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Insulation Coordination of a UHV AC Transmission Line Considering the Switching Overvoltage Waveshape

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Abstract

This paper presents the determination of insulation coordination for phase-to-ground switching over voltages by a practical method in which the effect of the switching overvoltage waveshape, especially the impact of the time to crest on insulation strength is considered. This work is carried out on the world's first 1200 kV transmission line by modelling it in PSCAD.

Keywords: Insulation-Coordination, Line Energization, Line Re-Energization, SSFOR, UHV AC Transmission

1. Introduction

The economy of most countries is growing every year, for which electrical energy is one of the most important inputs. The electricity-dependent development causes an increase in power demand which necessitates the development of large-sized resource-based generating stations in resource-rich regions to ensure optimal utilization of unevenly distributed energy resources which are far away from load centres. To keep pace with this increase in generation, transmission system capacity had to be increased for the transfer of this bulk power to the long-distance load centres. To meet this requirement majority of the countries have adopted UHV AC transmission systems between generating stations and load centres. In the UHV range, Switching Over Voltages (SOVs) determine the insulation level rather than lightning overvoltages[1,2].

Insulation coordination in its most fundamental form is defined as the "selection of the insulation strength". If we want to add performance/reliability criterion and something about the electrical stress placed on the insulation then the definition would become "selection of the insulation strength consistent with the expected SOVs to obtain an acceptable Switching Surge Flashover Rate (SSFOR)"[3]. This definition clearly states that the insulation strength is selected based on some quantitative or perceived degree of SSFOR which is the number of flashovers per switching operation.

The insulation coordination process for the transmission line begins with the selection of the reliability criteria (specified SSFOR), followed by the determination of electrical stress experienced by the transmission line insulation due to SOVs and the determination of the insulation strength of the transmission line when SOVs are subjected to it. From the electrical stress and insulation strength thus determined, actual SSFOR is estimated. Finally, insulation strength is selected by comparing the estimated SSFOR with the specified SSFOR. Hence, the central concept in the insulation coordination process is an estimation of the SSFOR.

The recent trend is to apply statistical methods to estimate SSFOR. Various researchers estimated the SSFOR by neglecting the effect of SOV waveshape on insulation strength considered a traditional method[2,4–6]. But this paper estimated the SSFOR by considering the effect of SOV waveshape on insulation strength considered a practical method. R.R. Nunes *et al.*,[7] and Y. Li *et al.*,[8] used practical methods to estimate SSFOR, but they did not cover actual UHV AC system parameters.

2. Overview of the UHV AC System and Modelling Approach

This complete work is carried out on the single-circuit 1200 kV UHV AC transmission line which is under construction between Wardha-Aurangabad (about 405 km). The finalized technical parameters of 1200 kV UHV AC transmission lines on a base MVA of 100 MVA and base kV of 1200 kV are given in Table 1[9].

Table 1. Transmission line parameters

Sl. No.	Parameter	Value
1	Nominal Line Voltage	1150 kV
2	Maximum Line Voltage	1200 kV
3	Resistance	4.338 x10^{-7}p.u./km
4	Reactance	1.772 x10^{-5}p.u./km
5	Susceptance	6.447 x10^{-2}p.u./km
6	Surge Impedance Loading (SIL)	6030 MW
7	Surge Impedance	239 Ohm

The Single Line Diagram (SLD) of the 1200 kV UHV AC transmission system considered for simulation studies in PSCAD[10] is shown in Figure 1.

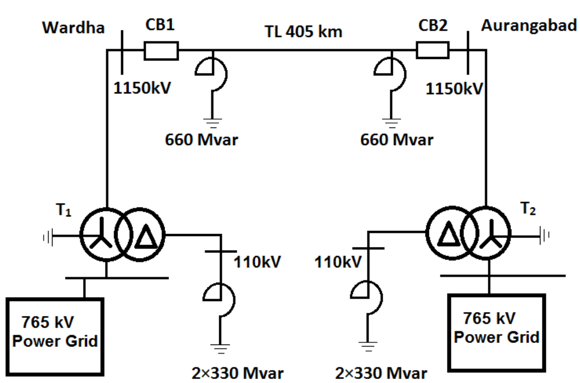

Figure 1. The SLD oF 1200 kV UHV AC system for simulation studies.

The modelling suggestions for all components in PSCAD[10] are as follows:

Sources: Generators are modelled as voltage sources in series with sub-transient reactance (Thevenin's impedance)[11,12]. The calculated zero and positive sequence impedances at the Wardha bus end based on the source short circuit level of 15000 MVA[13] are given in Table 2[14].

Table 2. Equivalent source parameters

SI.No.	Parameter			Value
1	Zero sequence	Resistance	R_0	4.33 Ω
		Reactance	X_0	34.64 Ω
2	Positive sequence	Resistance	R_1	0.866 Ω
		Reactance	X_1	17.32 Ω

Transmission lines: They are modelled as a frequency-dependent (phase) model[11,12] and the parameters used to model the line in PSCAD are given in Table 3[9,13,14]. The considered transmission line is not transposed[13]. The ground resistivity is assumed as 100 Ω.m.

Table 3. Parameters of 1200 kV transmission line

SI.No.	Parameter	Value
1	Rated voltage	1150 kV
2	Frequency	50 Hz
3	Line length	405 km
4	Conductor configuration	
	(i) Bundle conductor type	ACSR Bersimis/ Moose
	(ii) No. of sub-conductors in the bundle	8
	(iii) Spacing between the sub-conductor	0.46 m
	(iv) Bundle radius	0.6 m
	(v) Conductor radius	2.315 cm
5	Hight of the Phase conductor above the ground	37 m
6	Distance between phase conductors	24 m
7	No. of ground wires	2
8	Height of the ground wire above phase conductor	5 m
9	Distance between ground wires	10 m

Transformer: T1 and T2 in Figure 1 are UHV AC autotransformers, with a rated capacity of 333/333/111 MVA, a rated voltage of 1150/765/110 kV, and a short-circuit impedance of HV-IV 18%, HV-LV 40%, IV-LV 20%. The transformers are modelled by the classical method[11,12].

Circuit breaker: CBs are modelled as simple time-controlled switches. For SOV studies, the switch is modelled as an open circuit when open and an ideal conductor when closed. PSCAD provides multiple options to vary the closing times of CB ranging from one-shot deterministic closings to multi-shot systematic or statistical closings[10,12]. In this work, the closing times of CBs are modelled by statistical closing. These CBs are equipped with PIR to limit switching surges and in practice, the value of PIR will be around the surge impedance of the line (239 Ω). Although generated SOVs are minimum with a PIR of 300 Ω but considering thermal stresses on resistor discs under severe phase opposition conditions, it was envisaged to adopt a PIR of 600 Ω which will be inserted in the circuit for an initial 10 ms[9,13]. Hence PIR of 600 Ω with an insertion time of 10 ms is provided in its model.

Shunt reactors: These are modelled as a simply lumped inductance with a series resistance[11,12].

3. Characteristics of Switching Over Voltages

In UHV AC power transmission system, the important switching operations which produce SOVs are Line Energization (LE), Line Re-Energization (LRE), fault initiation and fault clearing, switching of EHV reactors, transformer switching with no load on the secondary and with a load of shunt reactors on the secondary, switching of capacitor banks, load rejection and line dropping. However, LE and LRE switching operations produce larger overvoltages[15]. Hence, this work considered the over voltages produced by LE and LRE switching operations for the determination of insulation coordination.

3.1 Line Energization Over Voltages

Line Energization (LE) over voltages are generated by the initial closing of a Circuit Breaker (CB) to energize an unloaded transmission line.

When the line is connected to the source, due to the voltage difference between both ends of the transmission line, a voltage surge propagates along the line towards the receiving end and reflects at receiving end (open end) of the transmission line and causes an overvoltage.

A typical LE overvoltage of the considered 1200 kV UHV AC transmission line at receiving end is shown in Figure 2.

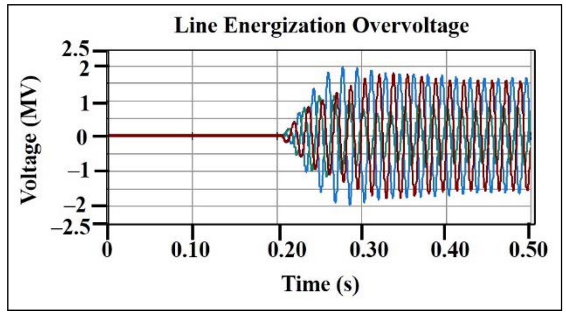

Figure 2. LE overvoltage of 1200 kV UHV AC transmission line at receiving end.

3.2 Line Re-Energization Over Voltages

Line Re-Energization (LRE) over Voltages may occur after a normal breaker opening or after a fault on the line, here, the former situation is used for representing LRE switching operation.

If the CB at the energizing end of a no-load line is opened then a charge will be trapped on the line due to the line capacitance. If the line is re-energized in the presence of the trapped charge, a higher overvoltage is seen because re-energizing the power frequency voltage on the feeding point side superimposes the residual voltage corresponding to the trapped charge across the CB gap. The discharge of the trapped charge depends on the equipment remaining connected to the line after opening the CB such as insulators and shunt reactors because they would drain off the trapped charges.

Here, the CB at the energizing end of the no-load line is opened at 0.2 sec then a charge of 1 p.u.[15] is trapped on the line and is re-closed at 0.22 sec during the presence of a trapped charge of about 0.4 p.u. so the line is re-energized at 0.22 sec (the time between CB opening and re-closing is 0.02 sec). A typical LRE overvoltage of the considered 1200 kV UHV AC transmission line at the receiving end is shown in Figure 3.

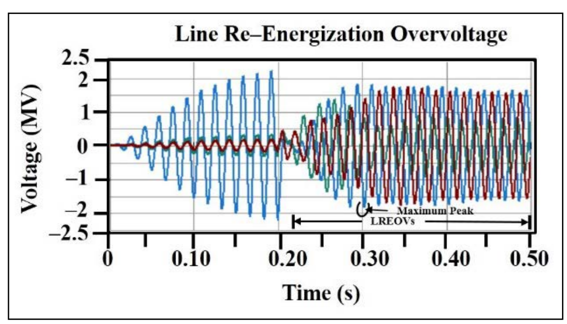

Figure 3. LRE overvoltage of 1200 kV UHV AC transmission line at receiving end.

4. Mathematical Modelling of Insulation Coordination

According to the statistical methods and probabilistic concepts, the selection of the insulation strength i.e., insulation coordination for SOVs is based on SSFOR[2,13,16]. This SSFOR is estimated by calculating the probability that the electrical stress along the transmission line exceeds the insulation strength of the transmission line. The SSFOR for a transmission line consisting of only one tower under SOVs is given in Equation (1)

$$\mathrm{SSFOR} = \frac{1}{2}\int_{E_1}^{E_m} p f_s(V)dV \tag{1}$$

where, E_1 is the minimum value of SOV (1.0 per unit)

E_m is the maximum value of SOV

$f_s(V)dV$ is the probability of occurrence of an SOV

p is the probability of a flashover for a given SOV

The SSFOR for a transmission line consisting of n towers for an SOV can be calculated by using Equation (2)

$$\mathrm{SSFOR} = \frac{1}{2}\int_{E_1}^{E_m} [1-q^n] f_s(V)dV \tag{2}$$

where, q^n is the probability of no flashover on n towers

When SOV changes from one tower to another tower, the SSFOR for all the switching operations is given by Equation (3)

$$\mathrm{SSFOR} = \frac{1}{2}\int_{E_1}^{E_m} [1-\Pi_{i=1}^{n} q_i] f_s(V)dV \tag{3}$$

where, q_i is the probability of no flashover at the i^{th} tower for SOV of crest value V at the i^{th} tower.

$f_s(V)$is the statistical distribution of the occurrence of SOVs.

The solution of equation (3) for one tower and n towers is given by Equations (4) and (5).

$$\mathrm{SSFOR}_1 = \frac{1}{2}\left[1-F\left(\frac{\mathrm{CFO}-\mu_0}{\sqrt{\sigma_o^2+\sigma_f^2}}\right)\right] \tag{4}$$

$$\mathrm{SSFOR}_n = \frac{1}{2}\left[1-F\left(\frac{\mathrm{CFO}_n-\mu_0}{\sqrt{\sigma_o^2+\sigma_{fn}^2}}\right)\right] \tag{5}$$

5. Estimation of SSFOR

SSFOR is estimated by determining the electrical stress experienced by the transmission line insulation due to SOVs and determining the insulation strength of the transmission line when SOVs are subjected to it.

5.1 Determination of Electrical Stress along the Line

The representative electrical stress is characterized by the statistical distribution of SOVs. To derive the statistical distributions of SOVs, the exact instant on the voltage wave at which three poles of the CB contacts close and reclose is used as randomness for LE and LRE over voltages respectively because the magnitude of these over voltages depends on these instants. These randomness's are modelled by statistical switching[17].

In the statistical switching, the closing time of any one pole is varied uniformly over one time period (20 ms) which is assumed as the mean closing time and closing times of the other two poles follow a Gaussian distribution with an SD (σ) of 1 ms and truncated at ±3σ[6,8].

Using these randomness's, 526 switching operations are performed on the line. Next, statistical analysis is performed on these 526 SOVs and calculated characteristic parameters of statistical distributions, such as mean, standard deviation and 2% over voltages in each case and are given in Table 4.

Table 4. Statistical information of SOVs

Value in p.u.	LE	LRE
Mean (μ_0)	1.9846	1.9729
S.D (σ_0)	0.0353	0.0314
2% SOV	2.0552	2.0357

Table 4 clearly shows that LE over voltages are higher compared with LRE over voltages because the considered transmission line has permanently connected shunt reactors which would drain off the trapped charges. For this kind of transmission line (CBs equipped with PIR and permanently connected shunt reactors) generally, LE over voltages are higher compared with LRE overvoltages[15,18–20].

5.2 Determination of Insulation Strength of Transmission Line

The statistical distribution of insulation strength or insulation strength characteristic of the transmission line for which electrical stress is applied could be represented by any cumulative distribution function. This work uses Gaussian cumulative distribution function[2–8,16] P(V) which is described by its mean value - 50% flashover voltage ($U_{50\%}$) and an SD (σ_f). P(V) is given by Equation (6).

$$P(V) = \frac{1}{\sqrt{2\pi}\sigma_f}\int_{V=-\infty}^{V=+\infty} e^{-\frac{(x-U_{50\%})^2}{2\sigma_f^2}} dx \tag{6}$$

Equation (6) clearly shows that the insulation strength characteristic is defined by two parameters, $U_{50\%}$ and σ_f.

5.2.1 Traditional Method

In this method $U_{50\%}$ and σ_f both are fixed and associated with the critical wave whose time to crest is 250 µs irrespective of the actual generated SOV waveshape. For the critical wave $U_{50\%}$ is minimum i.e., $U_{50\%,\ min}$ and σ_f is equal to the 5% of $U_{50\%,\ min}$[3,6,7,16].

The literature gives various methods[21] to calculate $U_{50\%,\ min}$. This work uses the $U_{50\%,\ min}$ given by the UHV study committee formed by CRIEPI[22] that was also endorsed by IEC, given by Equation (7)

$$U_{50\%,min} = K_a\, K1080 \ln(0.46d + 1) \tag{7}$$

where, $U_{50\%,min}$ – minimum $U_{50\%}$ in kV
K_a – altitude correction factor
K – gap factor
d – gap length in meters and its range is from 1 to 25 m

In this work, standard atmospheric conditions are considered hence, K_a = 1 and K is considered as 1.26 for conductor cross-arm (side phase) configuration and 1.17 for conductor-window (middle phase) configuration[8,21]. For the considered 1200 kV UHVAC transmission line the gap length () for the side and middle phases is 8.3 meters[9,23]. Using this information and Equation (7) $U_{50\%,min}$ is calculated for the side and middle phases for the considered 1200 kV UHVAC transmission line and are given as 2.1833 p.u. and 2.0274 p.u. respectively.

With the above procedure and Equation (5), the SSFOR is estimated for LE and LRE SOVs and is given in Table 5.

Table 5. SSFOR by traditional method

Phase	LE	LRE
Side	7.879×10-4	7.626×10-4
Middle	9.436×10-4	9.416×10-4

5.2.2 Practical Method

In this method $U_{50\%}$ and σ_f are varied depending on the generated SOV waveshape particularly on the time to crest (T_{cr}). Therefore, in this method for each generated SOV, two equivalent times to crests are calculated using Equations (8) and (9)[8].

$$T_{cr}\,(0.7 - m) = 1.56\,(T_p - T_{0.7}) \tag{8}$$

$$T_{cr}\,(0.85 - m) = 2.07\,(T_p - T_{0.85}) \tag{9}$$

where, $T_{0.7}$, $T_{0.85}$, and T_p are times required for SOVs to reach 70%, 85% and 100% of peak value respectively.

In this work, depending on the randomness total of 526 SOVs are generated on the line for each case. A typical SOV is shown in Figure 4 and the procedure to measure T_p, $T_{0.7}$ and $T_{0.85}$ are shown in Figure 5. After measuring T_p, $T_{0.7}$ and $T_{0.85}$ for all the 526 generated SOVs, T_{cr} (0.7 – m) and T_{cr} (0.85 – m) are calculated for each generated SOV and statistical information of these equivalent time to crests is given in Table 6.

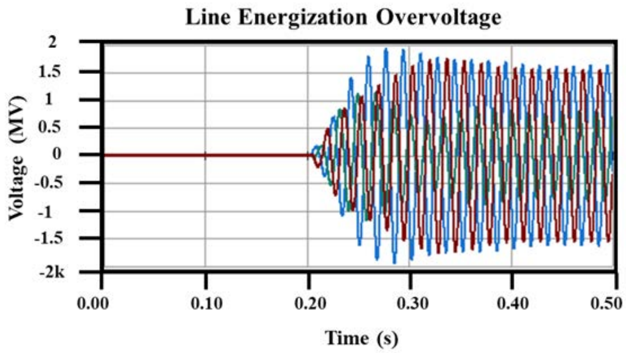

Figure 4. A typical generated SOV.

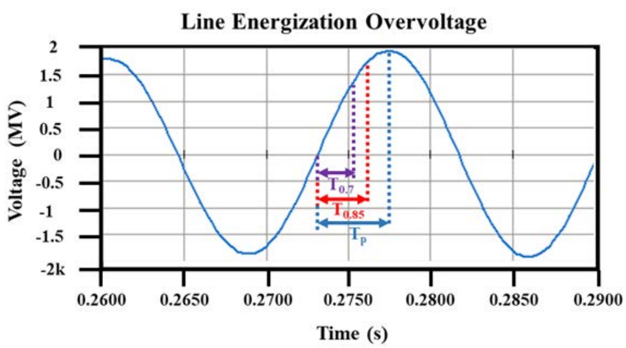

Figure 5. A typical generated SOV with $T_{0.7}$, $T_{0.85}$ and T_p

Table 6. Statistical information of equivalent time to crests

Type of SOV		LE	LRE
Minimum	T_{cr} (0.7-m)	3.16 ms	3.16 ms
	T_{cr} (0.85-m)	2.83 ms	2.83 ms
Maximum	T_{cr} (0.7-m)	3.59 ms	3.60 ms
	T_{cr} (0.85-m)	3.41ms	3.41 ms
Mean	T_{cr} (0.7-m)	3.36 ms	3.37 ms
	T_{cr} (0.85-m)	3.10 ms	3.12 ms

Depending on these equivalent time to crests $U_{50\%}$ and σ_f are calculated for each generated SOV.

$U_{50\%}$ corresponding to any T_{cr} which is longer than T_{crit} can be calculated by Equation (10)[24].

$$U_{50\%}(T_{cr}) = U_{50\%,min}\frac{NX^2 + AX + B}{X2 + C} \tag{10}$$

where, $U_{50\%,min}$ is a minimum 50% flashover voltage

$N = [1.17 - 0.17 (K - 1)]$

$X = T_{cr}/T_{crit}$ (T_{cr} and T_{crit} both are in μs)

$A = 0.35$

$B = 3.8/(2 - K)^{1.4}$

$C = 4.3/(2 - K)^{1.3}$

According to laboratory results the approximate relation between σ_f and T_{cr} is given in reference[8].

With the above procedure and Equation (5), the SSFOR is estimated by the practical method for LE and LRE SOVs and is given in Table 7.

Table 7. SSFOR by practical method

Phase	Tcr	LE	LRE
Side	T_{cr} 0.7	3.926×10^{-5}	3.330×10^{-5}
	T_{cr} 0.85	4.430×10^{-5}	3.738×10^{-5}
Middle	T_{cr} 0.7	1.586×10^{-4}	1.416×10^{-4}
	T_{cr} 0.85	1.692×10^{-4}	1.505×10^{-4}

6. Calculation of Insulation Coordination

The estimated values of SSFORs by considering the SOV waveshape for different values of gap length are given in Table 8. The Table clearly shows that to meet the required SSFOR i.e., 1×10^{-3} [2,25] the gap length of 7.3 m is sufficient instead of 8.3 m if SSFOR is calculated by the practical method.

Table 8. SSFORS by practical method

d	Phase	Tcr	LE	LRE
8.3	Side	T_{cr} 0.7	3.926×10^{-5}	3.330×10^{-5}
		T_{cr} 0.85	4.430×10^{-5}	3.738×10^{-5}
	Middle	T_{cr} 0.7	1.586×10^{-4}	1.416×10^{-4}
		T_{cr} 0.85	1.692×10^{-4}	1.505×10^{-4}
7.75	Side	T_{cr} 0.7	9.380×10^{-5}	8.179×10^{-5}
		T_{cr} 0.85	1.012×10^{-4}	8.861×10^{-5}
	Middle	T_{cr} 0.7	3.016×10^{-4}	2.717×10^{-4}
		T_{cr} 0.85	3.095×10^{-4}	2.829×10^{-4}
7.3	Side	T_{cr} 0.7	1.810×10^{-4}	1.618×10^{-4}
		T_{cr} 0.85	1.906×10^{-4}	1.709×10^{-4}
	Middle	T_{cr} 0.7	4.577×10^{-4}	4.285×10^{-4}
		T_{cr} 0.85	4.668×10^{-4}	4.377×10^{-4}

7. Conclusions

SSFOR due to LEOVs is more compared to LREOVs.
SSFOR for the middle phase is more compared to the side phase.
SSFOR estimated by the practical method is at least one order less compared to the traditional method.
SSFOR decreases with a longer wavefront.

The gap length is reduced by applying the practical method in the determination of insulation coordination. Therefore, the distance between the phase conductor and the grounded tower sides and upper truss can be reduced which leads to the saving in cost.

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