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Flashover Performance of 380 kV V-Strings with Composite Insulators under Lightning and Switching Impulses

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***Abstract*—This study presents simulation and experimental test results regarding potential and electrical field distribution along 380 kV V-strings in Turkish national electric power transmission system which are composed of silicon-rubber insulators. A two-dimensional (Electro 2D) and a three-dimensional (Coulomb 3D) simulation programs are used for transient and electrostatic field calculations, respectively. Simulations are conducted only for clean insulators under dry conditions. The effects corona rings and types, lengths of conductors, conductor sags, protection lines, phase conductors, tower configurations and arc distances on the field distributions are analyzed. Experimental studies are conducted at Fuat Kulunk High Voltage Laboratory of Istanbul Technical University.**

***Index Terms*— Corona Rings, Electric Field and Potential Distribution, V-Suspension Set, Transient Voltages, Transmission Tower**

I. INTRODUCTION

Composite insulators are being increasingly used by utilities because of their advantages [1,2]. The ratio of nonceramic insulators used in Turkish Power Transmission Systems is around 5 % and is expected to increase in the near future. This paper is devoted to simulation and experimental studies of those sets for the transient voltages under dry and clean conditions.

Simulations are conducted for V-suspension sets for 3x954 MCM ACSR CARDINAL conductors and 3x1272 MCM ACSR PHESANT conductors. 3A1 - 3B1 -3C1 and 3PA - 3PB - 3PC type 380 kV transmission towers are used for CARDINAL and PHEASENT conductors, respectively.

Non-symmetric structure of V-strings requires three dimensional (3D) modeling. Coulomb 3D [3] is used for AC simulations, whereas ELECTRO 2D [3] is preferred for lightning and switching impulses. Silicone rubber and fiber glass rode of composite insulators are assumed to be homogeneous, isotropic materials having zero volume conductivity.

Preliminary simulations are conducted to obtain optimal parameters that produce the most probable service conditions. Following simulations are performed for the different insulator sets, corona rings, and tower profiles.

Experiments are performed for an actual tower at Fuat Kulunk High Voltage Laboratory of Istanbul Technical University.

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II. BASIC DIMENSIONS OF THE MODELS

Fig. 1 and Fig.2 show the silicone rubber insulator used in the string and the tower used in 380 kV transmission systems, respectively.

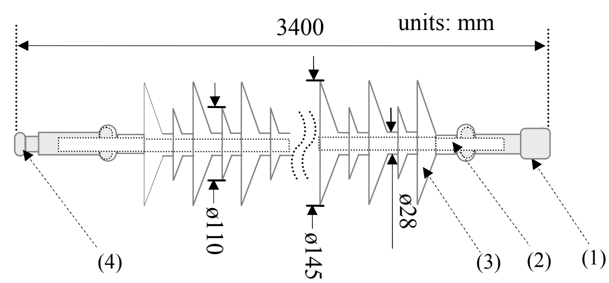

Fig. 1. Composite insulator used in the simulations: (1) ground end (2) fiber glass rod (3) silicone rubber material and sheds (4) line end

Direct flashovers from the corona rings to the transmission tower are preferred instead of flashovers along the insulator sheds. Therefore, it is important to determine optimal arc distance for the best system flashover performance. In addition, it is also important to control electric field intensity on the corona ring itself. Generally, circular corona rings are used at both ends of composite insulators (Fig.3.).

Yoke plates used for mounting the three bundle conductors are illustrated in Fig.4. The diameters of the conductors are 30 mm and 35 mm for 3x954 MCM (bundle diameter of 457 mm) and 3x1272 MCM (bundle diameter of 500 mm), respectively. Towers are equipped with two lightning protection conductors each having 10 mm of diameter. Smooth aluminum metal tubes with the same overall diameter are used to simulate the actual power line conductors.

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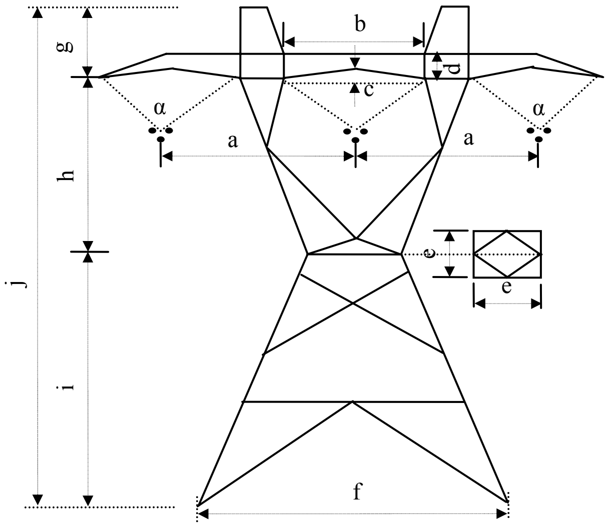


	380 kV Tower Type (units: mm)			
Symbol	3B1	3C1	3PB	3PC
a	7500	8500	7600	8300
b	5740	6596	6080	6894
c	630	1290	450	620
d	1630	2340	1450	1700
e	3900	3900	3900	3900
f	11200	11200	11500	11500
g	4980	5540	4910	5153
h	12520	11960	12590	12440
i	27000	27000	27000	27000
j	44500	44500	44500	44593
α	90°	110°	90°	100°

Fig. 2. Major dimensions of 380 kV suspension towers

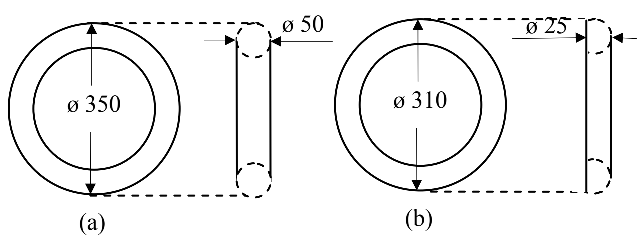
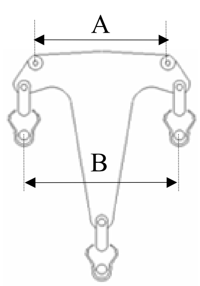


Fig. 3. Basic dimensions of circular corona rings (a) Full circle (b) Half circle (units: mm)



	Parameters (mm)	
3x954 MCM	A	B
90°	376	457
110°	511	457
3x1272 MCM	A	B
90°	456	500
100°	513	500

Fig.4. Basic dimensions of yoke plate for all V-suspension insulator sets

III. PRELIMINARY SIMULATIONS

A. Field Distribution under AC Voltages

Preliminary simulations are conducted to determine optimum parameters providing potential and field distributions as in actual service conditions. 100 m x 100 m conducting reference earth plane is positioned under the transmission tower. Simulations are conducted for the centre phase of 3x954 MCM 90° V-suspension string equipped with full circle corona rings. The set is energized with 100 kV_{rms} line-to-ground AC voltage. Relative permittivity of silicone rubber and fiber glass rode are assumed to be 4.5 and 7.2, respectively.

Fig.5 shows the potential distribution along the suspension set having full circular corona rings at both ends for the horizontal line (no conductor sags). Simulations showed that 24 m and longer conductor lengths give approximately the same field gradients at the vicinity of the insulators. Maximum electrical field strengths, E_{max}, on the rings are 10.145, 6.819, 6.526, 6.452, 6.445 and 6.444 kV_{rms}/cm for 0 m, 6 m, 12 m, 24 m, 50 m and 100 m conductor lengths, respectively.

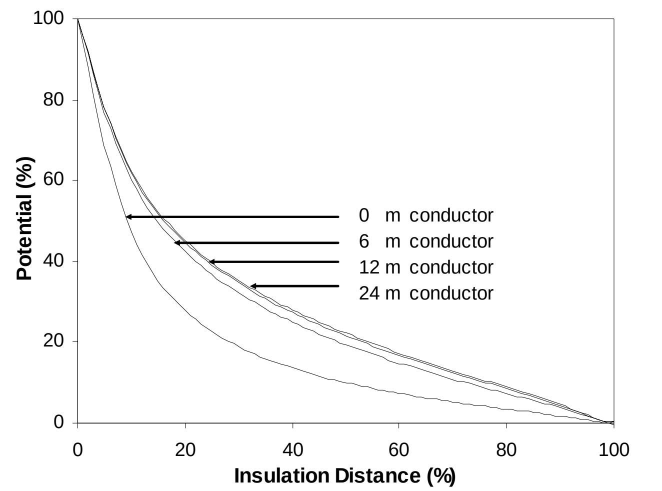


Fig.5. Potential distribution along the string for 3-phase AC excitation (no conductor sag)

Conductor sags are approximated by parabola equation [4]. Two adjacent towers of equal heights are assumed to be 450 m apart than each other. The most probable conductor sag for 380 kV V-suspension towers of the same altitude is about 15 m and it is assumed as a reference one. Fig. 6 illustrates the potential distributions along the V-string for 0 m and 15 m conductor sags.

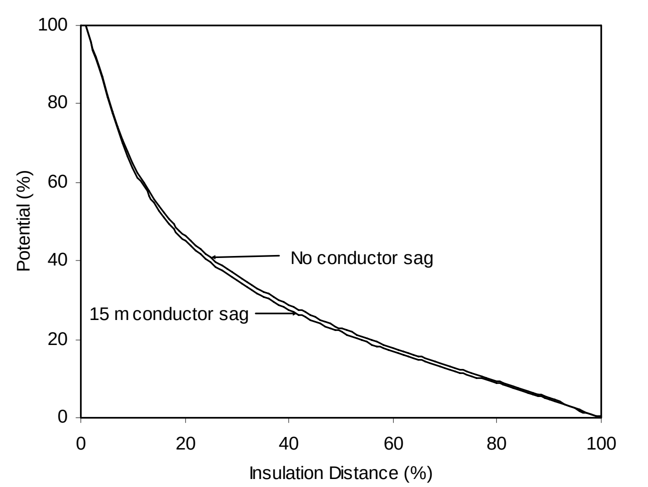


Fig.6. Effects of conductor sag on potential distribution along the centre line of the insulator string for 3-phase excitation (conductor length = 100 m)

Maximum electrical field strengths, E_{max}, on the corona rings are found to be 6.444, 6.481, 6.541, 6.627 and 6.704 kV_{rms}/cm for 0 m, 5 m, 10 m, 15 m and 20 m maximum conductor sags, respectively. The results show that the more conductor sags, the more electrical field intensity on the surface of the corona rings.

Simulations are also performed for a single isolated phase to represent the test conditions in the laboratory. Single phase and 3-phase simulations results are compared in Fig.7. E_{max} on the corona rings are calculated to be 6.161 and 6.444 kV_{rms}/cm for a single-phase and three-phase excitation, respectively. This shows that the existence of adjacent phases results in an increase of 5 % in E_{max}.

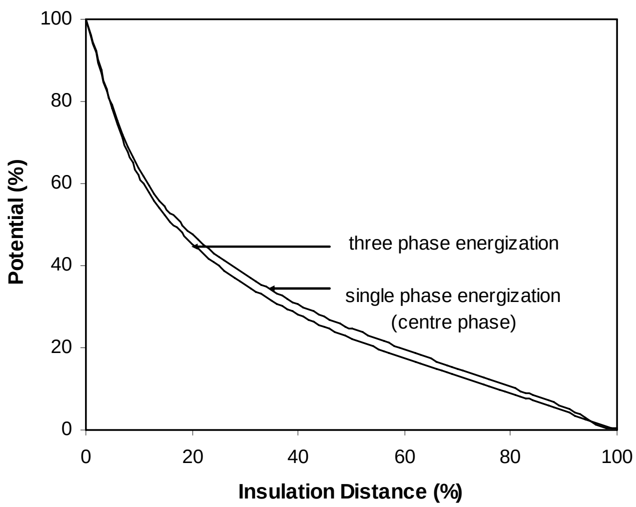


Fig.7. Potential distribution along the centre line of the insulator string for 3-phase and single phase excitations (conductor length = 100 m)

On the other hand, the existence of protection lines is calculated to be no more than 0.1 % on the field distributions.

According to preliminary simulations 100 m of conductor lengths, 15 m of conductor sags, three-phase systems and protection lines are determined as optimal values providing actual distributions and are used as "*reference parameters*" for the remaining simulations.

B. Field Distributions for Transient Voltages

Simulations are performed with Electro 2D for lightning and switching impulses again for the clean insulator (Fig.8) under dry conditions. The results show that the distributions are the same as in 50 Hz power frequency excitation.

Electro 2D is not able to analyze 3D transient fields for the string because of non-symmetrical conditions. However, since the alternating and transient field distributions are the same for clean, dry and pure silicone insulating material; 3D simulations obtained by Coulomb is used for the same operating conditions. Instantaneous lightning and switching impulse voltages at points along the insulator are in the same form of standard transient voltages. That is, there is no any waveform distortion.

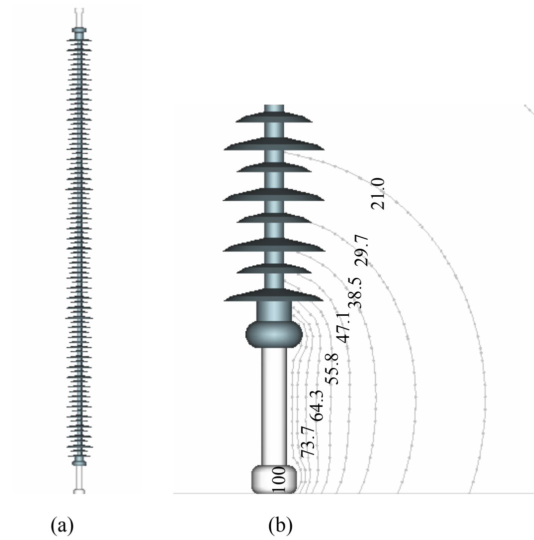


Fig.8 (a) Composite insulator model used in transient field analysis (b) Euipotential contours around the composite insulator under the transient voltages for dry and clean cases

IV. POWER FREQUENCY FIELD DISTRIBUTIONS FOR PRACTICAL V-STRINGS

A. Field Distributions under Practical Designs

Potential and electrical field distributions are simulated along 90^o and 110^0 V-suspension sets of 3x954 MCM ACSR Cardinal conductors and 90^o and 100^o V-suspension sets of 3x1272 MCM ACSR Pheasent conductors with 3B1, 3C1, 3PB and 3PC towers, respectively. Simulations are conducted with the *reference parameters* determined by preliminary studies. Fig.9 shows the full simulation model, where the term straight tower is used for the towers having zero "c" values (see Fig.2).

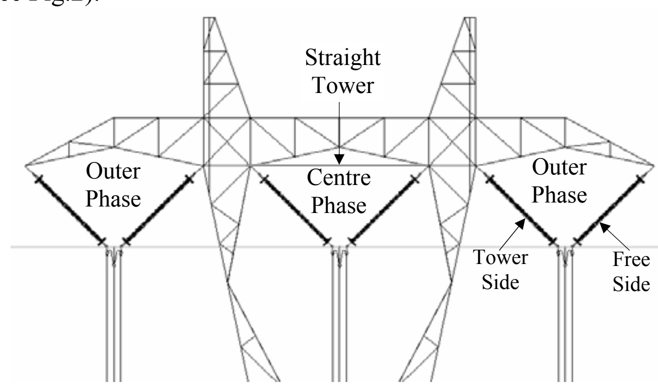


Fig.9 Full simulation model definitions

Fig.10 shows the potential distributions around the ACSR Cardinal 90^o. Maximum electric field strengths on the surface of full circle corona rings are 6.62, 6.73, 6.10 and 5.91 kV_{rms}/cm for centre phase, centre phase (straight tower), outer phase (tower side) and outer phase (free side), respectively. Center phase of the straight tower shows the maximum field strength because of reduced arc distances. Therefore, we will concentrate our studies on centre phases where most of the flashovers occur in practice.

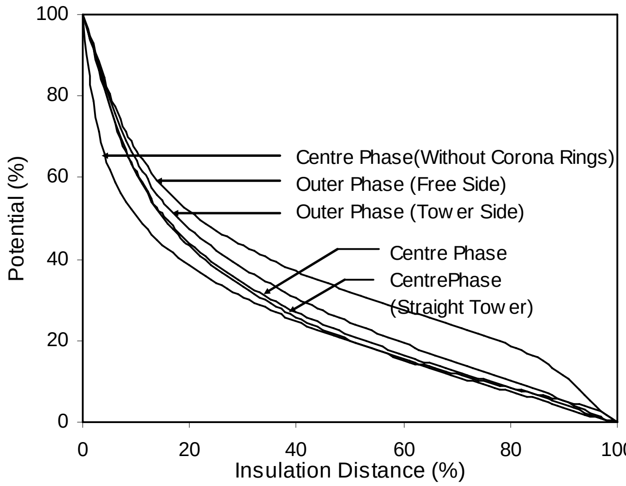


Fig.10 Potential distributions along 3x954 MCM ACSR Conductor 90º V-suspension set. (Full circle corona ring)

Simulations show that full circle and half circle corona rings generate similar potential distributions with a maximum difference of 3%. Potential distributions for 90^o and 110^o V-strings of 3x954 MCM conductors are also found to be approximately the same. Similar distributions are also valid for for 3x1272 90^o and 100^o insulator sets.

The effects of tower design are shown in Fig.11. Maximum fields on the grading devices are for straight towers as expected because of reduced arcing distances.

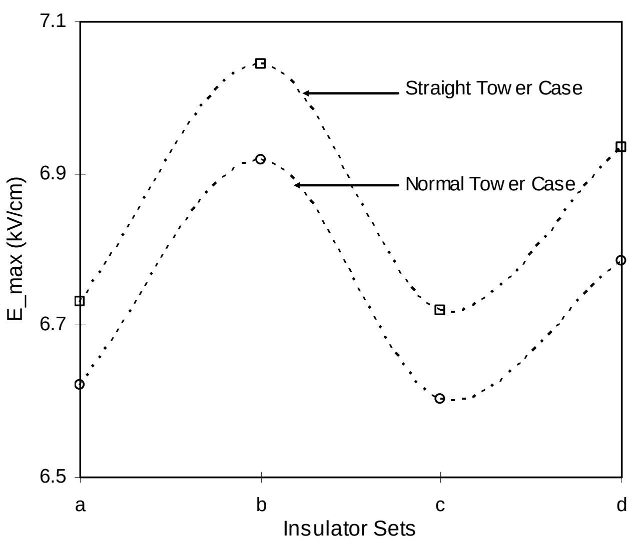


Fig.11 Maximum field strengths on the surface of the full corona rings (a) 3x954 MCM 90^o-V (b) 3x954 MCM 110^o-V (c) 3x1272 MCM 90^o-V (d) 3x1272 100^o-V

B. Field Distributions at Laboratory Conditions

Transmission lines are terminated by circular rings of Ø 650 mm to reduce terminal effects. The length of simulated power lines is 11 m positioned parallel to the earth plane. Fig.12 illustrates the potential distributions for the laboratory model and the reference model for 3x1272 MCM conductors.

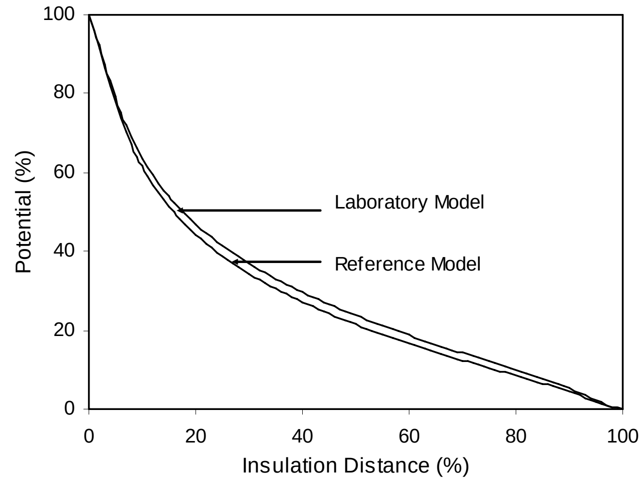


Fig.12 Potential distribution for 3x1272 MCM 90º V-suspension set under laboratory and reference practical models (Full circle corona ring)

Laboratory model and practical model give similar potential distributions. Maximum electrical field strengths on full circle corona rings are 6.60 and 6.08 kV_{rms}/cm for reference practical model and laboratory model, respectively. Conductor sags, adjacent phases, protection lines and the conductor lengths in practical model are the reasons of the differences between the practical and the laboratory model.

V. EFFECTS OF DRY ARCING DISTANCE AND OPTIMUM VALUES

Transient flashover voltages and routes depend on the tower designs, minimum arcing distances, voltage types, field distributions on the vicinity of insulator string, atmospheric conditions and contamination of the insulator surfaces. Several distances are shown in Fig.13. Flashovers along the insulators may result in surface tracking and affect the flashover performance of the system. So, it is important to determine optimal arcing distances to prevent these surface discharges.

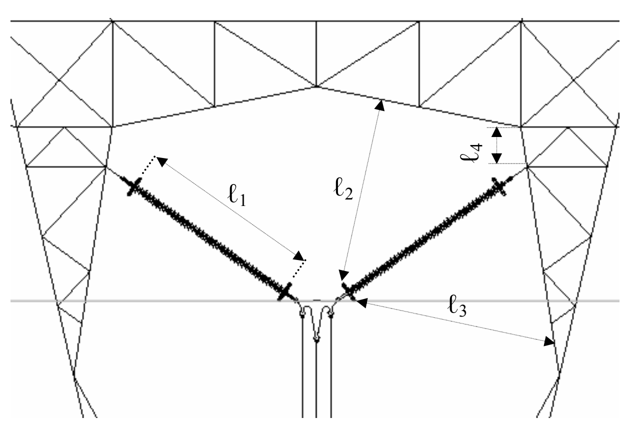


Fig.13 Arcing distances dominating the route of flashover

Table I shows the major distances for V-suspension sets. There is no need to modify arc distances of 3x954 90^o-V, 3x1272 90°-V and 3x1272 100°–V suspension sets for normal towers. However, minimum arc distance is the one along the insulator surface for 3x954 110°–V set and needs to be increased. For the straight tower cases, all the ℓ^{**}_2 distances must be increased. Moving the corona rings along the insulator axes can not itself provide the desired settings. Therefore, longer insulators must be hanged at suitable points from the uppermost tower parts (ℓ_4). Appropriate ℓ_4 values are 465, 387, 430 and 564 mm for 3x954 90°, 110°, 3x1272 90° and 100° V-suspension sets, respectively. Fig.14 shows the field strength distribution along the corona ring for different configurations.

TABLE I
ARC DISTANCES FOR INSULATOR SETS

Parameters (mm)	3x954 MCM 90°-V	3x954 MCM 110° -V	3x1272 MCM 90°-V	3x1272 MCM 100°-V
ℓ_1	2900	2900	2900	2900
ℓ^*_2	2934	3017	2839	2839
ℓ^{**}_2	2435	2513	2471	2336
ℓ_3	2893	3066	2854	3111
ℓ_4	0	640	0	0
ℓ^*_2 : Normal Tower, ℓ^{**}_2 : Straight Tower				

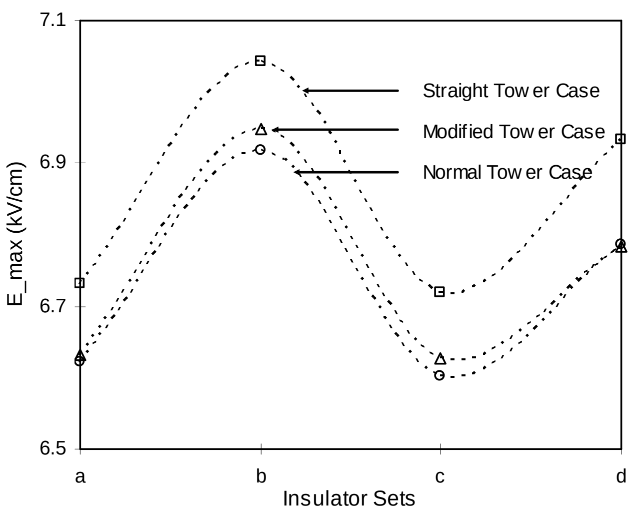


Fig.14 Maximum electrical field strengths on the surface of the full corona rings (a) 3x954 MCM 90°-V (b) 3x954 MCM 110°-V (c) 3x1272 MCM 90°-V (d) 3x1272 100°-V

VI. EXPERIMENTAL STUDIES

Indoor tests are conducted at Fuat Kulunk High Voltage Laboratory of Istanbul Technical University. The main laboratory hall has a floor area of 25x35 m and a ceiling height of 21 m. Test setup is constructed in accordance with actual service conditions. Flashover performance of 3x1272 MCM 90° V-suspension set is investigated for standard lightning impulses and switching impulses for different corona rings. 50 % flashover voltages and flashover times are recorded.

1,17/57 µs lightning impulse voltages and 260/2750 µs switching impulse voltages are used. 50 % flashover voltages are calculated by up-and-down method. Fig. 15 shows the positive full and chopped lightning and switching impulses during the tests.

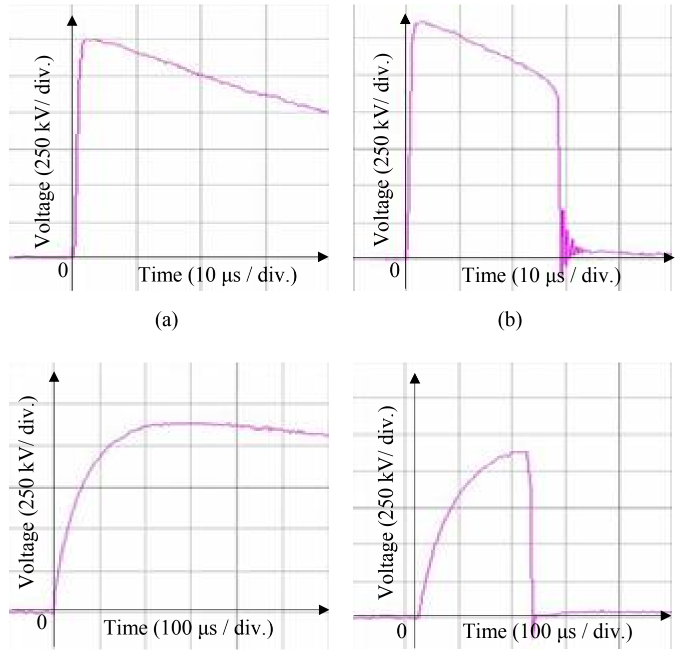


Fig. 15 (a) Full wave (b) Chopped lightning impulse voltage
(c) Full wave (d) Chopped switching impulse voltage

Table II shows the minimum arc distances measured on the laboratory test setup for full circle, half circle corona rings and without corona ring cases.

TABLE II
ARC DISTANCES FOR INSULATOR SET

Parameters (mm)	3x1272 MCM 90°-V Insulator Set		
	Full Circle Corona Ring	Half Circle Corona Ring	Without Corona Ring
ℓ_1	2900	2945	3100
ℓ_2	2770	2780	2860
ℓ_3	2850	2820	2910

Table III illustrates the 50 % flashover voltages and average flashover times for lightning impulses. Flashover times are measured to be between 15 µs to 40 µs on the wave tail. Flashover times for 1600, 1650 and 1700 kV positive polarity lightning impulses are about 15, 13 and 9 µs, respectively. Almost all flashovers occurred between the corona ring and the uppermost tower side, (Fig.13,ℓ_2) along the shortest arc distance of the set. Flashover paths for negative test voltages are shown in Fig.16. Full circle and half circle corona rings lowered the 50 % flashover voltages from 2% to 5 %.

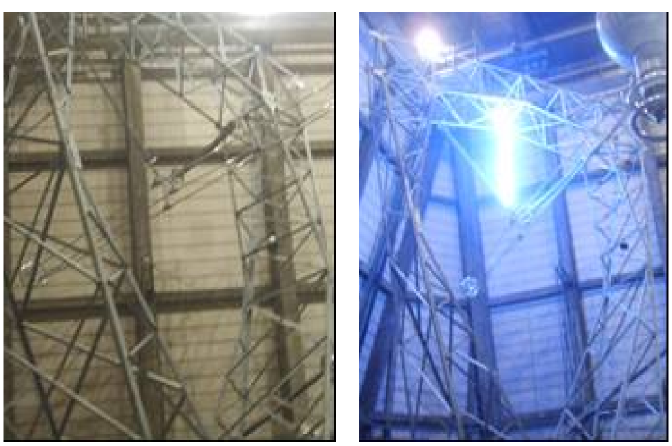
Switching impulse voltage tests are performed only for positive polarity. 50% flashover voltages and average flashover times are illustrated in Table IV. All the flashovers occurred on the wave front between 125 and 240 µs. The lowest switching impulse flashover voltage occurred near the wave crest. Nearly half of the flashovers occurred along ℓ_3 (Fig.16) path. The remaining half occurred along ℓ_2 path and a few flashovers happened along the silicone insulator string. 50 % flashover voltages slightly decrease by the corona rings

TABLE III
LIGTNING IMPULSE TEST RESULTS

Test Arrangement	Lightning Impulse Voltage 50 % Flashover Voltages (kV_{peak})		Average Flashover Times(µs) Positive / Negative
	Positive pol.	Negative pol.	
Full circle corona ring	1450	1800	30 / 25
Half circle corona ring	1485	1890	29 / 17
Without corona ring	1520	1910	26 / 25

TABLE IV
SWITCHING IMPULSE TEST RESULTS

Test Arrangement	Switching impulse voltage 50 % Flashover voltages (kV_{peak}) Positive polarity	Average flashover times(µs) Positive polarity
Full circle corona ring	1030	150
Half circle corona ring	1050	172
Without corona ring	1060	157



(a) (b)

Fig.16 (a) Laboratory test setup (b) Flashover path under impulse voltages

VII. CONCLUSIONS

This study has presented both the simulation and the experimental studies for V-suspension sets with composite insulators under transient voltages. Simulation studies include potential and electrical field distributions around 3x954 MCM cardinal and 3x1272 MCM pheasant conductors of V-suspension sets under different practical cases. Conductor lengths, grading devices, existence of conductor sags, phase conductors and protection lines affect the potential and electrical field distribution around the insulators to some degree. Field results for alternating and impulse voltages are exactly the same for clean and dry cases. Electrical field and potential distributions at laboratory conditions and for practical models show some differences which is mainly because of the length of the conductors, conductor sags and the existence of adjacent phases

Laboratory tests showed that the flashovers for lightning impulse voltages occur along the minimum clearance between the insulators and the transmission tower. On the other hand, for switching impulses, flashovers may not occur along the minimum clearances. Flashovers occur at the wave tail of standard lightning impulse and wave front of standard switching impulse voltages. To get optimum flashover performance under switching impulses, several laboratory tests are required under different clearances.

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IX. BIOGRAPHIES

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