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Application of Line Surge Arresters for Switching Over-voltages in UHV Transmission Systems

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Abstract

Switching Overvoltages (SOV) are critical for systems operating at Ultra High Voltage (UHV) level. Pre-insertion resistors (PIR) are usually used to suppress the switching overvoltages in UHV systems. PIR are effective in suppressing SOV's, but their shortcomings prompt utilities to explore other protection schemes. In this paper, the application of Line Surge Arresters (LSA) to suppress switching over voltages is studied. The statistical overvoltage analysis is carried out for a typical UHV system to compute the highest overvoltage magnitudes. The location and number of LSA's to be placed along the transmission line are decided based on the overvoltage profile along the line, observed during switching operations. The switching impulse withstand values of the equipment are calculated for proposed non-gapped line arrester arrangements and also compared with the withstand values for conventional system. The energy absorbed by the LSA's when placed along the transmission line is also observed. The simulations are performed using Electro-Magnetic Transient Program for the 1200 kV Indian transmission system. The results of this study show that the LSA's can be considered an alternate protection measure to suppress SOV's in a UHV system.

Keywords: Co-ordinations, EMTP, Insulation, Switching Over-voltage, Transient, Ultra High Voltage

1. Introduction

Transmission of bulk power is possible by establishing long length transmission lines operating at high voltage levels (800 kV to 1200 kV level). The transmission at this level proves to be economical and also unburdens the power network. The feasibility of UHV transmission was studied by countries like China, Russia (Former USSR), Japan, United States of America and Italy. At present only China has commercial lines operating at an ultra-high voltage level. India, considering its growing power demand, is planning to have a 1200 kV UHV transmission line network. A line of length 400 km from Wardha to Aurangabad is considered for up-gradation to 1200 kV[1–6].

When planning a new power system, in particular at new voltage level, insulation coordination is one of the most important concern. The main task is the determination of stresses and the assessment of the system and equipment installed. Insulation co-ordination of UHV line is important not only from reliability point of view but also makes the line cost effective.

Switching overvoltages (SOV) are generally decisive in determining the insulation design of extra and ultra-high voltage transmission lines. The highest SOV's are generated during the switching operations such as energisation and re-energisation of transmission lines. The magnitude of this overvoltages is dependent on transmission line length, the presence of remnant charges on the line, the degree and location of shunt compensation, the circuit breaker characteristics, the feeding source strength and transmission line parameters[7]. The most severe SOV's occur in the case of three phase reclosing with trapped charges on the line. SOV's can endanger external insulation because of its lower insulation strength under overvoltages with front time in the range of 50-500 μs, which is typical for SOV's [8,9]. The SOV's also severely stress the internal insulations of the UHV substation equipment. The traditional method to reduce switching overvoltages

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is to install pre-insertion resistors in transmission line circuit breakers. Most utilities have dispensed the use of PIR's because in addition to its cost and complex technology its failure rate is sometimes unacceptably high[10,11]. Another important alternative method to reduce switching overvoltages is the installation of LSA at suitable locations along the transmission line. The choice of line surge arrester specifications influences the overall insulation characteristics of the UHV equipment[12–14].

2. Modelling of UHV System

Indian utilities are planning to operate a 1200 kV UHV transmission line from Wardha to Aurangabad in Maharashtra covering a distance of 400 km. The initial parameters of the proposed line[2], provided by Power Grid Corporation of India (PGCIL), are shown in Table 1. This 1200 kV UHV system was considered for the computation of SOV's. The system was modelled and simulated in the well-known standard software Electro-Magnetic Transient Program (EMTP). The EMTP is a general purpose computer program for simulating fast transients in electric power systems.

Table 1. Typical parameters of Indian 1200 kv transmission system

Parameters	Value	Units
Nominal Operating Voltage	1150	kV
Highest Operating Voltage	1200	kV
Resistance	4.338×10^{-7}	pu/km/circuit
Reactance	1.772×10^{-5}	pu/km/circuit
Susceptance	6.447×10^{-2}	pu/km/circuit
Surge Impedance Loading	6030	MW
Surge Impedance	239	Ω

All calculations in EMTP are performed in time domain. The program features a wide variety and range of modeling capabilities of power system equipment 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.[15]. The schematic single line diagram of the studied UHV system is shown in Figure 1.

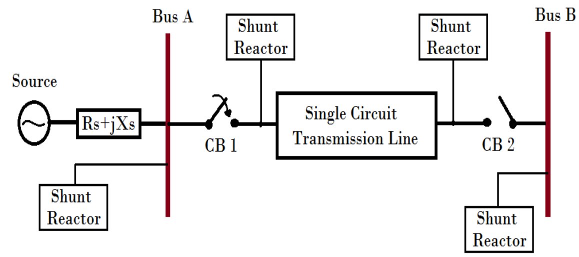

Figure 1. Single Line Diagram (Sld) of the uhv system studied.

2.1 Transmission Line

The line considered for the study is a single circuit 1200 kV transmission line[2]. The length of the line considered was 400 km. The structure of the single circuit transmission line is illustrated in Figure 2. Frequency dependent line model was used for modelling of the transmission line. Phase conductors were bundled and consist of 8 sub-conductors. The line parameters were computed using the line constants routine of EMTP and were found has shown in Table 2. The characteristics of the conductor data considered are shown in Table 3.

Table 2. Computed line parameters

	Zero Sequence	Positive Sequence
Resistance (Ω/km)	1.065	1.6272×10^{-2}
Inductance (mH/km)	1.651	7.9891×10^{-1}
Capacitance (μF/km)	9.765×10^{-3}	1.4461×10^{-2}

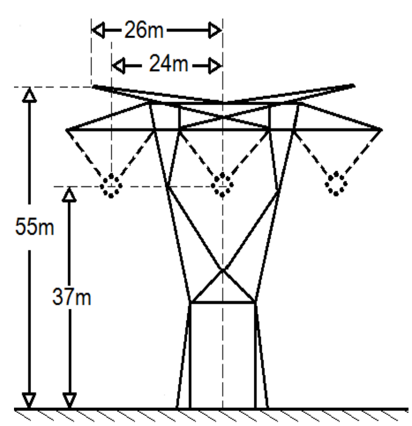

Figure 2. Single circuit uhv tower configuration.

Table 3. Conductor specifications

Description	Value	Units
Conductor Diameter	46.3	mm
Conductor DC resistance	0.0394	Ω/km
Earth wire diameter	15	mm
Earth Wire DC Resistance	0.221	Ω/km
Sag	12.7	m
Bundle	8	Nos.
Bundle spacing	46	cm

2.2 Source Impedance

The source impedance representing the network behind the line ends was modelled as a constant voltage source in series with impedance. The impedances have been calculated based on the Short Circuit levels. Table 4 shows the zero and positive sequence impedance calculated at Bus A end.

Table 4. Equivalent source impedance

Description			Bus A End (Ω)
Zero sequence	Resistance	R_0	4.33
	Reactance	X_0	34.64
Positive sequence	Resistance	R_1	0.866
	Reactance	X_1	17.32

2.3 Shunt Reactors

Shunt reactors as shown in Figure 1 were considered in the study[16]. Each of the three-phase shunt reactors has been modelled by a reactance in series with a resistance. Table 5 gives the shunt reactor ratings considered.

Table 5. Shunt reactor rating

Description Shunt Reactor Rating	Value (3 Phase)	Units
Bus reactor	660	MVAr
Line reactor	660	MVAr

2.4 Circuit Breakers

Circuit Breakers have been modelled as time dependent switches (with an option for statistical operation) at either end of the transmission line.

2.5 Surge Arresters

Conventional Surge arrester (CSA) were modelled according to the nonlinear V-I characteristics shown in Table 6. A surge arrester with rated voltage of 850 kVrms, energy class 5, and discharge capacity of 55 MJ was considered in the simulation.

Table 6. Nonlinear V-I characteristics of the surge arrester

Sl. No.	Surge Arrester Current (kA)	Residual Voltage (kVpeak)
1	0.5	1380
2	1.0	1440
3	2.0	1500
4	10.0	1600
5	20.0	1700

Line Surge Arrester (LSA) considered for the study is a low residual voltage surge arrester[12,17]. The V-I characteristics of the LSA considered is shown in Table 7. The non-linear waveforms of the Conventional Surge Arresters (CSA) and the considered LSA is shown in Figure 3. A surge arrester with rated voltage of 850 kVrms was considered in the simulation.

Table 7. Nonlinear V-I characteristics of the line surge arrester

Sl. No.	Surge Arrester Current (kA)	Residual Voltage (kVpeak)
1	0.5	1180
2	1.0	1240
3	2.0	1300
4	10.0	1400
5	20.0	1500

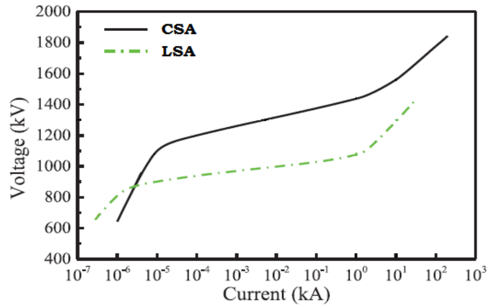

Figure 3. Nonlinear V-I characteristics of the Conventional Surge Arrester (CSA) and Line Surge Arrester (LSA).

3. Computation of Switching Overvoltages

The worst possible SOV occurs generally either during Line Energisation / reclosing of the line (with trapped charge). Thus to determine the maximum overvoltages in this study, trapped charges on the transmission line were considered. The receiving end (Bus B) of the transmission line was kept open (open ended lines give the highest overvoltages) as shown in Figure 1. The circuit breaker reclosing instant (point-on-wave) also influences the transient magnitude. The statistical switching of the circuit breaker switch was performed considering one hundred simulations and the closing was considered according to the Gaussian distribution, with a mean value of 95 ms, and standard deviation of 1.4 ms. SOV's were computed at various locations (ten points) along the transmission line, including the line end. Out of the hundred simulations performed, the case which showed the highest overvoltages was considered for obtaining overvoltage profile along the transmission line.

Figure 4 shows the phase-to-ground voltages at the receiving end of the transmission line when the switching operation was performed with all the shunt reactors in service. Initially, the line was charged to operating voltage of 1200 kV L-L. At 55 ms all the 3-poles of the sending end circuit breaker was opened and then reclosed after a dead time of 40 ms. It is seen from Figure 4 that during the dead time the trapped charge on the line is discharged though the line connected shunt reactors. Then depending on the instant of reclosing, large transients were observed just after reclosing with the peak value of the phase voltage as shown in dotted red circle (Figure 4).

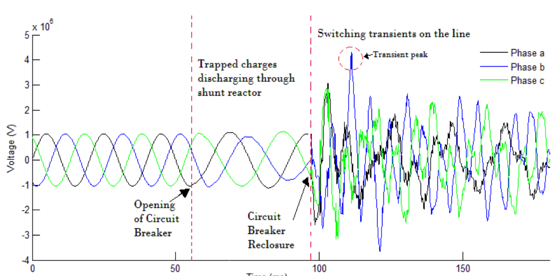

Figure. 4 voltages at the receiving end.

3.1 SOV Control

The convensional method uses a PIR for suppressing SOV's. The CSA's present at the ends of the transmission line are basically to absorb lightning transients but in case of UHV system they also help in suppresing switching transients. The single line diagram of the system considered is shown in Figure 5. The PIR value considered is 600 Ω with insertion time of 10 ms. Switching operations were performed as detailed in Section 3.

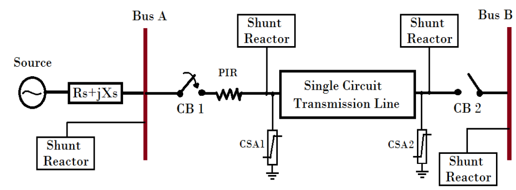

Figure 5. Single line diagram of UHV system with pir protection.

The overvoltage profile observed is plotted in Figure 6. The maximum observed overvoltage level is 1.57 pu and the 2% overvoltage value obtained from cumulative distribution function was found to be 1479 kVp (1.51 pu). However permissible value of SOV for a 1200 kV system is 1.7 pu[18].

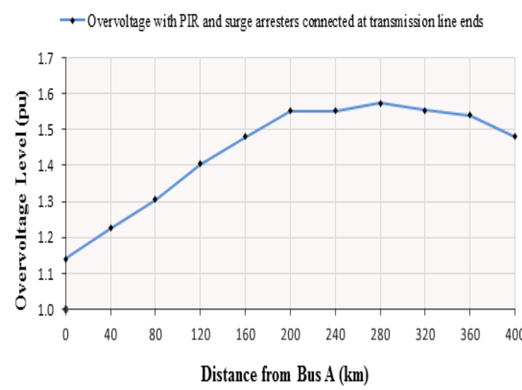

Figure 6. Overvoltage profile along the transmission line with pir and surge arresters.

4. Application of Line Surge Arresters

One of the alternate measure to suppress switching transients in UHV transmission system is the use of LSA's along the transmission line. In this system low residual voltage surge arresters are placed at selected locations on the transmission line which clips the voltage to their switching impulse protection level during switching transients and also absorb large transient energy. The installing of LSA's has following advantages:

- Reducing cost of new line by using same tower configuration for an increased operating voltage.
- Simplification of breaker design without PIR.
- Increased line reliability against switching overvoltages.

At present only China has transmission lines operating at UHV (1000 kV) level. There have been simulation works carried out by the researchers in China on application of LSA's and have been published in reference[12–14].

Initially the LSA's (LSA1 and LSA2)are placed at transmission line end of the system shown in Figure 1. The statistical operations are performed and the overvoltage profile along the transmission line is recorded as shown in Figure 7. Based on the peak overvoltage level observed in the profile the location of the next LSA is decided. Observing Figure 7, it is decided to place the next LSA (LSA3) at 280 km from Bus A since the peak is observed between 280 km to 320 km of line length. This precedure is continued and the fourth and fifth LSA's are placed based on peak observed in overvoltage profiles. The location of forth LSA (LSA4) is 200 km and fifth LSA (LSA5) is 120 km from Bus A end. Any furthur incease in the number of LSA's would be un-economical. Hence, totally five LSA's are connected along the line. The single line diagram of this system is shown in Figure 8. The arrangement of LSA's is symmetric with connection at 0%, 30%, 50%,70% and 100% of the transmission line length. The overvoltage profile along the transmission line for the system with all five LSA's connected to the line is shown in Figure 9. The maximum overvoltage value is observed at 240 km from BUS A. The addition of LSA (LSA5) at 30% of the line the maximum observed overvoltage level is reduced 1821.33 kVpeak(1.86 pu). The 2% overvoltage value obtained from cumulative distribution function was found to be 1.37 pu.

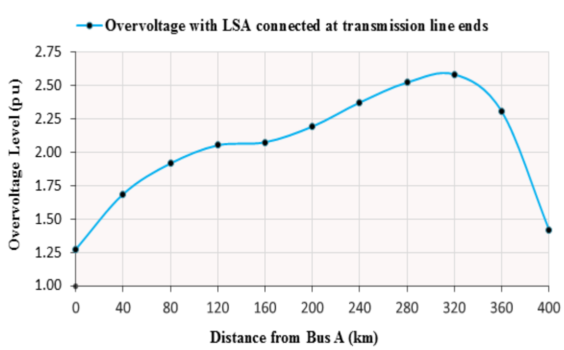

Figure 7. Overvoltage profile along the transmission line with lsa's connected at line ends.

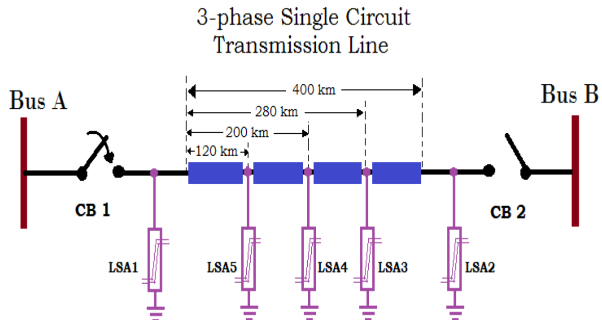

Figure 8. A schematic representation of LSA'S placed at different locations along the line.

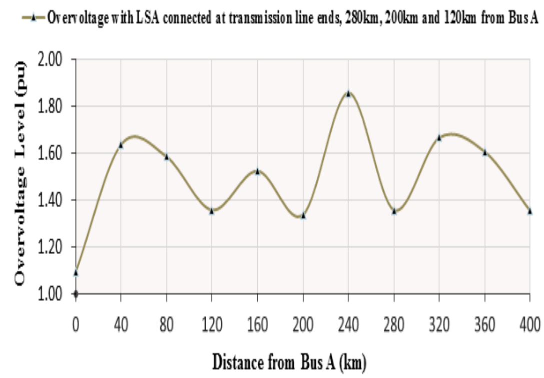

Figure 9. Overvoltage profile along the transmission line with lsa's at different locations along the line.

5. Energy through Line Surge Arresters

The energy absorbed by each LSA for various cases was recorded and plotted. The calculation of energy absorbed by the line surge arresters showed that with increase in the line surge arresters along the line reduced the stress on the individual LSA. The plot showing the value of energy absorbed by a LSA when placed at a particular location is shown in Figure 10. It can be observed that when only two LSA's are placed at line ends the energy absorbed by the single LSA at line end is very high. With LSA's at all the five locations i.e., at 120 km, 200 km, 280 km and at line ends the energy absorbed by each arresters reduces drastically. From these observations it can be suggested to use higher class arresters at transmission line ends and a lower class arrester along the transmission line.

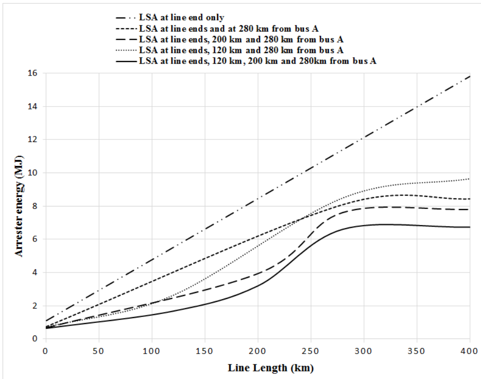

Figure 10. Energy absorbed by the lsa's placed at various locations.

6. Calculation of Withstand Values

IEC Standards provide the procedure to obtain the withstand voltage levels for the system. The simplified statistical method presented in [19] is considered to calculate the switching impulse (SI) withstand value. Initially, the statistical withstand voltage (Ub10), which has 10 % probability of breakdown and 90% probability of withstand, is calculated using (1).

$$U_{b10} = K_{es} \times U_{e2} \quad (1)$$

where, K_{es} is Statistical Co-ordination factor and U_{e2} is Statistical overvoltage which has 2% probability of being exceeded.

K_{es} is selected to meet the required risk of failure (R). The typical variation of risk of failure with respect to K_{es} is shown in Figure 11. The acceptable level of risk of failure according to standards is generally between 10^{-1} to 10^{-4} per switching operations[19,20]. Therefore K_{es} value considered is 1.04. U_{e2} is obtained from the cumulative distribution function of overvoltages occurring at Bus B end.

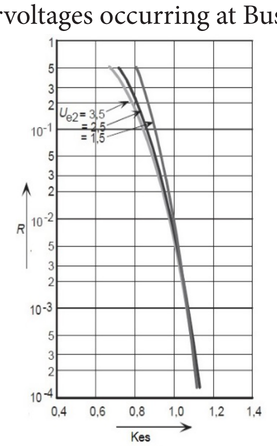

Figure 11. Risk of failure as a function of statistical co-ordination factor.

The required withstand value (U_{rw}) is calculated by the equation (2).

$$U_{rw} = K_s \times U_{b10} \quad (2)$$

where, K_s is safety factor which considers factors such as manufacturing tolerance, environmental conditions and aging. The values to be considered for K_s are:

K_s (internal insulation) = 1.15

K_s (external insulation) = 1.05

The withstand values for the conventional PIR protected system and the system with LSA protection are calculated and tabulated in Table 8.

Table 8. The calculated switching impulse withstand values

	Switching impulse required withstand value (U_{rw}) (in pu)	
	Conventional PIR protection	**LSA protection**
External insulation	1.65	1.5
Internal insulation	1.8	1.64

7. Conclusions

The switching transients occurring in a typical 1200 kV transmission systems are estimated. The conventional method adopted to suppress SOV's ie, use of PIR is compared with the use of LSA's along the transmission line.

For the system with PIR protection against SOV's, the required withstand value obtained is 1.8 pu (for internal insulation). Similarly, for the system with LSA's connected, the required withstand value obtained is 1.64 pu. The percentage reduction obtained in withstand value is found to be 8.89 %. This reduction in withstand value gives the opportunity to UHV system equipment manufacturers to reduce the insulation used in their equipment and test the system with the reduced withstand value. The lower the insulation requirement in an equipment, lower will be the cost of the equipment. Therefore the use of LSA's to protect UHV system against SOV's has an impact on the cost of the equipment.

With the increase in number of line surge arresters connected along the transmission line, the energy absorbed by individual arrester is reduced. Therefore it is proposed that a higher class (Class 5) LSA be placed at the transmission line end and Lower class (Class 4 or Class 3) LSA be placed at 30 %, 50 % and 70 % of the transmission line.

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