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Optimization of Air Insulation Clearances for EHV/UHV Transmission Lines

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This paper presents the results of the study conducted on 400 kV, 800 kV and 1200 kV transmission line insulator strings and conductor–tower window geometries with an aim to optimize air insulation clearances. Laboratory investigations were carried out to evolve the switching impulse performance of phase–to–earth and conductor–window configurations in addition to the reference rod plane air gap lengths in EHV/UHV range. Tests were conducted on 400 kV, 800 kV and 1200 kV line configurations of I, Vee, double Vee, etc., by simulating the tower windows. The paper also presents results of the study on optimization of conductor-tower air insulation clearances for adoption in 1200 kV AC transmission lines using 8 bersimis conductor bundle carried out for establishment of 1200 kV Test Station at BINA, Madhya Pradesh, by Power Grid Corporation of India. Results of the tests and the data presented in the paper will be useful for design of phase-to-ground air insulation for adoption in EHV/UHV Transmission lines.

1.0 INTRODUCTION

The evaluation of the switching impulse performance of large electrodes for UHV line design was carried out by many researchers [1–4]. These studies have pointed out the great importance of switching impulses of positive polarity and suggested that these are to be used for the design of external air gap insulation in the UHV range. While different line configurations are encountered in UHV line, the lowest breakdown voltage was yielded with rod-plane gaps and thus used as reference air gap. The breakdown voltage also depends on the shape of the impulse, i.e. on the front time for slow front impulses. For air insulation, it is typical that for each gap length, there is an impulse time to peak for which the breakdown voltage is least. The lowest voltage is called Critical Flashover Voltage (CFO) and the peak time corresponding to minimum value is called time to peak [T_{cr}]. In order to use the concept of gap factors, applied to other configuration normally encountered in the line, studies were conducted on the reference rod-plane gap for varying gap lengths in the UHV range. The CFO at various front times of positive switching impulse was determined for various gap lengths spanning the UHV range. It was proved in reference [4] that the spark over voltage of any electrode configuration subjected to switching impulses is proportional to that of a rod-plane gap of the same length. The coefficient of proportionality being called the gap factor (k) depends on the electrode configuration. The data obtained from the rod-plane configuration was applied to the actual line configuration at higher gap distances, for which the optimization is intended. The breakdown voltage of the tower simulation at smaller gap length in the 400 kV range is obtained and the gap factors were determined for a particular configuration for use at higher gap distances. These gap factors were used to preliminarily calculate the gap distances required for 800 kV and 1200 kV line configurations.

For the experimental work on the evaluation of critical flashover voltage of the rod-plane

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configurations, the mild steel (MS) rod of 400 mm^2 cross-section and a length of about 1 meter are hung between impulse voltage divider and the load capacitor. The load capacitor will additionally act as capacitive load and help in obtaining the proper switching impulse wave shape. The plane was simulated by 5 m × 5 m wide MS plates of 6 mm thickness properly earthed to a reference earth. Generator parameters were varied to obtain various peak times of the switching impulse voltage. Tests were conducted using up and down method as given in IEC 60060-1 [5] to determine the spark over voltages for various crest times.

For optimization test setup, the simulated tower windows are hung along with the insulator assembly and simulated bundle conductor between two anchor towers. The height of the bottom most conductor was at least 1.5 times the length of the insulator string or more so as to avoid any flashover to the ground. Figure 1 gives a view of a 5 MV/500 kJ Impulse Voltage Generator along with 5 MV Damped Capacitive Divider used in the studies. The laboratory procedure for optimization of window clearances is to simulate the required tower window based on the type of tower and conduct flashover voltage/withstand voltage tests keeping the gap at the estimated gap distance. The required gap is estimated from the concept of gap factor discussed in the next section. The study was conducted on the common window configurations by varying the gap distances in the range of 2.25–4 meters and common gap factor was obtained for tower side and tower top. These gap factors were used to estimate the required clearances for 800 kV and 1200 kV line. After fixing this estimated clearances, the experimentations of determining the $U_{50\%}$ and conforming of $U_{10\%}$ was carried out in accordance with [5], to arrive at the rated basic switching impulse levels [BSL] as given in IEC 60071-1 [6]. The gaps can be increased or decreased from the estimated values by 0.1 m to arrive at the optimized clearance [7] to obtain the rated BSLs for the given system voltage.

2.0 REFERENCE ROD-PLANE AIR GAP CHARACTERISTICS

Test setup and the procedure described in section 1.0 are used to obtain the so-called U-curves. Only the positive polarity was attempted based on the experience and the literature [3,4]. The gap lengths varied from 2.5 m to 15 m to cover the EHV/UHV range air gap clearances. The $U_{50\%}$ flashover voltages were obtained for various peak times. Figure 2 shows a view of rod-plane

FIG. 1 A VIEW OF 5000 kV/500 kJ OUTDOOR IMPULSE VOLTAGE GENERATOR WITH DAMPED CAPACITIVE DIVIDER

FIG. 2 A VIEW OF ROD-PLANE GAP FLASHOVER

gap flashover. Figure 3 gives the variation of $U_{50\%}$ breakdown voltage as a function of peak time T_p of the switching impulse with gap length as a parameter for gap lengths up to 15 m.

It can be observed from Figure 3 that the critical flashover voltage increases with the gap distance and the critical front times is around 200 µs for gap distance of about 4 m. The critical flashover voltages (CFOs) obtained from this study were plotted as a function of the gap distances and is as shown in Figure 4. The data obtained were fitted into the curves results in expression of type

$$U_{CFO}=3750 / (1+8/D) \text{ for } D<15 \quad (1)$$

The results obtained were compared with the formula suggested by Gallet and Leroy [4] and it was found that the estimated CFO was well within ±3% of the experimental results obtained in this study and thus validating our results. For gap lengths in the range 2.5 m to 5.5 m, the variations of CFO with gap distance was found to fit the straight line fit and for the data it can be given as

$$U_{CFO}=140 + 254 D \quad (2)$$

for 2.5 < D < 5.5 m

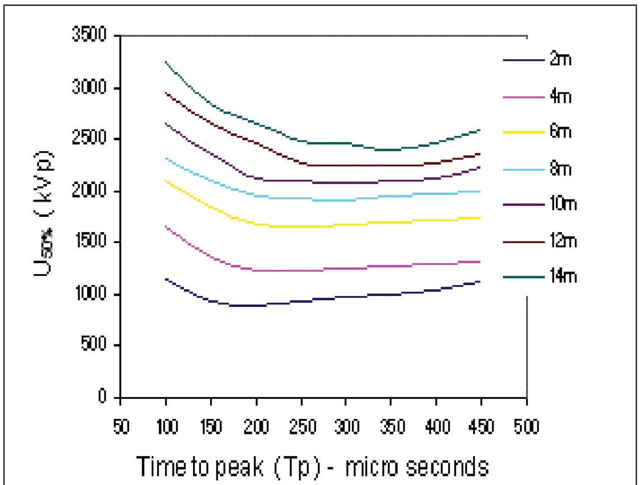

FIG. 3 U-CURVES FOR ROD-PLANE GAP

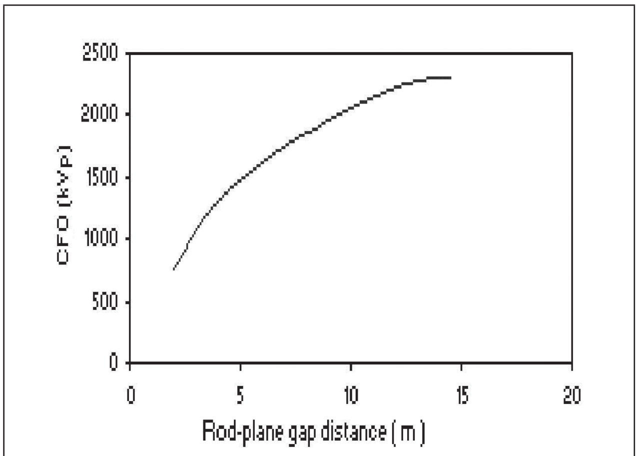

FIG. 4 CFO AS A FUNCTION OF ROD-PLANE GAP LENGTH

The variation of critical time as a function of gap distance is plotted in Figure 5. The data fits the straight line equation and is as

$T_{cr} = 21\ D + 80$ (3)

for $4 < D < 15$

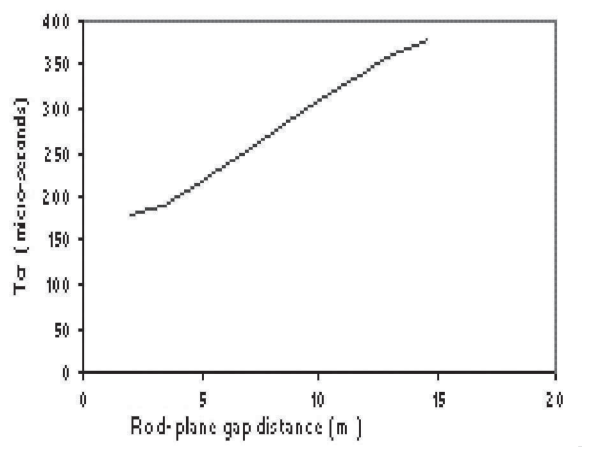

FIG. 5 CRITICAL FRONT TIME AS A FUNCTION OF ROD-PLANE GAP LENGTH

For the rod-plane gap, the $U_{50\%}$ for the standard switching impulse, i.e. 250 µs/2500 µs, was obtained for gap distances 2.5 m to 5 m and the data was best fit to the curve given by the expression.

$U_{50\%} = 564\ D^{0.56}$ (4)

The results of the test were compared with empirical formula suggested by [2] for the $U_{50\%}$ voltages with the gap length for standard 250 µs/2500 µs wave shape and it was observed that the mean deviation of the two results is less than 2 %.

3.0 DETERMINATION OF GAP FACTOR FOR TOWER SIDE

Experimental study was conducted on 400 kV 'I' string by simulating the side tower and is as shown in Figure 6. $U_{50\%}$ for the standard switching impulse voltages was obtained. The gap distances were varied and the results were tabulated. Rod-plane gap data obtained from equations 3 was also tabulated for gap distance 2.25 m to 4.5 m in steps of 0.25 m. The average gap factor was found as 1.25. Table 1 gives the results as obtained for the side tower and from the expression as obtained from the rod-plane configuration study.

FIG. 6 A VIEW OF 400 kV STRING WITH TOWER SIDE SIMULATION FOR GAP FACTOR DETERMINATION

TABLE 1			
DETERMINATION OF GAP FACTOR			
Gap Distance (m)	**$U_{50\%}$ (kV)**		**Gap factor (kW)**
	Grading ring – tower side	**Rod plane**	
2.75	1135	907	1.251
3.00	1185	960	1.234
3.25	1278	1027	1.244
3.50	1350	1066	1.266
3.75	1410	1122	1.256
4.00	1450	1134	1.278
4.25	1482	1177	1.259
4.50	1489	1227	1.213
		Average k	1.25

4.0 OPTIMIZATION OF TOWER WINDOW CLEARANCES FOR INSULATOR STRINGS

Estimation of the window clearances was made with the BSL considerations and with the use of equation U_{CFO}=3400/(1+8/D) making the first approximation of BSL as the critical flashover voltage of the rod-plane gap. Using the gap factor, the gap distance required for the BSL will be approximately obtained. The BSL considered will be $U_{10\%}$, i.e. the withstand voltage with 10 % flashover probability obtained from the $U_{50\%}$ as:

$$U_{10\%} = U_{50\%}/(1-1.3\sigma) \quad (5)$$

where σ is the conventional standard deviation.

For statistical calculations of the expected performance in the field, the value of σ considered is 3 %. This $U_{50\%}$ will be considered as CFO and the required gap distance considering the gap factor will be estimated as

$$U_{50\%} = k \times 3400/(1+8/d_e) \quad (6)$$

where k is the gap factor and d_e is gap distance estimate.

For a given geometry and the gap distance estimate, the tower window was simulated and the determination of $U_{50\%}$ was carried out. The tower window, top and side, and conductor configuration and the hardware used were according to the current practice for 400 kV and 765 kV transmission lines and extrapolated dimensions for 1200 kV transmission line hardware. Figures 7 and 8 show the 800 kV and the 1200 kV tower window optimization study view of the test setup. The number of impulses

FIG. 7 A VIEW OF 800 kV INSULATOR STRING WITH SIMULATED TOWER

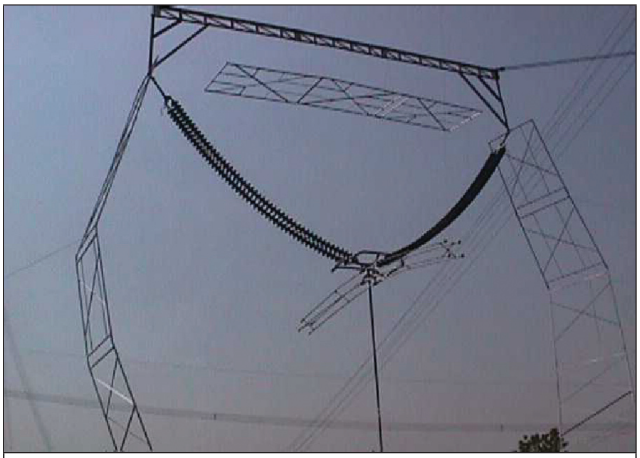

FIG. 8 A VIEW OF 1200 kV INSULATOR STRING WITH SIMULATED TOWER

applied corresponding to the $U_{10\%}$ or BSL are 40 for an estimated gap distance. If the initial test results in number of flashover more than 4, the gap distance in experimental test setup would be increased by 0.1 m and again 40 numbers of SI positive polarity impulses of standard wave shape were applied. If the number of flashovers were less than 4, the gap distance was reduced by 0.1 m and the experiment repeated. This way the optimized clearance for number of flashover ≤4 out of 40 was obtained. Additional tests with negative polarity SI and positive and negative polarity lightning impulse test on the same optimized setup were carried out. The test program was specifically conceived to generate UHV tower design data.

Results in Table 2 show the tower window electrical clearances obtained experimentally based on the rated BSL of the line insulation. However, it is generally agreed that the line to ground switching surge over voltage, for typical 400 kV lines do not exceed 1.7 pu [8]. This finding is corroborated by the results of the EMTP calculations on typical 400 kV, 800 kV and 1200 kV lines [9], wherein, it was found that the case of double line ground fault gave 1.69 pu as 2 % probability switching over voltage.

Hence, for all the three different voltage class transmission lines under consideration, it could be confidently assumed that the maximum line to ground SI would not exceed 1.75 pu. Hence, it is inferred that the electrical clearances corresponding to 1.75 pu could be used in the window size determination rather than the clearance required for BSL, which proves to be very large and uneconomical. Table 2 also shows the experimentally optimized electrical clearances considering 1.75 pu as the $U_{10\%}$ voltage and the overall electrical clearances taking into account the mechanical swing of the insulator strings.

These clearances were found to withstand 1.75 pu SI at respective critical fronts obtained from Figure 4 when simulated and tested. Hence, the system designer has the option

TABLE 2

WINDOW CLEARANCES FOR 400 kV 800 kV AND 1200 kV LINES

System voltage (kV)	Type of string	BSL (kV)	1.75 pu voltage (kV)	Window electrical clearances in meters		Reduced overall clearances taking into account mechanical swing	
				Based on BSL	**Based on 1.75 pu**	**With BSL**	**Based on 1.75 pu**
400	I V	1050 1050	600 600	2.75 3.0	1.44 1.91	2.75+1.6 = 4.3 3.0	1.44+1.6=3.04 2.0*
800	I V	1550 1550	1143 1143	4.9 6.75	3.44 4.75	5.3 (7.2 to 7.8) 6.75	3.44+2.3= 5.74 4.75*
1200	V	1800	1550	7.25	5.1	8.75	5.1*

*Mechanical swing considered as zero.

TABLE 3

OVERALL TOWER WINDOW CLEARANCES

System voltage (kV)	Type of string	Minimum window clearances (m)						
		With 1.75 pu		With BSL		With contingency of one arm snapping (m)	Existing tower clearance (m)	
		Tower top*	Tower side	Tower top*	Tower side			
400	I	–	3.04	–	4.30	–	4.7	4.3
	V	3.00	2.00	3.00	3.00	3.30	4.3	4.3
800	I	Not really used as independent string–only pilot strings used						
	V	5.30	4.75	5.30	6.75	5.90	5.1	5.3
1200	V	7.20	5.10	7.20	8.75	7.92	–	–

*Tower top clearance is a function of string length.

of using the window clearances based on the system BSL or based on 1.75 maximum line to ground switching impulse voltage. Additional clearances are required for line maintenance and other contingencies for V strings, such as 1 pu power frequency voltage withstand capability of the window at a maximum swing angle of 55° mechanical corresponding to contingency of one arm of the V snapping (55° being half the V angle).

An exercise was made to calculate the tower clearance required for the contingencies mentioned above. Table 3 shows all the three estimates namely estimate for the 1.75 pu over voltage, BSL as over voltage and contingency of one arm snapping for V strings. In case of one arm snapping of V string, the final healthy string position from central arm is obtained by multiplying the minimum tower top clearance by sin 55°. Total clearance under such contingency is obtained by adding to this clearances required for withstanding 1 pu voltage at 300 kV per meter. A swing angle of 20° mechanical is considered for 400 kV-I string, 23° mechanical swing for 800 kV-I string, 5° swing for V string of 400 kV and no swing for 800 kV and 1200 kV strings. It is evident that a minimum of 3.3 m, 5.90 m and 7.92 m are required for 400 kV, 800 kV and 1200 kV line towers, respectively, to meet the contingency of one arm snapping. These clearances are, in general, higher than the estimated electrical tower side clearances from 1.75 pu SI over voltage point of view. The minimum dimensions of tower windows for 400 kV, 800 kV and 1200 kV lines presented in a concise manner in Table 3 and variation in this could occur only due to the changes in lengths of insulator strings required to meet the pollution performance.

Therefore, even with 1.75 pu as over voltage tower, top clearance is determined from BSL considerations only. It also has dependency on the pollution performance of insulator string.

5.0 OPTIMIZATION OF CONDUCTOR-WINDOW AIR INSULATION CLEARANCES FOR 1200 kV TEST STATION AT BINA OF POWER GRID [10]

Studies on switching surge flashover characteristics of long insulators strings and their equivalent air-gaps, the results of which are essential for the coordination of EHV and UHV transmission systems, have been carried out. A study on optimization of conductor-tower air insulation clearances for adoption in 1200 kV AC transmission lines using 8 bersimis conductor bundle was also carried out for establishment of 1200 kV Test Station at BINA, Madhya Pradesh, by Power Grid Corporation of India.

The assembly area for carrying out the proposed study called Mock up test tower facility comprises of two dead end towers each of 48 m height and 20 m width and located 80 m apart. These two towers are used to tension the required conductor configuration along with insulator strings on either ends of the conductor bundle. The facility is provided with motorized winches to tension the required conductor. A Central portal tower, of 60 m height, is located centrally between the two dead towers and has a width of 48 m between the legs. This central portal is also provided with motorized winches and is used to suspend different tower simulations at any desired height. A view of this facility is shown in Figure 9. The tower top, tower side and tower window as required at various stages of the tests were simulated in the central portal tower by aluminum sections having dimensions similar to those obtained in 1200 kV suspension tower design.

The studies included determination of critical time to peak (T_{cr}) for switching impulse wave shapes corresponding to conductor to tower air gap clearance of 7 m and 10 m. Only the tower top and one tower side was simulated for above purpose as shown in Figure 10. 50 % Flashover voltage corrected for atmospheric conditions plotted as a function of T_p for the gap distances 7 m and 10 m for tower top and one side simulation is given in Figure 11. It can be observed from the Figure that the critical time to peak for which the CFO occurs is between 220 to 230 microseconds. 50 % Flashover voltage at standard peak time of 250 µs is little higher than the critical flashover voltage value. 50 % Switching flashover voltage corresponding to T_{cr} was then obtained for air gap distances of 7 m, 8 m, 9 m and 10 m. The results obtained for CFO corresponding to the obtained T_{cr} of 220 µs are tabulated in Table 4.

FIG. 9 A VIEW OF MOCK UP TEST FACILITY SHOWING TWO AND THE DIVIDER DEAD END AND CENTRAL PORTAL TOWER

FIG. 10 SET UP FOR OBTAINING CRITICAL TIME TO PEAK FOR SWITCHING IMPULSE VOLTAGES

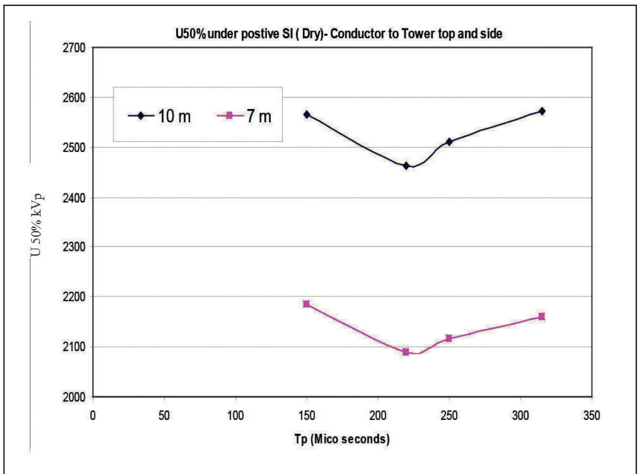

FIG. 11 50 % FLASHOVER VOLTAGE CORRECTED FOR ATMOSPHERIC CONDITIONS PLOTTED AS A FUNCTION OF TP FOR THE GAP DISTANCES 7 M AND 10 M FOR TOWER TOP AND ONE SIDE SIMULATION

TABLE 4

SWITCHING CFO FOR VARIOUS AIR GAP DISTANCES WITH ONE SIDE AND TOWER TOP AND WITHOUT INSULATOR ASSEMBLY

Air gap distance (m)	Crest time(T_{cr}) (μs)	$U_{50\%}$ (CFO) (kVp)
7	220	2090
8	220	2225
9	220	2375
10	220	2463

It can be observed from the results that for the CFO value of 2090 kVp seems to be very high even for 7 m air gap clearance for the tower top and side simulation. The withstand voltage determined as $U_{10}=U_{50}$ (1–1.3σ), even for σ = 0.06, will be 1927 kVp, which is much higher than the required switching impulse withstand voltage of 1800 kVp. However, for the tower configurations comprising insulators and associated hardware, this will not be the case because of the change in gap configuration leading to different values of $T_{cr.}$ and CFO. Since the obtained CFO even for the lowest air gap of 7 m was quite high compared to targeted CFO corresponding to a withstand value of 1800 kV peak, it was decided to conduct the 50 % switching flashover test along with complete tower top as well as insulator string with hardware for 8 m and 8.5 m live-metal distance to tower. The insulators used were polymeric insulators forming the configuration as given in Figure 12. As the setup included the insulators and tower window, the critical time to crest T_{cr} for which CFO voltage occurs will be different from what is obtained before. The arrangement of the total setup with bundle conductor along with insulator string and tower window simulation is shown in the photograph given in Figure 12. For this test setup and with 8 m and 8.5 m air gap clearance, CFO voltages

FIG. 12 THE ARRANGEMENT OF THE TOTAL SET UP WITH BUNDLE CONDUCTOR ALONG WITH INSULATOR STRING AND CONDUCTOR-TOWER WINDOW SIMULATION

are therefore obtained for optimizing the air gap clearances. The setup was arranged for minimum gap clearances of 8 m from corona ring on line end to tower top and conductor to either side of the tower window.The conductor was strung at a height of 23 m above ground. Bottom simulation of the tower window was simulated at 11.5 m below the conductor and distance between the bottom window and the ground was 11.5 m. During the test, flashovers were evenly observed to the top, Insulator string and two sides of the window simulation.

50 % Flashover voltage corrected for atmospheric conditions plotted as a function of T_p for the gap distances 8 m and 8.5 m conductor-insulator string-tower window configuration to determine the critical time T_{cr} for which CFO voltage is obtained is as shown in Figure 13. It can be observed from Figure 13 that T_{cr} is in the range of 250–290 μs for which the flashover voltages were minimum. Table 5 gives the results on 50 % flashover voltage values obtained for 8 m and 8.5 m for the wave shape corrected for ambient atmospheric conditions.

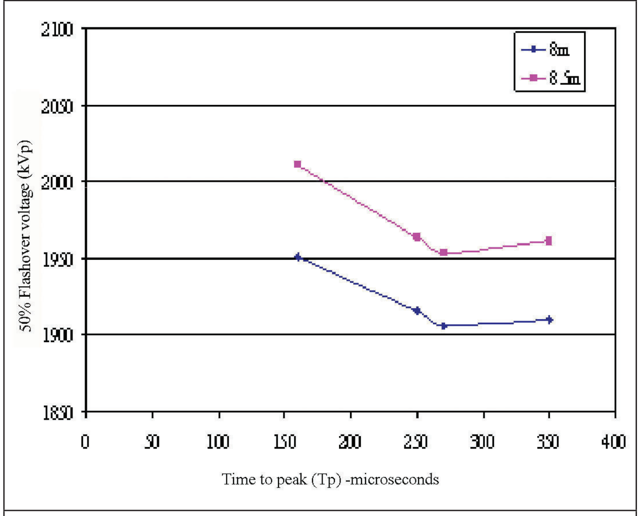

FIG. 13 50 % FLASHOVER VOLTAGE CORRECTED FOR ATMOSPHERIC CONDITIONS PLOTTED AS A FUNCTION OF T_p FOR THE GAP DISTANCES 8 M AND 8.5 M CONDUCTOR-INSULATOR STRING-TOWER WINDOW CONFIGURATION

It can be seen from Table 5 that for conductor-window clearance of 8 m, the CFO voltage obtained was 1906 kVp for which the withstand voltage determined as $U_{10}=U_{50}(1–1.3σ)$, for σ=0.03 (instead of 0.06) will be 1832 kVp. This level is just about 1.75 % higher than the required 1800 kVp withstanding level. In order to ascertain the positive polarity switching impulse withstand voltage of 1800 kVp withstand voltage procedure with 15 impulses is followed. Fifteen positive polarity switching impulse voltage levels corrected for ambient atmospheric conditions corresponding to withstand voltage level of 1800 kVp were applied for the air gap clearance of 8 m. No flashovers were observed for the 15 impulses applied even though two flashovers were allowed out of 15 impulses in withstand test. The all-round gap clearance was reduced to 7.5 m and withstand voltage test was carried out. Fifteen positive polarity switching impulse voltages for test voltage 1800 kVp corrected for ambient atmospheric conditions were applied. Out of 15 impulses applied, four flashovers were observed for 7.5 m gap clearance giving very low withstand probability for 1800 kVp test voltage. Thus, air clearances of 8 m seems to be the optimized air clearances for tower window configuration in 1200 kV transmission lines with BSL requirement of 1800 kVp.

TABLE 5

THE CFO OBTAINED FOR CRITICAL T_{CR} OF 270 MS FOR 8 m AND 8.5 m CLEARANCES

Air gap distance (m)	**Crest time (T_p)(μs)**	**$U_{50\%}$ (CFO) (kVp)**
8	270	1906
8.5	270	1953

Withstand voltage test with critical switching impulse voltage wave shape under wet conditions was carried out then for optimized air clearance of 8 m for the tower window along with the insulator string of dimensions considered in this study. Wetting procedure and resistivity of water used in test are as described in IEC60060-1[6].

Fifteen positive polarities with critical wave shape switching impulse voltage levels but corrected for ambient atmospheric conditions corresponding to withstand voltage level of 1800 kVp under wet condition were applied. No flashovers were observed for the 15 impulses applied even though two flashovers were allowed out of 15 impulses in withstand test. Test was carried out with negative polarity switching impulse for the same voltage and wave shape. No flashover was observed for the configuration arranged. Thus, optimized air clearances of 8 m is found adequate under wet condition also for tower window configuration in 1200 kV transmission lines with BSL requirement of 1800 kVp.

6.0 CONCLUSIONS

An attempt has been made to obtain the tower window clearances for 400 kV, 800 kV and 1200 kV transmission lines. Comprehensive tests had been conducted and an approach for effective and economic tower designs for transmission lines up to 1200 kV lines has been established. The limited data presented in this paper can be considered as critical gap lengths for the various transmission system voltages presented.

Experimental work on optimization of conductor–tower air insulation clearances for adoption in 1200 kV AC transmission lines using 8 bersimis bundle conductor optimal window clearances of tower were intended to be arrived at for the Basic Switching impulse voltage Level of 1800 kVp required for the 1200 kV transmission lines. Positive polarity switching impulses are considered in the study as they give minimum flashover voltages.

Experiments to determine CFO voltages for Top and Side tower simulation were carried out for 10 m and 7 m clearances and it is observed that the critical time to peak for which the CFO occurs is between 220 and 230 microseconds. For tower configurations comprising insulators and associated hardware lead to different values of $T_{cr.}$ and CFOs. Experiments to determine CFO voltages with insulators and Tower Window simulation were carried out for 8 m and 8.5 m all-round clearances. Critical time to peak (T_{cr}) in the range of 250–290 μs was observed for which the flashover voltages were minimum. For window clearance of 8 m, the CFO voltage obtained was 1906 kVp. The withstand voltage determined as $U_{10}=U_{50}(1-1.3\sigma)$, for $\sigma=0.03$ was 1832 kVp. Withstand voltage test procedure was adopted and 15 positive polarity switching impulse voltage levels corrected for ambient atmospheric conditions corresponding to withstand voltage level of 1800 kVp were applied for the air gap clearance of 8 m. The configuration successfully withstood 1800 kVp level. Withstand voltage test under wet conditions was carried out for optimized air clearance of 8 m. The configuration under study successfully withstood the wet test under both positive and negative polarities. Thus, air clearances of 8 m seem to be the optimized air clearances for conductor-tower window configuration in 1200 kV transmission lines with BSL requirement of 1800 kVp.

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