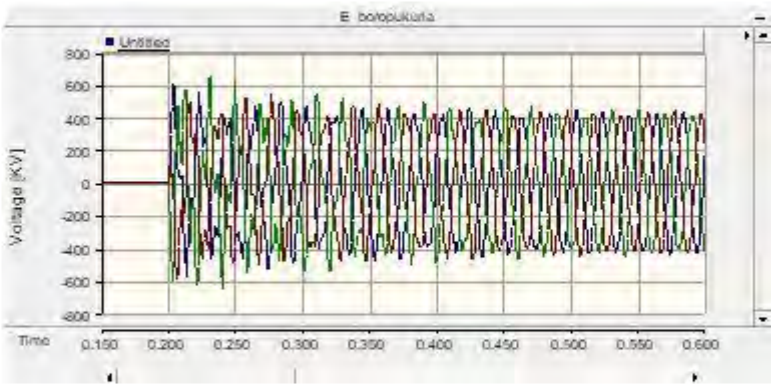


Figure 3.13: Voltage at Boropukuria 400KV bus due to energization of transformer at Boropukuria

The voltage of the Boropukuria bus reaches to a maximum value than the normal value at transient period. The switching operation was executed at time, t=0.2 second.

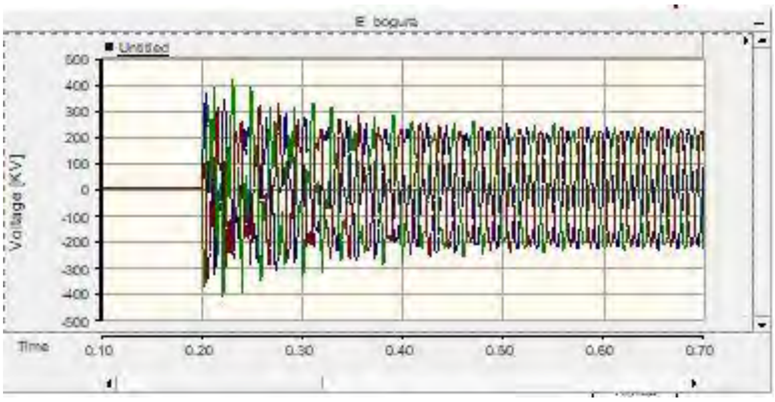


Figure 3.14: Voltage at Bogura bus due to energization of transformer at Boropukuria

Under these conditions, voltage is measured in Fig 3.14 has a maximum of 407KV at 0.23 second. The time needed to mitigate the overvoltage was 0.37second.

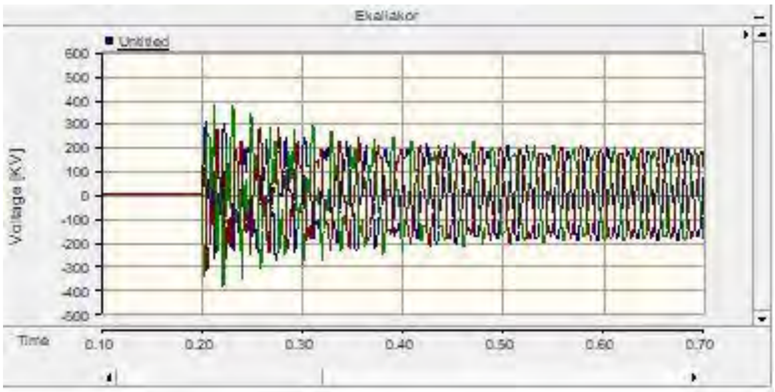


Figure 3.15: Voltage at Kaliakair bus due to energization of transformer at Boropukuria.

Transient condition also develops in Kaliakair bus during transformer switching. The voltage decreases a bit than its nominal value in Fig 3.15. It was recorded 337KV and it is cleared within 0.32 second.

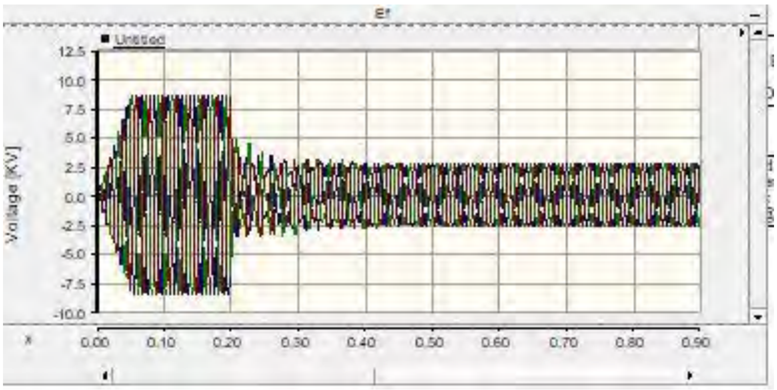


Figure 3.16: Voltage at Bibiyana 400KV bus due to energization of transformer at Boropukuria

Transient condition also appears at the end of the line. The magnitude in per unit was 0.903pu. This is shown in Fig 3.16.

The above analysis is summarized in Table-3.13 showing the nominal value, maximum voltage recorded and duration time.

Table 3.13: Recorded voltage of different buses during transformer switching at Boropukuria side

Serial No.	Type of Switching	Bus Name	Nominal Voltage [KV]	Max Voltage [KV]	Max Recorded Voltage [PU]	Mitigation Time [s]
01.	Energization of Transformer at Boropukuria side	Boropukuria	400	624	1.56	0.26
		Bogura	400	407	1.01	0.37
		Kaliakair	400	337	0.84	0.32
		Bibiyana[Ef]	13.8	8.33	0.903	0.2

3.4.2 Three phase fault on 400KV line of the single circuit

In this simulation shown in Fig (3.17), a three phase to ground fault is injected in the transmission line between Bogura and Kaliakair bus and the currents at the transmission lines are all measured to see the response to a fault.

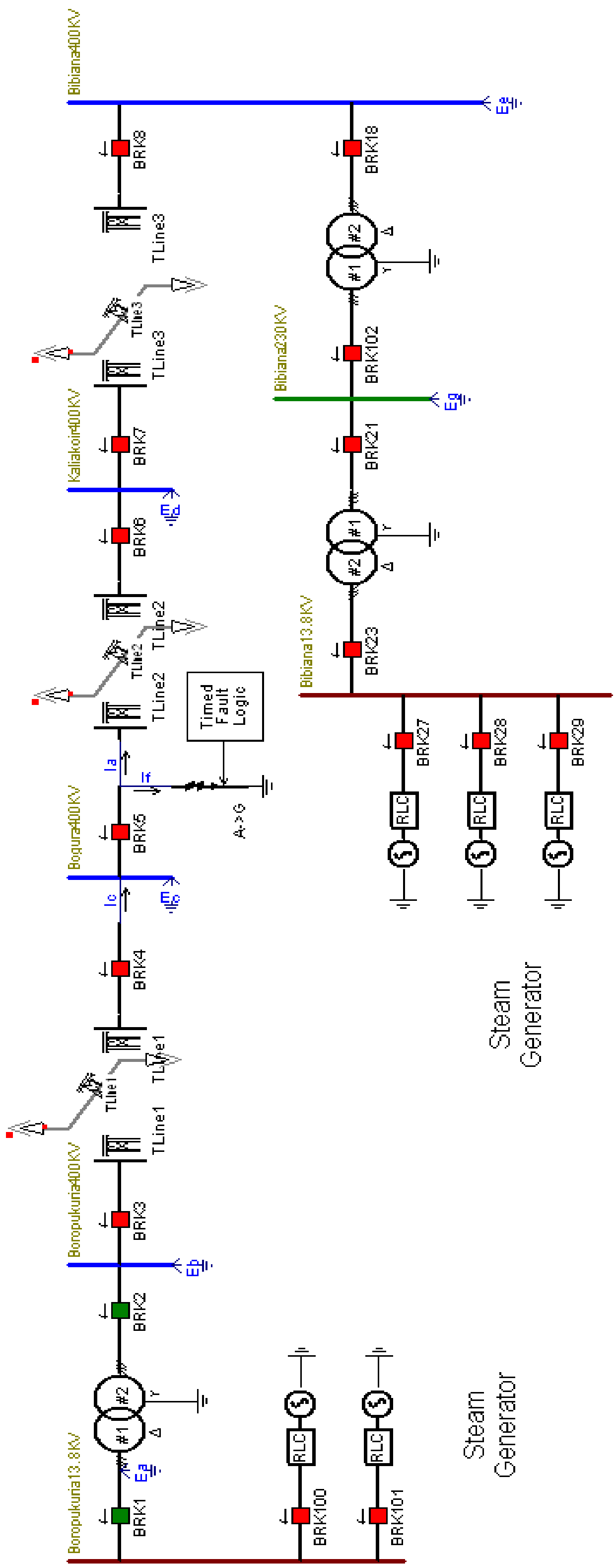


Figure 3.17: 400KV single transmission line from Boropukuria to Bibiyana with fault

The current waveforms are shown below:

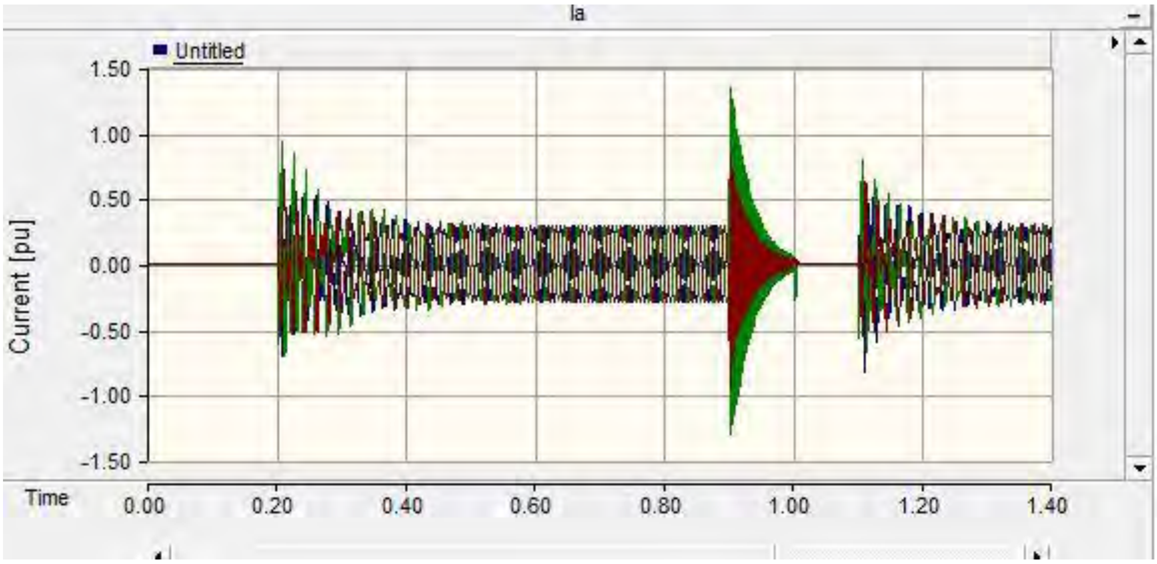


Figure 3.18: Current at Bogura-Kaliakair 400KV line at fault condition.[Bogura – Kaliakair]

When the fault is in Bogura 400KV bus, the current condition of Bogura to Kaliakair; 133Km length line is shown in Fig 3.18. This current reaches 1.39pu which has cleared within 0.1 second.

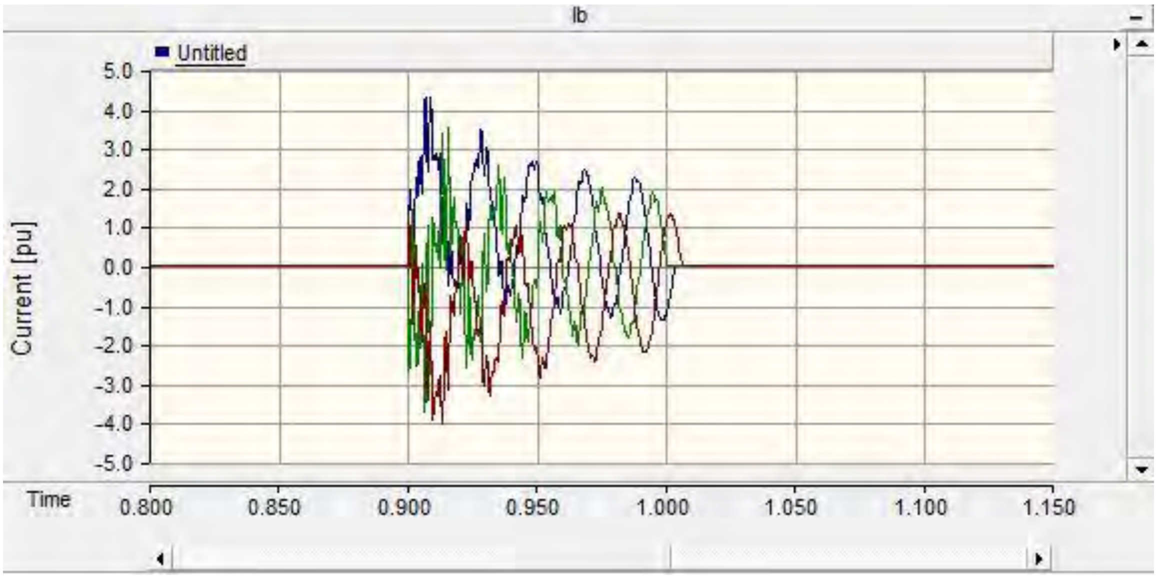


Figure 3.19: Current at Bogura400KV line at fault condition. [Fault current]

The fault bus has its maximum current generate in fault condition which is recorded 4.3pu in Fig 3.19. Though we gave 0.11 second duration of the fault but it took longer than the given time.

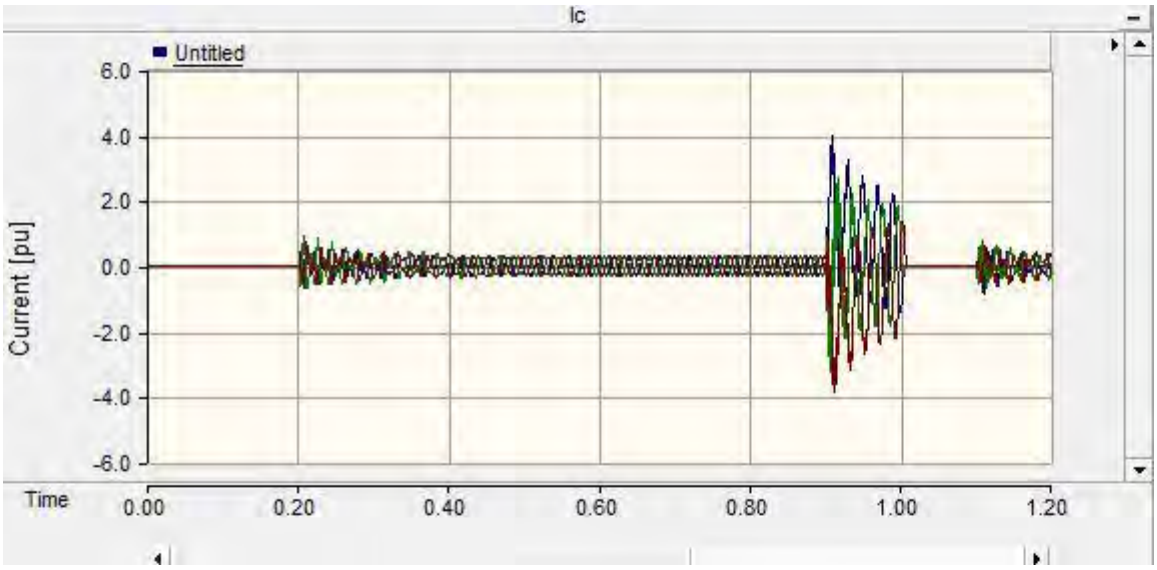


Figure 3.20: Current at Boropukuria - Bogura 400KV bus at fault condition.

Under the three phase fault condition, fault is injected in Bogura three phase line and the current condition before entering the fault line is in Fig 3.20.Current is recorded 3.97pu in Boropukuria and Bogura 400KV line and it is cleared at 1.07 second.

Table 3.14: Recorded current of different buses during single circuit 3-phase fault

Serial No.	Types of fault	Bus current	Max recorded current [pu]	Mitigation Time [s]
01.	Three phase to ground fault	Boropukuria-Bogura	3.97	0.1
		Bogura line[fault line]	4.3	0.11
		Bogura -Kaliakair Bus	3.97	0.11

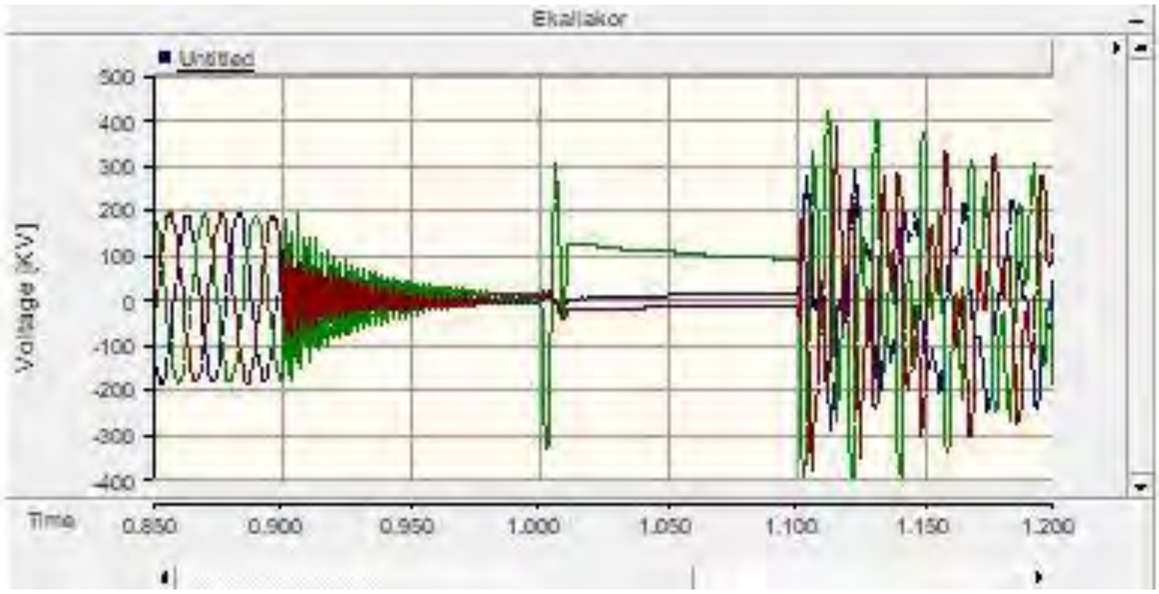


Figure 3.21: Voltage at Kaliakair 400KV bus at fault condition.

Voltage during fault time at Kaliakair 400KV bus was gradually going to zero in Fig 3.21. It started exactly our given time 0.9 second and it took 0.07 seconds to mitigate the fault. When the line became reenergized, it took a small time to reach the pick value.

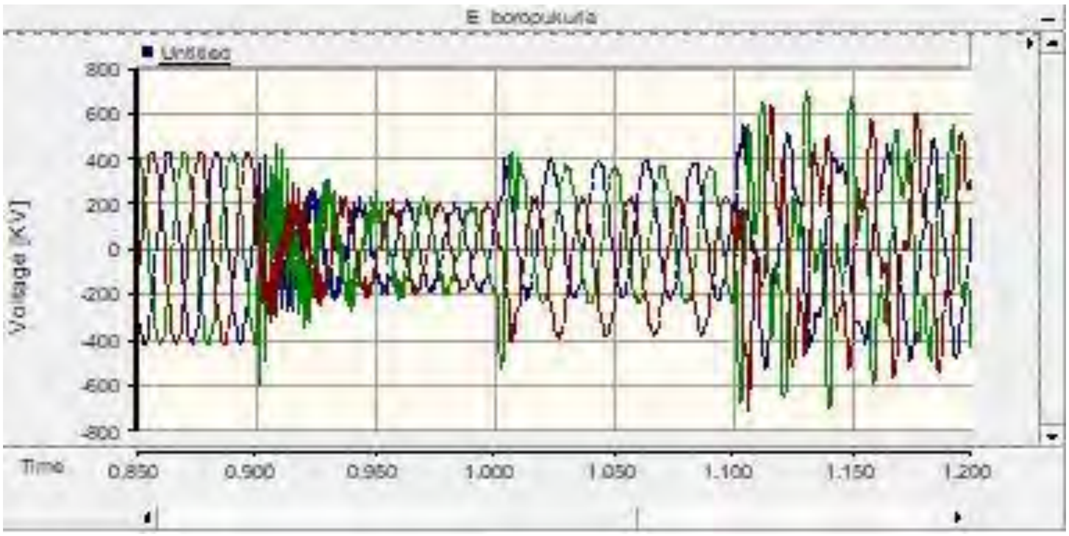


Figure 3.22: Voltage at Boropukuria 400KV bus at fault condition.

As the Boropukuria is generating the power, fault in Bogura minimize the voltage side a little bit in Fig 3.22. It starts dropping the voltage at 0.9 second and clears it at 1.01 second. The line becomes its normal condition at 1.1 second.

Figure 3.23: Voltage at Bogura 400KV bus at fault condition.

During the fault in Bogura, the voltage in Bogura was almost zero at that time in Fig 3.23.

The above analysis is summarized in Table-3.15 showing the nominal value, maximum voltage recorded and duration time

Table 3.15: Recorded voltage of different buses during single circuit 3-phase fault

Serial No.	Types of fault	Bus Voltage	Nominal Voltage [KV]	Max recorded Voltage [KV]	Max recorded voltage [pu]	Mitigation Time [s]
01.	Three phase fault	Bogura Bus	400	450	1.125	0.1
		Kaliakair Bus	400	435	1.08	0.07
		Boropukuria Bus	400	681	1.7	0.11

3.4.3 Single phase fault on 400KV line of the single circuit

This time on the same circuit as in Fig (3.17), the simulation is carried out but only for a single phase to ground fault this time while all the arrangements are kept the same.

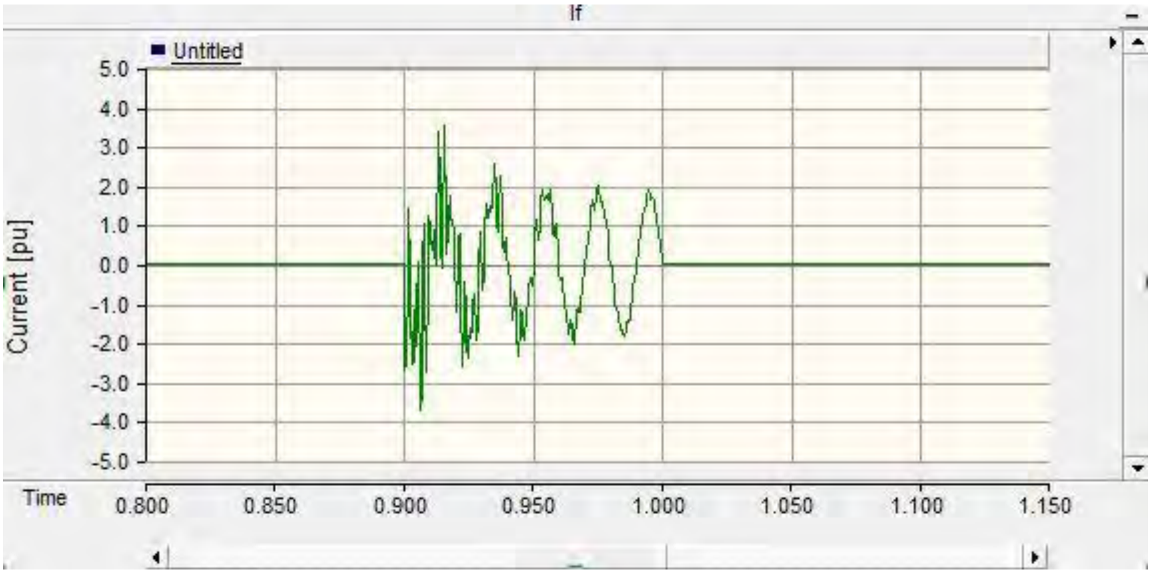


Figure 3.24: Current at Bogura 400KV line at fault condition.

The fault current associated with the single phase fault is given in Fig.3.24 it was seen that the response that the faulty current was many times greater than the nominal current. The fault occurs at time, t= 0.9second and was mitigate at time, t=1.0 second.

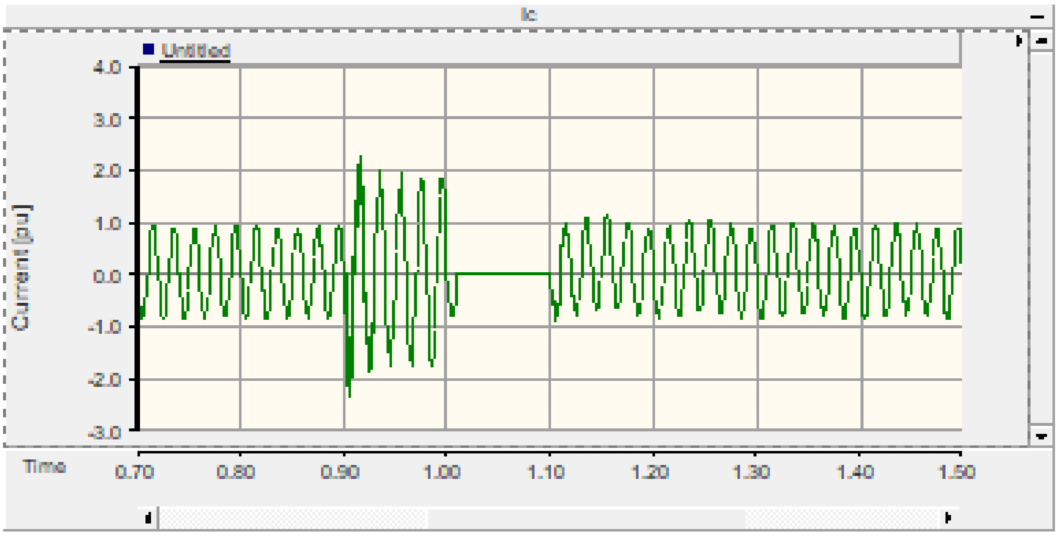


Figure 3.25: Current at Boropukuria-Bogura 400KV bus at fault condition [Before entering Bogura bus]

When a single phase to the ground fault is injected in the Bogura 400KV line, the current increases than its nominal value in the Boropukuria-Bogura line. The fault current is 2.2pu which is cleared at 1.02 second in Fig 3.25.

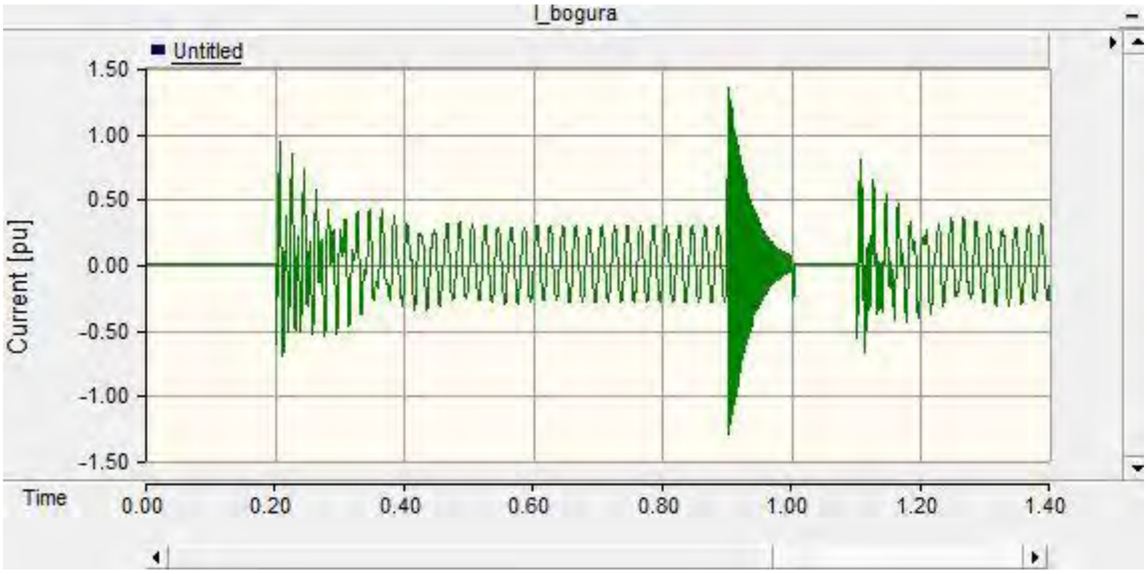


Figure 3.26: Current at Bogura-Kaliakair 400KV bus at fault condition.[Bogura bus line]

During this unsymmetrical fault in this double circuit line in Bogura- Kaliakair line fault current is recorded 1.32pu which is cleared in 1.01 second in Fig 3.26.

Table 3.16: Recorded current of different buses during single circuit 1-phase fault

Serial No.	Types of fault	Bus Voltage	Max recorded current [pu]	Mitigation Time [s]
01.	Single phase to ground fault	Boropukuria-Bogura	2.2	0.11
		Bogura line[fault line]	3.6	0.10
		Bogura -Kaliakair Bus	1.32	0.11

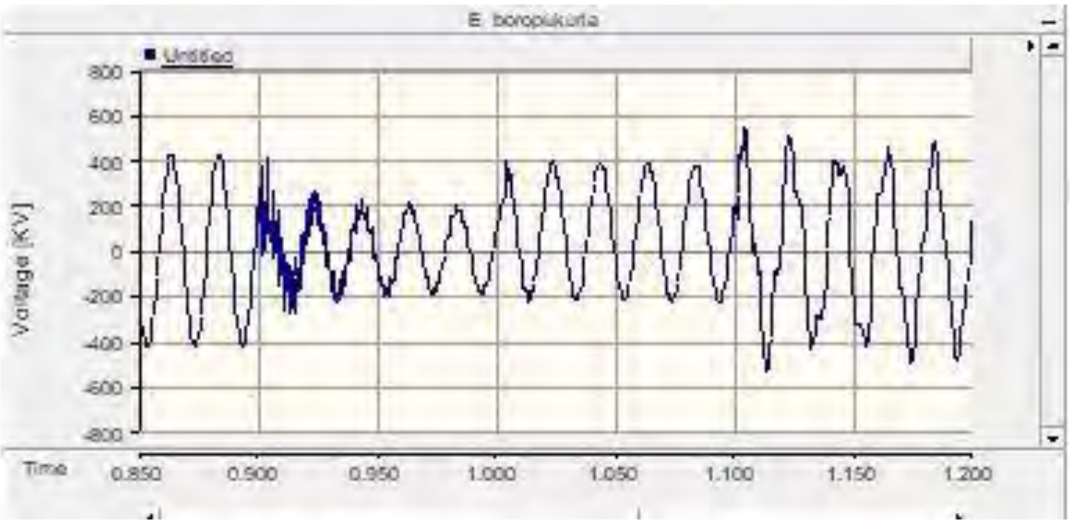


Figure 3.27: Voltage at Boropukuria 400KV bus at fault condition [at fault bus]

After the fault when the line was reenergized the voltage gives maximum overvoltage at Boropukuria bus at 1.17 second in Fig. 3.27. The line does not give any voltage to the Bogura bus. Voltage does not reach to zero as it is connected with generation bus.

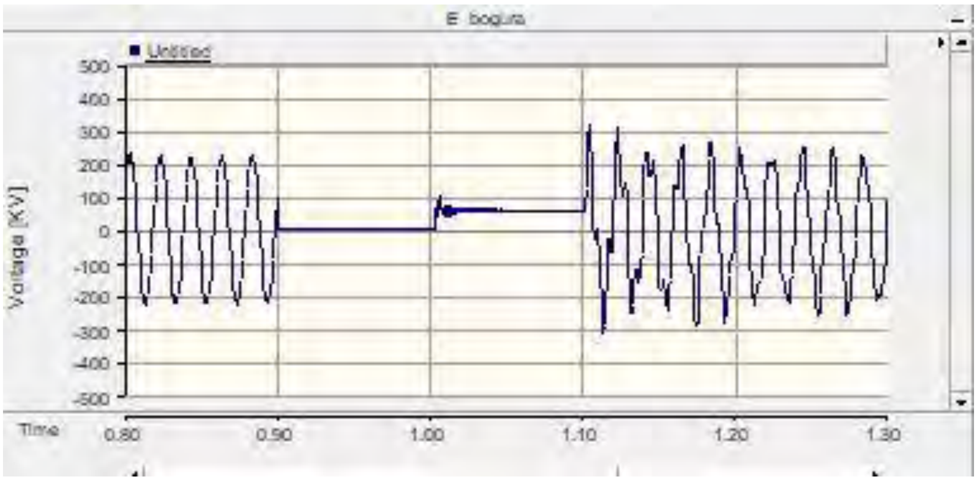


Figure 3.28: Voltage at Bogura 400KV bus at fault condition.

In this bus the voltage is zero at the fault occurs at this bus. After energization of the line, the voltage becomes normal at 1.1 second in Fig 3.28.

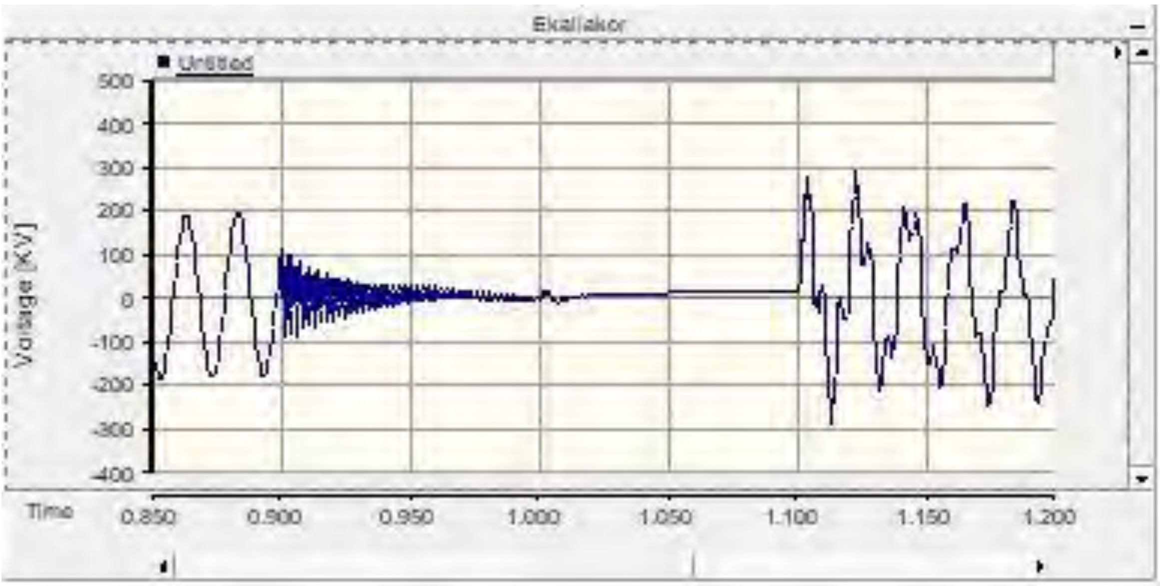


Figure 3.29: Voltage at Kaliakair 400KV bus at fault condition.

Voltage during fault time at Kaliakair 400KV bus was almost zero in Fig 3.29. Duration was exactly same as our give time.

The above analysis is summarized in Table-3.17 showing the nominal value, maximum voltage recorded and duration time.

Table 3.17: Recorded voltage of different buses during single circuit 1-phase fault

Serial No.	Type of Fault	Bus Name	Nominal Voltage[KV]	Max Voltage recorded [KV]	Max Voltage recorded [pu]	Mitigation Time [s]
01.	Single To Ground Fault	Boropukuria	400	456	1.14	0.05
		Boropukuria	400	315	0.7875	0.1
		Kaliakair	400	253	0.6325	0.09

3.5 Simulation of BPS 400KV-230 KV Double Circuit Transmission Line

From the data of BPS 400KV-230KV, we designed a double circuit transmission line. After designing the double circuit transmission line we have analyzed the switching transient in different location and then we have created a fault at different in a fixed location and examined it sequentially based on the fault type.

3.5.1 Transformer Switching of Double Circuit Transmission Line

Transformer switching of double circuit transmission line happened in the both side of the generation such Boropukuria and Bibiyana. All the analysis of transformer switching is stated below in details.

3.5.1.1 Transformer Switching of Double Circuit Transmission Line from Boropukuria

In this simulation, there are eleven bus bars in a double, stretched out, long transmission line starting from Boropukuria to Bibiyana via Bogura and Kaliakair. The total distance of the transmission lines is 421.64 km for 400KV line and 575.5 km for 230KV line. Two steam generators are connected in Boropukuria end with a 13.8 KV bus bar. With the help of two transformers, the voltage gets step up to 230KV and then to 400 KV from 13.8KV and is connected to 400KV bus bar as shown in the Fig (3.30) below. From Boropukuria 400KV bus, electricity is first transmitted to Bogura 400KV bus and then onwards to Kaliakair and Bibiyana 400KV buses. Three steam generators and three gas generators are connected to Bibiyana 400KV bus bar via two step up transformers: first stage is 13.8KV to 230KV and second is 230KV to 400KV. For the 230KV line, from Boropukuria 230KV bus, the line is connected to Bogura 230KV bus at a distance of 120 km apart. From Bogura 230 KV bus outgoes two lines. One line connects with 400KV Bogura bus by the help of a step up transformer. The other line from Bogura 230KV bus connects to Bibiyana 230KV bus via Shirajgonj, Shrepur, Ashuganj and Cumilla North covering a total distance of 455.5 km from Bogura.

For transformer switching, Boropukuria 400KV bus and 230KV bus are switched on at a time of 0.2 second with the help of breaker 6 and breaker 7.

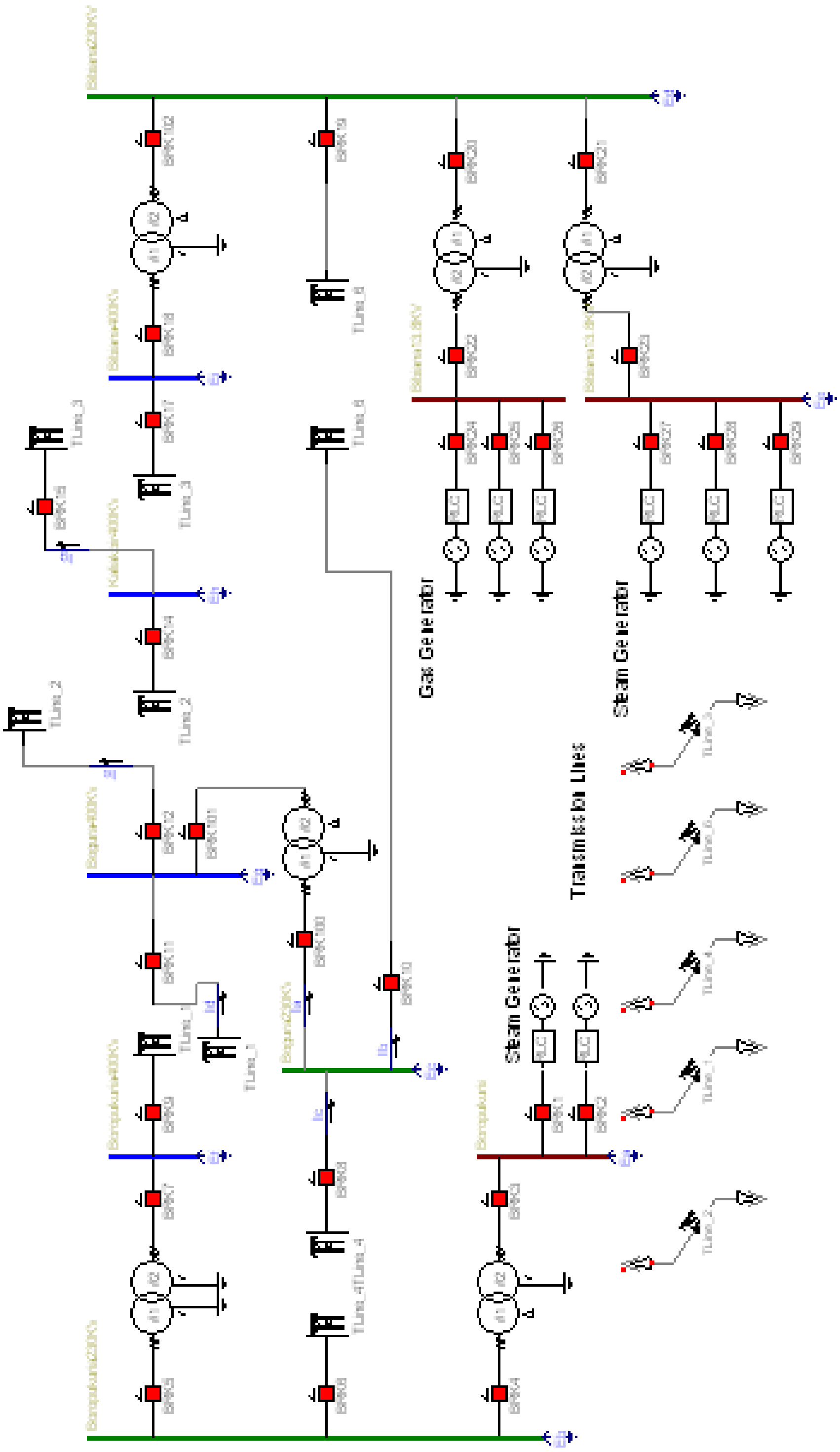


Figure 3.30: 400KV-230KV double transmission line from Boropukuria to Bibiyana

Transformer switching is done by closing breaker 6 and breaker 7 at 0.2 second.

The voltage of the bus bar at Boropukuria bus reaches to a value higher than the normal steady state value at transient period. The switching operation was done at t=0.2 second.

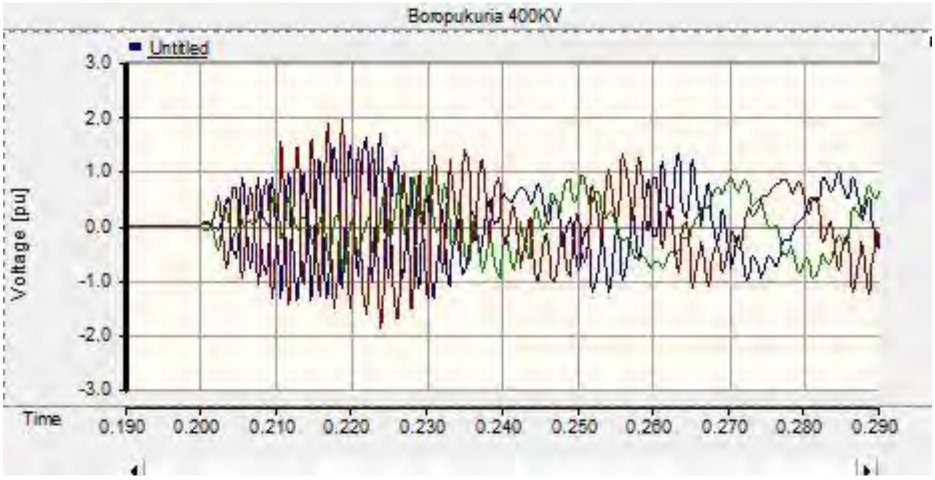


Figure 3.31: Voltage at Boropukuria 400KV bus due to energization of transformer at Boropukuria

The graph observed in Fig 3.31 shows the voltage at 400KV bus bar in Boropukuria to have a maximum value of 1.87 pu at 0.018 second after switching.

To keep in mind, the energization of transformer at Boropukuria 400KV bus bar will have an effect on the other end of the line (Bogura 400KV bus bar). These are shown through output waveform in Fig(3.32).

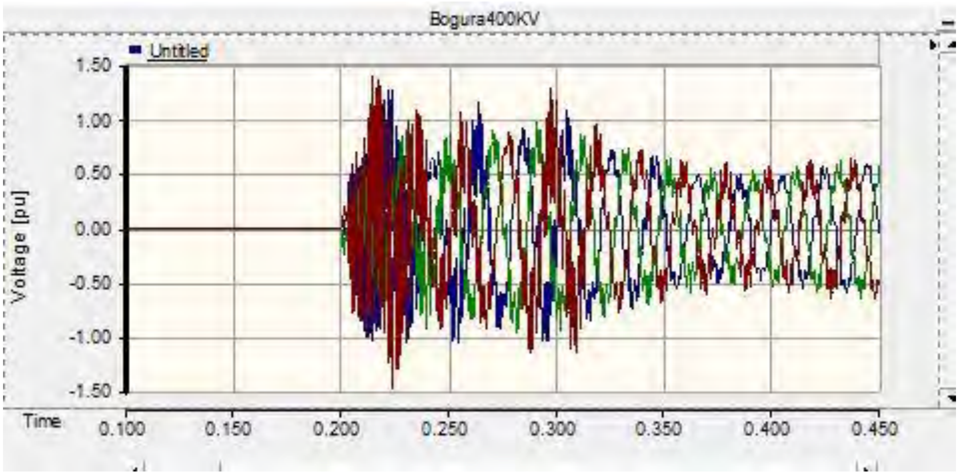


Figure 3.32: Voltage at Bogura 400KV bus due to energization of transformer at Boropukuria

The output voltage waveform in Fig(3.32) shows the Bogura bus bar to reach a maximum value of 1.34 pu. The time needed to mitigate the overvoltage was 0.016 seconds.

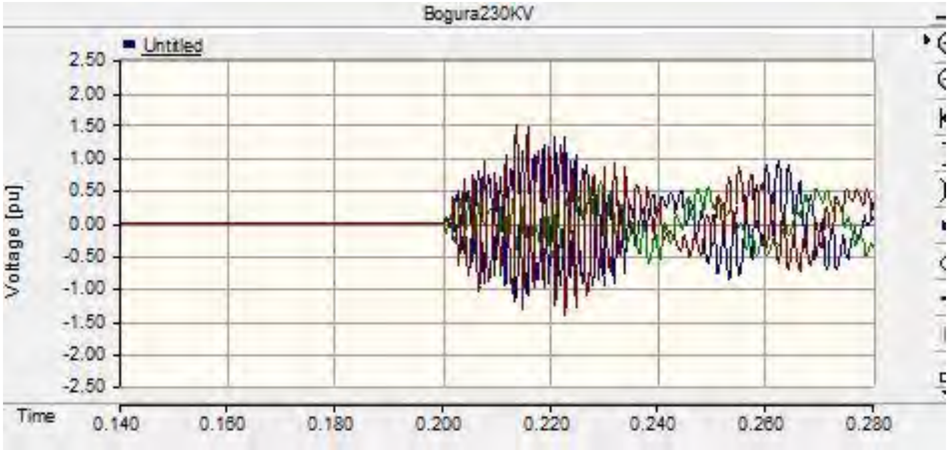


Figure 3.33: Voltage at Bogura230KV bus due to energization of transformer at Boropukuria

The voltage in Fig (3.33) is of the 230KV bus bar located in Bogura. The bus bar reaches a maximum of 1.50 pu at 0.01 second after switching.

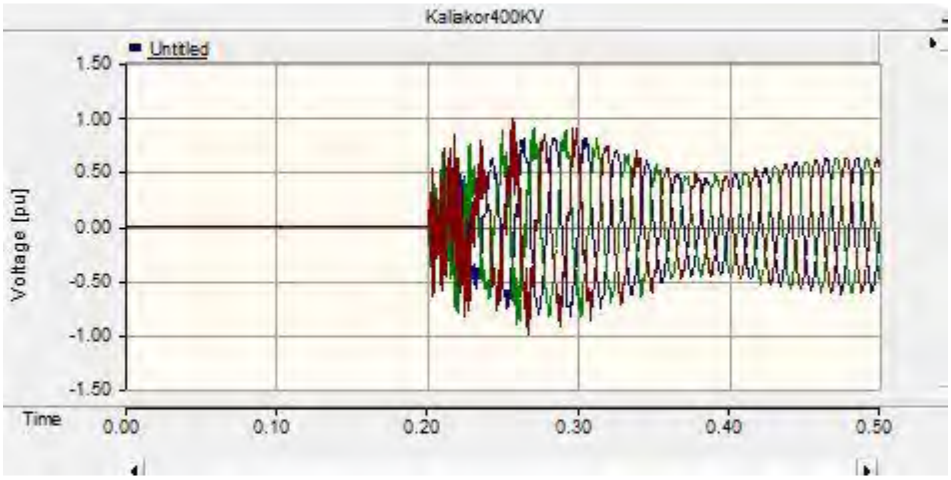


Figure 3.34: Voltage at Kaliakair 400KV bus due to energization of transformer at Boropukuria

In Kaliakair bus bar of the 400KV line, the Fig (3.34) shows to reach a maximum value of 1.27 pu. The time needed to mitigate the overvoltage was 0.05 seconds.

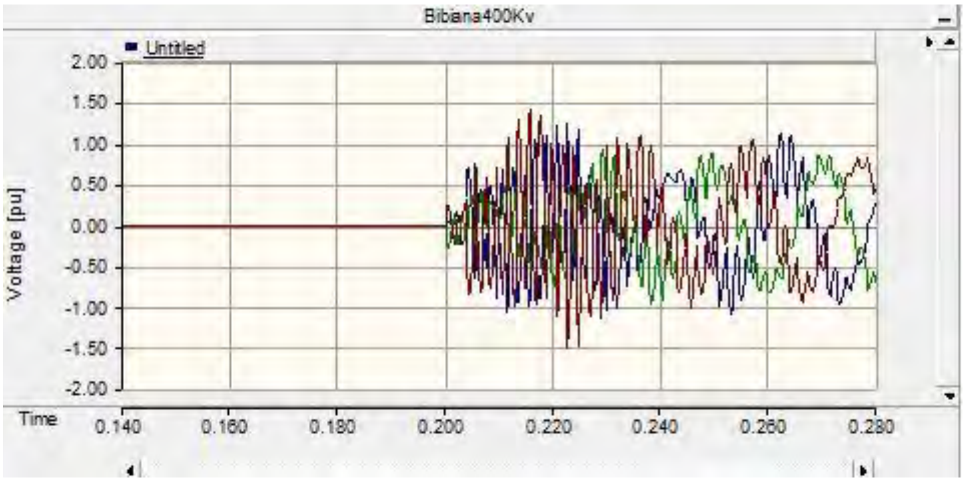


Figure 3.35: Voltage at Bibiyana 400KV bus due to energization of transformer at Boropukuria

The other end of the line is at Bibiyana. Fig (3.35) highlights the voltage of the 400KV bus bar located in Bibiyana. It has a highest value of 1.30 pu. The time needed to mitigate the overvoltage was 0.02 seconds.

The above analysis is summarized in Table-3.18 showing the nominal value, maximum voltage recorded and duration time.

Table 3.18: Recorded voltage of different buses during transformer switching from Boropukuria end.

Serial No.	Type of switching	Bus Name	Nominal Voltage [KV]	Max recorded voltage [KV]	Max recorded Voltage [PU]	Mitigation Time [s]
01.	Energization of Transformer at Boropukuria 230KV bus	Boropukuria	400	748	1.87	0.018
		Bogura	400	536	1.34	0.016
		Bogura	230	345	1.5	0.01
		Kaliakair	400	508	1.27	0.05
		Bibiyana	400	520	1.3	0.02

3.5.1.2 Transformer Switching of Double Circuit Transmission Line from Bibiyana

In this simulation, the circuit is same as Fig (3.30), except the switching is applied from Bibiyana.

Transformer switching is done by closing breaker 20 and breaker 21 at 0.2 second. Here, the switching operation is same as before except the switching is done from Bibiyana.

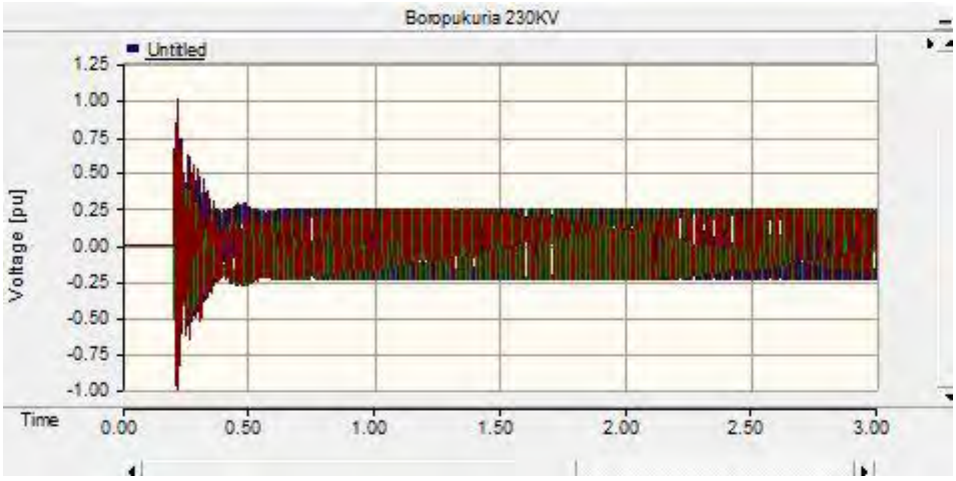


Figure 3.36: Voltage at Boropukuria 230KV side due to energization of transformer at Bibiyana

The graph observed in Fig (3.36) shows the voltage at 230KV bus bar in Boropukuria to have a maximum value of 1.00 pu. The time needed to mitigate the overvoltage was 0.2 seconds.

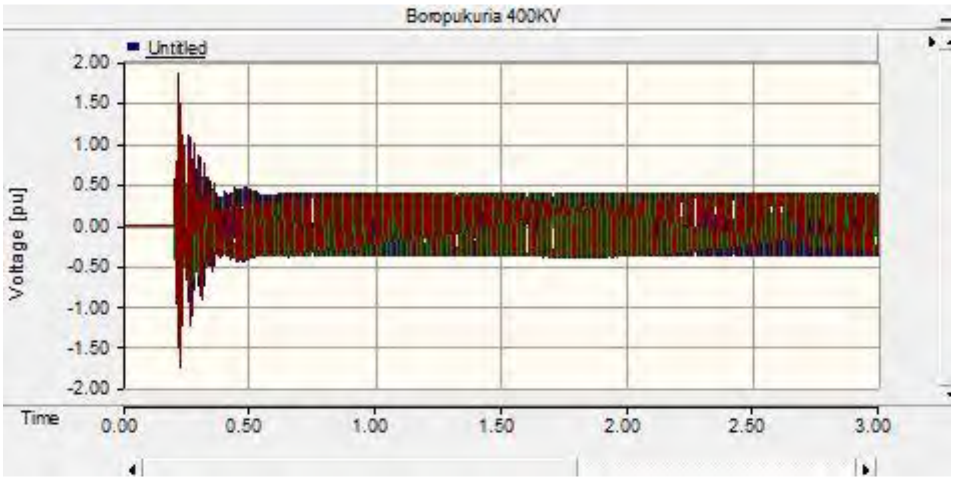


Figure 3.37: Voltage at Boropukuria 400KV side due to energization of transformer at Bibiyana

The graph observed in Fig (3.37) shows the voltage at 400KV bus bar in Boropukuria to have a maximum value of 1.96 pu. The time needed to mitigate the overvoltage was 0.36 seconds.

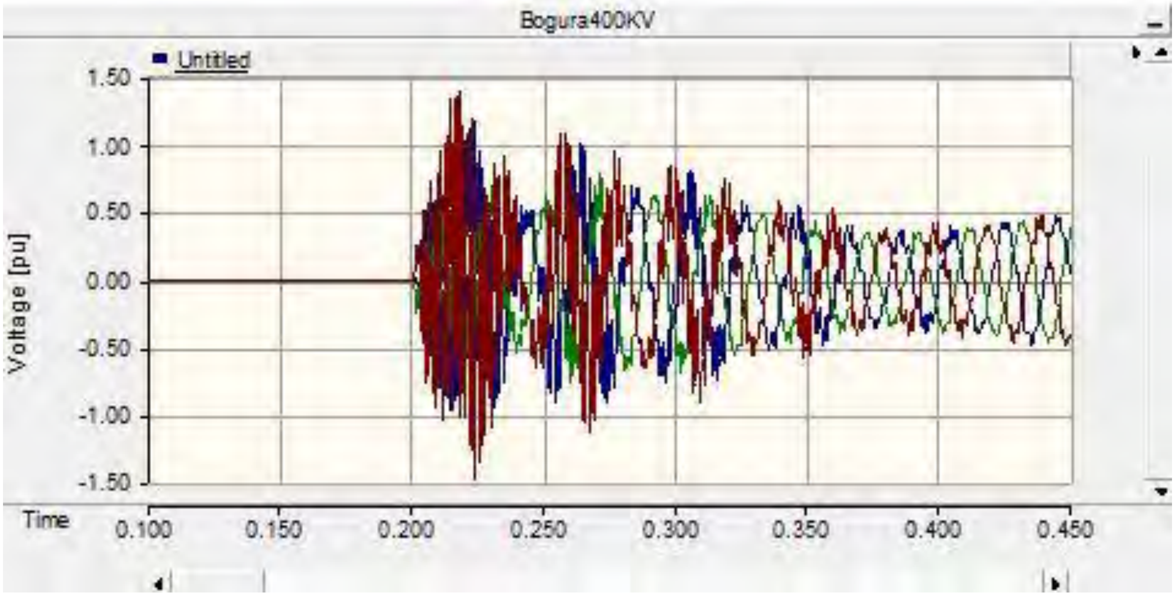


Figure 3.38: Voltage at Bogura 400KV side due to energization of transformer at Bibiyana

The output voltage waveform in Fig (3.38) shows the Bogura bus bar to reach a maximum value of 1.37 pu. The time needed to mitigate the overvoltage was 0.2 seconds.

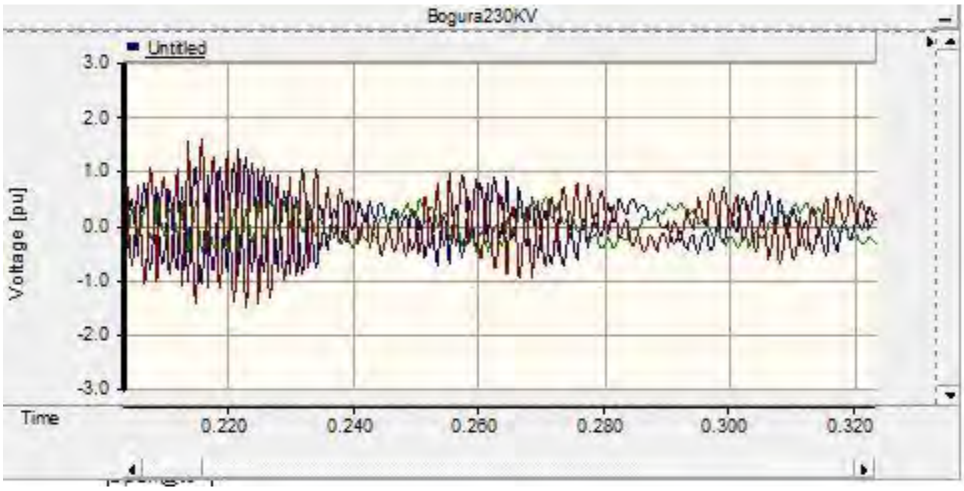


Figure 3.39: Voltage at Bogura 230KV side due to energization of transformer at Bibiyana

The voltage in Fig (3.39) is of the 230KV bus bar located in Bogura. The bus bar reaches a maximum of 1.56 pu at 0.173 second after switching.

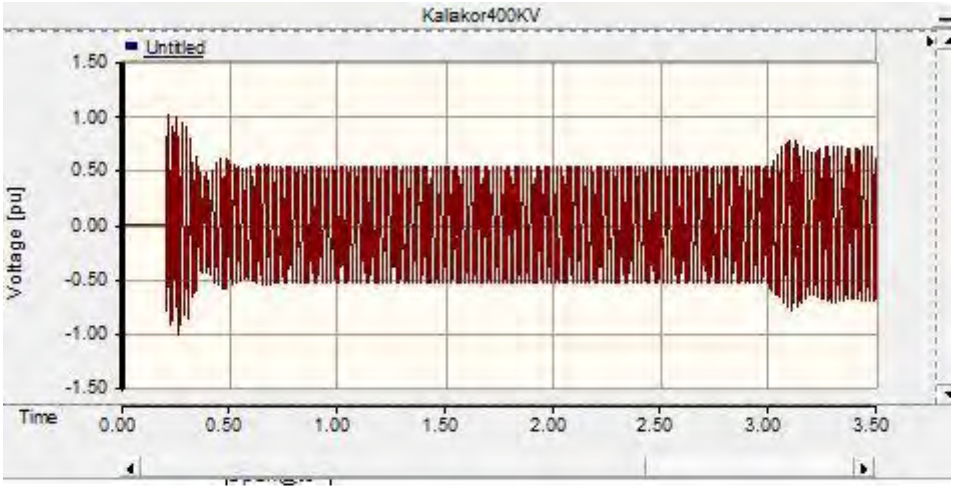


Figure 3.40: Voltage at Kaliakair 400KV side due to energization of transformer at Bibiyana

In Kaliakair bus bar of the 400KV line, the Fig (3.40) shows to reach a maximum value of 1.02 pu. The voltage takes 0.28 seconds to come at a steady state situation.

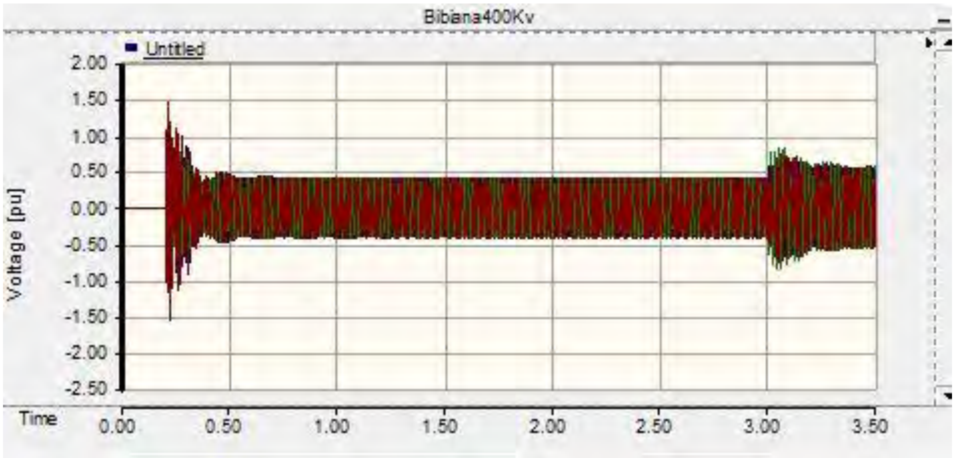


Figure 3.41: Voltage at Bibiyana 400KV side due to energization of transformer at Bibiyana

The output voltage waveform in Fig (3.41) shows the Bibiyana bus bar to reach a maximum value of 1.47 pu. The time needed to mitigate the overvoltage was 0.108 seconds.

The above analysis is summarized in Table-3.19 showing the nominal value, maximum voltage recorded and duration time.

Table 3.19: Recorded voltage of different buses during transformer switching from Bibiyana

Serial No.	Type of switching	Bus Name	Nominal Voltage [KV]	Max recorded voltage [KV]	Max recorded Voltage [PU]	Mitigation Time [s]
01.	Energization of Transformer Bibiyana 400KV side	Boropukuria	230	230	1.00	0.2
		Boropukuria	400	784	1.96	0.36
		Bogura	400	548	1.37	0.2
		Bogura	230	358.8	1.56	0.173
		Kaliakair	400	408	1.02	0.28
		Bibiyana	400	588	1.47	0.108

3.5.2 Simulation of Double Circuit Transmission Line with fault

In 400KV-230KV double circuit transmission line, we created a fault at a fixed location and analyzed the situation comparing with the two individual line.

3.5.2.1 Three phase fault on 400KV line of the Double Circuit

On this simulation, all the arrangements were kept fixed as the Fig (3.30) except a three phase fault is injected in the 400KV line between Bogura and Boropukuria 400KV buses as shown in Fig (3.42). The fault is injected at 0.9 second and at 1.0 second, the breakers trip and finally at 1.1 second, they closes when the fault clears.

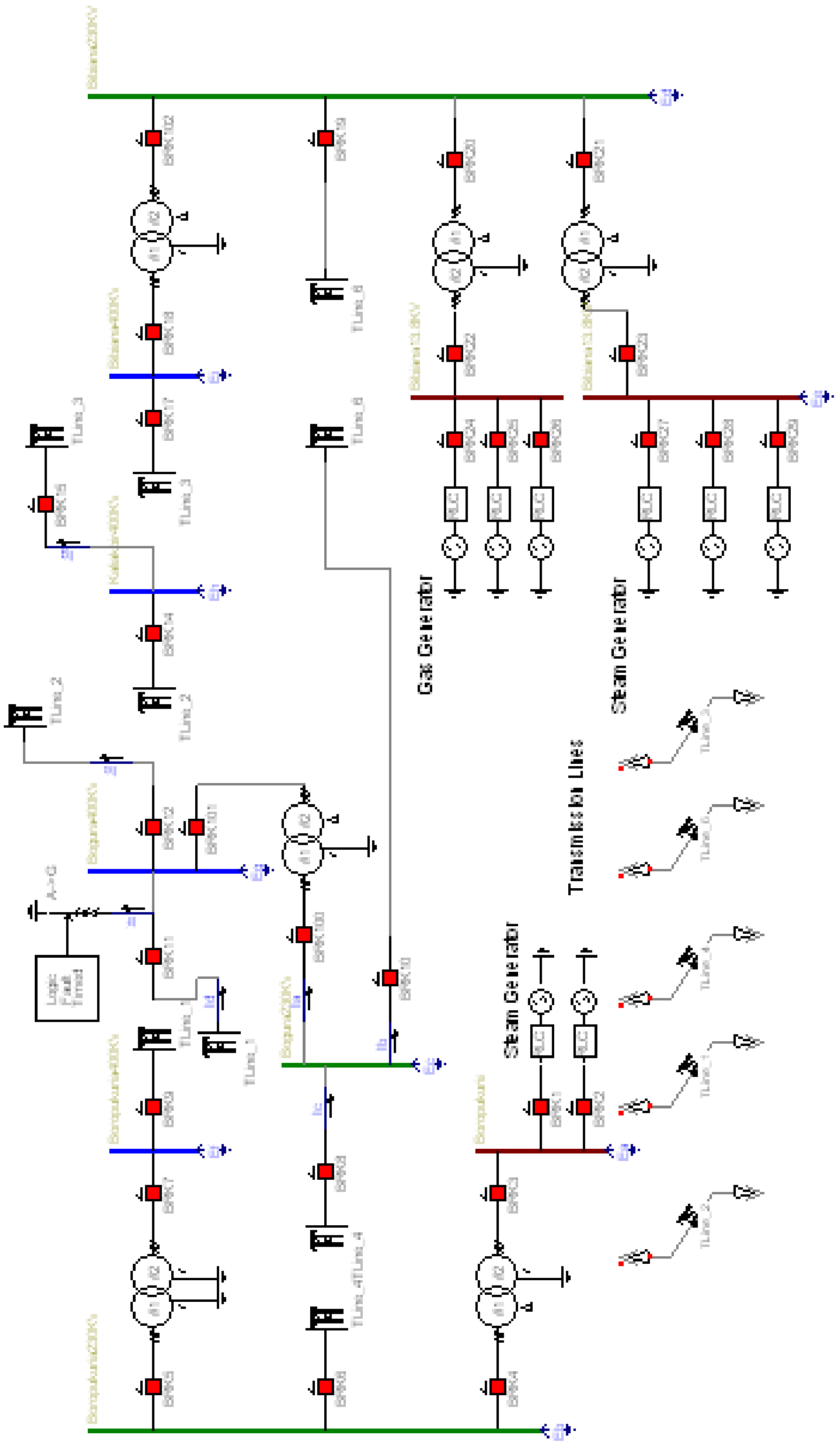


Figure 3.42: 400KV-230KV line with fault on 400KV line

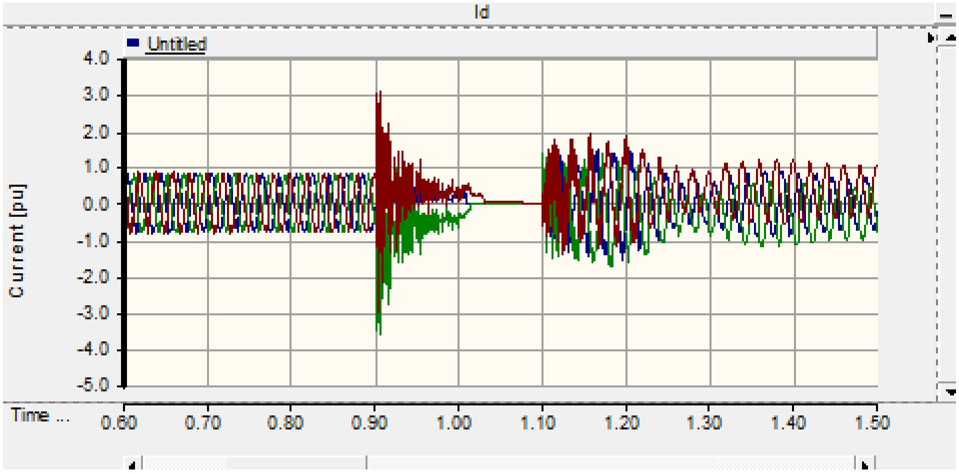


Figure 3.43: Boropukuria - Bogura 400KV current at 3 –phase fault condition

Under the three phase fault condition, fault is injected in Bogura three phase line and the current condition before entering the fault line is in Fig 3.43. Current is recorded 3.1pu in Boropukuria and Bogura 400KV line and it is cleared at 1.07 second.

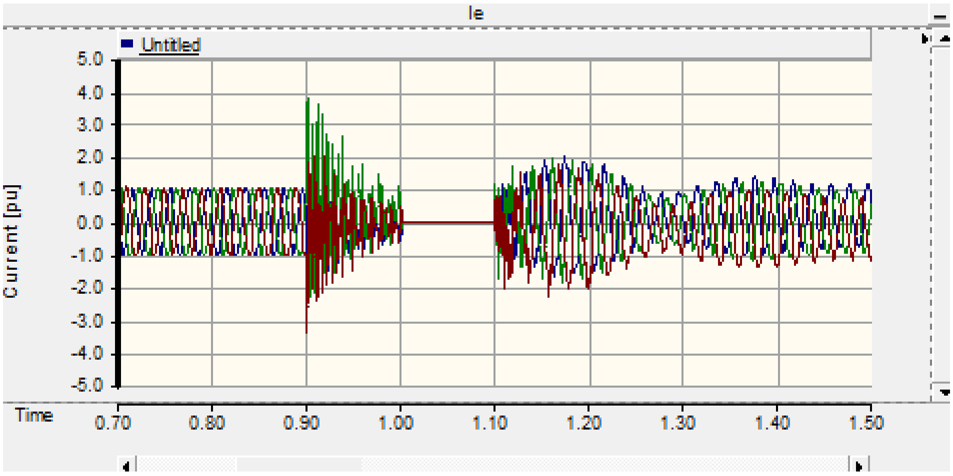


Figure 3.44: Bogura - Kaliakair 400KV current at fault condition

When the fault is executed in Bogura 400KV bus, the current of Bogura to Kaliakair, 133Km length line, increases. The current reaches at 3.8pu which has cleared within 0.1 second as shown in Fig 3.44.

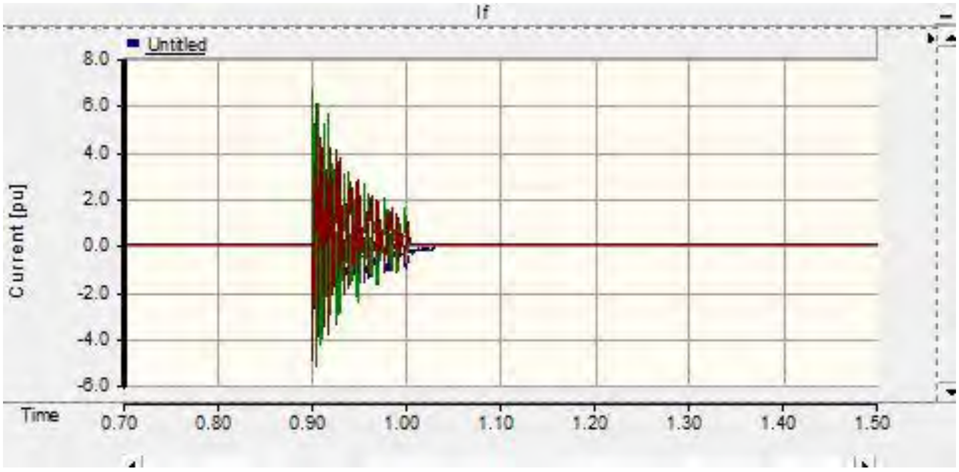


Figure 3.45: Three phase Fault current at Bogura400KV line. [At fault bus]

The fault current at Bogura 400KV line generate maximum current in fault condition which is recorded 6.1pu in Fig 3.45. Though we gave 0.1second duration of the fault but it took a bit longer than the given time.

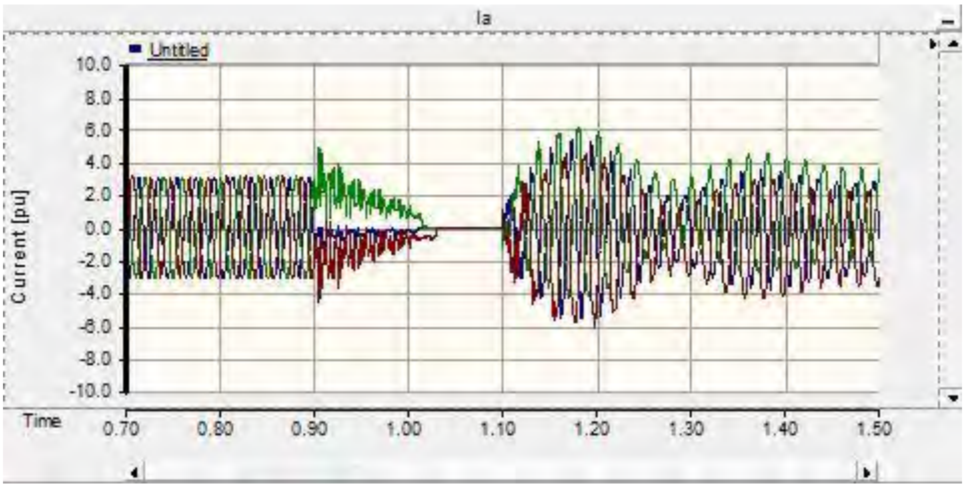


Figure 3.46: Bogura 230KV at fault condition

In three phase fault condition, maximum fault current was recorded at Bogura 230KV bus. It took longer time than other line to mitigate the fault shown in Fig 3.46.

Table 3.20: Recorded current of different buses during double circuit 3-phase fault

Serial No.	Types of fault	Bus Current	Max recorded current [pu]	Mitigation Time [s]
01.	Three phase fault	Boropukuria-Bogura	3.1	0.17
		Bogura line[fault line]	6.1	0.12
		Bogura -Kaliakair Bus	3.8	0.1
		Bogura230KV line	4.9	0.13

Three phase voltage:

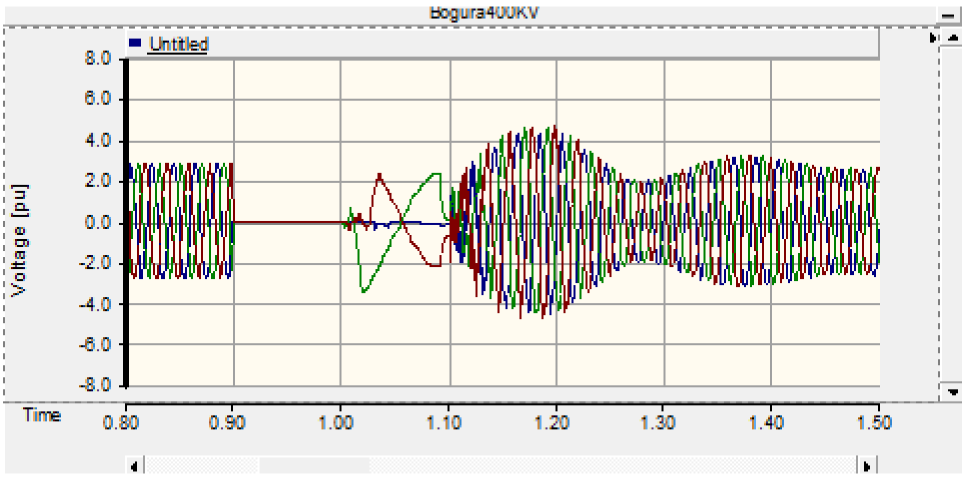


Figure 3.47: Bogura 400KV line voltage at 3 phase voltage

Since the fault was transient fault it was cleared at 1.10 second. At the time of clearing of fault, transition conditions occurred during that transition. The voltage recorded at Bogura230KV bus is shown in Fig 3.47 the fault Orchid at time equal to 0.1 seconds and it was clear that time=1.10 second.

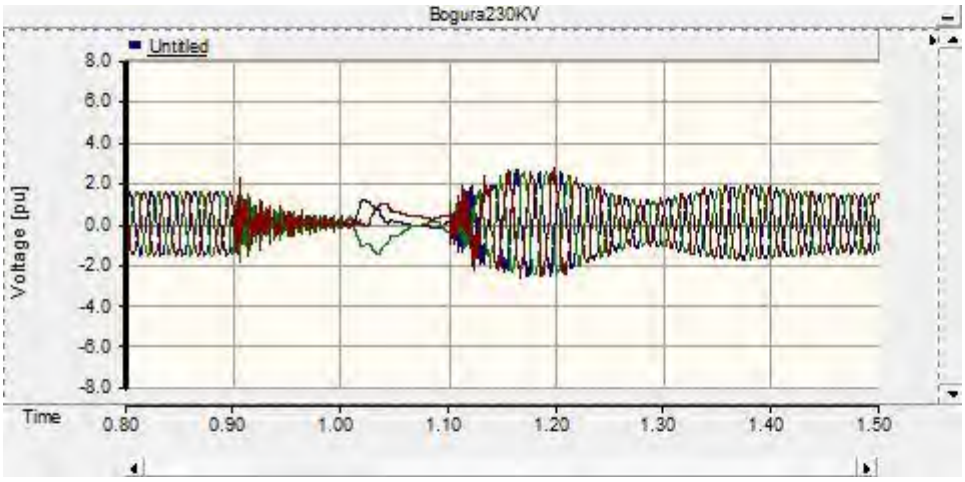


Figure 3.48: Bogura 230KV voltage

During single line to ground fault the voltage recorded at bus station that is at Boropukuria400KV side is shown in Fig 3.48 the maximum voltage appeared at this bus was almost 26.56 pu where the nominal voltage was only 1.0 pu.

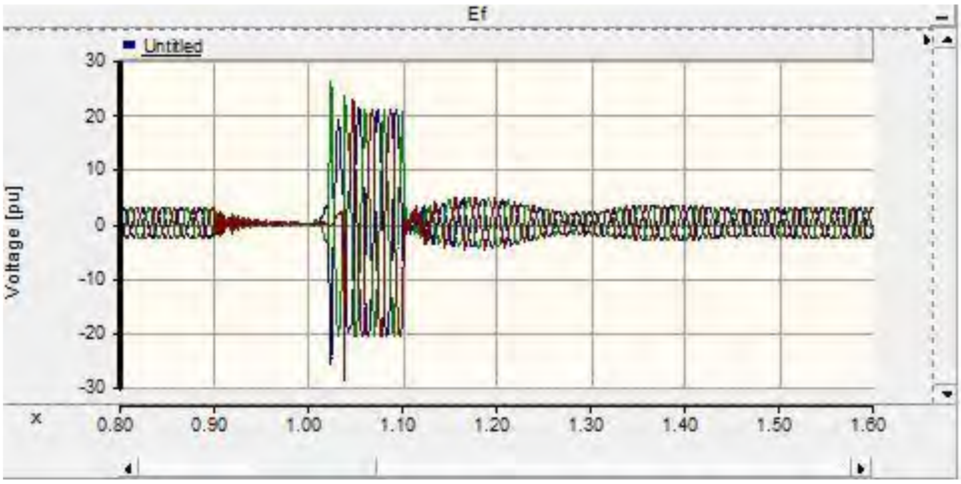


Figure 3.49: Boropukuria400 KV bus voltage

The voltage reaches its maximum at Boropukuria 400KV bus. As the generator is connected in this side therefore, the voltage reaches its maximum value when the line become reenergize. In fault time, the voltage becomes almost zero as shown in Fig 3.49.

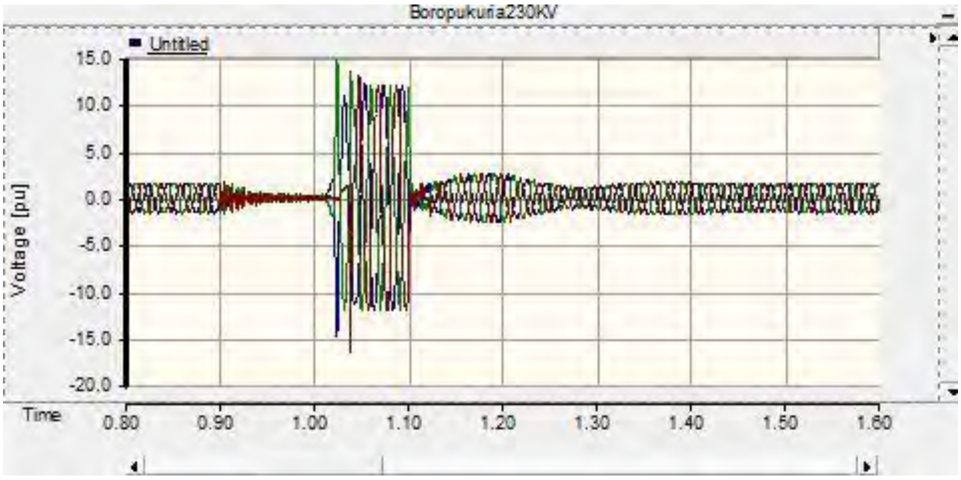


Figure 3.50: Boropukuria 230KV line voltage

Boropukuria 230KV bus voltage in Fig 3.50, voltage reached higher value when the line become re-energize as the generator is connected in this bus.

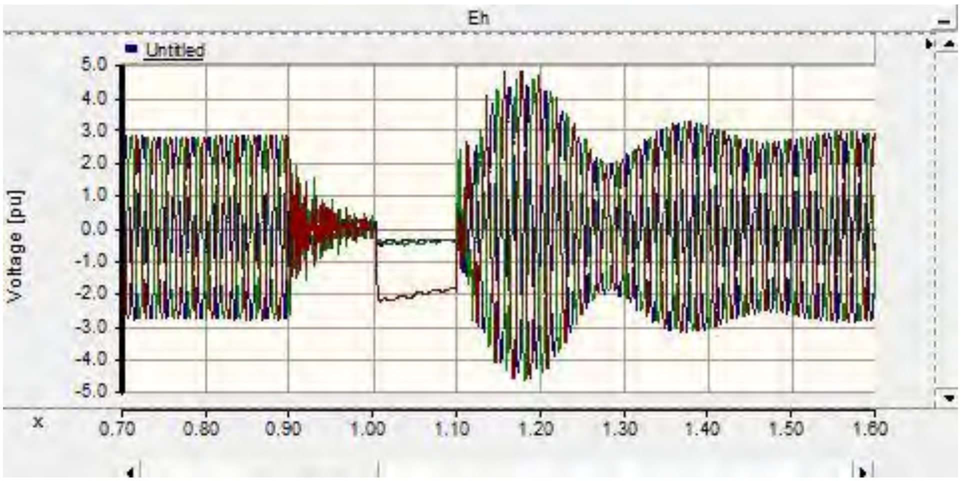


Figure 3.51: Kaliakair 400KV line voltage at 3 phase fault

In three phase fault condition, the voltage at Kaliakair becomes lower than normal condition in Fig 3.51.

The above analysis is summarized in Table-3.21 showing the nominal value, maximum voltage recorded and duration time.

Table 3.21: Recorded Voltage of different buses during single circuit 3-phase fault

Serial No.	Types of fault	Bus Voltage	Nominal Voltage [KV]	Max recorded Voltage [KV]	Max recorded voltage [pu]	Mitigation Time [s]
01.	Three phase fault	Bogura Bus	400	52	0.13	0.09
		Boropukuria Bus	230	213	2.6	0.13
		Kaliakair Bus	400	318	2.0	0.11
		Boropukuria Bus	400	281	2.6	0.13

3.5.2.2 Single phase fault on 400KV line of the Double Circuit

This time a single phase to ground fault is injected in place of three phase to ground fault.

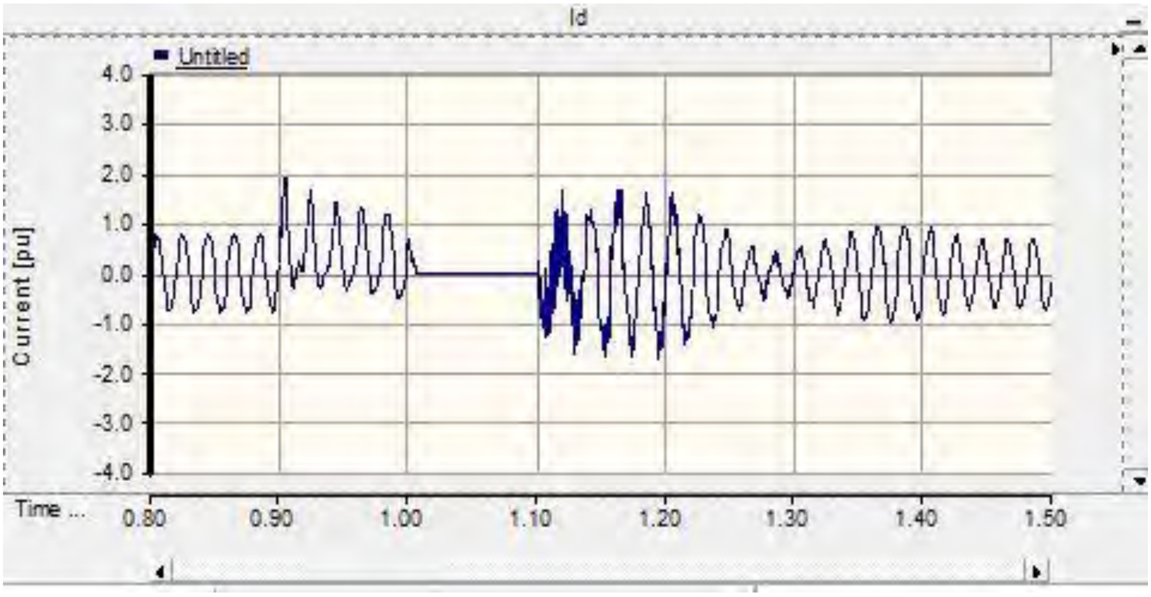


Figure 3.52: Boropukuria- Bogura 400KV line single phase

When the single phase to ground fault is injected in Bogura- Boropukuria 400KV line, current increases compared to its nominal value in the Boropukuria -Bogura line. The fault current is 2.0pu which is cleared at 1.01 second shown in Fig 3.52.

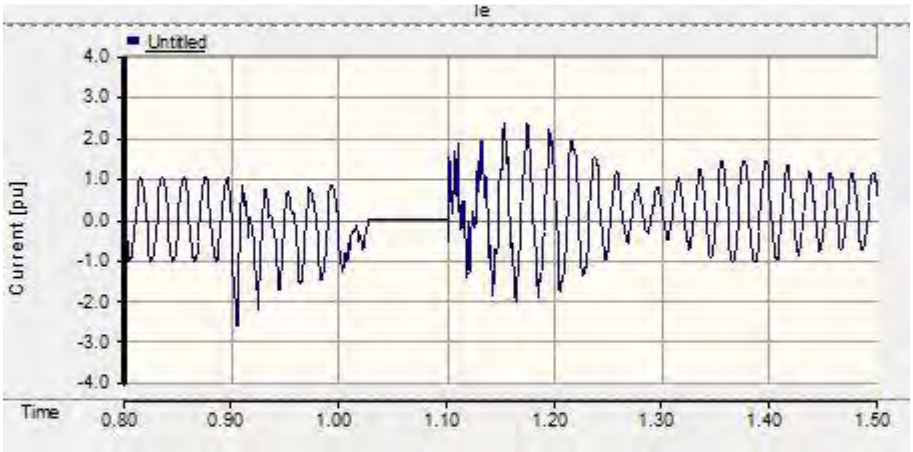


Figure 3.53: Bogura – Kaliakair 400KV line

During this unsymmetrical fault in this double circuit line in Bogura- Kaliakair line, fault current is recorded 2.6pu which is cleared in 1.03 second in Fig 3.53.

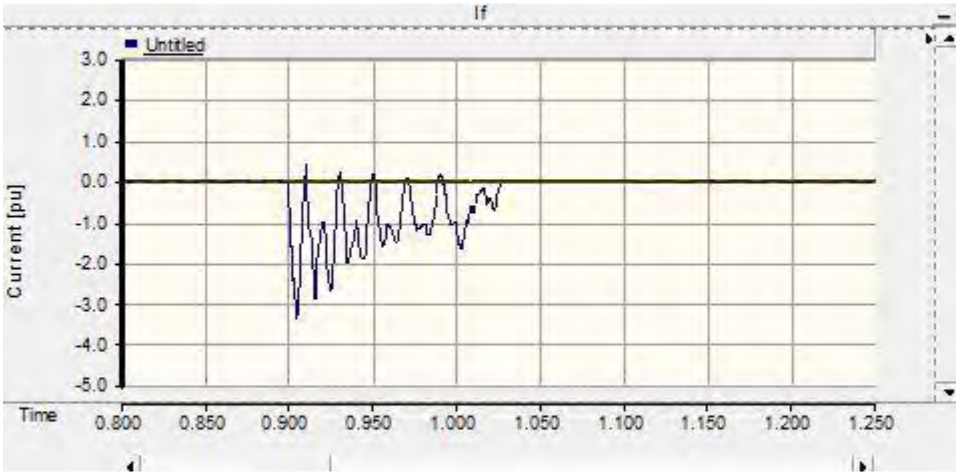


Figure 3.54: Current condition at fault point

The fault current associated with the single phase fault is given in Fig 3.54.it was seen that the response that the faulty current was many times greater than the nominal current. The fault occurs at time, t= 0.9 second and at time, t= 1.0 second, the breakers tripped which then closes at t=1.1 second.

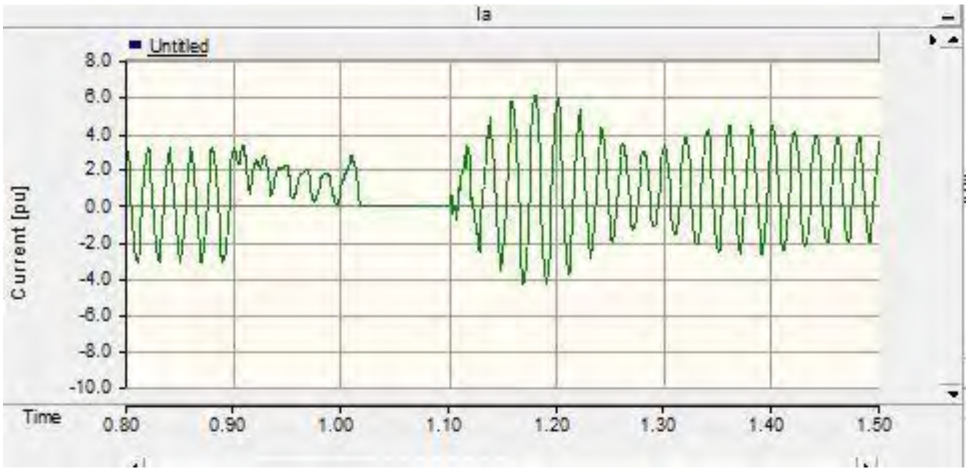


Figure 3.55: Bogura 230KV single phase

Maximum current recorded is 3.03 pu with mitigation time of 0.12 second as shown in Fig 3.55.

Table 3.22: Recorded current of different buses during single circuit 1-phase fault

Serial No.	Types of fault	Bus Voltage	Max recorded current [pu]	Mitigation Time [s]
01.	Single phase to ground fault	Boropukuria-Bogura	1.98	0.11
		Bogura line[fault line]	6.1	0.13
		Bogura -Kaliakair Bus	3.01	0.13
		Bogura230KV line	3.03	0.12

Figure 3.56: Voltage at Bogura 400KV bus at single phase fault.

During fault time voltage reach almost zero to mitigate the fault. After clearing the fault when the line reenergizes, a transient over voltage generate in 1.17 second shown in Fig 3.56. The clearing time of the fault is 1.1 second.

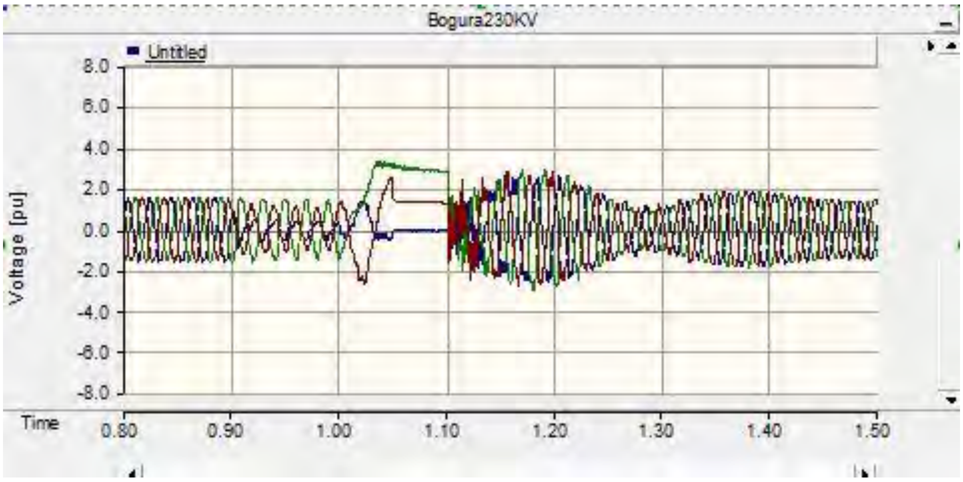


Figure 3.57: Voltage at Bogura 230KV bus.

Injecting fault in Bogura 400KV line also gives minimum voltage in Bogura 230KV line of our double circuit line. The duration of the fault is 0.1 second. It gives transient overvoltage when the line become reenergize.

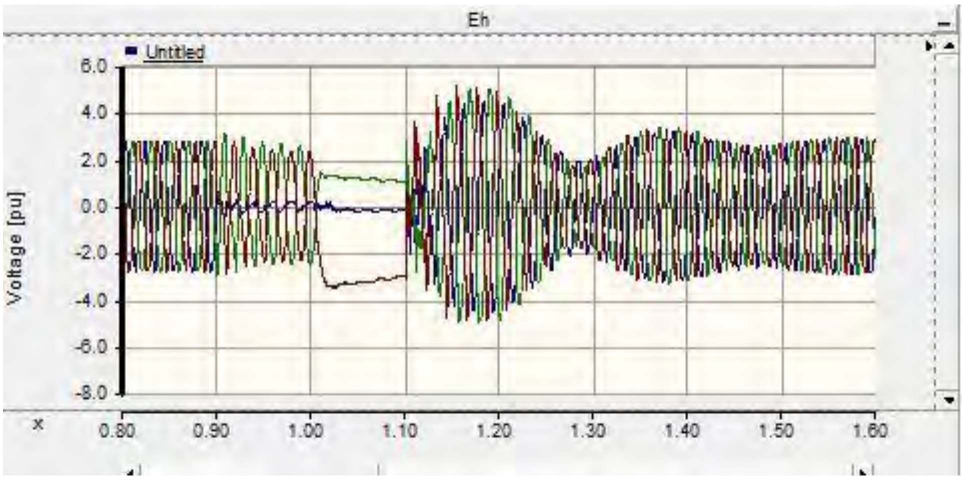


Figure 3.58: Voltage at Kaliakair 400KV bus.

Voltage during fault time at Kaliakair 400KV bus was almost zero in Fig 3.58. Duration was exactly same as our give time.

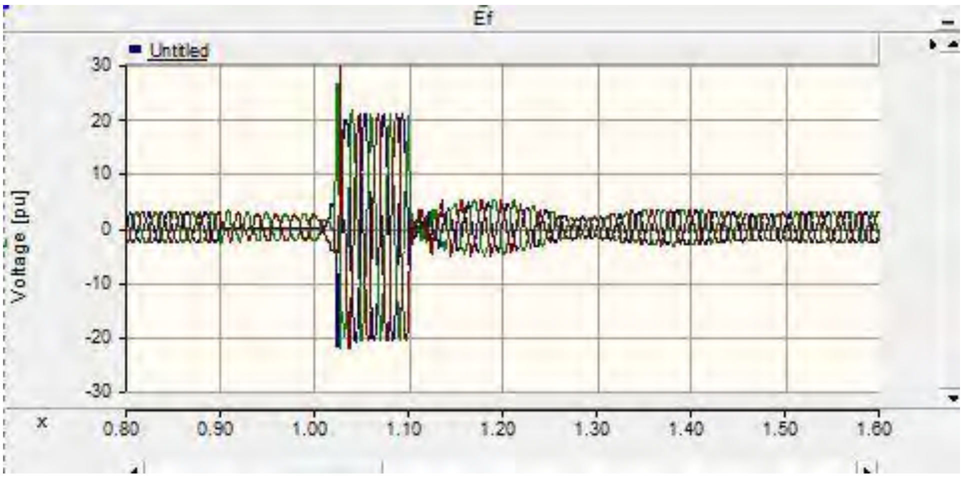


Figure 3.59: Voltage at Boropukuria 400KV bus.

After the fault, the voltage starts to decrease as shown in Fig 3.59.

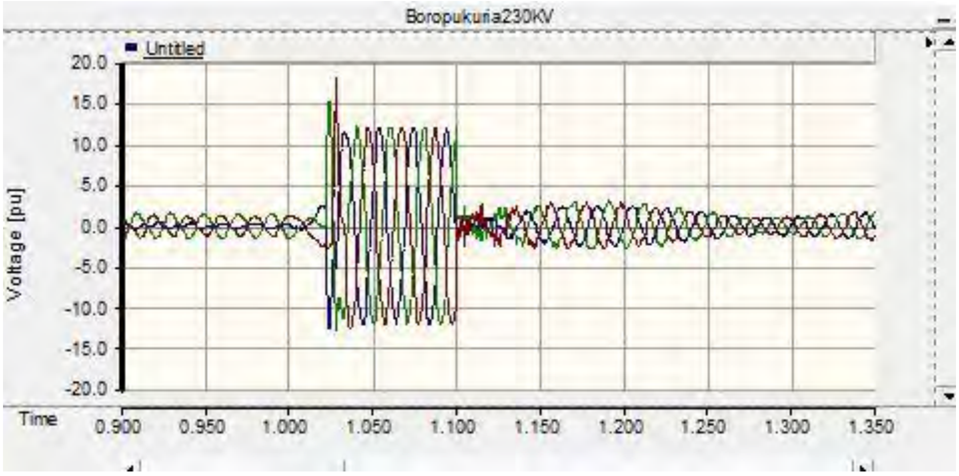


Figure 3.60: Voltage at Boropukuria 230KV bus.

The above analysis is summarized in Table-3.23 showing the nominal value, maximum voltage recorded and duration time.

Table 3.23: Recorded voltage of different buses during single circuit 1-phase fault

Serial No.	Types of fault	Bus Voltage	Nominal Voltage [KV]	Max recorded Voltage [KV]	Max recorded voltage [pu]	Mitigation Time [s]
01.	Single phase to ground fault	Kaliakair Bus	400	450	4.6	0.07
		Bogura Bus	400	416	3.1	0.04
		Boropukuria Bus	400	435	2.8	0.03
		Boropukuria Bus	230	298	1.8	0.02
		Bogura Bus	230	282	1.7	0.24

3.5.2.3 Single phase fault on 230KV line of the Double Circuit

The circuit diagram on Fig (3.61) is the same as the previous except the fault is now injected to the 230KV transmission line between Bogura and Bibiyana 230KV buses and the following graphs are produced as outputs. The fault is injected at 0.9 second and the breakers trip at 1 second and finally the breakers close at 1.1 second when the fault is all clear.

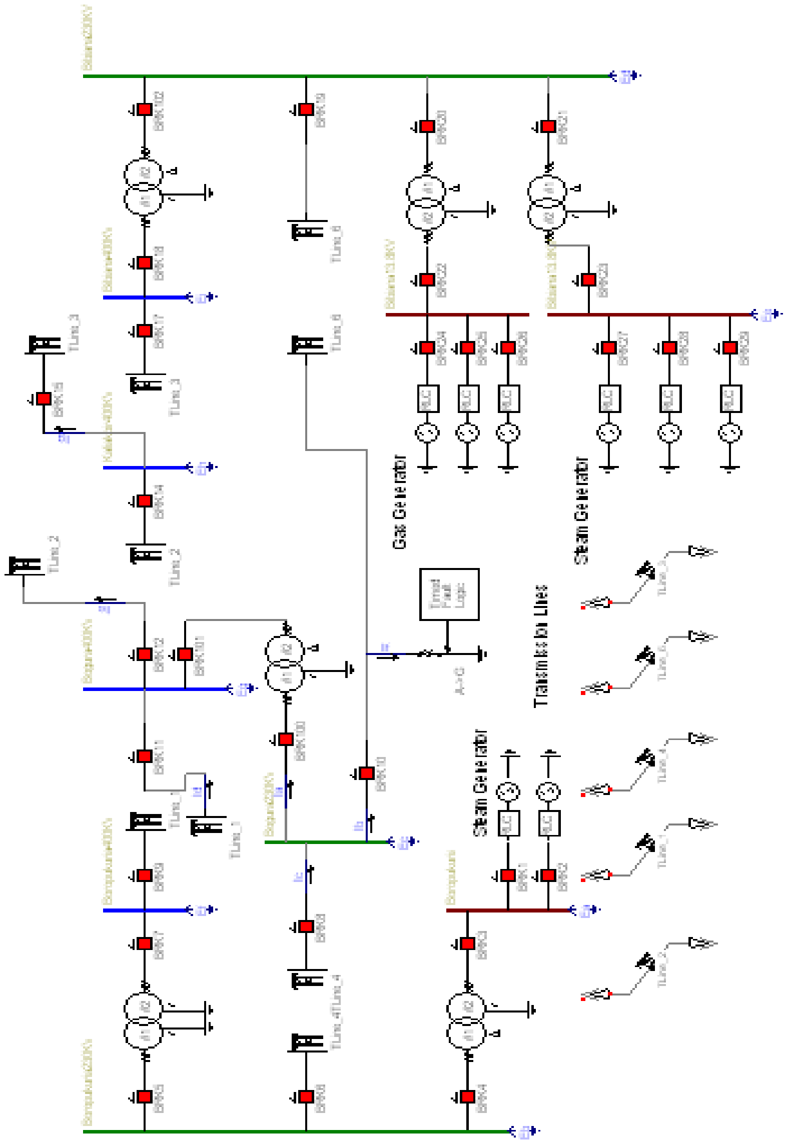


Figure 3.61:400KV-230KV line with fault on 230KV line

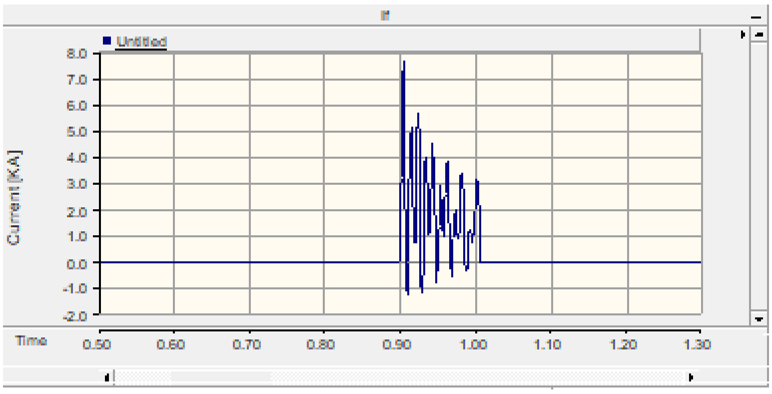


Figure 3.62: Fault current in 230KV line

In Fig (3.62), it can be clearly seen the huge amount of current flows to the ground during fault. The highest current recorded is 6217 A at 0.903 second.

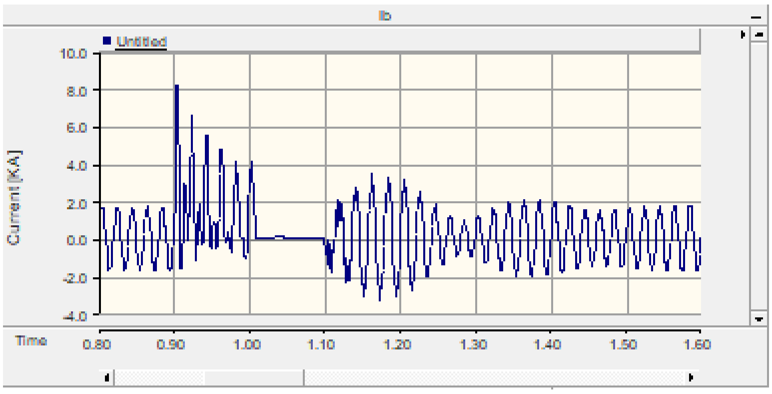


Figure 3.63: Current along the 230KV transmission line where fault occurs

In Fig (3.63), the maximum current reached is 6213A at 0.903 second. This current is close to the value of fault current.

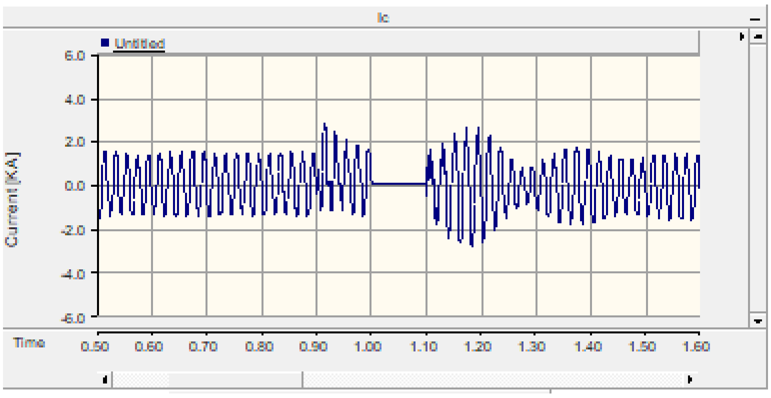


Figure 3.64: Current in 230KV line from Boropukuria to Bogura

In Fig (3.64), it is observed the current to reaches a maximum peak of 2821 A at a time of 0.914 second.

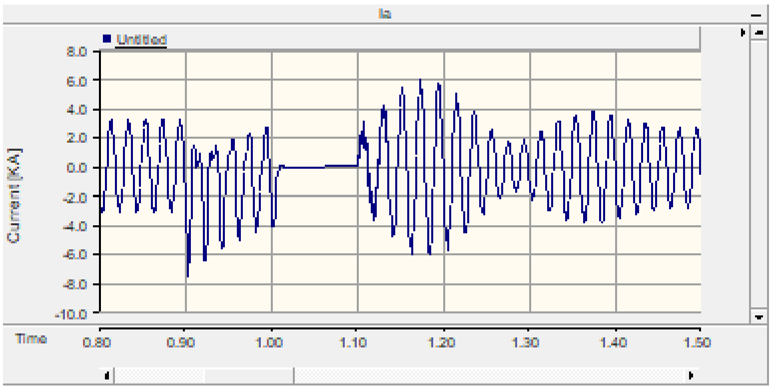


Figure 3.65: Current from Bogura 400KV line to 230KV line

In Fig(3.65), the current reaches a maximum value of 7561 A at 0.904 second. It can be observed that maximum amount of load is provided from Bogura 400KV to 230KV line at fault.

The above analysis is summarized in Table-3.24 showing the nominal value, maximum voltage recorded and duration time.

Table 3.24: Recorded currents of different lines during double circuit 1-phase fault

Serial No.	Types of fault	Bus Voltage	Max recorded current [A]	Mitigation Time [s]
01.	Single phase to ground fault	Boropukuria 230KV-Bogura 230KV	2821	0.014
		Bogura 230KV line[fault line]	6217	0.003
		Bogura 230KV-Bibiyana 230KV	6213	0.003
		Bogura 400KV to 230KV line	7561	0.004

3.6 Result Analysis and Recommendations

Table-3.13 show the results obtained during our analysis for easy of understanding. During energization of transformer Boropukuria side, the maximum voltage recorded 1.56pu in Boropukuria side which is mitigating within 0.26 second. At the last end of the line which is Bibiyana 13.8 KV bus, voltage recorded 0.903pu and the time recurred for reform in normal value was 0.2 second.

In double circuit line, when we energize 13.8/230 y-Δ transformer at Boropukuria side we observe maximum voltage at Boropukuria 400KV bus. We set the transformer to energize at 0.2 second for each of the line. We can see that Kaliakair 400KV bus has minimum transient voltage and it clears at 0.25 second. This result is shown in table-3.18. Table-3.19 shows the energization of transformer between Bibiyana 230KV and Bibiyana 400KV bus, maximum voltage reached at Boropukuria 400KV bus which was 1.96 pu. The time required for clearing it was 0.56second. The minimum transient voltage was seen in Boropukuria 230KV bus which is almost same as its nominal voltage. From our analysis we can see, Bogura 230KV bus is affected more than other bus of the double circuit line.

During a three phase fault in single circuit line, current was higher in both end of the fault line. Current reach its maximum in Bogura 230KV line. The result was shown in Table-3.14. Moreover, we create single phase to ground fault in same circuit. When the single phase to ground fault injected in Bogura 400KV line, current increases compared to its nominal value in the Boropukuria - Bogura line. The fault current is 2.2pu which is cleared at 1.02 second.

By injecting a three phase fault in the double circuit 400KV line at Bogura, current increase abnormally in Bogura 230KV line which is cleared within 0.1 second. Table-3.20 shows the maximum fault current was recorded at Bogura 230KV while fault was injected in Bogura 400KV line. The fault duration was 0.12 second. Table-3.22 shows maximum fault current in a single phase of double circuit line, which was recorded at Bogura 230KV while fault, was injected in Bogura 400KV line. The fault duration was 0.12 second. On the other hand when, a there phase fault is created in double circuit line in 230KV Bogura, current is increasing abnormally in 400KV Bogura which is just opposite of previous case.

Switching events and system disturbances the energy exchanges subject the circuit components to higher stresses, resulting from excessive currents or voltage variations, the prediction of which is the main objective of power system transient simulation. The long transmission line energization can cause high over voltage stresses mainly along the transmission line but also in the supply network. The switching over voltages depends on the normal voltage of the system and hence increases with increased system voltage. The over voltages thus generated last for longer durations and therefore are severe and more dangerous to the system. An optimum operation point on the reference voltage or current wave should be determined such that the resulting transient over voltage after the operation is minimum. In Table- 3.13 we can see that, in the single circuit line, maximum overvoltage was recorded

1.56pu at Boropukuria 400KV line. Also, in double circuit line maximum overvoltage was recorded 1.47pu in Bibiyana 400KV line. The instant to apply controlled switching operation command to the circuit breaker should be determined such that the circuit breaker operates at the pre-determined point. In order to accomplish this task, switching has to be at voltage zero point, to get minimum overvoltage.

3.7 Control of Switching Transient Overvoltage:

According to the IEEE Standard 399-1980 **[57]** recommends on the following "philosophy of mitigation and control" of switching transient overvoltage:

i. minimizing the number and severity of switching events

ii. restriction of the rate of exchange of energy that prevails among system elements during the transient periods

iii. extraction of energy

iv. provision of energy reservoirs to contain released or trapped energy within safe limits of current and voltage

v. provision of preferred paths for elevated-frequency currents attending switching

vi. Shifting particularly offensive frequencies.

IEEE Standard 399-1980 recommends the implementation of this control philosophy through the judicious use of the following means:

i. temporary insertion of resistance between circuit elements, for example, insertion resistors in circuit breakers

ii. inrush control reactors

iii. damping resistors in filter circuits and surge-protective circuits

iv. tuning reactors

v. surge capacitors

vi. filters

vii. surge arrestors

viii. necessary switching only, with properly maintained switching devices

ix. Proper switching sequences.

There are also some additional means of reducing switching overvoltage on EHV and UHV.

i. High- voltage shunt reactors connected to the line to reduce power frequency overvoltage

ii. Eliminating or reducing trapped charge by

   - Line discharge by magnetic potential transformer
   - Low-voltage side disconnection of the line
   - Opening resistors
   - Single phase reclosing
   - Damping the overvoltage oscillations after disconnecting a line equipped with HV reactors

iii. Damping the transient oscillations of the switching overvoltage

   - Single stage closing resistors insertions
   - Multi stage closing resistors insertions
   - Closing resistors in line between CB and shunt reactor
   - Closing resistors in line on the line side of the shunt rector
   - Resonance circuit connected to the line

iv. Limitations of the surge arresters when

   - Energizing a line at no-load
   - Disconnecting rector loaded transformers
   - Disconnecting high voltage reactors

v. Simultaneously closing both end of the line

3.8 Overvoltage Protection

In addition to the overhead ground wires or shield wires, air gaps, surge diverters, and surge arresters are used to protect a power system against severe overvoltage. The effectiveness of overhead ground wires (OGW) for lightning protection depends on a low-impedance path to ground. Therefore, all metal structures in transmission lines having over- head ground wires should be adequately grounded. They should be tied together at the top of each structure to reduce the impedance to ground, if there are two over-head ground wire. An array of ground wires would be very effective but too expensive in a sense. For that reason, the maximum number of ground wires used is normally two both for single circuit and double circuit.

The simplest form of a diverter is rod gap. It contains a preset air gap designed to flashover first if there is an excessive overvoltage. It is connected between a phase conductor and ground. But the rod gap cannot clear itself and for that reason it will persist at the 50-Hz voltages. Also its electrodes are damaged in the arcing process. For a certain air gap, the time for breakdown changes almost inversely with the applied voltage. The breakdown time for positive voltages is lower than those for negative. A rod gap is set to a breakdown voltage that is not less than 30 percent below the withstand voltage level of the protected power apparatus. The surge diverters pass no current at the 50-Hz voltage and prevent the 50-Hz follow-on current after a flashover and break-down quickly after the arrival of the excessive overvoltage. The surge diverter derives its name from the fact that when a high-voltage surge reaches its gap spark over takes place and therefore the surge energy is diverted to the earth.

Surge arresters are also called lightning arresters. They are applied on electric systems to protect equipment such as transformers, rotating machines, etc. against the effects of overvoltage resulting from lightning, switching surges, or other disturbances. Surge arresters are also connected in shunt with equipment to be protected. Basically, it has a nonlinear resistor so that its resistance decreases rapidly as the voltage across it rises. After the surge ends and the voltage across the arrester returns to the normally 50-Hz line-to-neutral voltage level and the resistance becomes high enough to limit the arc current to a value that can be quenched by the series gap of the arrester. For that reason, the surge arrester provides both gap protection and nonlinear resistance. A disruptive discharge between the electrodes of a surge arrester is called spark over. The highest value of applied voltage which an arrester will not flash is the withstand voltage. Current that flows through an arrester caused by the 50-Hz- system voltage across it and during and after the flow of surge current is called flow current **[55].**

Chapter 4

Conclusion

4.1 Environmental Effects of Overhead Transmission Lines:

The importance of minimizing the environmental effects of overhead transmission lines has increased substantially due to our increasing demand for the use of greater EHV and UHV levels. Furthermore, the effects and magnitude of audible noise, televisions interference, radio noise, magnetic field and electric field must not be predicted and analyzed in the line design stage but also measured directly. Measurements of corona-related phenomena must include televisions, audible-noise levels and radio station signal strengths. To determine the effects of a transmission line of these quantities, the necessary measurements should be taken at three different times **[58].**

1. Before construction of the line
2. After construction but before energization
3. After energization of the line.

Noise measurements should also be measured at several locations along the transmission line. Also, at each location, measurements might be taken at more than one point that might be of particular interest. Such points may include the edge of the right of way, the point of maximum noise, and the point 15.24m from the outer most conductors. Overhead transmission lines and stations also produce magnetic and electric fields, which have to be taken into consideration during the design process. The study of filed effects means induced voltages and currents in conducting bodies is becoming especially crucial as the operating voltages levels of transmission lines have been increasing due to the economics and operations benefits involved **[58]**. Nowadays, such study at UHV level involves the followings:

1. Calculations and measurements techniques for electric and magnetic fields.
2. Calculations and measurements of induced currents and voltages on objects of various shapes for all line voltages and design configurations
3. Calculation and measurement of currents and voltages induced in people as result of various induction mechanisms.

4. Investigation of sensitivity of people to various filed effects.
5. Study of conditions resulting in fuel ignition, corona from grounded objects, and other possible filed effects

The measurements of the transmission line electric filed must be made laterally at mid span and must extend at least to the edges of the right of way to determine the profile of the field. Even so, related electric filed effects such as voltages and currents induced in fences and vehicles should also be considered. Magnetic field effects are much less of concern than the electric filed effects for EHV and UHV transmission due to the fact magnetic field levels for normal values of load current is low. The quality and character of currents induced in the body by the magnetic effects have considerably less impact than those arising from that of an electric induction. For instance, the induced current densities in the human body are less than one-tenth those caused by the electric field induction. Furthermore, most of the environmental measurements are highly affected by the prevailing weather conditions and transmission line geometry. The weather conditions include precipitations levels, temperature, humidity, wind velocity and barometric pressure. **[59]**

4.2 Future Work

As the power system voltage becomes higher, the cost of the power system insulation greatly increases. The 400KV transmission system will be the back bone system in near future in Bangladesh and requires much higher system reliability. Therefore, a reasonable insulation design and coordination of power system need to be accomplished by limiting overvoltage effectively in power system. The insulation coordination and design can be divided into transmission line and substation part. The transmission lines used in this study are already constructed and are operating under PGCB. The results found can give us helpful insight during construction of the EHV and UHV transmission lines. Furthermore, this study includes referring to three-phase reclosing operation, which can be analyzed in future works. The settings of the circuit breaker and relay can be designed for EHV and UHV lines based on the results founds for a 400KV-230KV double circuit line for extensive protection as it has been observed that this type of connection leads to some drastic abnormalities. Even though while energizing or de-energizing, line safety procedures must be followed, for which our results can be considered as a helping tool during construction. Switching due to the lighting strike in the working location can also be an analytical part in the near future because lighting strike carries huge amount of current which will help to give an extensive protection in the EHV and UHV lines.

In addition, today switching method is applied using an external control device (controller), which takes system voltage and current signals as inputs. In the future, it is expected that these controllers will become internal equipment provided as a standard feature of circuit breakers. Furthermore, it also seems possible in the future that controlling algorithms will be integrated in the substation protection and control systems which leads to a result that the controlled switching will become a matter of software clicking only as well as the fault location can be detected automatically based on the fault information obtained from ETL and the resulting signal sent to the control center via GPS technologies. Finally, in future perspective of Bangladesh, it is much needed to continue such analysis because the power generation will increase exponentially in the near future as well as the voltage level of the transmission lines so to control the transient phenomena, the significance of transient analysis in HV, EHV and UHV transmission line cannot be overlooked.

4.3 Conclusion

Switching problems have been a general concern among utilities in ensuring a consistent quality of power supply, reliability as well as continuous prevention from transients and protection of system components in any network. In this study, the effect of transformer switching and fault is simulated and analyzed by using PSCAD software. Therefore, a detailed and thorough model simulation had to be developed which includes real operating conditions of 400 KV and 230KV transmission lines.

This analysis describes the switching transients and fault study of the 400KV-230KV Boropukuria to Bibiyana transmission line simulated by PSCAD or EMTP to ensure successful completion and reliable operation of the planned 400KV Boropukuria, Bogura, Kaliakair and Bibiyana transmission lines and the nearest substation of the particular area as well as the analysis showed that Bogura 230KV bus was affected the most than other buses of the 400KV-230KV double circuit line. Maximum effect of fault current was at Bogura 230KV bus. When a three phase ground fault injected in Bogura bus, current increased abnormally in response to the fault. These results indicated that a normal 400KV transmission line shows its regular characteristics during switching and faults but when a 400KV-230KV double circuit line is considered, the transient behavior changes aberrantly although they were cleared safely. In addition, availability of commercial viable and „quality‟ electrical energy in a bulk quantum is the basic need for the survival of the modern civilization. This is because electrical energy is the most convenient for generation, transmission, distribution, utilization, storage and control. The phase „Quality" refers to a target that electricity be delivered to the end users without exceeding the allowance limits in voltage deviation, frequency drift, wave shape distortion (pure sine wave) and outage. Typically the standard value is 5%, 1%, 5% and only 32 second/year (99.9999% availability) in the global context. So, the proper analysis is needed to fulfill the requirements to supply quality electricity.

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Appendix

ANSI - American National Standards Institute, a private, non-profit organization

That administers and coordinates the U.S. voluntary standards and conformity

Assessment system.

Transmission Line - A system of conductors that transfers electrical signals from one place to another.

SF_6 CB - Sulfur hexafluoride circuit breakers protect electrical power stations and distribution systems by interrupting electric currents, when tripped by a protective relay. Instead of oil, air, or a vacuum, a sulfur hexafluoride circuit breaker uses sulfur hexafluoride (SF_6) gas to cool and quench the arc on opening a circuit.

Transformer - A static electrical device that transfers electrical energy between two or more circuits through electromagnetic induction. A varying current in one coil of the transformer produces a varying magnetic field, which in turn induces a varying electromotive force (emf) or "voltage" in a second coil.

Generator - A device that converts mechanical energy into electrical energy for use in an external circuit. Sources of mechanical energy include steam turbines, gas turbines, water turbines, internal combustion engines and hand cranks.

Inrush Current - The instantaneous high input current drawn by a power supply or electrical equipment at turn-on. This arises due to the high initial currents required to charge the capacitors and inductors or transformers. The inrush current is also known as the switch–on surge, or the input surge current.

Ferranti effect - In electrical engineering, the Ferranti effect is an increase in voltage occurring at the receiving end of a long transmission line, above the voltage at the sending end. This occurs when the line is energized, but there is a very light load or the load is disconnected.

TRV - A transient recovery voltage (or TRV) for high-voltage circuit breakers is the voltage that appears across the terminals after current interruption.

Bewley‟s lattice diagram - Bewley's lattice diagram is a graphical method that has been widely used for determining value of a wave in transient analysis.

Bushing - In electric power, a bushing is an insulated device that allows an electrical conductor to pass safely through a grounded conducting barrier such as the case of a transformer or circuit breaker. Bushings are typically made from porcelain, though other materials are possible.

Ferroresonance effects - Ferroresonance or nonlinear resonance is a type of resonance in electric circuits which occurs when a circuit containing a nonlinear inductance is fed from a source that has series capacitance, and the circuit is subjected to a disturbance such as opening of a switch.

Travelling Waves - Travelling waves are the current and voltage waves which travel from the sending end of a transmission line to the other end.

Transient Current - an oscillatory or aperiodic current that flows in a circuit for a short time following an electromagnetic disturbance (as a nearby stroke of lightning)

RLC circuit - an electrical circuit consisting of a resistor (R), an inductor (L), and a capacitor (C), connected in series or in parallel. This configuration forms a harmonic oscillator.

Positive Sequence - It indicates three equal phasors which are 120 degrees apart and has same phase sequence as the original signal. In our case this will be the source/supply current/voltage.

Zero Sequence - It indicates three phasors of equal magnitude with zero phase displacement that is in phase.

Negative sequence - It indicates three equal phasors which are 120 degrees apart and has opposite phase sequence as the original signal.

EHV Transmission Line - In electric power transmission engineering, EHV is classified as voltages in the range of 345,000 - 765,000 volts.

UHV Transmission Line – Ultra High Voltage (UHV) line can transmit higher than 800 kV.

Current Chopping - Current Chopping in circuit breaker is defined as a phenomenon in which current is forcibly interrupted before the natural current zero. Current Chopping is mainly observed in Vacuum Circuit Breaker and Air Blast Circuit Breaker.

Corona Effect - A corona discharge or effect is an electrical discharge brought on by the ionization of a fluid such as air surrounding a conductor that is electrically charged.

Spontaneous corona discharges occur naturally in high-voltage systems unless care is taken to limit the electric field strength.

Sag in Transmission line - Sag in overhead Transmission line conductor refers to the difference in level between the point of support and the lowest point on the conductor.

Surge Arrestors - A surge arrester is a device to protect electrical equipment from over-voltage transients caused by external (lightning) or internal (switching) events.