SWITCHING TRANSIENTS AND FERRORESONACE IN THE POWER SYSTEM

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MAY 2013

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Major Project Report

Submitted in partial fulfillment of the requirements for the

degree of

Master of Technology in Electrical Engineering

(Electrical Power System)

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Undertaking For Originality of the Work

I **Miss. Rachana V. Parikh**,(**Roll No: 11MEEE11**), give undertaking that the Major Project entitled **SWITCHING TRANSIENTS AND FERRORESONCE IN POWER SYSTEM** submitted by me, towards the partial fulfillment of the requirement for the degree of Master of Technology in **Electrical Power Systems**, **Electrical Engineering**, under Institute of Technology,Nirma University,Ahmedabad is the original work carried out by me and I give assurance that no attempt of Plagiarism has been made.I understand that in the event of any similarity found subsequently with any published work or any Dissertation work elsewhere; it will result in severe disciplinary action.

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Certificate

This is to certify that the Major Project Report entitled ***SWITCHING TRANSIENTS AND FERRORESONCE IN POWER SYSTEM*** submitted by **Rachana. V. Parikh (11MEEE11)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in field of Electrical Power System of Nirma University is the record of work carried out by him/her under our supervision and guidance. The work submitted has reached a level required for being accepted for examination. The results embodied in this major project work to the best of my knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Acknowledgements

It is a matter of extreme honor and privilege for me to offer my grateful acknowledgement to my supervisors **Mr. Ramana Budha** for providing me a chance to work under their guidance and supervision, assisting with all kinds of support and inspiration, wide counsel, excellent guidance, which they proffered throughout this investigation and preparation of the thesis. I would also like to thank **Mr. J.D.Parmar**, **Vise president, Power System Consulting** for permitting me to carry out project work.

I am profound obliged to **Prof. C.R. Mehta** and **Prof. D.M. Mehta Nirma University, Institute of Engineering and Technology, Ahmedabad** for his constant encouragement and needful help during various stages of the work.I would also like to thank **Dr. K. Kotecha**, Director, Institute of Technology, Nirma University for allowing me to carry out my project work in industry. I am thankful to Nirma University for providing all kind of required resources.

I express my thanks to all the staff members of Electrical Depatment, Nirma University and staff of P.S.Consultancy for their help. I extent my heartfelt thanks to my family and well wishers.

I pay my regards to The Almighty for his love and blessing.

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Abstract

Over the last decades, power disturbances have become an important factor on the increase throughout electrical networks. It is worth mentioning switching transients and ferroresonance in the network. Ferroresonance is a special case of resonance involving non-linear inductances that mainly affects the functionality of transformers and it is originate from the switching transients. Little is known about this complex phenomenon as it is rare and cannot be analyzed or predicted by the computation methods, it's analysis is done by computer simulations.

Switching transients and ferroresonance phenomena were simulated in PSCAD software to study its effect. Simulation of Switching transients with Energization of transmission line with and without trapped charges, analyze TRV/RRRV for fault conditions and inductive current switching overvoltage to check this overvoltages are within BIL limits or not with as per standards.

Another case of ferroresonance can be simulated with single phase switching and with grading capacitance of circuit breakers. This simulation also include ferroresonance overvoltage mitigation with the help of reactor connected in tertiary winding. Also, simulated a real case of traction system where the potential transformers were failed because of overcoltages due to ferroresonance, simulated case to check ferroresonance condition.

List of Abbreviation

BIL .... Basic Insulation Level
CVT .... Capacitor Voltage Transformer
EHV .... Extra High Voltage
IEC .... International Electrotechnical Commission
HVDC .... High Voltage Direct Current
L-G .... Line to ground
PSCAD .... Power System Computer Aided Design
PT .... potential Transformer
pf .... pica farad
RRRV .... Rate of Rise of Restriking voltage
TRV .... Transient Recovery Voltage

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Chapter 1

Overview

Transient is an event in which a new path for current is created or an existing path eliminated including faults, circuit breaker operation and lightening strikes. It is basically momentary changes in voltage and current that occurs over a short circuit period of time. Two types of transient impulsive and oscillatory. Lightning and switching are the sources of transient.

Ferroresonance is an oscillating phenomena occurring in an electric circuit which must contain at least:

- a non-linear inductance (ferromagnetic and saturable),
- a capacitor,
- a voltage source (generally sinusoidal),
- low losses.

Power system contain large number of inductances and capacitance in the network . This Capacitance comes from protective elements (circuit breaker grading capacitance), power transmission elements (conductor to earth capacitance, cables capacitance, bus bar capacitance, coupling between double circuit lines, capacitor banks), isolation elements (bushing capacitance), measurement elements (capacitive voltage transformers) The saturable inductance from Transformer iron core saturation, Residual fluxes in transformer core. The Low losses from Low value resistance (low loss transformer, unload transformer low circuit losses).

The main feature of this phenomenon is that more than one stable steady state response is possible for the same set of the network parameters. Transients, lightning overvoltage, energizing or re-energizing transformers or loads, occurrence or removal of faults, initial conditions of the system, transformer iron core saturation characteristic, residual fluxes in the transformer core, etc may initiate ferroresonance. The response can suddenly jump from one normal steady state response (sinusoidal at the same frequency as the source) to an another ferroresonant steady state response characterized by high sustain over voltages and harmonic levels which can lead to serious damage to the equipment.

1.1 OBJECTIVE OF PROJECT

The switching transient analysis is primarily important in insulation co-ordination for EHV network and it helps to reduce the damage to the equipments by checking the equipment BIL is within limit or not. This switching transients can be suppressed by:

- Pre insertion Resistor of circuit breaker
- Controlled closing of circuit breaker
- Surge arrestor

Ferroresonance is nonlinear phenomenon which occurs due to ferromagnetic material which have nonlinear characteristics, and so it occurs between nonlinear inductance and capacitance that affect power networks. This creates large over voltage that damage the system. So, the main objective is to prevent the consequences of ferroresonance. Hence it is necessary to

- Understand the phenomenon
- Predict it
- Identify it and
- Eliminate it.

1.2 PLANNING OF THE PROJECT

PSCAD/EMTDC simulation tool being used in this project work to analyzes the ferroresonance behavior.

- Simulation switching phenomenon in PSCAD.
- Analysis switching transients by monitoring TRV/RRRV in the fault condition and shunt reactor switching.
- Creates ferroresonance case study using PSCAD. BY:
    a. Simulations with presence of capacitance and non-linear inductances.
    b. Single phase switching of breaker.
    c. Lightly loaded system components i.e. Transformer.
- Method to preventive ferroresonance.

Chapter 2

Literature Survey

Reference [1] provides standard voltage limits of temporary and transient over voltages and also provides standard data for transmission planning studies for different conductors and also provides planning philosophy for the transmission line[1].

Reference [2] Provides guideline about slow transients due to witch it occurs[2].

Reference [3] and Reference [4] provides guideline about the fast and Very fast transient in witch conditions it occurs and also provides guideline to modeling the equipment same[3][4].

Reference [5] provides basic definitions, principles and rules regarding insulation coordination switching transients and overvoltages. Also provides standard withstand voltages for example standard short duration power frequency withstand voltages, standard impulse withstand voltages, standard impulse voltages for different insulations for example phase to earth insulation and phase to phase insulation[5].

Reference [6] and Reference [7] provides basic theory of transients in the power system[6][7].

Reference [8] provides basics of overvoltages that occurs in the power system in detail and basics of insulation co-ordination between surge arrester and equipment in the power system network[8].

Reference[9] provides basic theory and equations related to TRV/RRRV[9].

Reference[10] provides standard values for TRV and RRRV[10].

Reference [11] provides theory and equations related to reactor switching[11].

Reference [12] includes the basic concept of transients in the power system and basic characteristics of resonance and ferroresonance in the power system[12].
Reference [13] It present one case of ferroresonance due to double circuit line and its remedy and also detail discussion about ferroresonance occurs particularly for this case[13].

Reference[14] provides description the basics of ferroresonance, credible prediction and evaluation of the rise of ferroresonance, examples of ferroresonance conditions and practical solutions to avoid the ferroresonance[14].

Reference[15] provides guideline of mitigating the ferroresonance[15].

Chapter 3

Introduction to PSCAD

PSCAD is a simulator of ac power systems, low voltage power electronics systems, high voltage DC transmission (HVDC), flexible AC transmission systems (FACTS), distribution systems, and complex controllers.The models used in PSCAD are:
Resistors, inductors, capacitors, Mutually coupled windings, such as transformers, Frequency dependent transmission lines and cables, Current and voltage sources, Switches and breakers, Protection and relaying, Diodes, thyristors, Analog and digital control functions, AC and DC machines, exciters, governors, stabilizers and inertial models, Meters and measuring functions, Generic DC and AC controls, HVDC, SVC, and other FACTS controllers, Wind source, turbines and governors.
The following are some of the studies that can be conducted with PSCAD:

- Insulation coordination of AC and DC equipment.
- Traditional power system studies, including TOV, TRV, faults, reclosure, and ferroresonance.
- Relay testing (waveforms) and detailed analysis of the CT/VT/CCVT responses and their impact on operation.
- Designing power electronic systems and controls including FACTS devices, active filters, low voltage series and shunt compensation devices.

- Incorporate the capabilities of MATLAB/Simulink directly into PSCAD/EMTDC.
- Sub synchronous oscillations, their damping and resonance.
- Effects of DC currents and geomagnetically induced currents on power systems, inrush effects and ferroresonance.
- Distribution system design, including transient overvoltage, with custom power controllers and distributed generation.
- Power quality analysis and improvement, including harmonic impedance scans, motor starting sags and swells, non-linear loads, such as arc furnaces and associated flicker measurement.
- Design of modern transportation systems (ships, rail, automotive) using power electronics.
- Design, control coordination and system integration of wind farms, diesel systems, and energy storage.
- Variable speed drives, their design and control.
- Industrial systems.
- Intelligent multiple-run optimization techniques can be applied to both control systems and electrical parameters.

Modelling of equipments when simulating:

a. **Source:**

Source models are represent with this existing information: magnitude of AC line to line rms value, voltage ramp up time, fundamental frequency, phase shift and branch positive sequence **source impedance types** which are purely resistive, parallel RL in series with resistive, ideal (R=0) source. For external inputs with connecting slider for convenient runtime manual adjustment or use control system output for dynamic adjustment witch are shown in fig. 3.1 (a) to 3.1(e) in witch 3.1(a) single phase view of RRL type source 3.1(b) three phase view of R/RL type source 3.1(c) ideal source without any short circuit impedance 3.1(d) source with external control of voltage frequency and phase 3.1(e) single phase source.

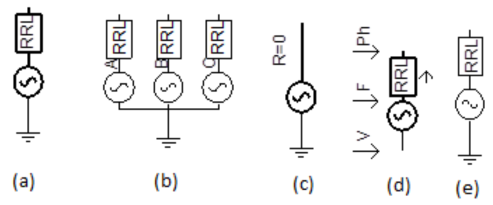


Figure 3.1: Figs of source impedance types

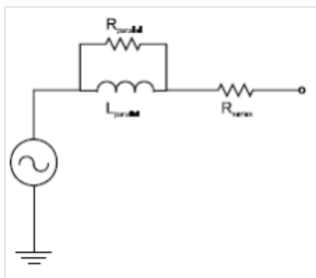


Figure 3.2: Equivalent circuit if contain RRL source impedance

b. **Transformer:**

Transformer models are represented with this existing information : MVA rating, wingding configuration and voltage, tap change range and normal setting, leakage reactance between windings, knee point of transformer core saturation characteristic in per unit of rate flux or voltage, and estimated saturated air core reactance. In PSCAD transformer represents as single or three phase model with different types classical and UMEC (unified magnetic equipment circuit).

This UMEC model is very accurate for transformer in saturation case indicated in fig.3.3. This with different transformer windings for example 2-winding, 3-winding, 4-winding etc.

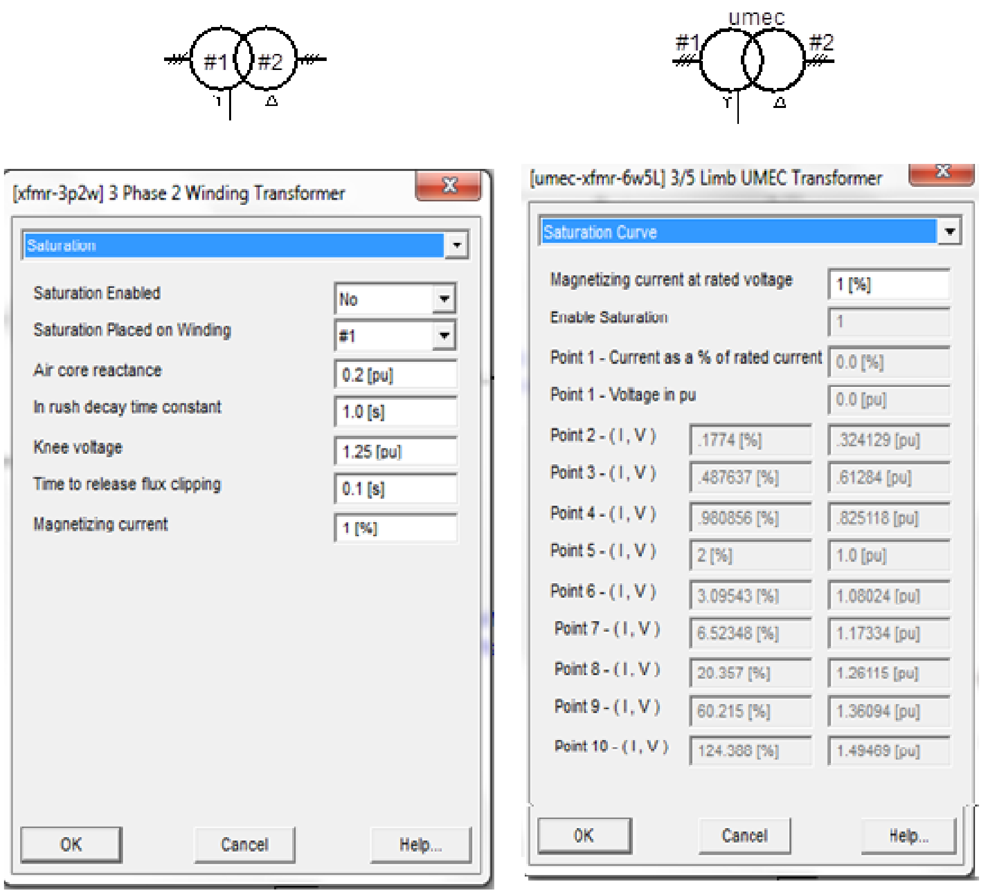


Figure 3.3: classical model and UMEC model and its characteristics

c. **Transmission line:**

The transmission line represented in network, dimensions and data are required. This can be given at the tower, and include conductor sag. Shield wire dimensions and resistance are also provided. The transmission line data require includes: transmission line conductor diameter and resistance per unit length of transmission line, phase transformation data and distance between phase bundle, spacing between phases, shield wire diameter and resistance per unit length, height of each conductor and shield wire at the tower and sag to midspan, tower dimensions, and ground conductivity. Transmission line model have two models:

- PI model
- Distributed model

PI Model: for frequency domain studies, transmission lines modeled with Pi

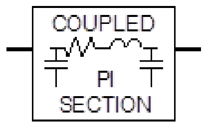


Figure 3.4: PI Model

lines can be precise, in the time domain, particularly for long lines (where propagation travel time spans many time steps), precision suffers. Pi line sections are most useful for very short transmission lines where the propagation travel time is less than one time step. Model represent with impedance/ admittance data in R,X_L,X_C in p.u. or ohms or R,X,B in p.u. or ohms,line rated frequency and line length.

Distributed Model:

The distributed transmission line models operate on the principle of traveling waves. A voltage disturbance will travel along a conductor at its propagation velocity (near the speed of light along overhead lines) until it is reflected at the end of the line. In a sense, a transmission line or cable is a delay function. Whatever is fed into one end will appear at the other end after some delay, perhaps slightly distorted. The calculation time step of the simulation should be less than the propagation time.

Distribution line model designed with Bergeron model, frequency mode model and frequency phase model. Bergeron model is very simple, constant frequency model based on travelling time. It is useful studies where it is most important to get the correct steady state impedance/admittance of line but should not be used where the transient or harmonic behavior is important. And frequency model are important in transient studies. Frequency dependent mode model is accurate for one conductor lines and two horizontal conductor or three phase line with ideally transposed line geometry. This frequency dependent model used with the tower model and Bergeron model used with manual data entry.

Circuit Breaker: The circuit breakers that will be switched are identified on the study system. Other parameters of the circuit breakers are determined: protection delay or clearing times, maximum fundamental frequency switching voltage, maximum capacitive switching capability, reclosing sequence, rated transient recovery voltage and maximum rate of rise of transient recovery voltage, mechanical closing time and variation in pole closing times, and closing resister. Breaker is work by its logic it is set as shown in fig.3.5 as a block.

Surge Arrester: They are very important in the determination of economic insulation level. It is the best way to choose arresters with the lowest possible protective consistent with the remainder of the system. The installed location and rating of surge arresters are provided. The maximum ratings, and in particular the energy absorption capability will be determined with study and characteristic V-I of surge arresters are provided. Fig.3.6 shows the arrester and the its V-I characteristics .

Output Signal: This component records the signal connected to it, for the purpose of display in a graph, meter, or for insertion into an output file. The signal name given as a an input only that name is given to the output signal. fig. 3.7 indicates output signal.

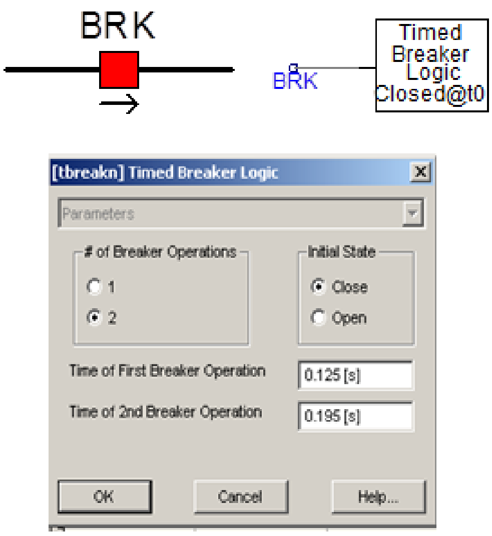


Figure 3.5: Circuit Breaker and its logic

Modelling of Electrical Equipments in Case of Transient Studies: Substation equipments, such as circuit breakers, substation transformers, and instrument transformers, are represented by their stray capacitances to ground. The capacitance of CVTs should also be represented. Disconnecter switches or breakers have more than one support, appropriate capacitances should be added to the model. As shown in figure 3.9.

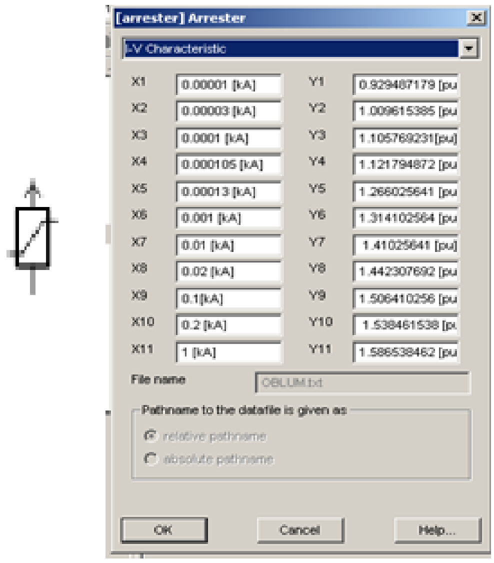


Figure 3.6: Surge Arrester And Its Characteristic

Figure 3.7: Output Signal

Equipment	Capacitance –to - ground		
	115kV	400kV	765kV
Disconnector Switch	100 pF	200 pF	160 pF
Circuit Breaker (Dead Tenk)	100 pF	150 pF	600 pF
Bus support Insulator	80 pF	120 pF	150 pF
Capacitor potential Transformer	8000 pF	5000 pF	4000 pF
Magnetic Potential transformer	500 pF	550 pF	600 pF
Current Transformer	3500 pF	2700 pF	5000 pF

Figure 3.8: Values of capacitance of equipment used in substation

Chapter 4

Transients and Overvoltages in Power System

Transients in power system: It is short duration overvoltage of few milliseconds or less, oscillatory or nonconciliatory usually highly damped phenomenon. It is classified according to is frequency range is given below:

a. Switching Transient

b. Slow Transient

c. Fast Front Transient

d. Very Fast Front Transient

a. **Switching Transient:** It occurs in Frequency range of fundamental power frequency to 10KHz It occurs due to the various power system components such as transmission lines, cables, transformers, source equivalents, loads and circuit breakers. Switching over voltage is proportional to the operating voltage. It is important above 400KV level[1].

b. **Slow Transient:** It occurs in Frequency Range of 0.01Hz to 1000HZ. It occurs due to Torsional oscillations (5 to 120 Hz), Transient torsional torques (5 to

120 Hz), Fast bus transfer (1 to 1000 Hz), Controller interactions (10 to 30 Hz), Harmonic interactions and resonances (60 to 600 Hz), ferroresonance (1 to 1000 Hz)[2].

c. **Fast Front Transient:** It occurs in Frequency Range of 10KHz to 1MHz. It occurs due to lightning surge. The lightning overvoltages are caused by either shielding failures or backflashovers of the tower insulation on the transmission lines. These overvoltages will provide the data required for detailed arrester specifications. Then, the insulation levels (i.e., BIL) of the substation equipment can be coordinated with the protective level of the arresters[3]. The objectives of these studies:

- To characterize the magnitude of the lightning overvoltages for insulation requirements, and/or to find the critical lightning stroke current that causes insulation flashovers.
- Determine transmission or distribution Line Flash Over Rates (LFOR).
- Establish line arrester application guidelines.
- Find optimum location for surge arresters for lightning surge protection.
- Determine minimum phase-to-ground and phase to- phase clearances.
- Calculate Mean Time Between Failure (MTBF) for the substation.
- Determine optimum location of capacitances to reduce steepness of surges.

d. **Very Fast Front Transient:** It occurs in Frequency Range of 100KHz to 50MHz. This transients typically occur in the gas insulated substations (GIS) any time there is an instantaneous change in voltage. Most often this change occurs as the result of the opening or closing of a disconnect switch, operation of a circuit breaker, the closing of a grounding switch, or the occurrence of a fault, can also cause VFT. These transients generally have a very short rise time, in the range of 4 to 100 ns, and are normally followed by oscillations having frequencies in the range of 1 to 50 MHz. Their magnitude is in the range of 1.5 to 2.0 per unit of the line-to-neutral voltage peak, but they can also reach values as high as 2.5 per unit. These values are generally below the BIL of the GIS and connected equipment of lower voltage classes[4].

Overvoltage: It is defined as any voltage between one phase conductor and earth or across a longitudinal insulation having a peak value exceeding the peak of the highest voltage of the system which is:

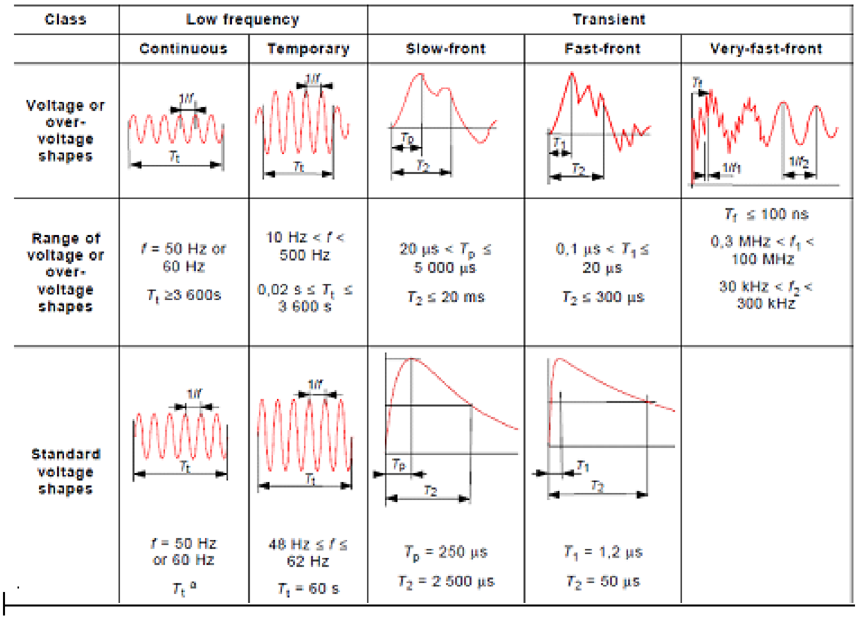
$$highestvoltage = supplyvoltage * \sqrt{2/3} \tag{4.1}$$

or - between phase conductors having a peak value exceeding the amplitude of the highest voltage of the system.

a. **Continuous power-frequency voltage:** A power-frequency voltage with r.m.s. value equal to the highest voltage of the system, and with duration corresponding to the lifetime of the equipment. power-frequency voltage, considered having constant r.m.s. value, continuously applied to any pair of terminals of an insulation configuration[5].

b. **Temporary overvoltage:** power frequency overvoltage of relatively long duration which occurs due to sudden load rejection and single phase to ground fault. For example Temporary Over voltage: 400 kV system = 1.5pu peak phase to neutral (1pu=343kV)[1]. With power frequency voltage with r.m.s. value equal to the assumed maximum of the temporary overvoltages divided by 2 [5]

c. **Transient overvoltage:** short-duration overvoltage of few milliseconds or less, oscillatory or non-oscillatory, usually highly damped generated by the switching of transmission line or transformer. For example FOR 400kV= 2.5pu peak phase to neutral[1]. Its further classification given below[5].



Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz $T_t \geq 3\,600$s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20 µs T_2 ≤ 300 µs	T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	f = 50 Hz or 60 Hz T_t a	48 Hz ≤ f ≤ 62 Hz T_t = 60 s	T_p = 250 µs T_2 = 2 500 µs	T_1 = 1,2 µs T_2 = 50 µs	

Figure 4.1: Types of overvoltages

Chapter 5

Switching Study

Objective Of Switching Study[6]

- Insulation Co-ordination to determine overvoltage stress on the equipment
- Determining energy of arrester.
- Determining the TRV across circuit breaker.
- Determining effectiveness of transient mitigation device. For Example: pre insertion Resistor, Inductor, controlled closing device etc.

Switching operation is originate in the system itself by the[6]

- De-energization of transmission line, cable, shunt capacitor, capacitor banks.
- Disconnection of unloaded transformer, reactor
- Sudden shutting off of loads
- Short circuit and fault clearing
- Resonance phenomenon like ferroresonance.

Switching over voltage reduced by the following[6]

- Line energization by pre-insurtion Resistor

- Point on wave switching
- Limits the over voltage by using surge arresters.

PHENOMENON INVOLVE IN SWITCHING STUDY

Travelling Wave Phenomenon: When fault occurs or breaker reclose in overhead transmission lines systems, the abrupt changes in voltage and current at the point of the fault generate high frequency electromagnetic impulses called traveling waves which propagate along the transmission line in both directions away from the fault point. Surge Impedance of the line is the

$$\frac{V}{I} = \sqrt{L/C} = Zn \tag{5.1}$$

It is purely a characteristic of the transmission line. The value of this impedance is about 400Ω for overhead transmission line and 40Ω for cables. when they reach the other end of the lines or whenever they see a change in the impedance (impedance other than characteristic impedance of the line).

Open End Line: When line is the open at receiving end where the wave is going to see a change in impedance other then the characteristic impedance which is infinite. current at the open end is zero, the electromagnetic energy vanishes and is transformed into electrostatic energy. This means the potential of the open end is raised by V volts; therefore, the total potential of the open end when the wave reaches this end is: V+V=2V. The wave that starts travelling over the line when the switch S is closed, could be considered as the incident wave and after the wave reaches the open end, the rise in potential V could be considered due to a wave which is reflected at the open end and actual voltage at the open end could be considered as the refracted or transmitted wave and is thus incident wave + reflected wave = refracted wave. We have seen that for an open end line a travelling wave is reflected back with positive sign and coefficient of reflection as unity. At that time the current at the receiving end is zero so the current is reflected by its negative sign. After the voltage and current waves are reflected back from the open end, they reach the source end, the voltage over the line becomes 2V and the current is zero[7].

Short Circuited Line: When line is the short circuited at the receiving end where

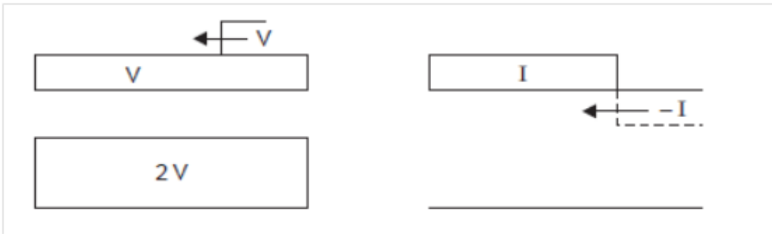


Figure 5.1: voltage and current in case of open end line

the wave is going to see change in impedance other then the characteristic impedance which is zero. Voltage at short end is zero so the electrostatic energy is converted to the electromagnetic energy. This means current at short circuited end is raised by I amperes. So the total current at the short end is I+I=2I. At that time the voltage at the receiving end is zero so it reflected by its negative sign. So at the source end the current value is 2I an the voltage value is zero[7].

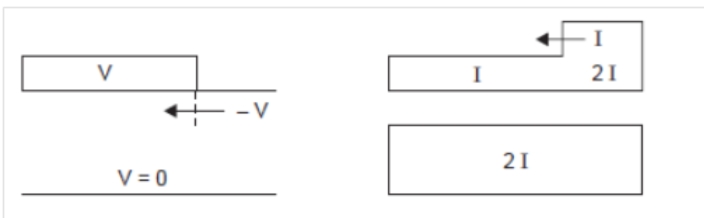


Figure 5.2: voltage and current in case of short end line

INSULATION CO-ORDINATION:

Insulation co-ordination: selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices[5]. It is means of correlation of the insulation of various equipment in the power system to the insulation of various equipment in power system to the insulation of the protective devises like lightning arrestor and protection of those equipment against over voltage like transformer or busbar. Figure shows the basic concept of insulation co-ordination. Curve A represents the characteristic of the protective device and Curve B represent the characteristic of equipment to be protected[7].

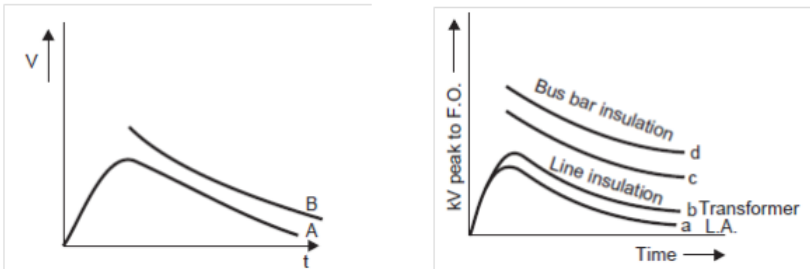


Figure 5.3: Insulation Co-ordination

Chapter 6

Case Study of Transmission Line Energization

Case Study of Line Energization is Based on Traveling wave Phenomenon and when circuit breaker is open near natural current zero at that time current through capacitance is 90 degree out of phase with voltage so this charge is trapped in the capacitor and when line is re-closed than this trapped charges of capacitance adds in system reflected voltage which results very high overvoltage. Two cases were Simulated for energization of Transmission line which are given below:

- Line energization without trapped charges
- Line energization with trapped charges

a. **Line energization without trapped charges:** For example energization of line by closing of breaker followed by initially open and closed at voltage peak.

b. **Line energization with trapped charges:** situation for an uncompensated line with trapped voltage during a reclosing operation. Energizing occurs at an instant with a large difference between (instantaneous) supply voltage and line voltage, a large traveling wave will be injected onto the line. When this wave reaches the open, far end of the line, it will be reflected and a high overvoltage will be initiated. Line energization with trapped charges was simulated by opening the breaker at current zero. The line voltage at the opening instant was at a peak value (for example at a positive peak). The breaker was reclosed at a bus voltage peak, with the polarity opposite to the line voltage (i.e. the D.C voltage across the capacitor) (negative peak, for this example). This results in the highest overvoltage and arrester energy for one restrike (reclosing) operation.

- **ENERGIZATION WITH TRAPPED CHARGES WITH SURGE ARRESTER:** Switching impulse voltage is approximately same in substation so that surge arrester provides to all equipments. Surge arresters are used to limits phase to ground switching overvoltages to level lower than about 0.7 p.u of switching overvoltage[8], because of its mov(metal oxide varistor) and it has property that it give high impedance to current at normal condition and low impedance path to current when high voltage condition i.e lightening and switching overvoltage condition. so, it reduce over voltage drastically.

- **Inrush Current:** The capability of circuit breaker to handle the inrush current normally expressed in terms of the product of inrush current peak times the inrush current frequency. Equation of inrush current is given below.

$$(\frac{di}{dt})_{max} = 2\Pi f_i t_{ipeak} \tag{6.1}$$

- **Description of Case study:** In this case with 400kV network with all equipment were considered, and 400kV Twin Moose conductor with length 140km shown in fig.6.1 in this case breaker breaker(BRK) operation is considered. First case is of Energization of Transmission line without trapped charges in this case breaker is closed at t=0.105 Second shown in fig.6.1 to fig. 6.5, second case is of Energization of transmission line with trapped charges in simulated case line open at t=0.125 Second and reclosed at t=0.195 Second witch shown in fig 6.6 to fig. 6.8. The third case is with arrester with trapped charges this can be shown in fig.6.9 to fig.6.11. All three case results are shown with supply side voltage, remote end side voltage and with charging current. The table represents the observed quantities for all cases with standard BIL limit is shown in fig 6.1. The observations and table from the observation are given below:

a. For Line Energization without trapped charges the maximum overvoltage observed was 620kV which is within the BIL limit of 950kV for 400kV system as per IEC-60071-1[5].

b. For Line Energization with trapped charges meximum voltage observed was 940kV which near about BIL limit i.e. 950kV.

c. With the help of arrester over voltage is 782kV. So that with help of arrester the overvoltage can be reduced. The metal oxide surge arrester are used to limit phase to ground switching overvoltages to level lower than about 0.7 p.u of switching overvoltages[8].

Switching Operation	Phase Voltage (kV) for 400 kV	BIL(kV) for 400kV (As per IEC-60071-1)	Length of Line (km)	Supply Side Voltage (kV)	Remote End side Voltage(kV)
Energization of Line without Trapped Charges	326.6	950	140	564	620
Energization of Line with Trapped Charges	326.6	950	140	795	940
Energization of Line with Trapped Charges with Surge Arrester	326.6	950	140	500	782

Figure 6.1: Observation Table for all cases

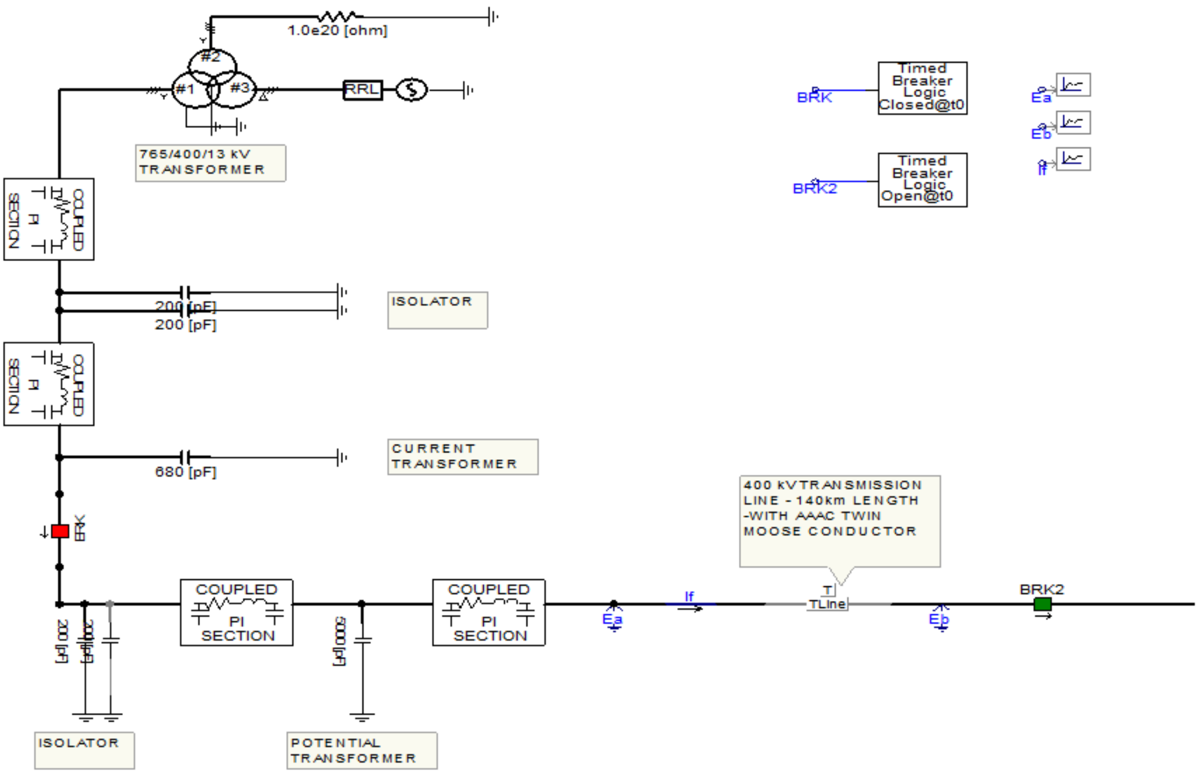


Figure 6.2: PSCAD Circuit for Line Energization and Reclosing case study

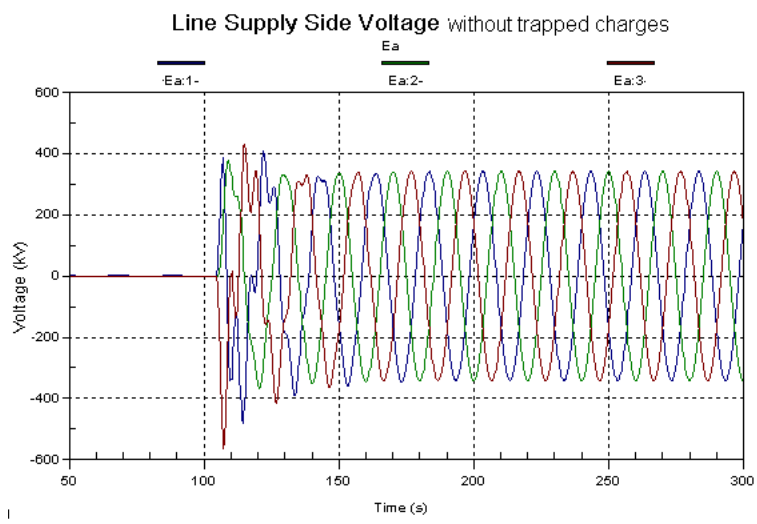


Figure 6.3: Line Supply Side Voltage without trapped Charges

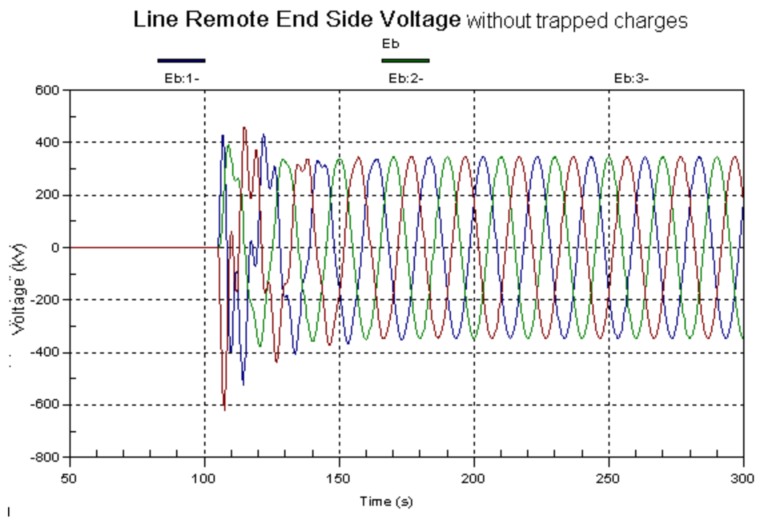


Figure 6.4: Line Remote Side Voltage without trapped Charges

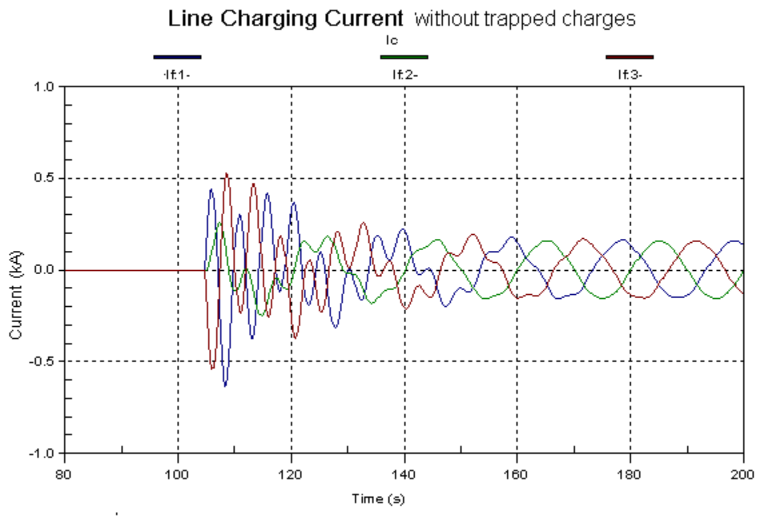


Figure 6.5: Charging Current Without trapped charges

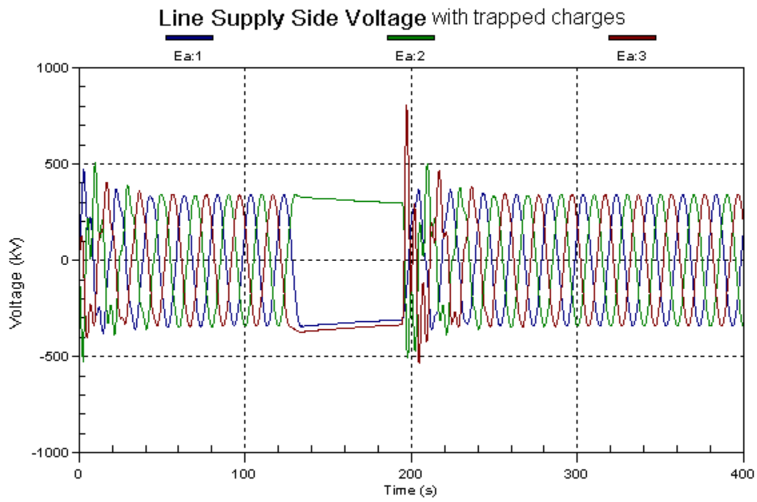


Figure 6.6: Line Supply Side Voltage with trapped Charges

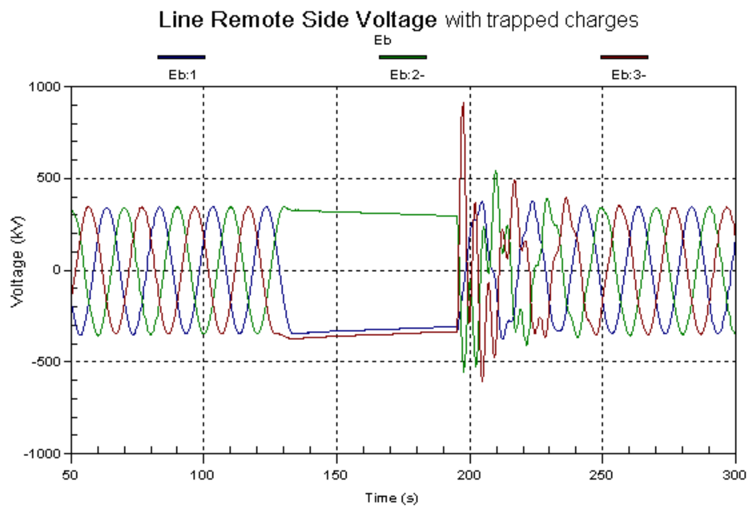


Figure 6.7: Line Remote Side Voltage with trapped Charges

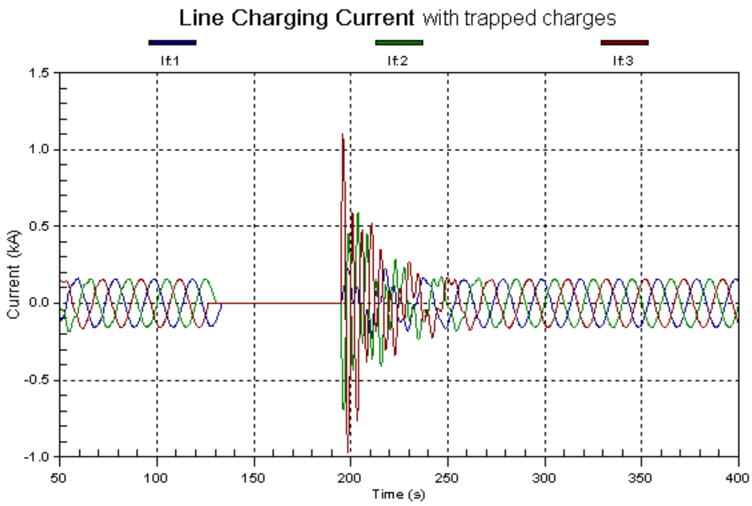


Figure 6.8: Charging Current With trapped charges

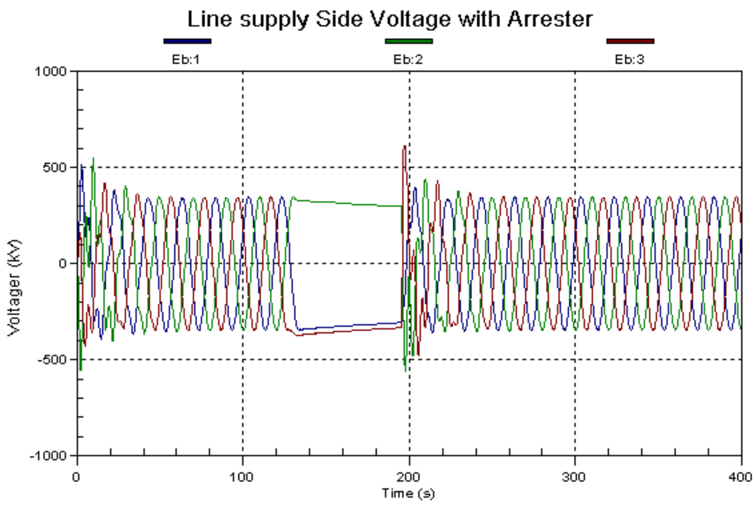


Figure 6.9: Line Supply Side Voltage with trapped Charges with Arrester

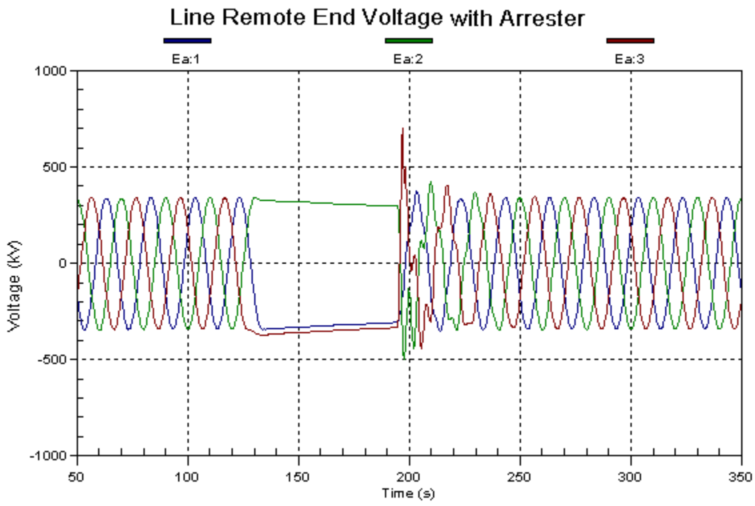


Figure 6.10: Line Remote Side Voltage with trapped Charges with Arrester

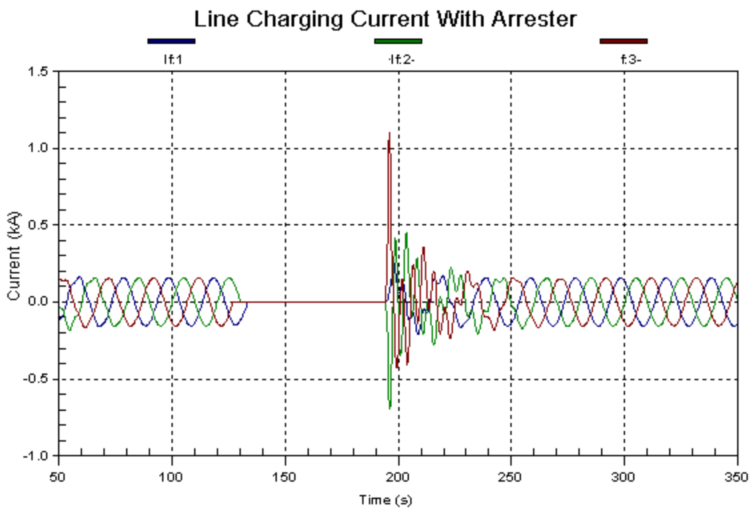


Figure 6.11: Charging Current With trapped charges with Arrester

Chapter 7

Analysis of Switching Transient by TRV/RRRV of Breaker

TRV is the transient voltage that appears across the poles of a circuit breaker upon interrupting a circuit. When arc gets extinguished a frequency voltage transient appears across the contacts which is superimposed on power frequency system voltage. This high frequency transient voltage tries to restrike the arc. Hence, it is called restiking voltage or transient recovery voltage. Power frequency system appearing between the poles after arc extinction called recovery voltage. So, TRV is equal to power frequency component which is continuous and oscillatory component due to inductance and capacitance present in the network which is subsides after few milliseconds. Power frequency of transient component is

$$f = \frac{1}{2\Pi\sqrt{L/C}} \tag{7.1}$$

Which is ranging from few Hz to several thousand of Hz depending on circuit parameters. Here TRV Analysis is done by analysis of fault condition and measure the TRV across the breaker. Fault occurance and removal is one of the reasons of occurrence of ferroresonance. This TRV is the difference of supply side voltage and load side voltage. TRV defined in standard are inherent values that would be obtained during interruption by ideal circuit breaker without arc. Exponential, oscillatory, triangular is the types of TRV. Exponential and oscillatory TRV are most sever in 3-Φ faults and triangular TRV associated with line faults. Test are required at 100, 60, 30 and 10 percent of rated shot circuit current with the corresponding TRV and recovery voltage.

If the dielectric strength of the medium between the contacts does not build up faster than the rate of rise of transient recovery voltage, the breakdown takes place causing re establishment of the arc. If dielectric strength of contacts space builds up very rapidly so that it is more than the rate of rise of transient recovery voltage of circuit breaker interrupts successfully. If contacts space breaks down within a period of one fourth of cycle seconds from initial arc extinction the phase is called re-ignition and after one fourth of cycle the phenomenon called resrike.

TRV refers to breaker pole to first clear. It is the voltage across the first pole to clear, the same is generally higher than across the two poles which clears later. First pole to clear factor is ratio of RMS voltage between healthy phase and faulty phase to phase to neutral voltage when fault removed or ratio of power frequency voltage across the interrupting pole before current interruption in other poles to power frequency voltage occurring across the pole to poles after interruption in all three poles. This first pole to clear factor 1.5 ungrounded faults or not effectively ground system. It is 1.3 for effectively grounded neutral. A 3-Φ ungrounded fault produces high TRV peaks but probability of occurrence is low. Less than 100kV - TRV rating assume that system can be operated ungrounded. 100kV to 170kV TRV assume that system can be operated both un grounded and grounded. Above 170kV TRV assume that system operated as effectively ground system. Two and four parameter envelop for TRV are shown in the figure 7.2 and 7.3 below[9].

Neutral	X_0/X_1	Pole-to-clear factor k_p		
	Ratio	First	Second	Third
Ungrounded	Infinite	1.5	0.87	0.87
Effectively grounded	3.0	1.3	1.25	1.0
See NOTE	1.0	1.0	1.0	1.0

NOTE—Values of the pole-to-clear factor are given for $X_0/X_1 = 1.0$ to indicate the trend in the special case of networks with a ratio X_0/X_1 of less than 3.0.

Figure 7.1: Table of pole to clear factor

- **Description of Case study:** Here 400kV network has considered with all equipment shown in fig 7.4 with fault on line remote end side fault and the doted line represents line Terminal fault and in this case breaker (BRK) operation is to be considered. Simulation results represents the waveforms of Fault current, TRV and RRRV across the circuit breaker. The waveform is represented for the LLL-G fault for grounded network for both line terminal fault shown in fig 7.5 to 7.7 and line remote end fault shown in fig 7.8 to 7.10 and observation values for all fault is shown in fig 7.11. So that the observations are given below.

  a. For Terminal Fault, highest TRV observed was 554kV witch is within the limit i.e. 624kV and RRRV is 1.3kV/s witch is within the limit i.e. 2kV/s as per IEC-62271-10[10].

  b. For Remote Fault, highest TRV observed was 386kv witch is within the limit i.e. 634kV and RRRV is 0.86kV/s witch is within the limit i.e. 2kV/s as per IEC-62271-10[10].

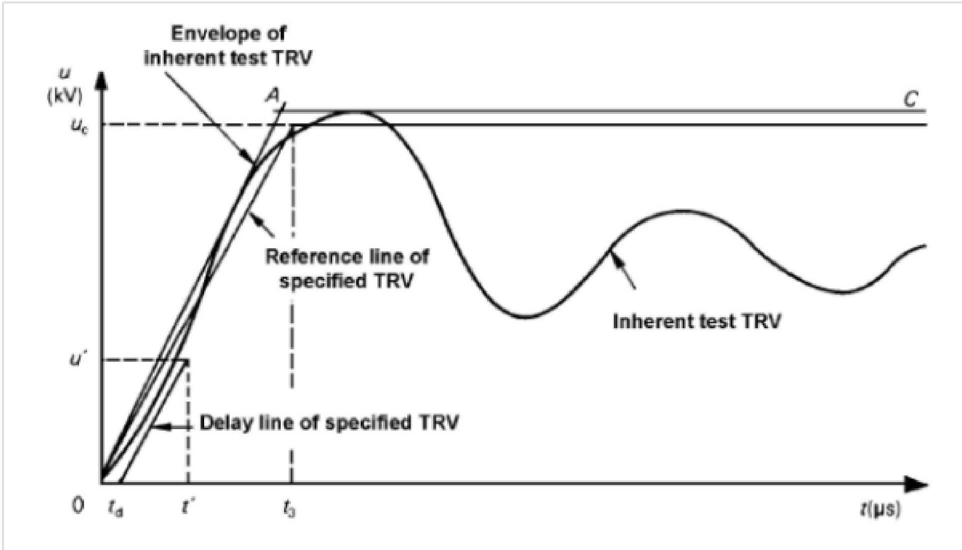


Figure 7.2: TRV two parameter envelop

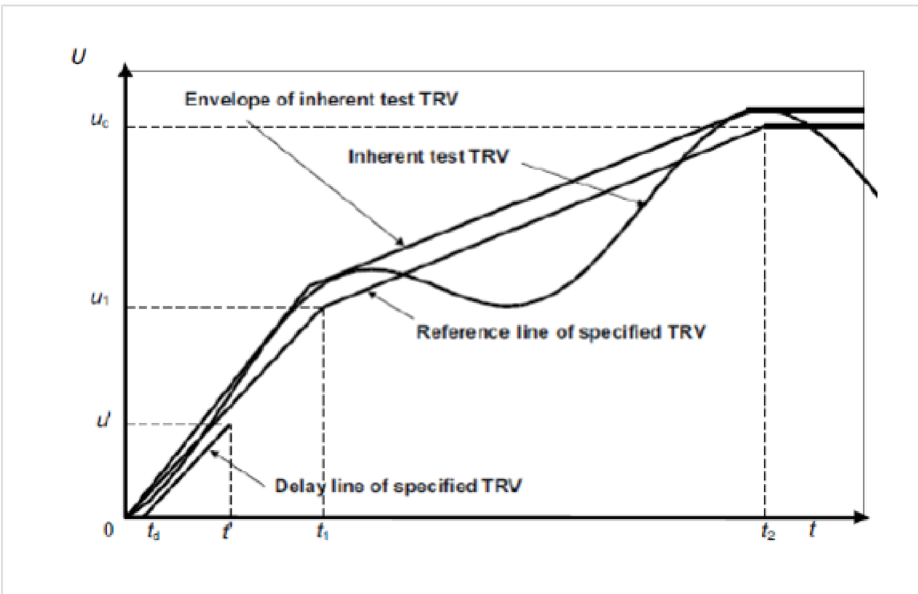


Figure 7.3: TRV four parameter envelop

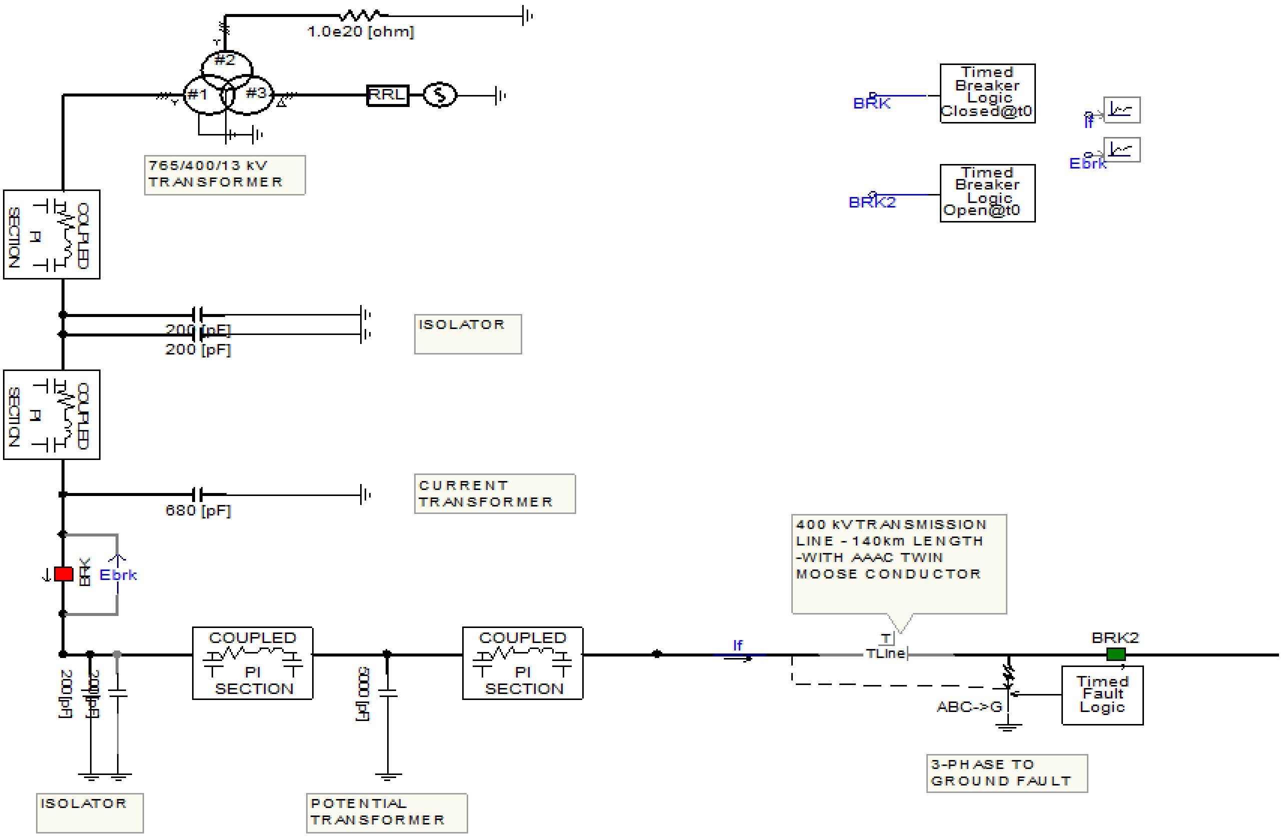


Figure 7.4: PSCAD circuit for fault case study

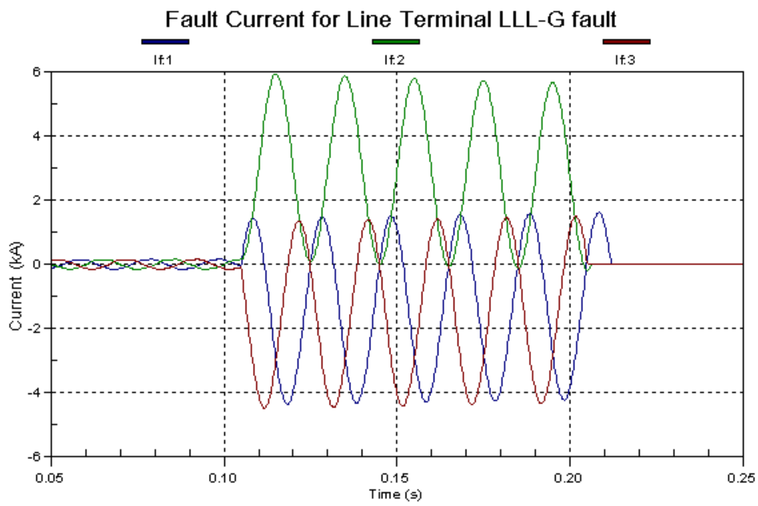


Figure 7.5: Fault Current for Line terminal LLL-G fault

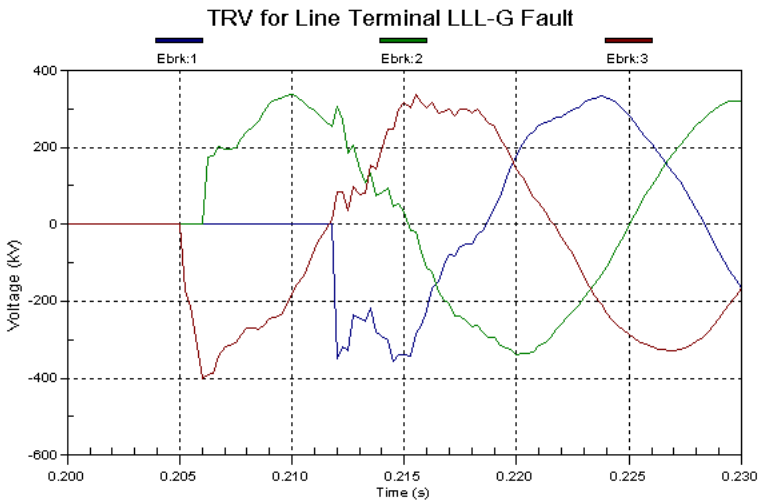


Figure 7.6: TRV for Line terminal LLL-G fault

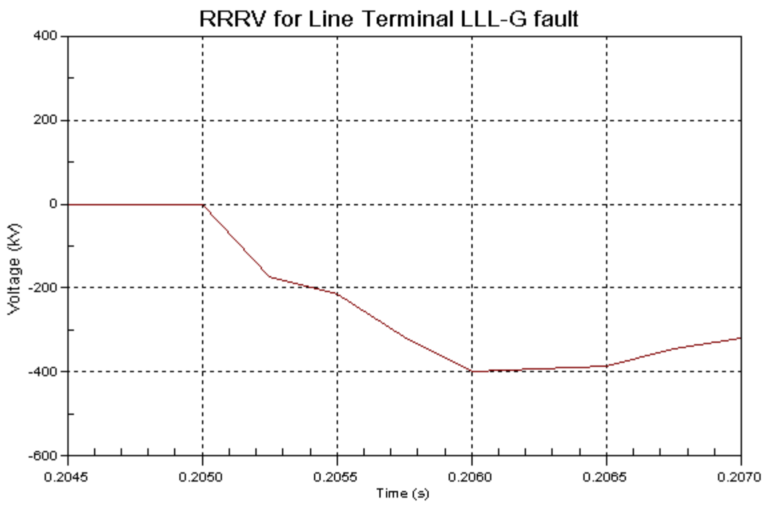


Figure 7.7: RRRV for Line terminal LLL-G fault

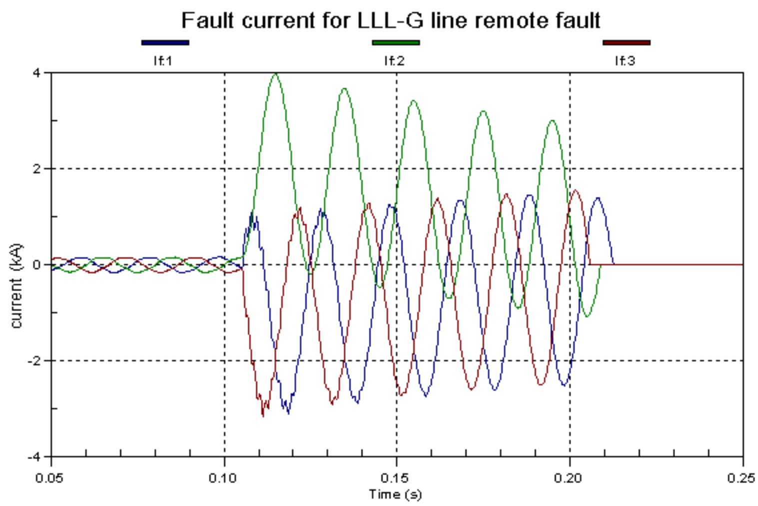


Figure 7.8: Fault current for Line Remote LLL-G fault

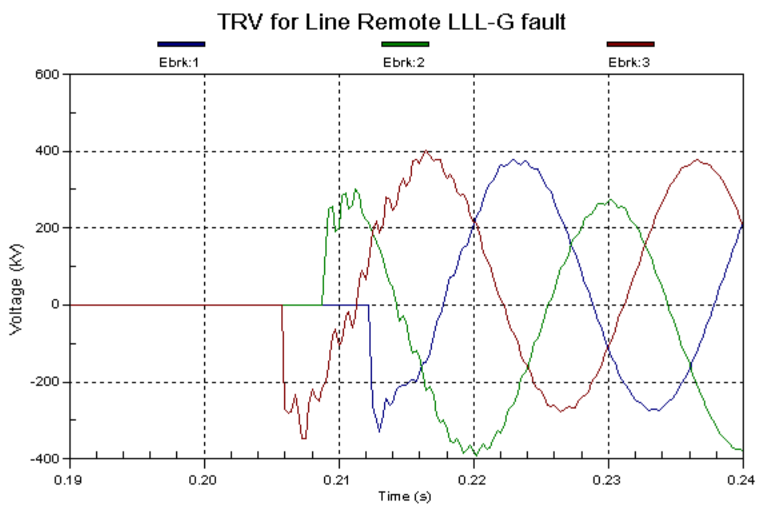


Figure 7.9: TRV for Line Remote LLL-G fault

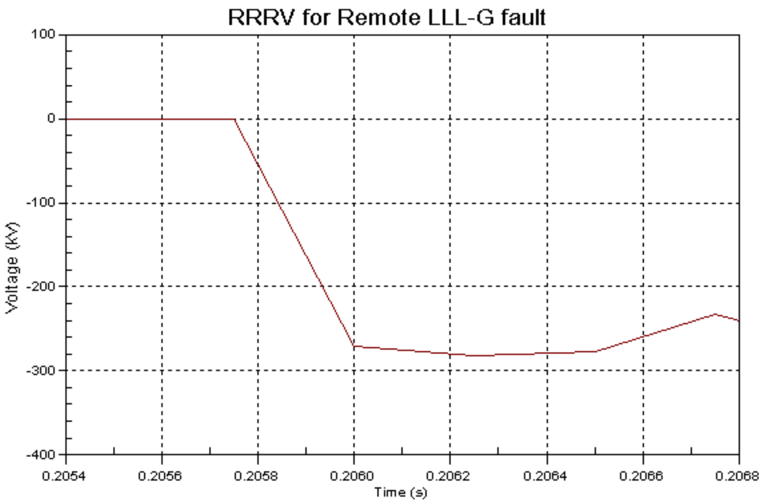


Figure 7.10: RRRV for Remote LLL-G fault

Type of Fault	Fault Current	TRV as per IEC-62271-10 (kV)	TRV (kV)	RRRV for IEC-62271-1 (kV)	RRRV (kV)
Terminal fault					
L-G	4.35	624	328.40	2	0.60
LL-G	4.9	624	328.69	2	1.06
LLL-G	6.0	624	400	2	1.2
Remote fault					
L-G	2.44	624	326.70	2	0.350
LL-G	3.63	624	326.77	2	0.357
LLL-G	4.0	624	360	2	0.50

Figure 7.11: obsevation table of all the faults

Chapter 8

Inductive Current Switching Overvoltage

Generally when loading in the transmission line is reduced or capacitive current is increased in the line due to no load or lightly load condition the shunt reactor is connected in the system network to support the inductive reactor power in the circuit. 60 kV and above system is commonly used which is directly grounded reactor or grounded through reactor and less than 60 kV system is ungrounded system. Current to be interrupted is generally less than 300A rms[11]. The purpose of the reactor switching are:

- To determine the interrupting window without re-ignition.
- To get the current chopping characteristic of circuit breaker.
- To determine the worst probable overvoltage that could appeare across the reactor and circuit breaker.

Two types of overvoltages generated as mention below:

- Chopping overvoltages (with frequency 5 Hz)
- Reigniting overvoltages (with frequency up to several hundreds of KHz)

a. **Chopping phenomenon:**

When interrupting low inductive current such as magnetizing current of transformer, shunt reactor , the rapid deionization of contacts space and blast effect may cause the current to be interrupting before it's natural current zero. It called current chopping. Energy stored in inductor is transferred to capacitor or inductive energy is transferred to electrostatic energy.

$$\frac{1}{2}Li^2 = \frac{1}{2}Cv^2 \tag{8.1}$$

$$V = i\sqrt{L/C} \tag{8.2}$$

$$f_n = \frac{1}{2}\Pi\sqrt{LC} \tag{8.3}$$

This transient voltage having high RRRV appears across the contacts, unless the arc continues. If it resrikes a further, chop may occurs or several chop may occurs before the current is finally interrupted, circuit breaker may fail to clear the fault. waveform of current chopping is shown in figure [11].

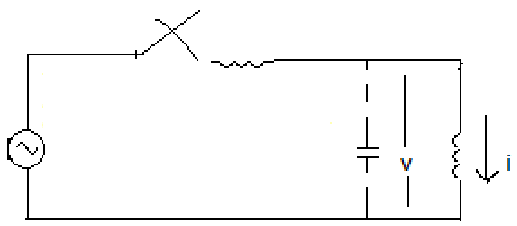


Figure 8.1: circuit of current chopping

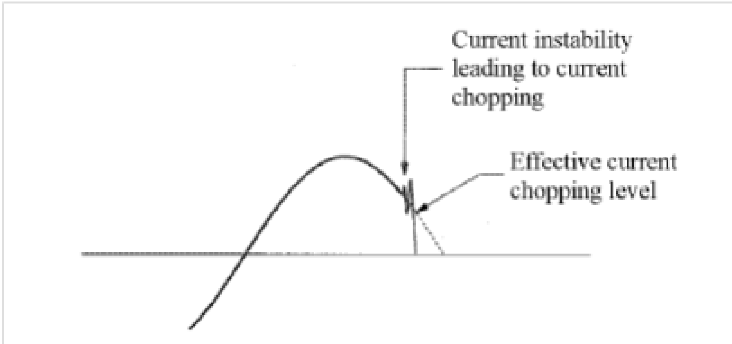


Figure 8.2: current waveform in current chopping

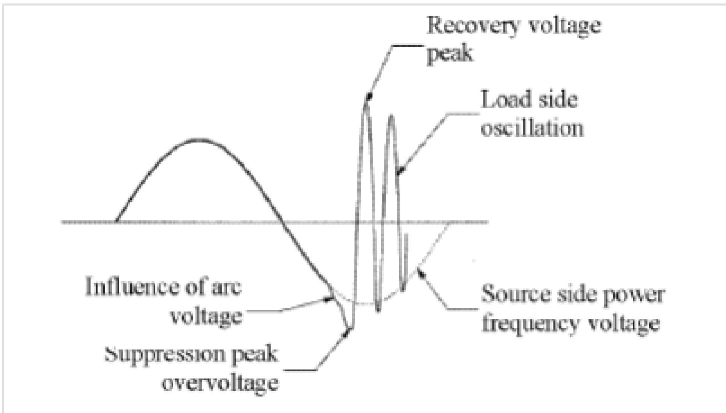


Figure 8.3: voltage waveform due to current chopping

b. **Re- ignition phenomenon:** During pre-strike or re-ignition the oscillating discharge of local capacitance results in high frequency current that flows between the contacts superimposed on power frequency current that progressively establish itself. This phenomenon concern all types of switchgear. The breaking of high frequency current generates a new applied TRV between the contacts the gap of which it has only slightly varied for this phenomenon occurs on a small time scale in comparison to the to the contact movement time which thus leads to new striking and repetition of same phenomenon. There is a succession of multiple striking associated with variable amplitude voltage waves depending

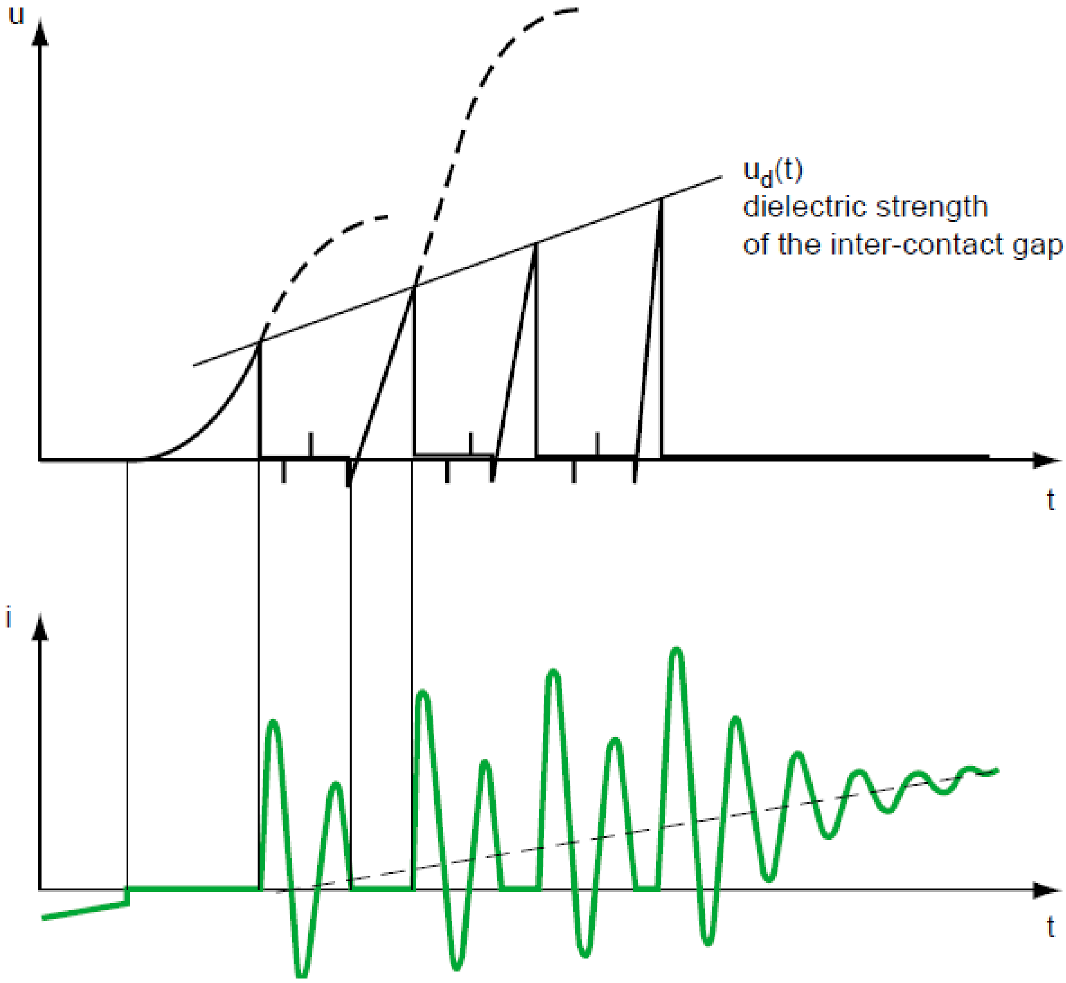


Figure 8.4: voltage waveform due to Re-ignition

on change of contact gap.
While closing amplitudes increase until the gap between the contacts is finally sufficient enough to withstand the recovery voltage which due to voltage escalation, still higher than voltage that corresponds to normal breaking. While opening only occurs if the arcing time (time interval between contact separation and current break) is low. In this case the contact gap is not sufficient enough to tolerate the TRV and there is another dielectric breakdown.

- **Description of Case Study:**

Here 400kV system with is considered all the substation equipment shown in fig. 8.6. In this operation of breaker (BRK1) is considered. In first case chopping phenomenon is shown in the breaker is first close and than open this can be shown in fig 8.7 to 8.9. The second case is case of chopping with arrester can be shown in fig 8.10 and fig 8.11. Third case is of reignition with arrester shown in fig 8.12 to 8.14. This cases shown the waveforms of TRV across circuit breaker and Voltage across reactor. Observation table is shown in fig 8.5. Following are the observations:

a. For Reactor Switching highest TRV across breaker is 1250 kV witch is violates its limit i.e. 624kV as per IEC-62271-10[10] for 400kV.

b. It can be limited with the help of surge arrester, but even if with the help of arrester TRV is become 640kV. It also out of its limit.

c. Hence, certainly re-ignition takes place across the breaker contacts. This TRV is become 800kV with surge arrester.

d. So, it can be reduced with the help of controlled opening of circuit breaker. It needs detail study.

Operation	Voltage Across Breaker (kV) As per IEC-62271-10	Voltage Across Breaker (kV)	Voltage Across Reactor (kV) As per IEC - 60071-10	Voltage Across Reactor (kV)
Current Chopping:				
Without Arrester	624	1250	950	1250
With Arrester	624	644	950	500
Re-Ignition				
With Arrester	624	800	950	500

Figure 8.5: Observation table of all the cases

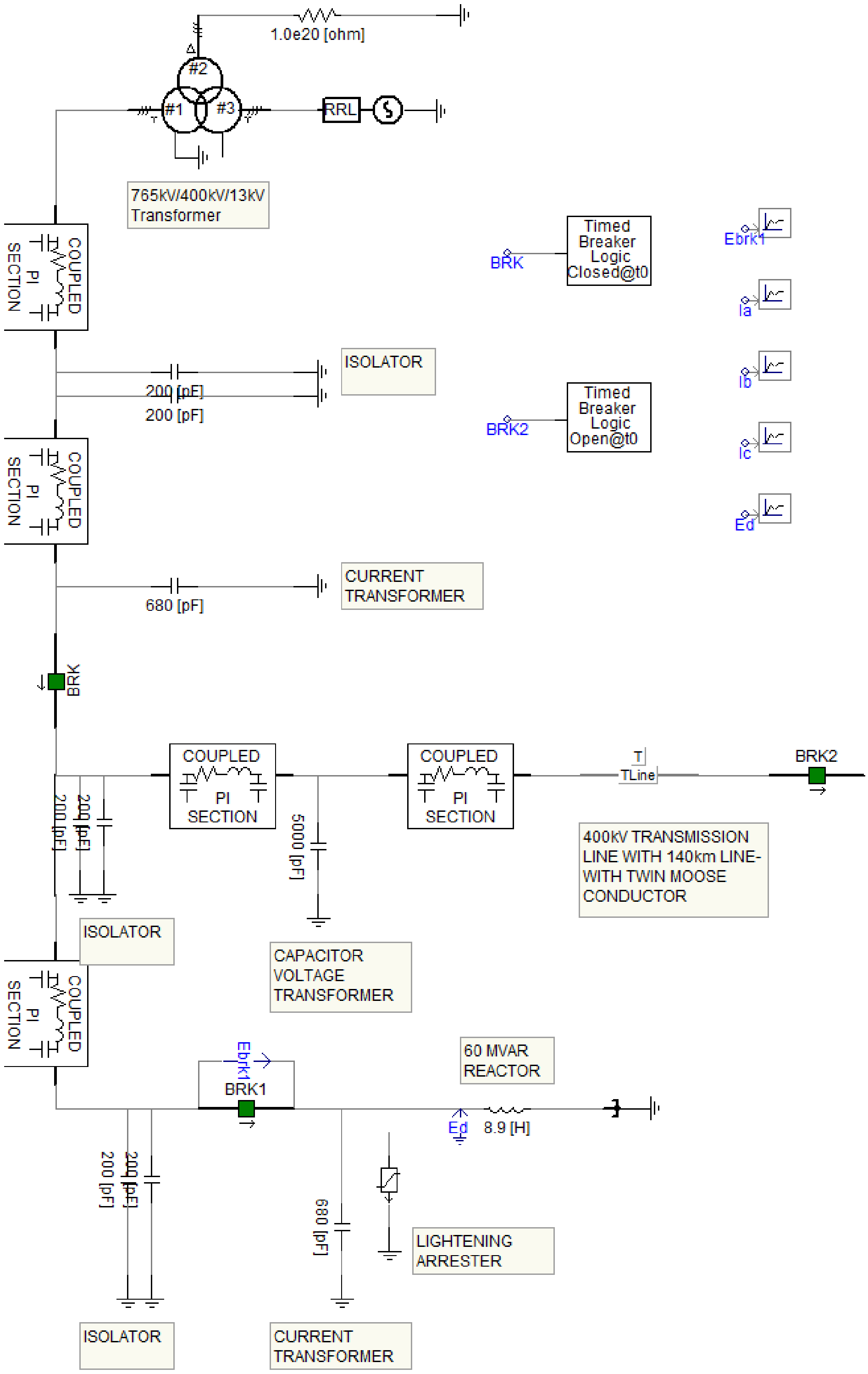


Figure 8.6: PSCAD circuit for Inductive current switching overvoltage

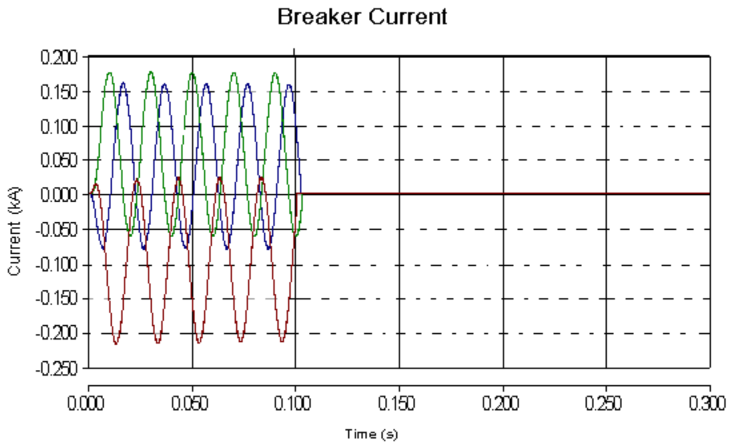


Figure 8.7: chopping Current

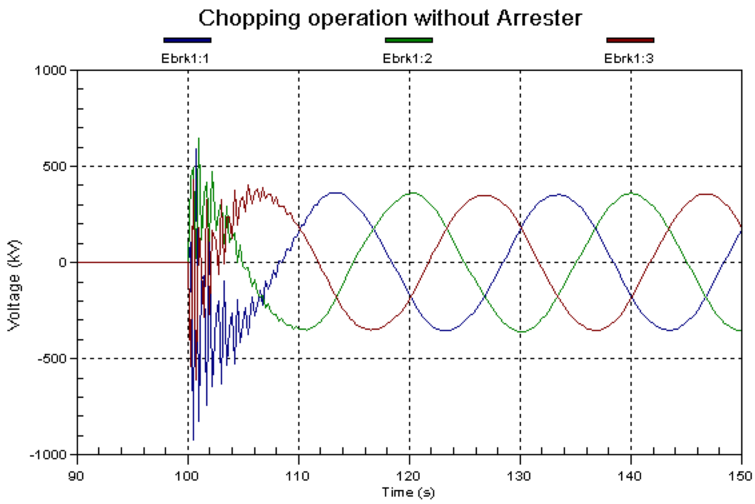


Figure 8.8: TRV across circuit breaker for case of chopping

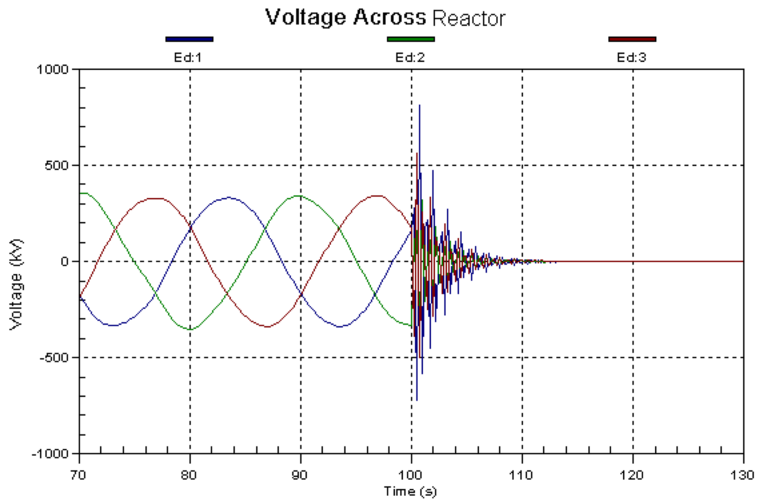


Figure 8.9: Voltage across Reactor for case of chopping

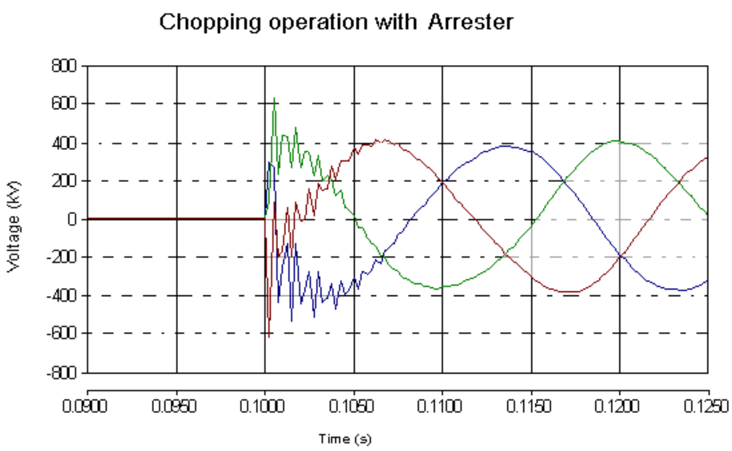


Figure 8.10: TRV across circuit breaker for case of chopping with Arrester

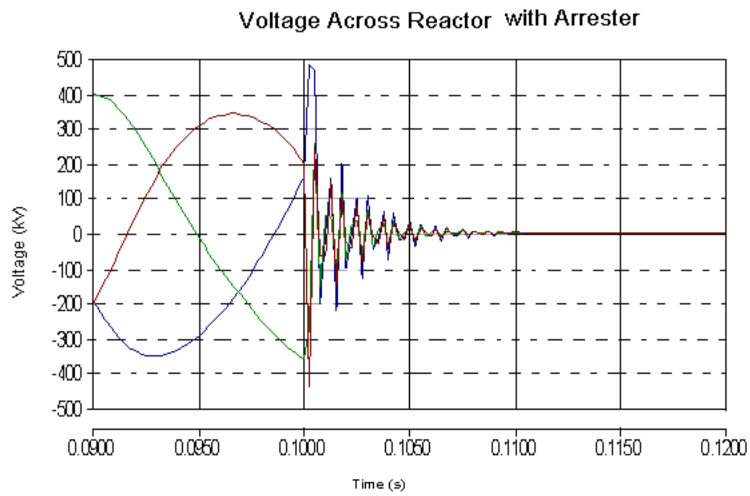


Figure 8.11: Voltage across Reactor for case of chopping with Arrester

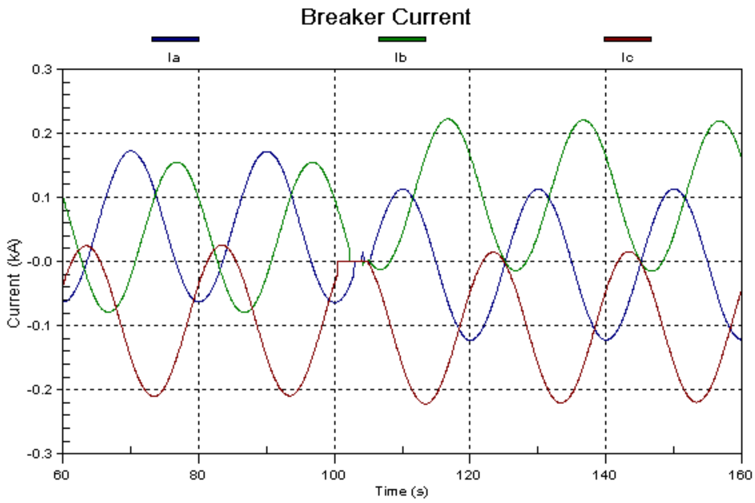


Figure 8.12: Current across breaker for case of re-ignition

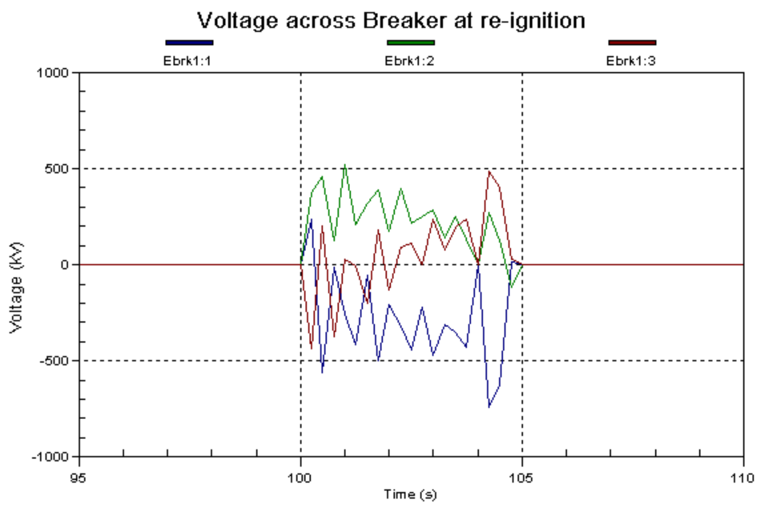


Figure 8.13: TRV across breaker for case of re-ignition

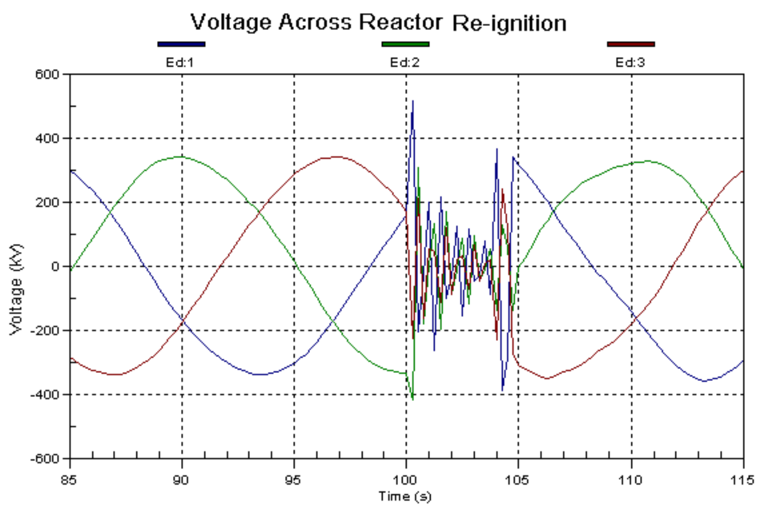


Figure 8.14: Voltage across Reactor for case of re-ignition

Chapter 9

Introduction to Ferroresonance

9.1 Introduction of Magnetic Material

Magnetic material is classified according to nature of its relative permeability (μ_r). Free space magnetic material have relative permeability equal to 1. There is normal magnetic materials are paramagnetic and diamagnetic material. This paramagnetic material have relative permeability greater than 1, and diamagnetic material have permeability less than 1 but it is much similar to the free space. But the ferromagnetic and ferromagnetic material have permeability very very greater than 1. Ferromagnetic material further divided in to two parts that is hard ferromagnetic material and soft ferromagnetic material. Permanent magnet material i.e. alnico, chromium steel, certain copper-nickel alloy etc. and soft ferromagnetic material i.e. iron and its alloy with nickel, cobalt, tungsten, aluminium. Silicon steel and cast steel are important ferromagnetic material for use of transformer and electric machines. Property of ferromagnetic material are basically based on saturation and hysteresis characteristics.As shown in figure 9.1.

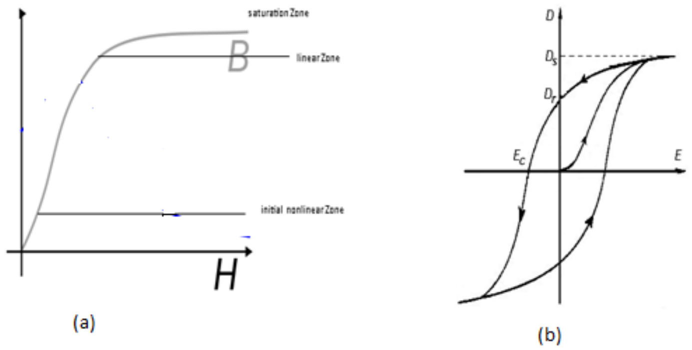


Figure 9.1: Properties of ferromagnetic material (a)saturation and (b)hysteresis respectively

Flux density is proportional to the system voltage and field intensity is proportional to the current. This current oscillate between +/-I_m and flux changes sinusoidally between +/- Φ_m. Voltage applied to the system is 90 degree leading to the flux. So, voltage applied is increases more and more flux demanded from core and current peak increases sharply and therefore core will be saturated. It also depends on the residual condition in the system. In case of which no residual condition in the system at that time steady state value of flux demanded at instant is -Φ_m but flux only start with zero the transient flux at the time of switching is equal to Φ_m so resultant flux is 2 Φ_m. It is called doubling effect and exciting current is large so core saturate. The worst case is with residual flux at that time resultant flux will be 2 Φ_m+Φ_r and current further increases and more the core saturate.

Ferromagnetism: A ferromagnet, like a paramagnetic substance, has unpaired electrons. In addition to the electrons' intrinsic magnetic moment's tendency to be parallel to an applied field, there is also in these materials a tendency for these magnetic moments to orient parallel . Thus, even when the applied field is removed, the electrons in the material maintain a parallel orientation. Every ferromagnetic substance has its own individual temperature, called the Curie temperature, or Curie point, above which it loses its ferromagnetic properties.

9.2 Resonance Phenomenon:

- It occurs between capacitance and linear inductance. Electrical resonance occurs in an electric circuit at a particular resonance frequency where the imaginary parts of circuit element impedances or admittances cancel each other. Resonance is the tendency of a system to oscillate at a greater amplitude at some frequencies. These are known as the system's resonant frequency. At resonance the power factor is exactly unity so, at resonance ω_2LC=1

$$f = 1/2\Pi\sqrt{LC} \tag{9.1}$$

- Series and Parallel is the types of resonance. In series Resonance the impedance of the complete circuit is at minimum. Current through the circuit is very large. Large voltage across individual L and C. This voltage can be many times greater than the supply voltage and this voltage across inductance and capacitance are of same magnitude in series resonance. And in parallel resonance the impedance of the complete circuit is at maximum. Current through the circuit is very small. Large current through individual L and C. This current can be many times greater than the current supplied by source and it is same in magnitude.

9.2.1 Characteristic of Resonance Phenomenon:

The strait line AB is the characteristic of the inductor. The characteristic of Capacitor is given by JK or J'K' according to the value of capacitor The operating point Is P and P'. At operating point P ω_L>1/ω_C, and at P' ω_L<1/ω_C. If C is reducing then the JK will be steeper and J'K' becomes less steep, so that, the line will become parallel to the AB the voltage V_L and V_C become infinite. There is no condition of the inductor in saturation[12].

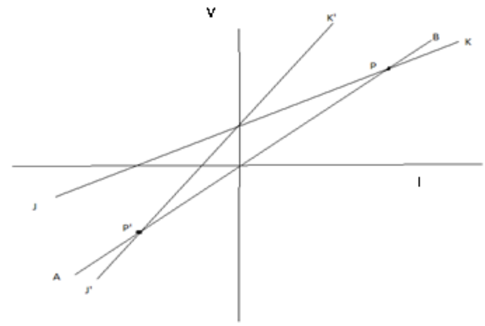


Figure 9.2: Characteristic of Resonance

9.3 Ferroresonance Phenomenon

It is nonlinear phenomenon of the resonance. It occurs between saturated or nonlinear inductance and capacitance. Inductance involved is usually iron core. The nonlinear character of iron core inductance introduces some particular effect.

9.3.1 Characteristics of Ferroresonance

It is nonlinear phenomenon of the resonance. It occurs between saturated or nonlinear inductance and capacitance. Inductance involved is usually iron core. The nonlinear character of iron core inductance introduces some particular effect.

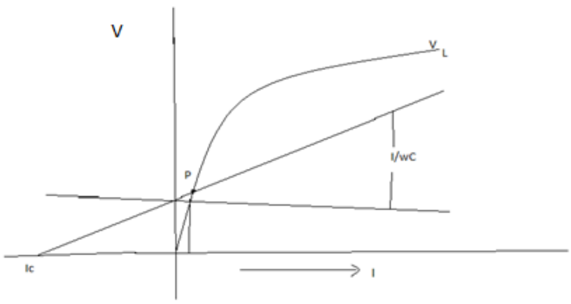


Figure 9.3: variation of inductance and capacitance in ferroresonace phenomenon

The voltage across the inductance depends on the frequency ω and the also a function of current f(I). so, we can write:

V_L= ωf(I) so, V_L plotted as a function of current shown in figure.This voltage lead current by 90 degree. Voltage across capacitance is given by

V_C= -I/ω_C the minus sign indicating that it antiphase with V_L and lags the current by 90 degree. So, the total voltage will be

V=V_L+V_C =ωf(I)-I/ω_C or V_L= V+I/ω_C so this V_L has fixed consistent V and one that is proportional to I. This also plotted in the figure indicating strait line. This both characteristics represent V_L. The operating point must be where the two lines crosses at P as shown in fig 9.3.

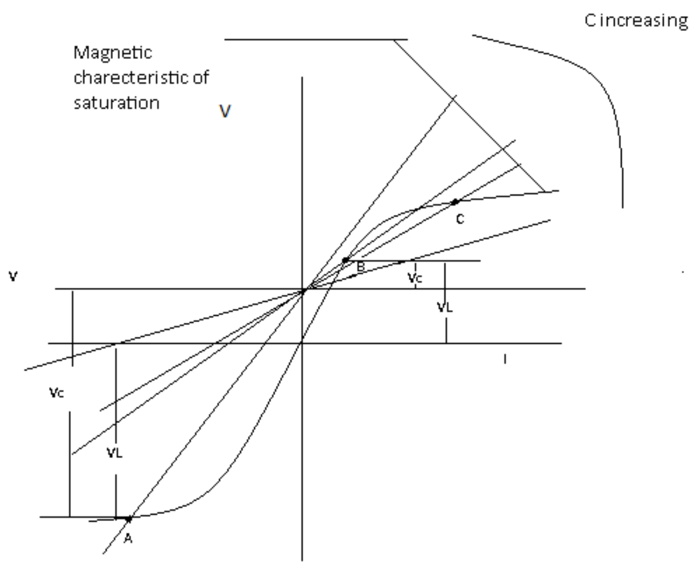


Figure 9.4: Full characteristic of ferroresonance

The slope of the line is given by

tan(α)=1/ω_C

This indicating that if either ωor C is reduced the slope will be increase and the operating point p will be progress up the curve. Fig 9.4 shows that capacitor line makes multiple interactions with the ωf(I) line. This interaction in this case A, Band

C. At point A the V_L and V_C are negative and V_C>V_L so the current I leads the voltage V. Where as at point B V_C<V_L also current I legs behind V. Both point A and B are stable operating points since any slight variation of current, it will cause voltage changes tending to restore current to initial value. Point C is not stable operating point. A momentarily variation in current I would cause changes in V_L and V_C such as to reinforce the deviation and destabilize rather than stabilize. So the point B is non ferroresonance stable operating point where X_L,US>X_C and V= V_L-V_C. Point A is the ferroresonant stable operation point where capacitive situation X_L,S<X_C and V=V_C-V_L and point C is the unstable operating point where X_L,S>X_C.
where S-saturated and US-unsaturated[12].

9.3.2 Voltage, Flux, Current Relationship During Ferroresonance

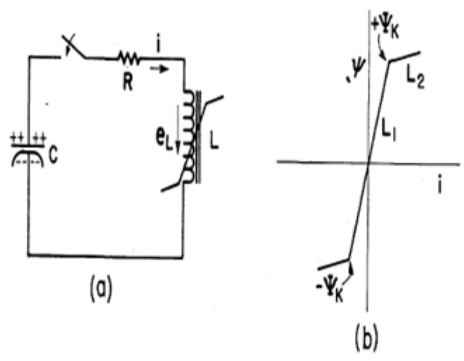


Figure 9.5: Circuit of ferroresonance

Figure 9.5 shows the RLC circuit with charged capacitor and inductor having magnetizing curve. The graph in the figure shows voltage, flux and current with respect to time.
According to Faradays low: Ψ=NΦ=$\int e_L$dt where eL is the voltage across the induc-

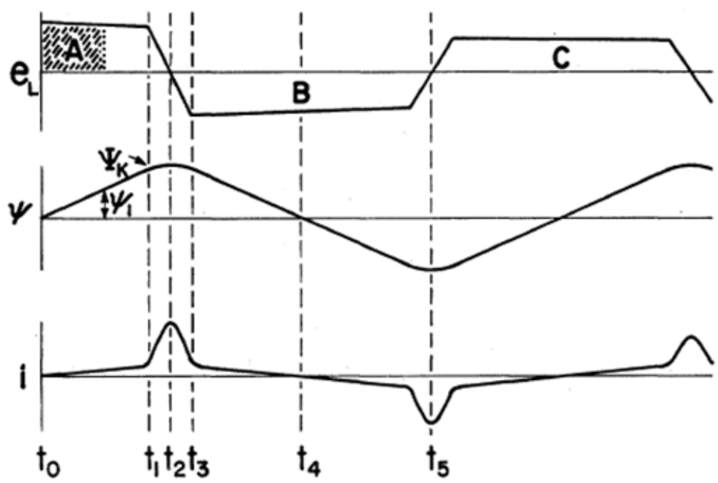


Figure 9.6: Representation of Voltage, Flux, Current Relationship during ferroresonance

tor, Φ is the magnetic flux in its core, N is the number of turns, and t is the time, Ψ is flux linkage. Magnetization of Ψ in core at any given time is depends on the length of a potential applied and the magnitude. As shown in fig3.6 the iron cored transformer into its saturation mode. Voltage applied for a long enough time irrespective of the magnitude. As shown in fig 9.6 Ψ_1 is equal to the shaded area A under voltage curve When the Ψ has built up to the knee of the magnetization curve at time t_1 the transformer iron is saturated and the inductance drops to a very low value L_2. A very large pulse of current then flows, transforming all the energy stored in the electric field of the capacitor into the magnetic field of the transformer. At time t_2 the potential has dropped to zero and the current is at its peak. The magnetic field then collapses, charging the capacitor to the opposite polarity at time t_3 At that time the Ψ has dropped back to the knee of the magnetization curve and under the influence of the negative potential begins to drive the Ψ downward. Ultimately the transformer core becomes saturated at the opposite polarity, a pulse of current flows, and the voltage is again reversed in polarity. The voltage magnitude decreases with each reversal of voltage because of I^2R losses during saturation.The oscillations eventually die out due to losses in the circuit. Sustained ferroresonance requires that these losses be supplied from an external source. If an ac voltage were coupled into the circuit, this decrease in the frequency of oscillation permits the circuit to search for and possibly lock in at either the fundamental frequency of the driving voltage or at a subharmonic of it. The frequency of the oscillation must lie between the limits[13].

$$f = 1/2\pi\sqrt{L_1C} \tag{9.2}$$

and

$$f = 1/2\pi\sqrt{L_2C} \tag{9.3}$$

Difference between Resonance and ferroresonance:

Resonance contains System Parameter of Resistance, capacitance, inductor. Resonance occurs at one frequency when the source frequency is varied. Only one sinusoidal steady state overvoltage and over current occurs.

Ferroresonance contains System Parameter of Resistance, capacitance, nonlinear inductor(ferromagnetic material). Ferro resonance occurs at a given frequency when one of the saturated core inductances matches with the capacitance of the network. It also contains Several steady state overvoltage and over currents can occur[14].

9.4 Classification of Ferroresonance Modes:

The four different ferroresonance types are:

a. Fundamental mode,

b. Subharmonic mode,

c. Quasi-periodic mode,

d. Chaotic mode.

a. **Fundamental Mode:** The periodic response has the same period, T as the power system. The frequency spectrum of the signals consists of fundamental frequency component as the dominant one followed by decreasing contents of 3rd, 5th, 7th and nth odd harmonic. In addition, this type of response can also be identified by using the stroboscopic diagram of Figure 9.7, which can be obtained by simultaneously sampling of voltage, v and current, i at the fundamental frequency[14].

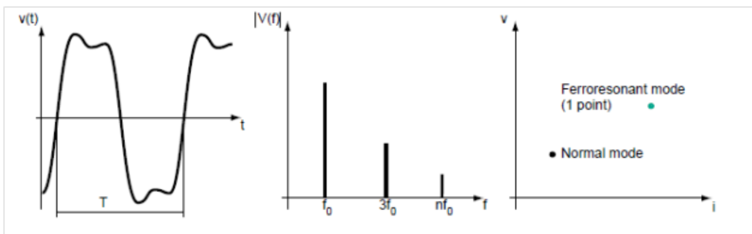


Figure 9.7: Fundamental Mode

b. **Subharmonic mode:**This type of ferroresonance signals has a period which is multiple of the source period, n_T. The fundamental mode of ferroresonance is normally called a Period-1 (i.e. f_0/1 Hz) ferroresonance and a ferroresonance with a sub-multiple of the power system frequency is called a Period-n (i.e. f_0/n Hz) ferroresonance. Alternatively, the frequency contents are described having a spectrum of frequencies equal to f_0/n with f_0 denoting the fundamental frequency and n is an integer. With this signal, there are n points exist in the stroboscopic diagram which signifies predominant of fundamental frequency component with decreasing harmonic contents at other frequencies[14].

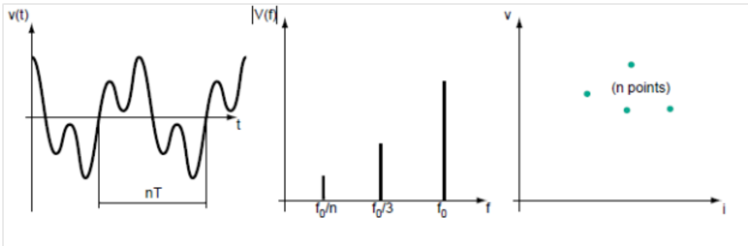


Figure 9.8: Subharmonic Mode

c. **Quasi-periodic Mode:**This mode (also called pseudo-periodic) is not periodic. The spectrum is a discontinuous spectrum whose frequencies are expressed in the form: nf_1+mf_2 (where n and m are integers and f_1/f_2 an irrational real number). The stroboscopic image shows a closed curve[14].

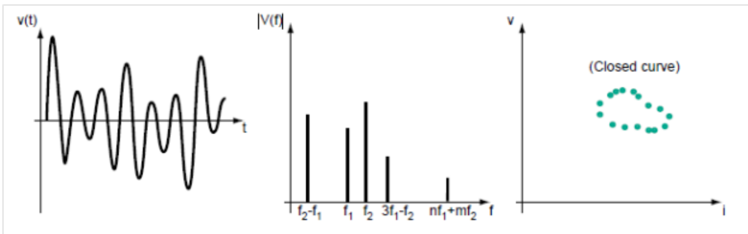


Figure 9.9: Quasi-periodic Mode

d. **Chaotic Mode:**The corresponding spectrum is continuous, i.e. it is not cancelled for any frequency. The stroboscopic image is made up of completely separate points occupying an area in plane V, I known as the strange attractor as shown in fig below[14].

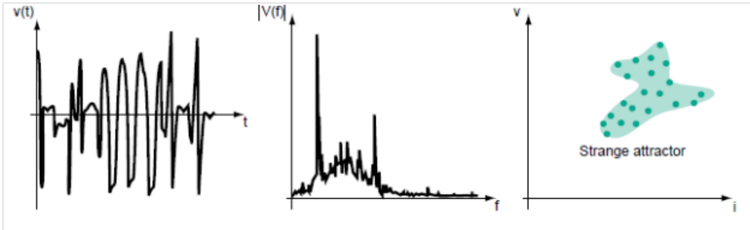


Figure 9.10: Chaotic Mode

Fetures of Ferroresonance[14]

The ferroresonant steady state response is characterized by presence of:

- High overvoltages
- High harmonic levels

This may lead to:

- Untimely tripping of protection devices, due to overvoltages.
- Destruction of equipment such as power transformers or voltage transformers
- Current through the windings and leakage current through the insulation increases due to increase in voltage.
- This leads to increase in winding and insulation temperature.
  a. Causing HV insulation failure due to thermal runaway.
  b. Production losses
- Unusual noises from transformers

Condition Favorable for Ferroresonance[14]

- Transformer energized through grading capacitance of open circuit breaker.
- Transformers connected to an isolated neutral system.

- Transformer accidentally energized in only one or two phases.
- Transformers and HV/MV transformers with isolated neutral.
- Power system earthed through a reactor.

General methods to Prevention of Ferroresonance[14]

- Avoid configurations susceptible to ferroresonance, through proper design and proper switching operations.
- Provide a safety margin to ensure that system parameters are in the risk area, even temporarily.
- In isolated neutral systems, the wye-connected PT primaries should not be earthed or a delta-connection of PTs should be used.
- Use design measures to make magnetic core at low flux density.
- Avoiding no load energizing.
- Prohibiting single phase operations or fuse protections.
- Prohibiting live work on cable-transformer assembly.
- Introducing losses with use of extra burden which damp out ferroresonance in Voltage transformer and in capacitor voltage transformer

Chapter 10

Ferroresonance Case Studies

This Chapter shows various case studies of ferroresonance with the help of simulation model. Here two case studies are given, first the occurrence of ferroresonance condition and mitigation of ferroresonance with the help of air core reactor. By connecting air core reactor connected across HV winding on tertiary winding because of this linear reactance in parallel with transformer nonlinear inductor effect of ferroresonance between nonlinear inductor and capacitor(in terms of transmission line or stray or grading capacitor) can be destroyed and disconnection of maximum energy transformer between them[15]. Usage of tertiary connected shunt reactor depends on available capacity on the tertiary winding.

CASE 1: Transformer energized through grading capacitance of open circuit breaker

This case model is shown in fig 10.1. The supply voltage is of 400kV and transformer rating is of 100MVA, 400kV/220kV/13kV. Fault occurs at 0.5 sec and it remains for duration of 0.07 sec. At 0.57 sec breaker 2 is operate i.e opens and after some time the breaker 1 operates at that time the capacitor connected to ground at bus terminal is discharges through the transformer. So, oscillation between grading capacitance and saturated transformer the path of ferroresonance is shown in fig. 10.2. The Waveforms of 400kV bus voltage is shown in fig. 10.3. It can be observed that higher the grading capacitance higher the over voltage and ferroresonance is visualizes for certain range of line to ground capacitance value. Typically in this case ferroresonance can occurs for grading capacitance range of 3000pf - 8000pf and stray capacitance range is of 1000pf - 6000pf. In this case over voltage is of 2 p.u or high and this is shows the subharmonic mode of ferroresonance. With the help of air cored reactor valued ferroresonance condition is totally mitigated. This mitigation simulation is done when highest overvoltage can occurs due to grading capacitance and stray capacitance combination i.e. 8000pf grading capacitance and 5000pf stray capacitance without reactor connected at tertiary winding and with different values of reactor. fig. 10.3 is shows waveform without reactor connected at tertiary winding. fig. 10.4 shows waveform of reactor connected valued 1MVAR and 5MVAR and fig. 10.5 with 10MVAR and 30MVAR value. Observations regarding voltage before and after connected different values of reactor at tertiary winding in fig.10.10.

CASE 2:Transformer accidentally energized in only one or two phases

In this case of ferroresonance 400kV feeds to transmission line and cabal fed transformer with rating 1000MVA 400kV/220kV/13kV [15]. Transmission line is of 200km and cable is of 1km long. Due to single phase switching of phase A, ferroresonance[16][14] between cable capacitance, transmission line capacitance and transformer magnetizing inductor. Circuit modeled in PSCAD is shown in fig 10.6 and the path of ferroresonance is shown in fig.10.7. The waveform of ferroresonance over voltage is shown in the fig. 10.8 without reactor connected at tertiary and with reactor valued 100MVAR and fig. 10.9 with reactor valued 200MVAR and 333MVAR. This ferroresonance overvoltage is of 2.7 p.u and it is fundamental mode of ferroresonance. fig. 10.10 shows observation table with and without reactors. This ferroresonance is observed for the certain rance of cable length typically for this case for 400kV the cable capacitance is 0.23μ/km and ferroresonance can occurs between range of 0.5km - 2km cable length.

- **Conclusion From Ferorrroresonance Case Studies**

a. Small variation in value of system parameters or transient may cause this phenomenon and initiate ferroresonance.

b. Ferroresonance occurs due to nonlinear inductor and stray, grading or cable capacitance in the system.

c. The frequency of voltage waves which may different from that of sinusoidal voltage source witch may be either fundamental, sub harmonic or chaotic modes.

d. This probability of ferroresonance situation in system is limited for certain range of capacitance. Typically

- In Case I: Grading Capacitance Range: 3000pf-8000pf. Stray Capacitance Range: 1000pf-6000pf
- In Case II: 400kV cable Capacitance is 0.23 F/km. In this case cable Range : 0.5km 2km.

e. By introducing linear Shunt Reactor at tertiary winding, ferroresonance effect can be reduced.

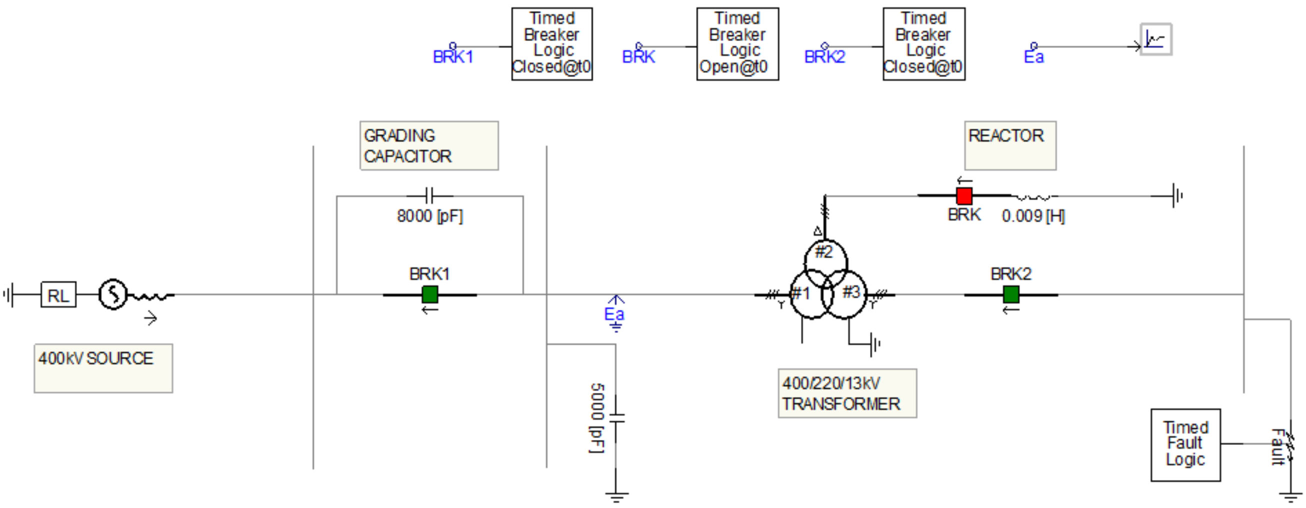


Figure 10.1: circuit of **Case 1** in the PSCAD

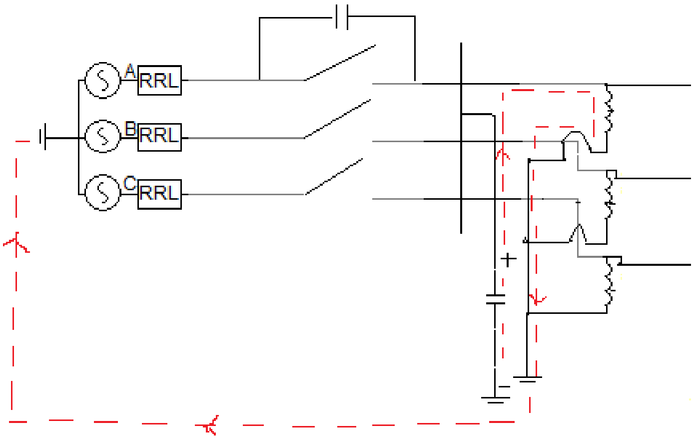


Figure 10.2: Path of ferroresonance for **case 1**

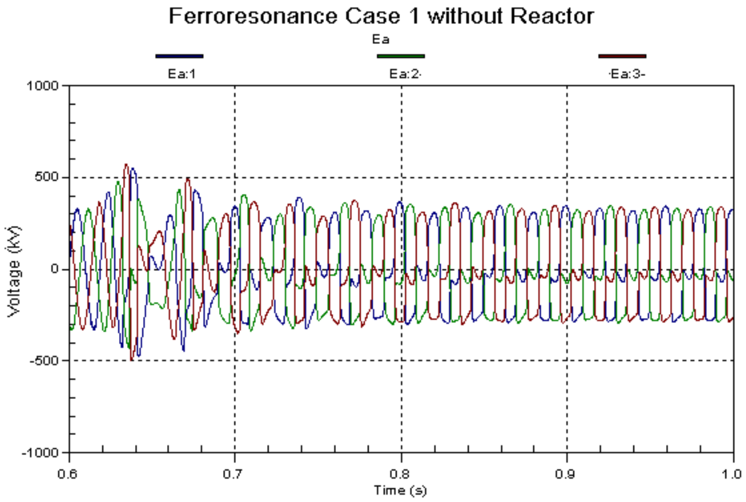


Figure 10.3: Ferroresonance overvoltage at 400kV bus without reactor connected at tertiary for **case 1**

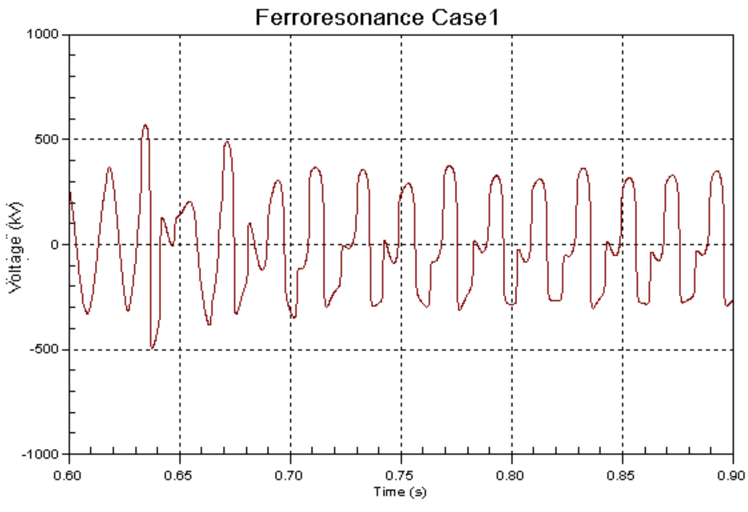


Figure 10.4: Ferroresonance overvoltage at 400kV bus without reactor connected at tertiary for **case 1**

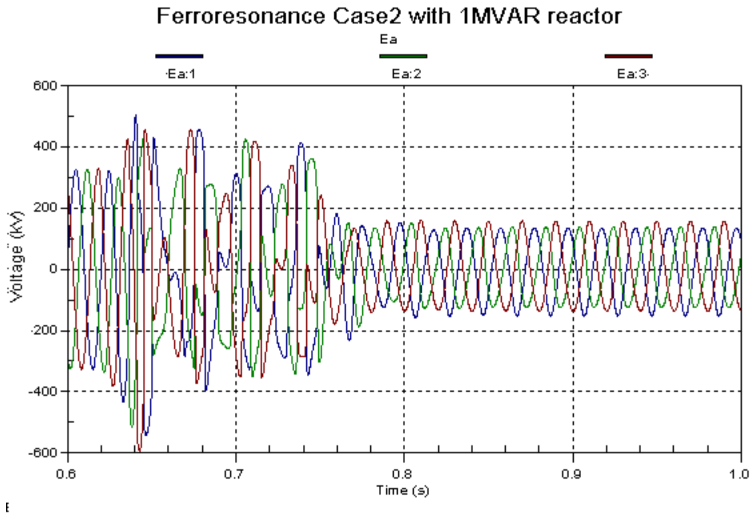


Figure 10.5: mitigation of ferroresonance for 1MVAR reactor at 400kV bus side for **case 1**

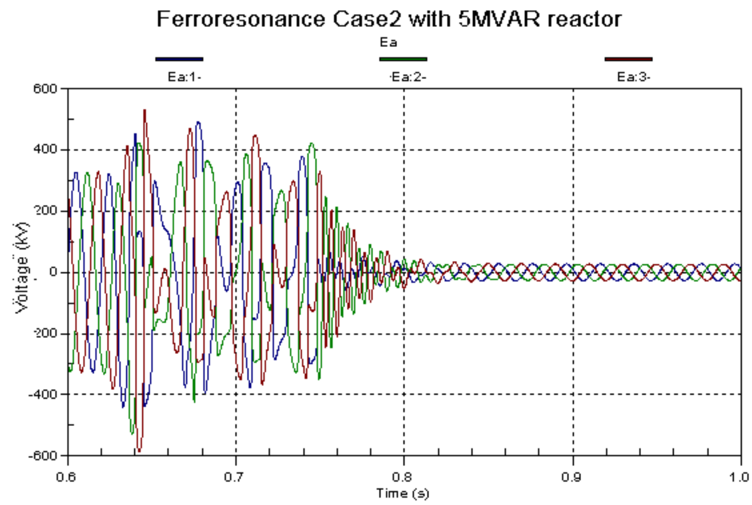


Figure 10.6: mitigation of ferroresonance for 5MVAR reactor at 400kV bus side for **case 1**

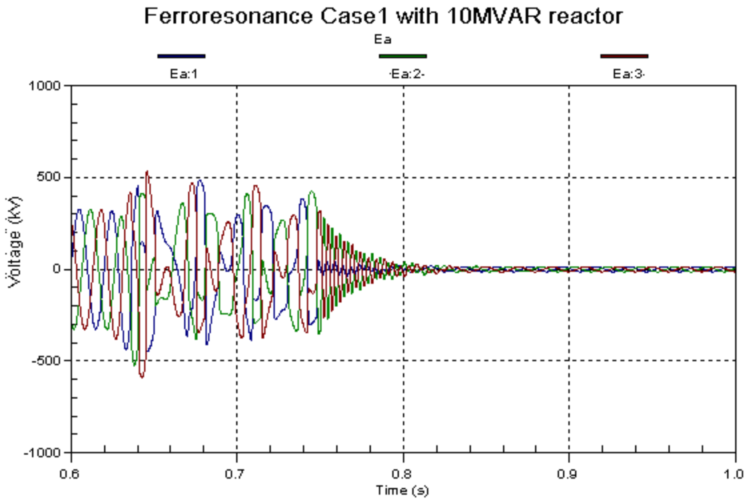


Figure 10.7: mitigation of ferroresonance for 10MVAR reactor at 400kV bus side for **case 1**

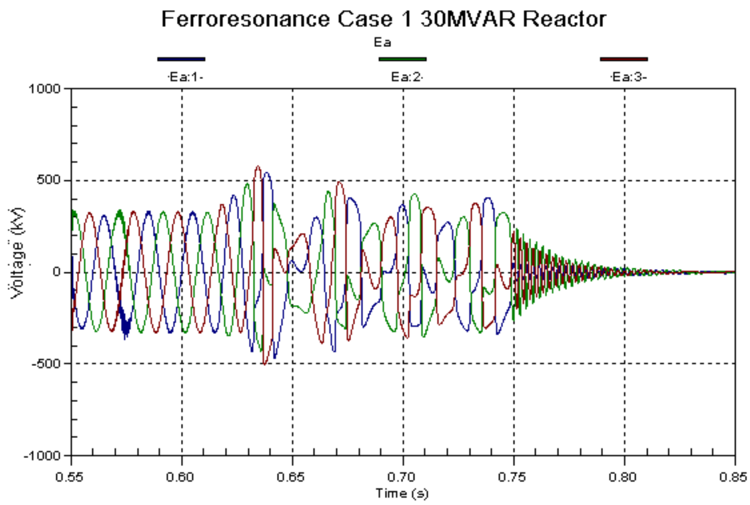


Figure 10.8: mitigation of ferroresonance for 30MVAR reactor at 400kV bus side for **case 1**

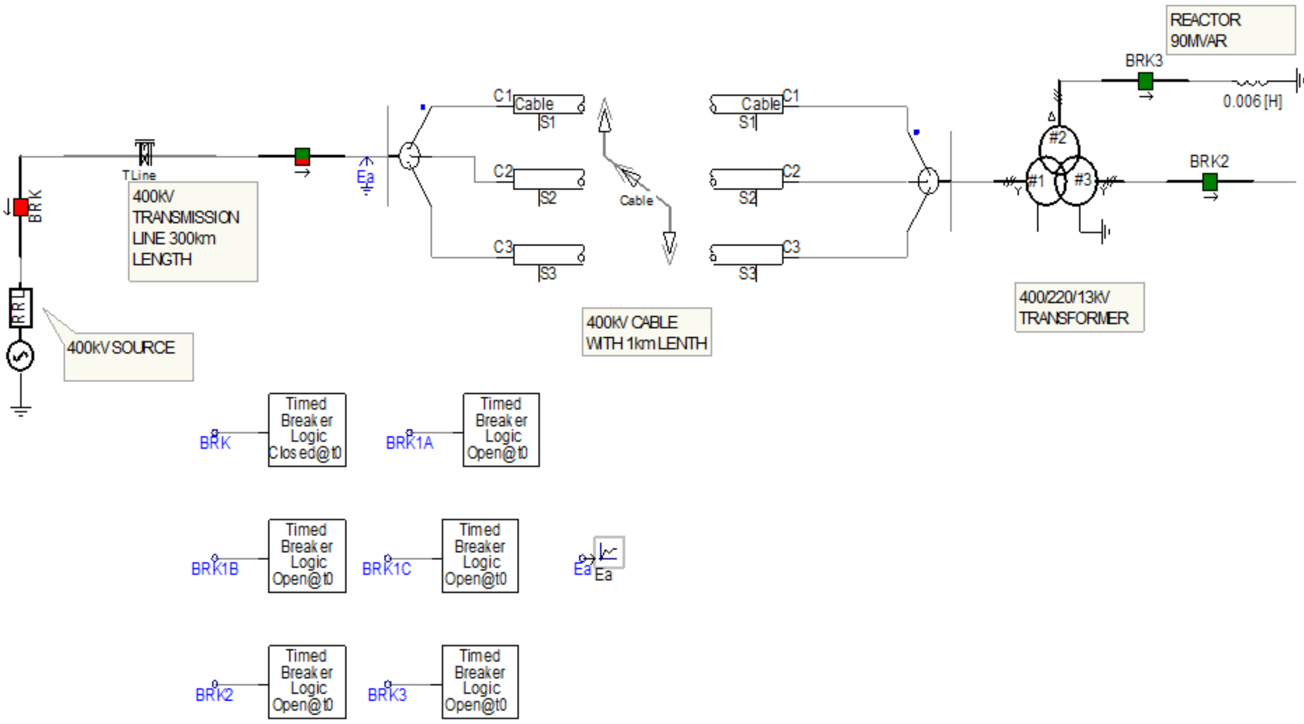


Figure 10.9: circuit of **Case 2** in the PSCAD

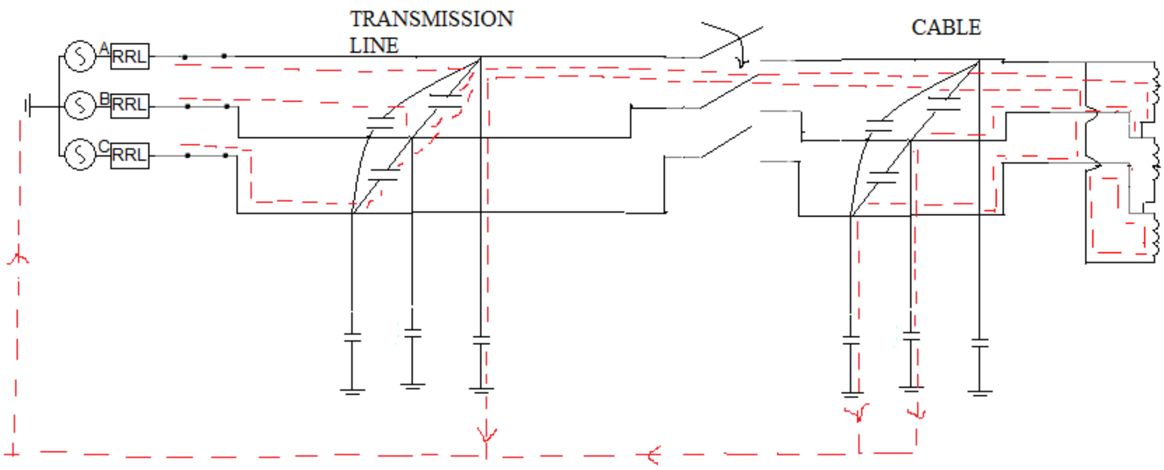


Figure 10.10: Path of ferroresonance for **case 2**

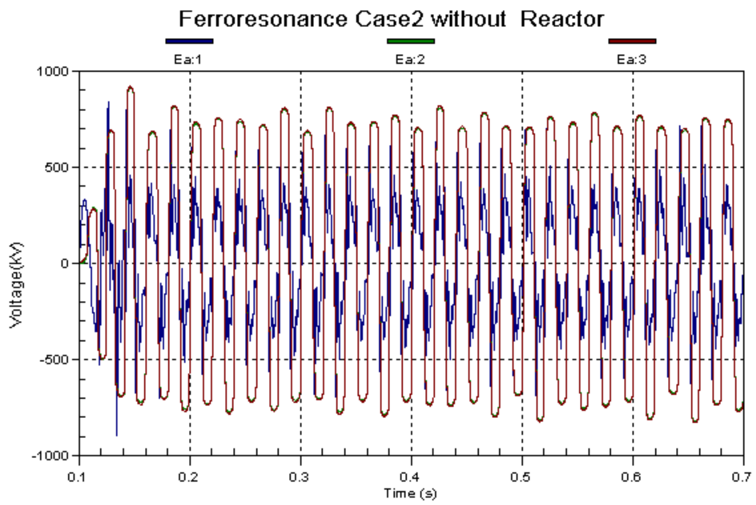


Figure 10.11: Waveform of ferroresonance over voltages without reactor at 400kV side **case 2**

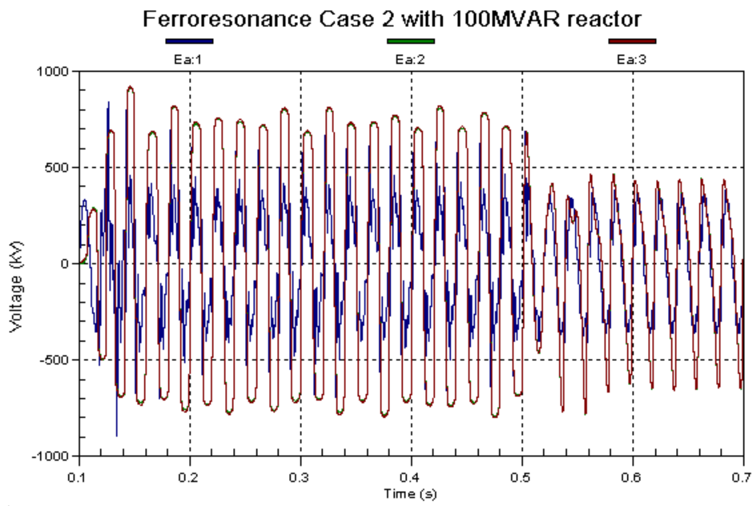


Figure 10.12: mitigation of ferroresonance for 100MVAR reactor at 400kV side**case 2**

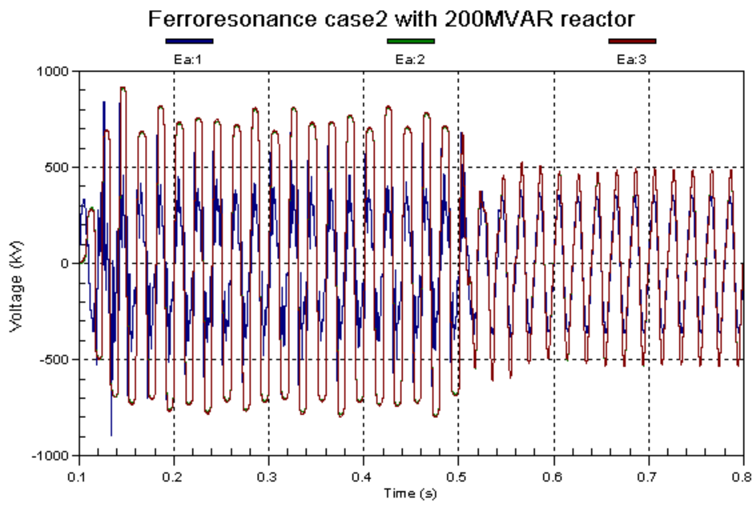


Figure 10.13: mitigation of ferroresonance for 200MVAR reactor at 400kV side**case 2**

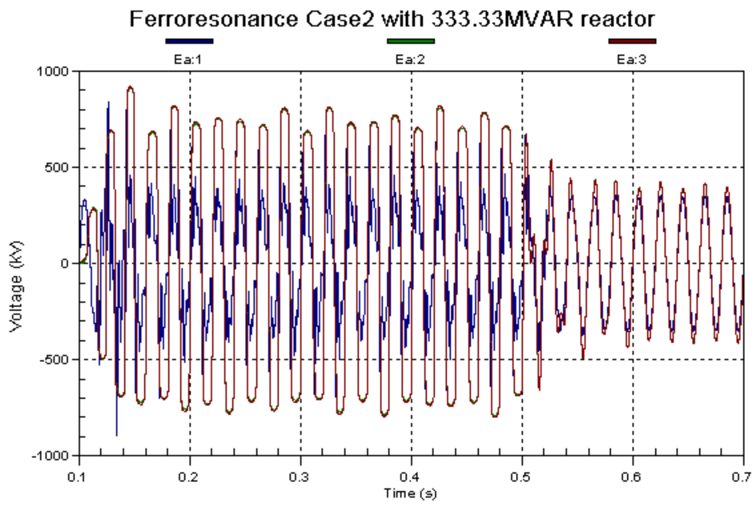


Figure 10.14: mitigation of ferroresonance for 333.33MVAR reactor at 400kV side**case 2**

REACTOR VALUE (MVAR)	OVER VOLTAGE(kV)
CASE 1: (100MVA TRANSFORMER, TERTIARY LOADED MAXIMUM – 33.33MVAR)	
NO REACTOR CONNECTED	550
5	40
10	25
20	9
30	3.5
33.33	1
CASE 2: (1000MVA TRANSFORMER, TERTIARY LOADED MAXIMUM – 333.33MVAR)	
NO REACTOR CONNECTED	850
100	800
200	430
333	340

Figure 10.15: Observations for Case 1 and 2 With and Without Reactor connected at tertiary winding

Chapter 11

Potential Transformer Failure Case

This system is basically traction system of 66/25 kV. In phase I and II PT burden is 30 VA and in phase III burden is replaced by 100 VA because of their requirement. So, in 100VA burden PT the area used is same so the flux density is higher than the 30 VA burden PT so that 100 VA burden PT is tending towards saturation. The saturation curves and data entered in the system shown in Appendix II. It also mention that PT failed during early hours of day time of charging. It is also noticed that power transformer sounds abnormal noise during initial period it is due to overvoltage. So, ferroresonance condition is created between the power transformer and the cable capacitance. The simulation results are shown in below figures. First Analysis is done without arrester in the system its circuit is shown in 11.1 and the second case is with Surge arrester shown in fig. 11.4. Fig. 11.2 and 11.5 shows the voltage waveform for overhead line length 2.74 km and cable length is 5.75 km without and with arrester respectively and fig. 11.3 and 11.6 shows the voltage waveform for overhead line length 15.91 km and cable length is 0.63 km without and with arrester respectively. Observation Table for this cases is shown in fig 11.7.

Following are the observations:

- It is investigate that the failure is attributed due to high magnetizing current and sustain overvoltage across PT primary. Hence, primary winding of 100VA PT burned. This is because of higher flux density of 100VA PT compared to 30VA PT.
- From above cases it is observed that, case (1) of 100VA burden PT fail because the total length is small than the case (2) of 100VA PT not failed So, the total length(cable and o/h line) is high in case (2) so capacitance is predominant than the saturated inductance in this case so this PT not fails.
- It is the only solution from the study that design should be such that saturation is transformer should not done. It can be done by increasing the air gap or by increasing the flux density.

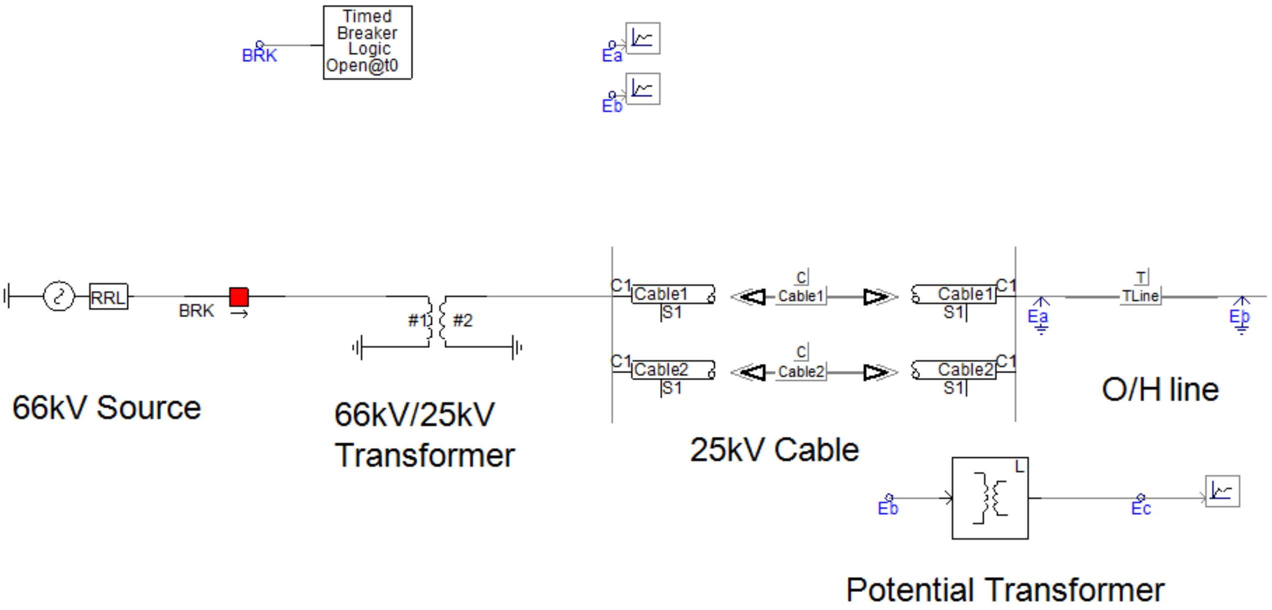


Figure 11.1: PSCAD circuit without Arrester

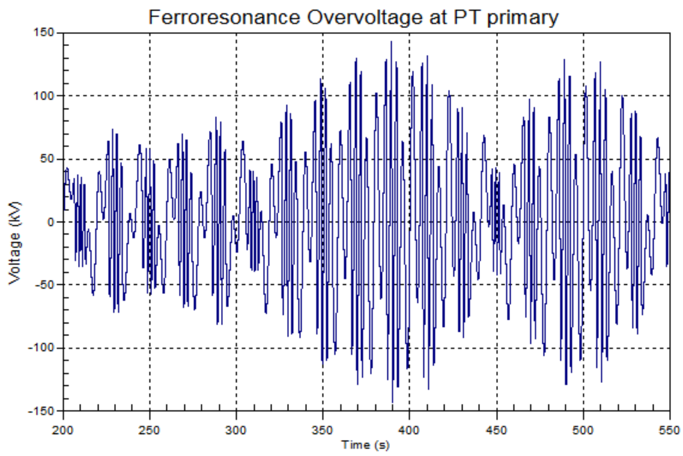


Figure 11.2: Waveform for O/H Line length 2.74 km and cable length is 5.75 km without arrester

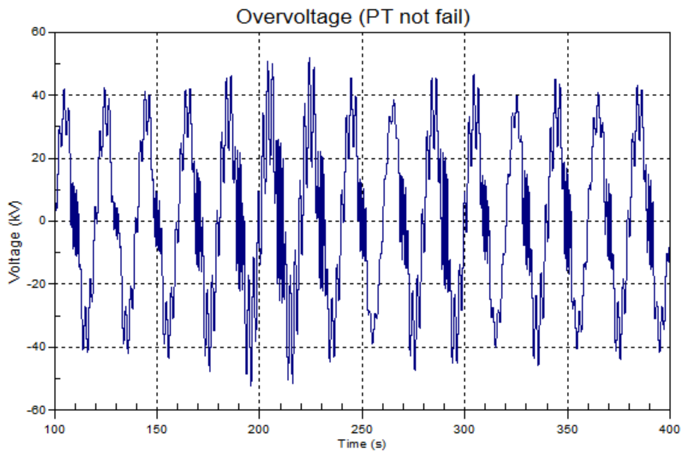


Figure 11.3: Waveform for O/H Line length 15.91 km and cable length is 0.63 km without arrester

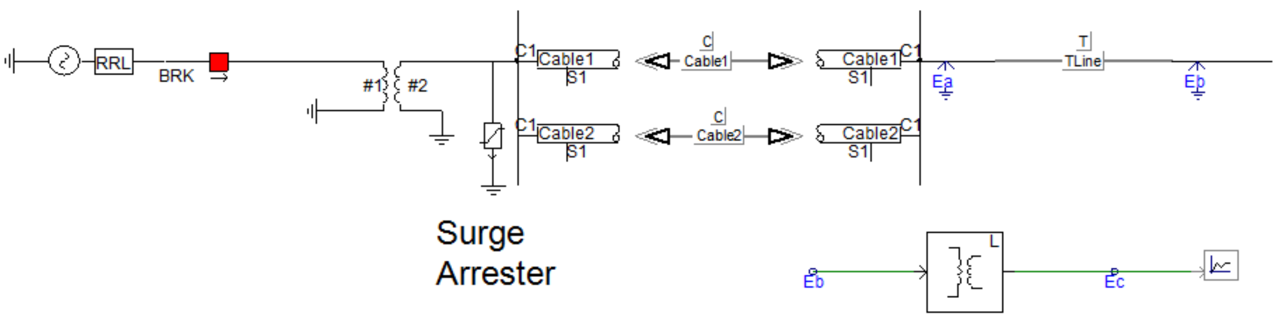


Figure 11.4: PSCAD circuit with Arrester

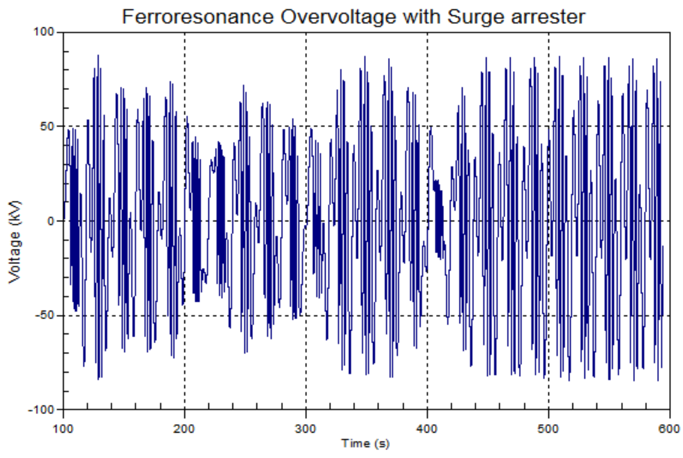


Figure 11.5: Waveform for O/H Line length 2.74 km and cable length is 5.75 km with arrester

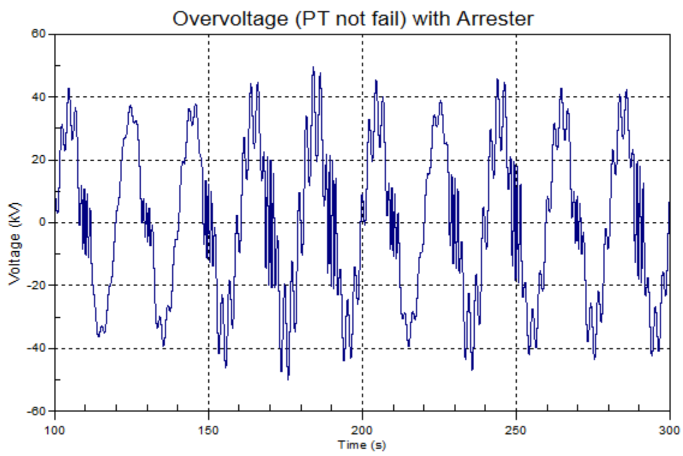


Figure 11.6: Waveform for O/H Line length 15.91 km and cable length is 0.63 km without arrester

Cases	Overhead Line Length(km)	Cable Length(km)	Over Voltage (in p.u)
100VA Burden	2.74	5.75	3.9
Without Arrester	15.91	0.63	1.6
100VA Burden	2.74	5.75	2.9
With Arrester	15.91	0.63	1.4

Figure 11.7: Observation Table of above Cases

Chapter 12

Conclusion and Future Scope

Conclusion

This report begins with brief introduction about transients in power system particularly switching transients which can be occurs in the range of 50Hz to 10kHz. It was clearly conclude from this project is, the switching transient case studies are used to check the equipment insulation within BIL or not. Also if BIL is not within the limit as per standards than it can be reduced with the help of surge arrester.

one of the transients which are likely to be caused by switching events is low frequency transient, i.e. ferroresonance. it is very rare to occur but it results into very dangerous overvoltages into power system network. This report presents theoretical background of ferroresonance, simulation of ferroresonance and also simulation for the mitigation of ferroresonance with help of tertiary winding loading with different values of reactor ratings.

From PT failure case we can conclude that PT should always designed with high flux density or sufficient air gap so that less magnetizing current flows from the core of PT and it prevent tending towards saturation.

Future Scope

In this report ferroresoance case studies are carried out for the transmission network it can be carry out in the distribution network for further studies. It can also simulation of ferroresonance in CVT and mitigation techniques with the help of Ferroresoance circuit in the CVT for further studies.

References

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Appendix A

Transmission Line Data

LINE VOLTAGE (KV)	CONDUCTOR CONFIGURATION	POSITIVE SEQUENCE			ZERO SEQUENCE		
		R	X	B	R	X	B
132	PANTHER	9.31E-4	2.216E-3	5.1E-4	2.328E-3	9.31E-3	
220	ZEBRA	1.547E-4	8.249E-4	1.42E-3	4.545E-4	2.767E-3	8.906E-4
400	TWIN AAAC	1.934E-5	2.065E-4	5.67E-3	1.051E-4	7.73E-4	3.66E-3
400	TWIN MOUSE	1.862E-5	2.075E-4	5.55E-3	1.012E-4	7.75E-4	3.584E-3

Figure A.1: Transmission line data

Appendix B

Data for Potential Transformer Failure Case

Source Data:

voltage magnitude - 66kV

Frequency - 50 Hz

Source type - RRL

this can be calculated from:

$$ShortcircuitMVA = \frac{V^2}{Z} \tag{B.1}$$

and

$$Z = \sqrt{R^2 + X^2} \tag{B.2}$$

Transformer Data:

Transformer MVA = 15MVA

knee Point voltage = 1.25p.u

Cable Data:

It is Shown in fig.B1

Potential Transformer 100VA Data:

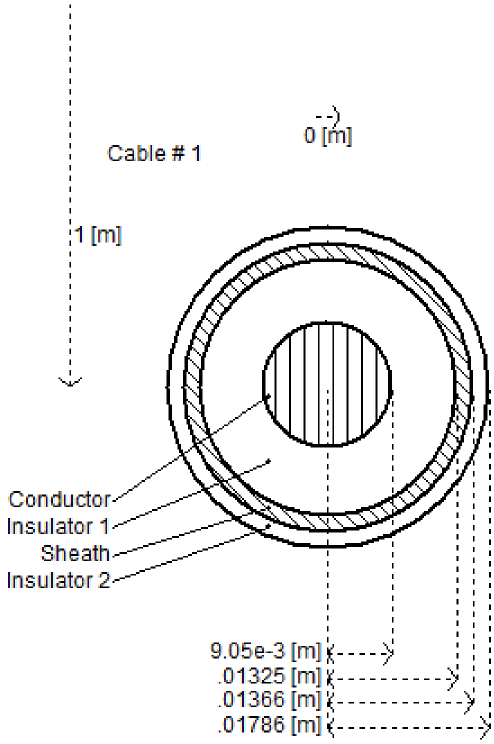

Figure B.1: cable data

VT Ratio: 227

Primary Inductance(referred to secondary): 5.5[H]

Primary Resistance(referred to secondary): 0.51[ohm]

Secondary Inductance: 0.121[H]

Secondary Resistance: 1.1[ohm]

Operating Flux density: 0.76[T]

Burden(R)= 121[ohm], (L)=0.63[H]

Potential Transformer 30VA Data:

VT Ratio: 227

Primary Inductance(referred to secondary): 0.227[H]

Primary Resistance(referred to secondary): 0.81[ohm]

Secondary Inductance: 0.429[H]

Secondary Resistance: 1.9[ohm]

Operating Flux density: 0.63[T]

Burden(R)= 431[ohm], (L)=0.97[H]

VT Saturation Data

Shown in fig B2 and B3 for 100VA and 30VA VT respectively: It can be calculated by below Equation:

$$log(H) = \alpha^1 * log(B) + log(K_1) \tag{B.3}$$

where-

α^1 - Index

K_1-co-efficient

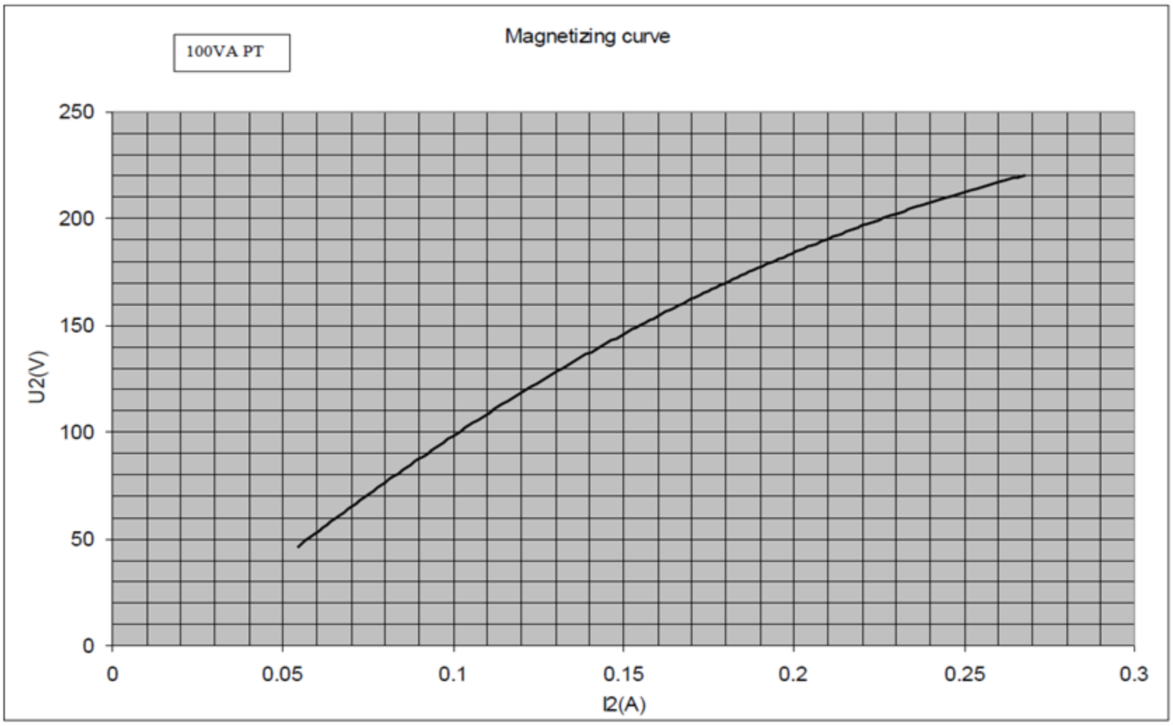

Figure B.2: 100VA Magnetization Curve

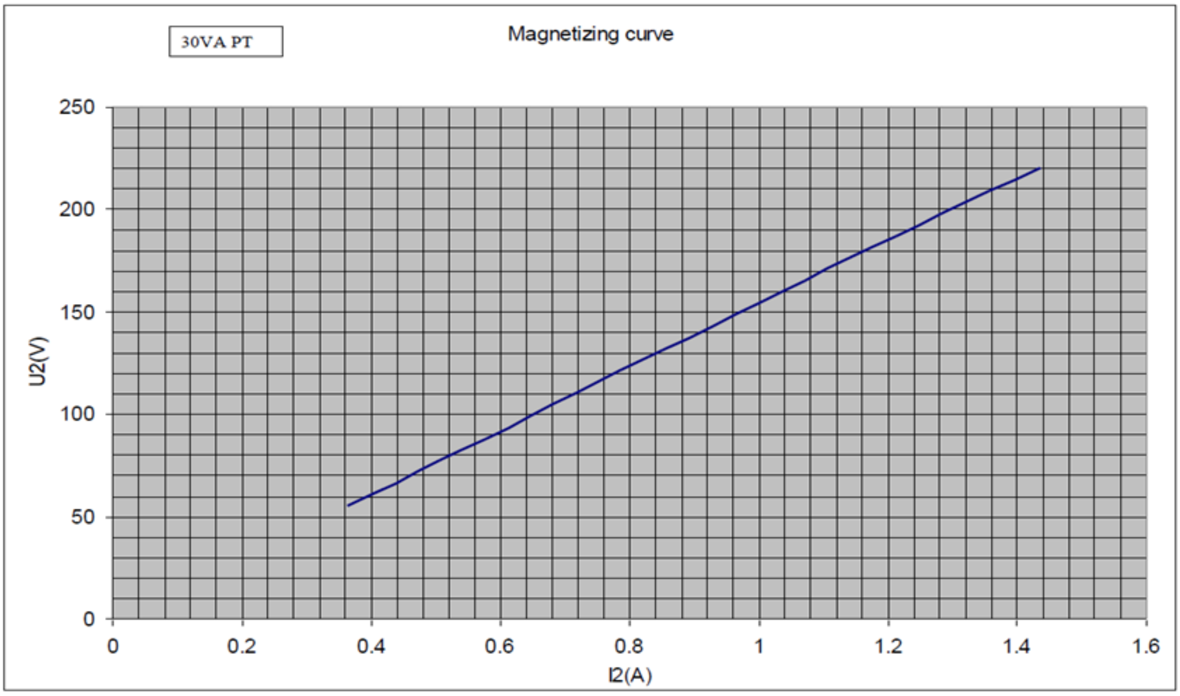

Figure B.3: 30VA Magnetization Curve