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Switching and Power Frequency Transients in EHV Systems A Review and Case study

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Overvoltages caused by transients are important in a power system as they cause stresses on electrical equipment. Majority of power system failures are directly or indirectly related to transient problems rather than steady state operation. The insulation level of each element in a power system is governed by the transient voltages originating as a result of lightning, short circuits and switching actions. In contrast to lightning, switching overvoltages originates on the system and is inherently measured in terms of the system voltage.

With the adoption of 400 kV voltages and above, it was clear that switching surges created in the system would determine the cost and strength of the major insulations to ground. This paper gives an insight to the electromagnetic transient phenomenon - switching and power frequency overvoltages and case study results of simulation for these overvoltages for a typical Indian 765 kV system.

Keywords: *Electromagnetic Transients, Overvoltages, EMTP (electromagnetic transients program)*

1.0 INTRODUCTION

Power System Networks are subjected to various types of transient phenomenon ranging from the relatively slow electromechanical oscillations (electromechanical transients) to comparatively faster variations in voltage and current brought about by sudden changes in the network (electromagnetic transients). Over the years, the voltage levels at which electrical power is transmitted has increased and many systems are now in operation at 400 kV, 765 kV and attempts are in progress for implementation of 1200 kV Transmission system in India.

Electrical transients in power system are manifold. Different kinds of transient phenomenon have been identified and investigated. Following are the important types of transient phenomenon:

- **Lightning overvoltages:**

  Direct lightning strokes

  Indirect lightning strokes, back flashover

  Induced lightning overvoltages

- **Switching Transients:**

  Energisation and re-energisation of transmission lines

  Energisation of transformers

  Capacitor switching

  Reactor switching

  Ferro-resonance

  Current chopping

  Restriking in circuit breakers

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Load rejection

Harmonic distortion

Fault clearing

Shaft torsional oscillations

- **Very fast transients:**

Disconnector operations

Faults within Gas insulated substation

The overvoltages caused by transients are important in a power system because of the stresses exerted on the insulation. The classifications of overvoltages based on the characteristics are as given below:

- Temporary / Dynamic overvoltage - Power frequency overvoltage of longer duration
- Slow-front overvoltage - Switching overvoltage : Transient overvoltage with time to peak 20 µs < T_{peak} ≤ 5000 µs and time to tail Ttail ≤ 50 ms
- Fast-Front overvoltage – Lightning overvoltage : Transient overvoltage with time to peak 0.1 µs < Tpeak ≤ 20 µs and time to tail Ttail ≤ 300 µs
- Very Fast-Front overvoltage: Transient overvoltage with time to peak Tpeak≤ 0.1 µs, total duration < 3 ms, with superimposed oscillations at frequency of 30 kHz < F < 100 MHz.

Electromagnetic transient phenomenon in power systems involves frequency ranging from DC to almost about 50 MHz, where as electromechanical transients involve frequencies below power frequency. Table 1 below gives the frequencies associated with various types of transients in a power system [1].

TABLE 1

OVERVOLTAGES AND THEIR FREQUENCIES

Sl No.	Type of Overvoltage	Origin	Frequency range
1	Switching	Transformer Energisation	DC – 1 kHz
2	Switching/ Temporary	Load rejection	0.1 Hz – 3 kHz
3	Switching	Line energisation Line re-energisation	50 Hz – 10 kHz DC – 20 kHz
4	Switching	Fault clearing Fault initiation	50 Hz – 3 kHz 50 Hz – 20 kHz
5	Switching	Restriking in Circuit Breakers	10 kHz – 1 MHz
6	Lightning	Lightning surges, faults in substations	10 kHz – 1 MHz
7	Switching	Transient Recovery voltages	50 Hz – 20 kHz 50
8	Very Fast Transients	Disconnector switching and faults in GIS	100 kHz – 50 MHz

2.0 OVERVOLTAGE CLASSIFICATION

(a) Power frequency / Temporary / Dynamic overvoltages (PFO / TOV / DOV):

According to IEC 71-1 standards [2], power frequency overvoltage is defined as ‘phase-to-earth or phase-to-phase overvoltage’ at a given location of relatively long duration, which may be undamped or only weakly damped. Undamped TOV occur in power systems in steady state conditions and are sustained by the emf of the generators. They can be modified only by the excitation system of the generators, tap settings of generators or switching in of shunt reactors.

The magnitude of TOV is indicated by the ratio of the power frequency component of a given voltage to the rated voltage of the system. High TOV’s are important for two electrical components viz. transformers and surge arresters. A high value of TOV causes saturation of transformers and in case of surge arresters lead to continuous conduction of the arrester.

Switching operations that most frequently lead to temporary overvoltages are:

- Energisation of transformer terminated line
- Load rejection

Figure 1 shows a typical temporary overvoltage wave shape.

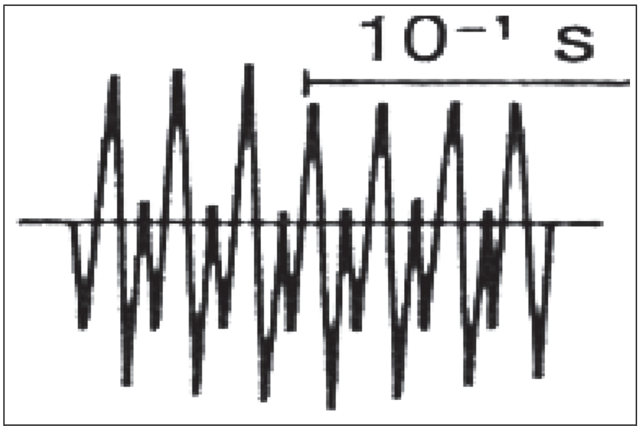

FIG 1: TEMPORARY OVERVOLTAGE

(b) Switching overvoltages:

According to IEC 71-1 standards, switching overvoltage is defined as ‘phase-to-earth or phase-to-phase overvoltage’ at a given locationin a system due to a specific switching operation, fault or any other cause, the shape of which can be regarded for insulation coordination purpose as similar to that of the standard impulse used switching impulse tests.

Switching overvoltages are generated in power system by sudden changes in the system configuration such as circuit breaker operation, fault initiation etc. that causes a voltage step or a current injection to be applied to the system. They occur during the transient period in which the system evolves from one steady state condition to another steady state condition. The time constants according to which the switching overvoltages decays are generally small, maximum upto few milliseconds. Thus the steady state condition is reached within two to three cycles of fundamental frequency. The highest frequencies involved in the phenomenon can range from few Hz to several hundred KHz as given in Table 1 above. Figure 2 shows a typical switching over voltage waveform.

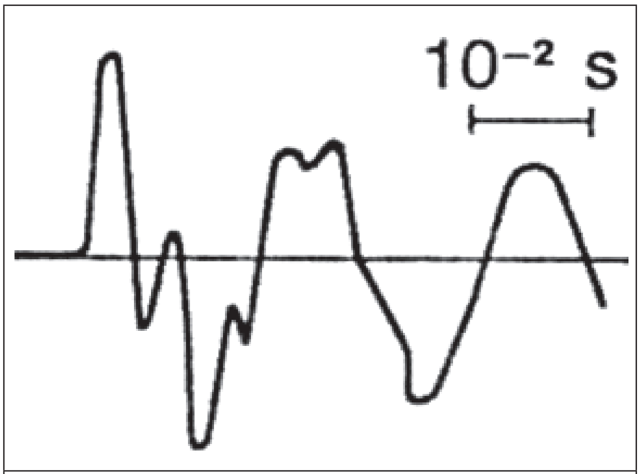

FIG 2: SWITCHING OVERVOLTAGE

The magnitude of switching overvoltage is defined by its per unit value i.e. the ratio of the absolute value of the overvoltage to a reference value equal to $\sqrt{2}/\sqrt{3}$ times the rated line-to line RMS system voltage.

The stress caused by switching surges on power system is mainly dielectric in nature. Generally there are no thermal effects, the only thermic stress indirectly caused by switching overvoltages is on the line connected surge arresters.

The main factors that affect the amplitude of the overvoltages are:

- Network configuration
- Network parameters – short circuit parameters
- Circuit behavior (closing instants, prestrike, preinsertion resistors, presence of trapped charge etc.)
- Fault initiation instant (in case of faults)

Line energisation and Re-energisation causes the highest switching overvoltages in EHV systems and are explained below in detail.

1. Line Energisation and re-energisation:

The overvoltages occurring during transmission line energisation / re-energisation comprises of two components – a transient overvoltage and a power frequency overvoltage. The PFO is originated by the charging MVAr of the line flowing into the reactance of the feeding network, resulting inan increase in the bus voltage at the sending end of the line. The Ferranti effect (in case of long open-ended line) also causes an increase in power frequency voltage at the receiving end of the line.

The transient overvoltages are originated by the propagation of the voltage waves caused by closing of the circuit breaker and decays within the first few cycles. The magnitude of the overvoltages due to line energisation, the maximum peaks of the phase-to-ground overvoltages are generally in the range of 2.5 pu at the open end of the line, and in the range of 1.5 pu to 2.5 pu at the switching bus bars. However, in case of three-phase line re-energisation the receiving end voltages can be as high as 4.0 per unit, in case of the presence of trapped charge on the line. However, such high values are not permitted in EHV and UHV systems. Means are required for reducing the magnitude of these overvoltages. The most commonly adopted methods are:

(i) Use of pre-insertion resistorsin line circuit breakers – each breaker pole will have an auxiliary contact that connects the two poles of the breaker through a series resistor. After a few milliseconds the main contact short circuits the resistor making the final contact. The reduction in SOV depends on the resistance value and on the insertion time of the resistors [3]. In case of uncompensated lines, the best value of the resistance is approximately close to the surge impedance ($\sqrt{L}/\sqrt{C}$) of the line, in case of compensated lines the value is much higher. The insertion time ranges from 5 to 12 milliseconds (depends on system characteristics). Beyond a critical value the SOV reduction is very minimal

(ii) Use of line connected Shunt reactors: Compensation of the line charging MVAr by means of shunt reactors reduces the power frequency overvoltages, but slightly affects the SOV.

(iii) Use of Surge Arresters: Use of Preinsertion resistors is being dispensed with, because in addition to its cost and complex technology, its failure rate is sometimes unacceptably high. Consequently using this method, reliability of the whole system is decreased. Instead, Surge Arresters located at transmission line ends have been used as a second line of defence to protect against switching overvoltages. This has been possible with the introduction of high-energy polymer-housed surge arresters.

3.0 POWER SYSTEM MODELING FOR OVERVOLTAGE STUDIES:

Computation of switching / power frequency overvoltage requires simulation study of the power system network. The type of model to be used in the simulation for each power system component must be tailor made to suit the scope of the study as no component modelis appropriate for all types of transient analysis. From the modeling viewpoint, it is appropriate to classify power system transients based on the time range of the study, which itself is related to the phenomena under investigation [4]. Thus the selection of model that realistically represents the physical power system component over the time frame of interest is a key issue in transient analysis.

The time frame for switching overvoltages is in the range of micro to milli seconds although the simulation can be carried out for few cycles,if system recovery from the disturbance is to be investigated. The simulation thus must be capable of reproducing adequately the frequency variations of both the lumped elements (machines, reactors etc) and distributed elements (lines, cables etc.) of the power system. The simulation must also represent non-linearities such asmagnetic saturation, surge diverter characteristics.

The simulation of transient phenomena relatedto circuit-breaker operation involves two issues. One is (a) representation of the non-linear characteristics of breaker (the arcing phenomenon) and (b) the accurate closing instants of switching which is random in nature i.e. the line breaker can close at any instant on the sine wave of the voltage wave form.

As the instant of closing (different in eachphase) is not normally controllable, a statistical switching overvoltage study should generally be carried out comprising of typically hundred two hundred separate simulations. The three poles that are mechanically linked close within a finite time (pole span) between the closing instants of the three poles. The closing times follow both Uniform and Gaussian distributions, with closing angles varying from 0 to 360 degrees.

4.0 SWITCHING AND TEMPORARY OVERVOLTAGE SIMULATION - CASE STUDY

A case study of (a) Switching overvoltages due to transmission line energisation and re-energisation (c) Temporary overvoltages due to load rejection for a typical 765 kV line in the Indian systemis presented in this paper. The main aimis to determine the maximum SOV and TOV and ensure that they are well within the prescribed limits [5]. Simulations reported in this paper have been carried out using Electro Magnetic Transient Program EMTP. The EMTP is a general purpose computer program for simulating fast transients in electric power systems. All calculations in EMTP are performed in time domain. The program features a wide variety and range of modeling capabilities for computation of electromagnetic and electromechanical transients. The program supports the modeling of travelling waves on overhead lines and cables, lumped linear elements, transformers along with saturation, synchronous machines, circuit breakers etc. [6].

The network configuration for SOV study is shown in Figure 3. There are three generators each rated 21 kV, 660 MW at Bus A. The voltage is stepped up to 765 kV, and power is evacuated over a double circuit 765 kV line oflength 378 km. Bus reactor of 330 MVAr isprovided at Bus A and 240 MV Ar reactor at Bus B. Similarly, the line is compensated with 330 MVAr line reactors at Bus A and 240 MV Arreactorsat Bus B of each line. For line energisation and re-energisation studies exact representation of the network only upto the first substation is sufficient in most cases, withrest of the system being represented by equivalents.

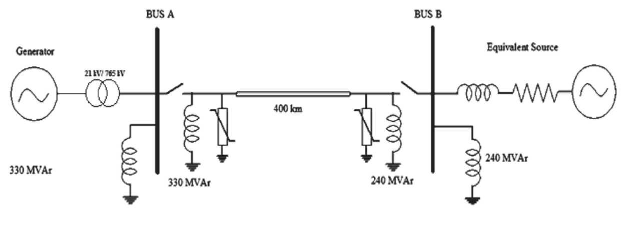

FIG 3: SLD OF SYSTEM – SOV STUDY

The system behind bus Bis represented by equivalent impedance (based on the short circuit contribution – 10,727 MVA) behind a voltage source. The various power system components modeled are discussed below.

Generators: The generators are modeled as voltage sources behind subtransient reactances for SOV studies and are modeled in detail along with its excitation system for TOV studies.

Equivalent Sources: Equivalent sources are represented using the positive and zero sequence impedances based on the short circuit contribution from the network behind the switching bus.

Transformers: The transformers are represented using the three phase transformer model available in EMTP (winding configuration, voltage ratio and leakage reactance and the saturation characteristic).

Shunt Reactors: Shunt reactors are modeled as star connected reactors with appropriate X/R ratio.

Transmission Line: Transmission lines are represented as a distributed parameter line with its positive and zero sequence -Resistance, Inductance and Capacitance per unit length of the line and length of transmission line (as given in Table 2 below)

TABLE 2

765 kV LINE PARAMETERS

Positive Sequence pu/km/ckt			**Zero Sequence pu/km/ckt**		
R1	X1	B1	R0	X0	B0
1.95e-6	4.88e-5	2.35e-2	4.5e-5	1.8e-4	1.406e-2

Surge Arresters: The Zinc oxide Surge Arresters are represented by their VI characteristics as given in Table 3.

Voltage rating: 624 kV RMS

Nominal Discharge current: 20 kA of 8/20 microsec wave

TABLE 3

V-I CHARACTERISTIC

Ampere (A)	Voltage (Vpeak)
1000	1180000
2000	1220000
10000	1430000
20000	1480000

Circuit Breakers: The line circuit breakers have been modeled as time controlled statistical switches. A single step closing resistor has been considered in the simulation to represent the preinsertion resistor. Thus each pole of the circuit breaker is modeled with two switches, one for the auxiliary contacts with the pre-insertion resistors and the other for the main contact.

5.0 CASE STUDIES:

(a) Line Energisation study:

The transient overvoltage study has been (energisation and re-energisation) carried out considering fifty numbers of random operations of the line breaker which has been represented as a statistical switch having Gaussian distribution function. A maximum pole span of 8 ms has been considered. Energisation of the line has been carried out from both line ends A and B. In each case, the line end at remote bus has been kept open. As the objective of the study is to determine the maximum overvoltages, the worstcase scenario of only one line and one generator in service has been considered.

The voltages (phase-to-ground) at both line ends at Bus A and Bus B are measured in either case of energisation. The following cases have been considered for Line Energisation studies.

Case (a): Open ended Line Energisation from Bus A, with no PIR and no Surge Arresters (SA)

Case (b): Open ended Line Energisation from Bus A, with PIR and Surge Arresters (SA)

Case (c): Open ended Line Energisation from Bus B, with no PIR and no Surge Arresters (SA)

Case (d): Open ended Line Energisation from end B, with PIR and Surge Arresters (SA)

Various values of PIR and insertion times have been considered in the study. However, the results of that particular case which gives the magnitude of overvoltages within the specified limits are reported in the paper. Table 4 gives the magnitude of overvoltages at both ends & B, considering PIR of 252.9 Ohms and insertion time of 10 milliseconds.

TABLE 4

ENERGISATION OVERVOLTAGES

Case	**Max. SOV (pu)***		**Fig no.**
	End A	**End B**	
Case (a)	2.01	2.40	Fig 4
Case (b)	1.85	1.88	Fig 5
Case (c)	2.41	1.56	Fig 6
Case (d)	1.48	1.30	Fig 7

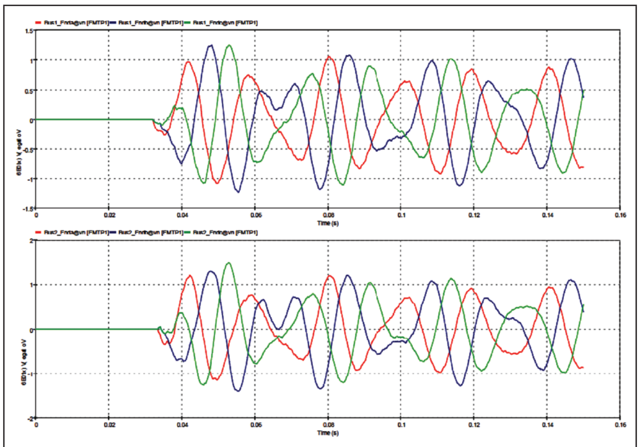

FIG 4: BUS VOLTAGES (A, B) – CASE (A)

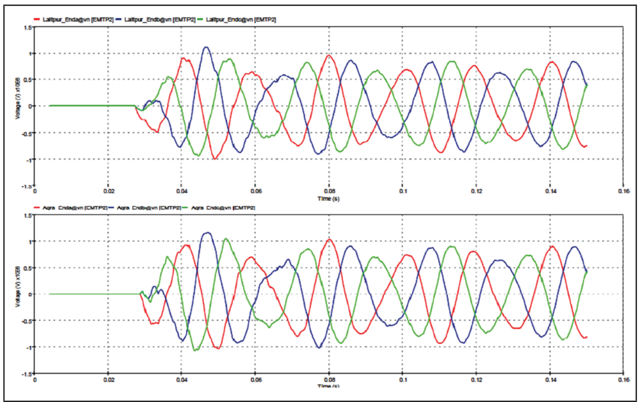

FIG 5: BUS VOLTAGES (A, B) – CASE (B)

It is found that for different cases studied the SOV are within the prescribed limits of 1.9 pu peak phase to neutral with use of both PIR and arresters at line ends [4]. The arrester energies were also monitored and found to be well within the rating of the arrester i.e 13 kJ / kV.

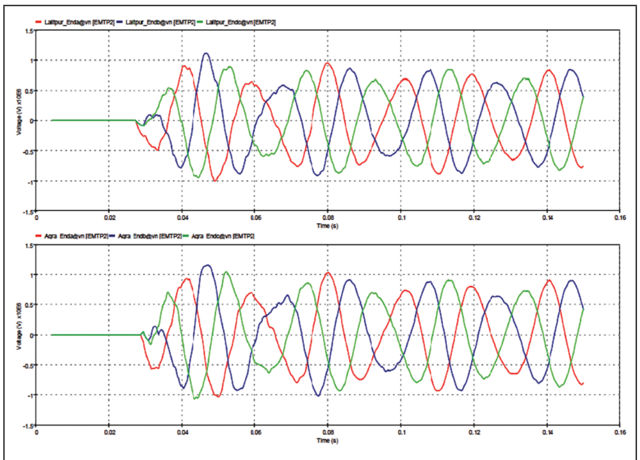

FIG 6: BUS VOLTAGES (A, B) – CASE (C)

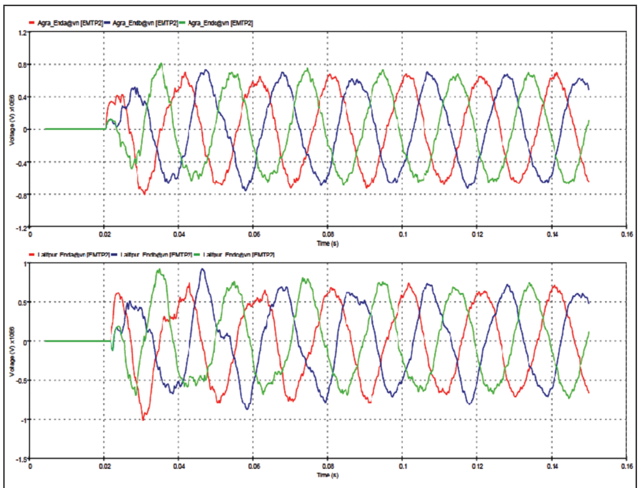

FIG 7: BUS VOLTAGES (A, B) – CASE (C)

(b) Re-Energisation study:

In case of re-energisation study, to simulate the trapped charge effect the switches representing the circuit breakers are initially kept closed followed by opening action of the switches. Thus the charges will be trapped on the line before the circuit breakers are reclosed. Both lines are assumed to be in service, and re-energisation of only one line is considered. The dead time is assumed to be 300 milliseconds. Table 5 gives the gives the magnitude of the re-energisation overvoltages.

TABLE 5

REENERGISATION OVERVOLTAGES

Case	**Max. SOV (pu)***		**Fig no.**
	End A	**End B**	
Case a	1.47	1.43	Fig 8
Case b	1.19	1.23	Fig 9

* 1 pu: 624.62 kV peak, phase- ground

It is seen from the above Table that the maximum overvoltages for the case of re-energisation was found to be 1.47 pu.

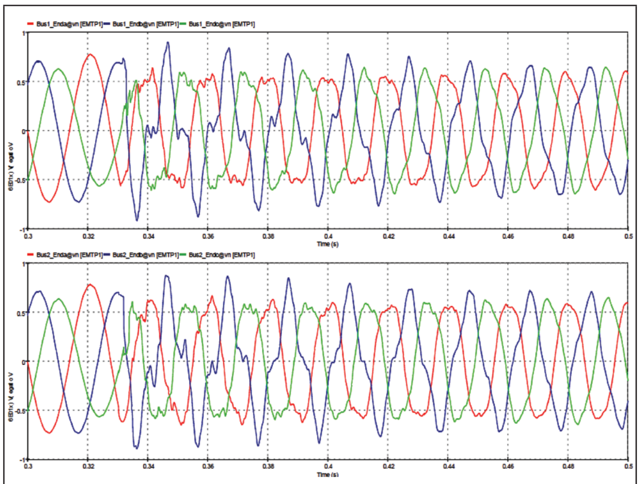

FIG 8: BUS VOLTAGES (A, B) – CASE (A)

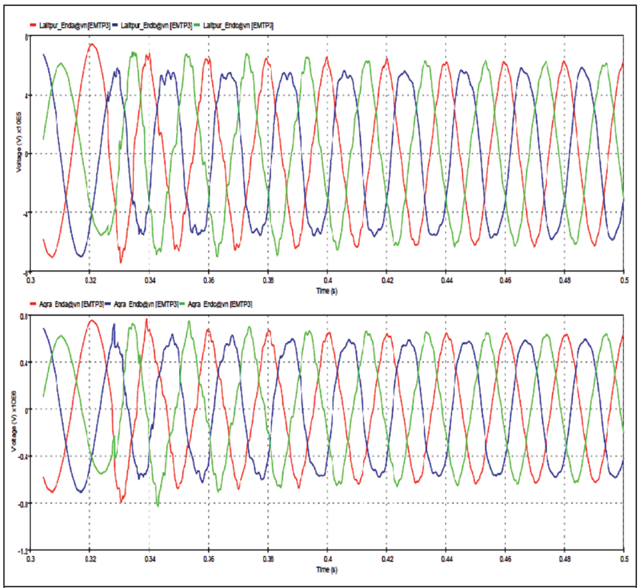

FIG 9: BUS VOLTAGES (A, B) – CASE (B)

(c) Temporary overvoltage study:

The TOV have been computed using the Masta module of the SIMPOW software. The system considered for the study is shown in Figure 10. Peak load condition having maximum power evacuation from generators with the proposed reactive power compensation on the lines andbus has been considered. This being a study for load rejection, maximum power generation i.e. all three generators inservice has been considered so that the active power flow on the line would be maximum. A single-line-to ground fault has been simulated at either end ofthe line followed by opening of all three poles of the line breaker at the faulted end to simulate complete load rejection on the line. It is assumed that the other circuit remains in service. The maximum peaks of the dynamic over voltages computed are given in Table 6.

TABLE 6

MAXIMUM TEMPORARY OVERVOLTAGES

Case	Max DOV (pu)		Fig No
	End A	End B	
Fault close to Bus A (ckt.1) followed by load rejection at Bus A	1.21	1.09	Fig11(a), 11(b)
Fault close to Bus B (ckt.1) followed by load rejection at Bus B	1.17	1.31	Fig 12(a), 12(b)

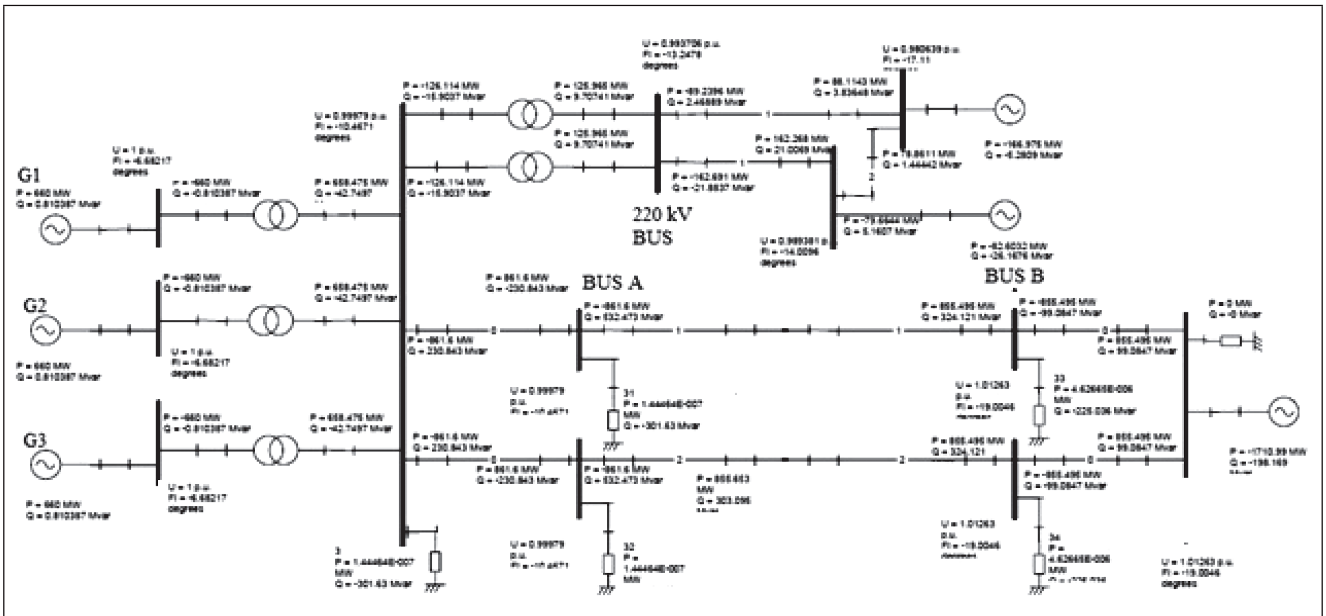

FIG 10: SLD OF THE SYSTEM – TOV STUDY

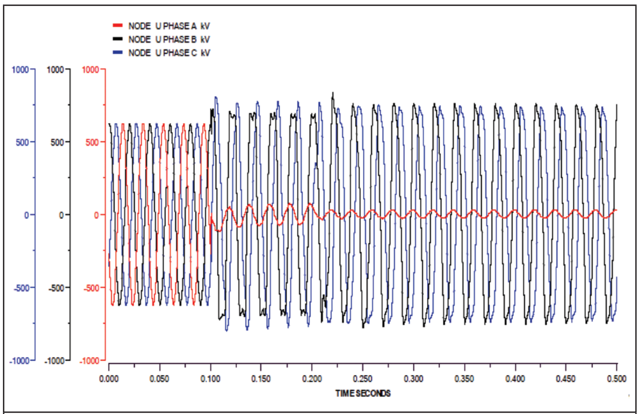

FIG 11(A): TOV AT BUS A END

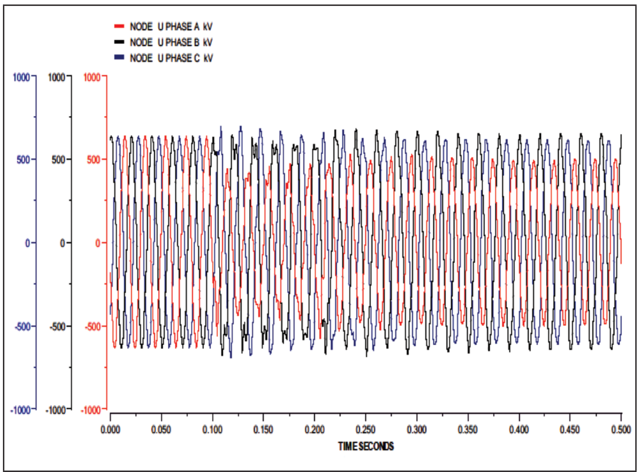

FIG 11(B): TOV AT BUS B END

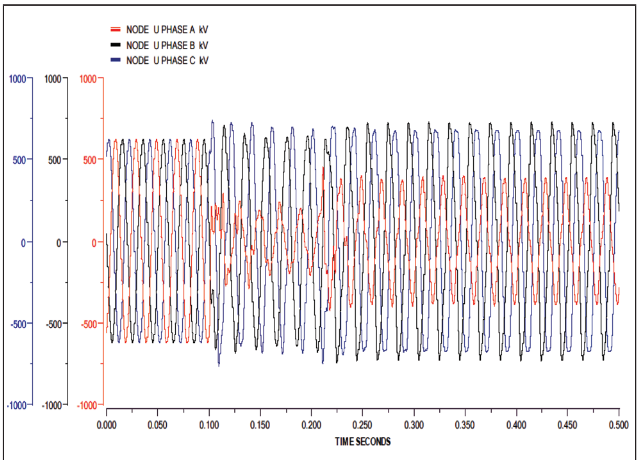

FIG 12(A): TOV AT BUS A END

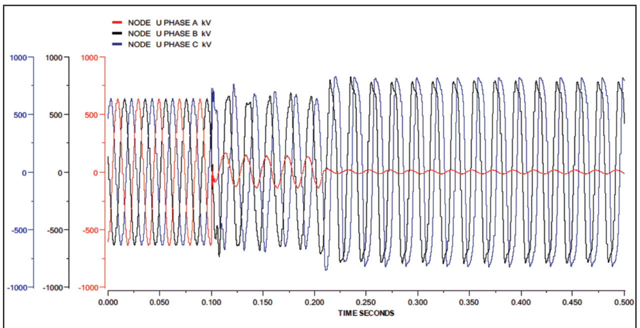

FIG 12(B): TOV AT BUS B END

TOV studies carried out show that the reactive power compensation of 330 MVAr line reactor on each circuit at line end A, 240 MVAr line reactor on each circuit at end B, Bus reactor of 330 MVAr at Bus A and 240 MVAr at Bus B are adequate to maintain the dynamic overvoltage within the limited value of 1.4 pu [6]

6.0 CONCLUSIONS

Electromagnetic transient studies involving computation of switching overvoltages are important as they are the deciding factors for the insulation level of various power system elements in EHV systems. IEC Standards give the insulations levels, both Switching surge Impulse levels and Lightning surge impulse levels that are to be provided for power system equipment at various voltage levels. Generally two to three insulation levels will be indicated and proper choice is to be made based on the maximum overvoltages experienced in the system. The maximum overvoltages occurring in the system should be well within the prescribed levels of insulation levels by a safe protection margin. Protective devices such as Surge Arresters are adopted to limit the over voltages within safe limits. The study results of switching and temporary overvoltages of typical 765 kV system have been presented in this paper indicating that they are well within the prescribed limits with the adopted values of preinsertion resistors, shunt reactors and surge arrester ratings.

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