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Lightning Critical Flashover Voltage of High Voltage Insulators: Laboratory Measurements and Calculations

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Abstract – *This paper presents the method for calculation of lightning critical flashover voltage (CFO) of high voltage insulators. Flashover occurrence on overhead transmission line insulators for 110 kV, 220 kV and 400 kV networks was studied using the leader progression model (LPM). Calculation results were compared to laboratory measurements and it was verified that presented method predicts CFO with good accuracy.*

***Keywords**: Lightning Critical Flashover Voltage, Leader Progression Model, High Voltage Insulators, Laboratory Measurements, Genetic Algorithm*

Nomenclature

CFO	Critical flashover voltage
LPM	Leader progression model
GA	Genetic algorithm
d	Distance between insulator arcing horns
σ	Standard deviation
k_L, E_0	Constants of the LPM
x	Distance of the unbridged gap
α, β	Parameters of double exponential function
A	Number proportional to the peak value of surge
T_1	Front time
T_2	Time to half
t_{max}	Time to peak
ε_{best}	Best fitness value
ε_f	Fitness function
ε	Percentage error
t_{fl}	Time to flashover

I. Introduction

The lightning critical flashover voltage (CFO) is the crest value of a standard lightning impulse for which the insulation exhibits 50 % probability of withstand. It is used in the insulation coordination studies to describe the lightning impulse strength of high voltage insulators [1], [2]. Therefore, it is very important to accurately determine the CFO when designing the high voltage insulators. The normal procedure for determining the dry lightning withstand voltage on insulator strings and insulator sets is by calculation from the CFO test results determined by the up and down method.

Therefore, it is important to accurately predict CFO in the development phase.CFO was calculated and compared to laboratory measurements for high voltage polymer and glass insulator strings with different arcing horns and grading rings fittings, used on transmission lines in 110 kV, 220 kV and 400 kV networks.

II. Laboratory Measurements of CFO

The lightning impulse tests were performed in dry conditions in order to verify insulation level of the insulator strings. The 50 % impulse flashover voltages were determined by applying an up and down method in accordance with [3]. The measurement of impulse voltages was carried out with impulse analyzing system and capacitor voltage divider in accordance with [4]. Equivalent diagram of the test circuit during lightning impulse voltage tests is shown in Fig. 1. The capacitor C_1 is slowly charged from a DC source until the spark gap G breaks down.

This spark gap acts as a voltage-limiting and voltage-sensitive switch, whose ignition time (time to voltage breakdown) is very short in comparison to front time T_1. The resistors R_1, R_2 and the capacitance of divider and the test object (high voltage insulator) form the wave shaping network. Resistor R_1 primarily damps the circuit and controls the front time T_1, while resistor R_2 discharges the capacitors and therefore essentially controls the wave tail.

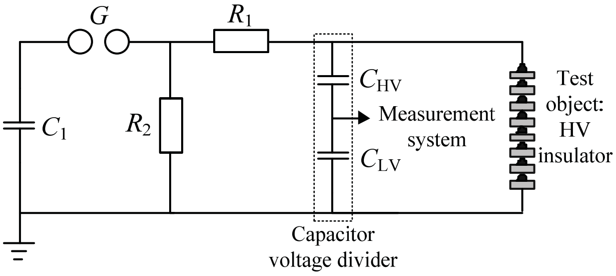

Fig. 1. Equivalent diagram of test circuit during lightning impulse voltage tests

Since the CFO of positive polarity is generally lower and thus more critical than negative polarity CFO, only positive polarity CFO was analyzed in this paper. Test arrangements in HV laboratory are shown in Figs. 2-7. Polymer and glass insulator strings used in laboratory measurements are equipped with different arcing horns and grading rings fittings.

Fig. 2. A: 110 kV single suspension polymer insulator string

Fig. 3. B: 110 kV double suspension polymer insulator string

Fig. 4. C: 220 kV single suspension polymer insulator string

Fig. 5. D: 220 kV double suspension polymer insulator string

Fig. 6. E: 400 kV "V" suspension glass insulator string

Fig. 7. F: 400 kV double tension glass insulator string

Test results are shown in Table I, where *d* represents the clearance between insulator arcing horns and *σ* standard deviation obtained from test results.

III. Volt-Time Curves and CFO

To establish more fully the short-duration strength of insulation, a volt-time or time-lag curve can be obtained. These are universally obtained by using the standard lightning impulse wave shape, and only self-restoring insulations are tested in this manner.

TABLE I
50 % LIGHTNING IMPULSE FLASHOVER VOLTAGE TEST RESULTS

Insulator	*d* (m)	*CFO* (kV)	*σ* (kV)
A: 110 kV single suspension polymer insulator string	1.515	942.4	13.49
B: 110 kV double suspension polymer insulator string		932.8	14.08
C: 220 kV single suspension polymer insulator string	2.364	1428.5	10.51
D: 220 kV double suspension polymer insulator string		1437.8	20.42
E: 400 kV "V" suspension glass insulator string	2.7	1638.0	28
F: 400 kV double tension glass insulator string	2.9	1726.0	22

The procedure is simply to apply higher and higher magnitudes of voltage and record the time to flashover [5]. A sample volt-time curve is illustrated in Fig. 8. and it tends to flatten out at about 16 μs. The asymptotic value of the volt-time curve is equal to the CFO. That is, for air insulations, the CFO occurs at about a time to flashover of 16 μs [6]. Times to flashover can exceed this time, but the crest voltage is approximately equal to that for the 16 μs point that is the CFO.

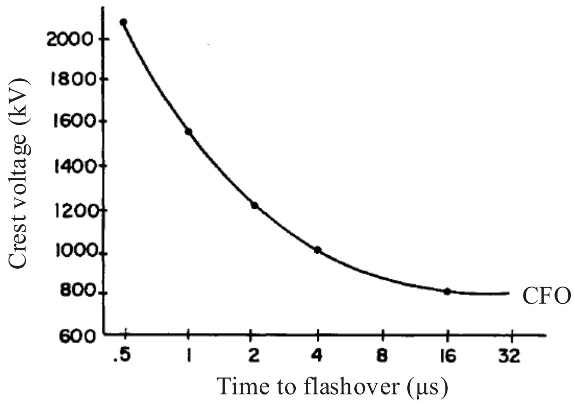

Fig. 8. A sample volt-time curve

Volt-time curves can be determined by applying the LPM.

IV. Leader Progression Model

The development of the leader [6] in the breakdown process is illustrated in Fig. 9. An impulse voltage $u(t)$ is applied across a gap with a spacing *d*. The leader begins its progress across the gap when the voltage gradient exceeds E_o. As the leader proceeds, the voltage across the gap increases, and the distance between the tip of the leader and the ground electrode decreases, thus increasing the voltage gradient across the unbridged gap *x*, which in turn increases the velocity *v* of the leader. As this process continues, the velocity of the leader increases until the leader reaches the ground electrode, at which time gap breakdown occurs. Models of this breakdown process consist of a single equation for the velocity of the leader. Many equations have been proposed and a summary of these is contained in [7], [8].

Expression (1) shows the differential equation selected by the CIGRE WG 33-01 for analysis of the voltage across the line insulation [9]:

$$v(t) = k_L u(t)\left[\frac{u(t)}{x} - E_0\right] \quad (1)$$

In the expression (1), $u(t)$ is the voltage as a function of time, x is the distance of the unbridged gap, E_0 is the gradient at which the breakdown process starts, and k_L is a constant.

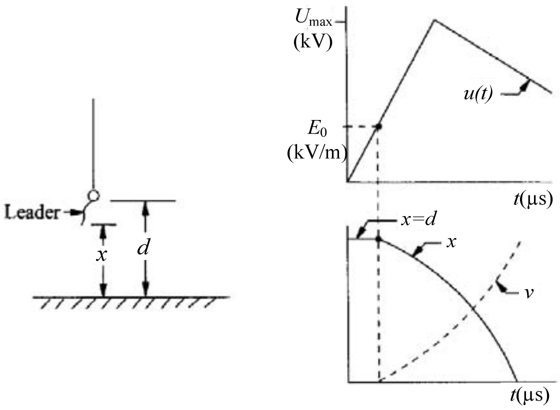

Fig. 9. The breakdown process

The calculation procedure consists of determining the velocity at each time instant, finding the extension of the leader for this time instant, determining the total leader length, and subtracting this from the gap spacing to find a new value of x. This process is then continued until the leader bridges the gap. The constants k_L and E_0 have been found to be dependent of the gap configuration and insulator type.

TABLE II
VALUES FOR CONSTANTS K_L AND E_0 [9]

Configuration	Polarity	k_L ($m^2/V^2/s$)	E_0 (kV/m)
Air gaps, post and long-rod insulators	+	$0.8 \cdot 10^{-6}$	600
	-	$1.0 \cdot 10^{-6}$	670
Cap and pin insulators	+	$1.2 \cdot 10^{-6}$	520
	-	$1.3 \cdot 10^{-6}$	600

Constants k_L and E_0 for air-porcelain and apparatus insulations can be found in [6]. Lightning impulse voltage $u(t)$ was simulated by using double exponential function:

$$u(t) = A \cdot \left(e^{\alpha t} - e^{\beta t}\right) \quad (2)$$

where:

α - negative number specifying falling slope.
β - negative number specifying rising slope.
A - number proportional to the peak value of surge.

Parameters of double exponential function were selected for standard lightning impulse voltage waveform (T_1/T_2= 1.2/50 μs): α=-14598.54, β=-2741703.81. Differential equation of LPM was solved numerically in Matlab software by using Runge-Kutta method of 4th order [10]. For different peak values of standard lightning impulse voltage (1.2/50 μs), leader velocity, length and voltage (time to flashover) are calculated. The Runge-Kutta method of order N=4 is a good choice for common purposes because it is quite accurate and stable. It is not necessary to go to a higher-order method because the increased accuracy is offset by additional computational effort. If more accuracy is required a smaller step size should be used. Time step of 0.1 ns was used in all simulations.

Calculation results for 220 kV suspension polymer insulator string (d=2,364 m) are shown in Figs. 10-15. Constants k_L=$0.6474 \cdot 10^{-6}$ $m^2/V^2/s$ and E_0=578 kV/m were used in calculations. Figs. 10-12. show calculation results in case when the amplitude of the applied voltage is 1450 kV and flashover occurs at t=13.5 μs. Figs. 13-15. show calculation results in case when the amplitude of the applied voltage is 1425 kV and there is no flashover on the insulator string.

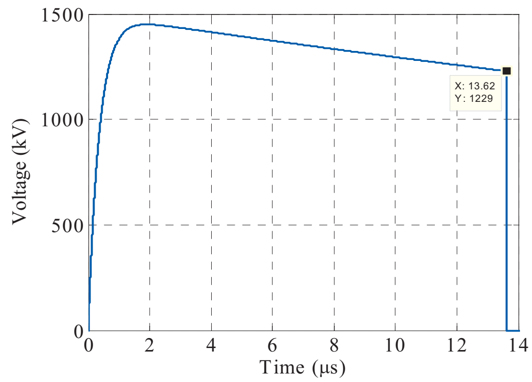

Fig. 10. Voltage on the 220 kV suspension polymer insulator string for U_{max}=1450 kV (flashover at t=13.5 μs)

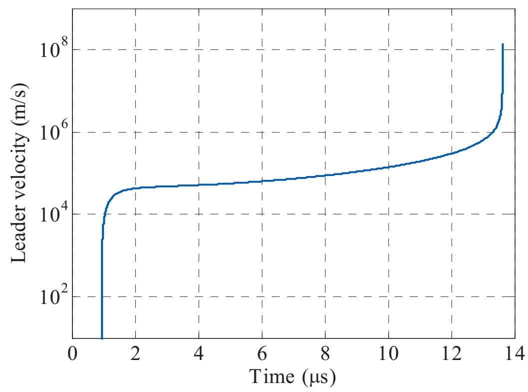

Fig. 11. Leader velocity on the 220 kV suspension polymer insulator string for U_{max}=1450 kV

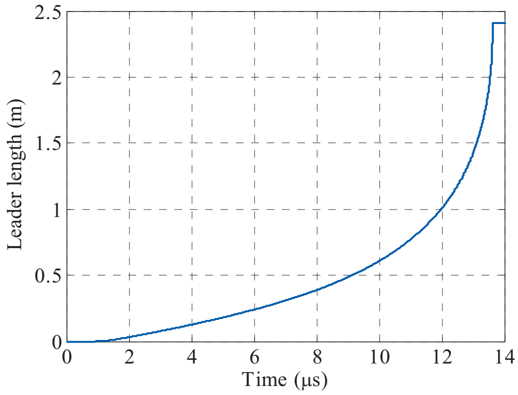

Fig. 12. Leader length on the 220 kV suspension polymer insulator string for U_{max}=1450 kV

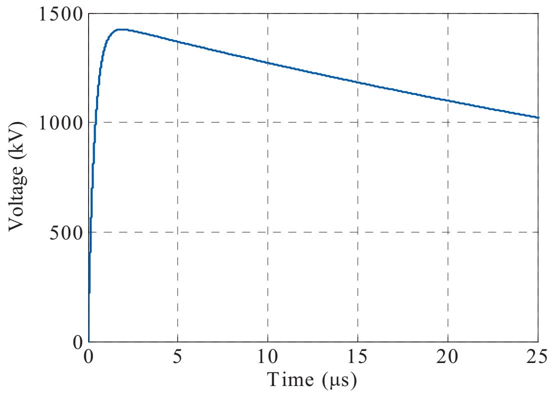

Fig. 13. Voltage on the 220 kV suspension polymer insulator string for U_{max}=1425 kV (no flashover)

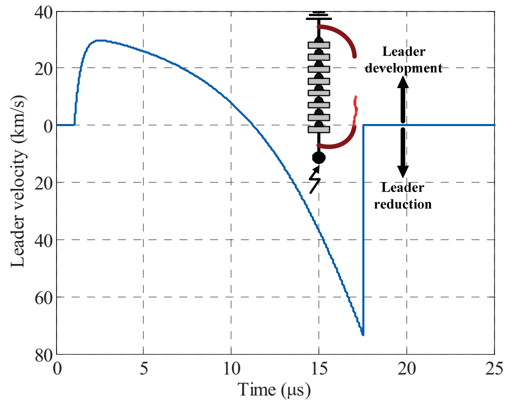

Fig. 14. Leader velocity on the 220 kV suspension polymer insulator string for U_{max}=1425 kV (direction of leader movement between arcing horns of the insulator string is shown figure)

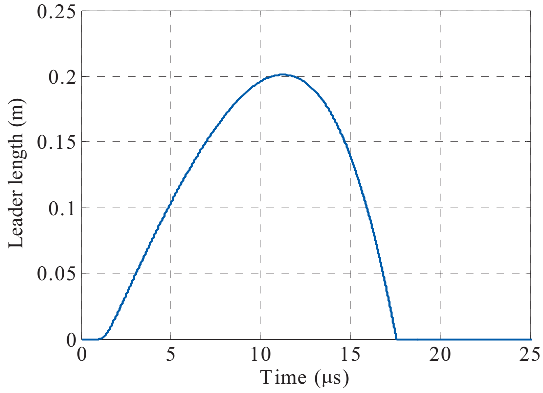

Fig. 15. Leader length on the 220 kV suspension polymer insulator string for U_{max}=1425 kV

V. Application of Genetic Algorithm for Determination of Double Exponential Function Parameters

Finding the parameters of double exponential function α and β was performed using Genetic Algorithm Tool, a part of the Matlab software, specialized for solving the optimization problems using genetic algorithm.

GA is a method for solving both constrained and unconstrained optimization problems based on the natural selection, a process that drives the biological evolution. It repeatedly modifies a population of individual solutions. In each step, the individuals are randomly selected from the current population to be parents and to produce the children for the next generation. Over successive generations, the population "evolves" towards an optimal solution [11]-[15]. The GA uses three main types of rules in each step in order to create the next generation from the current population:

1) The selection rules pick out the individuals, called parents, which will contribute to the population of the next generation.
2) The crossover rules combine two parents which will form children for the next generation.
3) The mutation rules apply random changes in individual parents which create children.

The fitness function ε_f is the objective function minimized by the GA, which in this case takes into account the percentage error for each calculated T_1 and T_2 regarding known values $T_{1default}$ and $T_{2default}$. The fitness function is calculated by using the following expression:

$$\varepsilon_f = max\left(\left|\frac{T_1 - T_{1default}}{T_{1default}}\right|,\left|\frac{T_2 - T_{2default}}{T_{2default}}\right|\right)\cdot 100\% \quad (3)$$

The flowchart of the algorithm for determination of parameters α and β of the double exponential function is shown in Fig. 16. At first, the GA generates a population of parameters α and β. Population size specifies how many individuals there are in each generation (in this case 1000 α and β elements per generation). Initial population is created randomly with a uniform distribution from a predefined range. After the creation of the initial population, T_1, T_2 and ε are calculated for each α and β element in the initial population. Each T_1 and T_2 is then rated according to the value of the fitness function. Time to peak of the lightning impulse voltage t_{max} needed for calculation of T_1 and T_2 is obtained by solving equation (4):

$$\frac{du(t)}{dt} = 0 \quad (4)$$

Expression (5) shows the solution of the equation (4):

$$t_{max} = ln\left(\frac{\alpha}{\beta}\right) \cdot \frac{1}{\beta - \alpha} \quad (5)$$

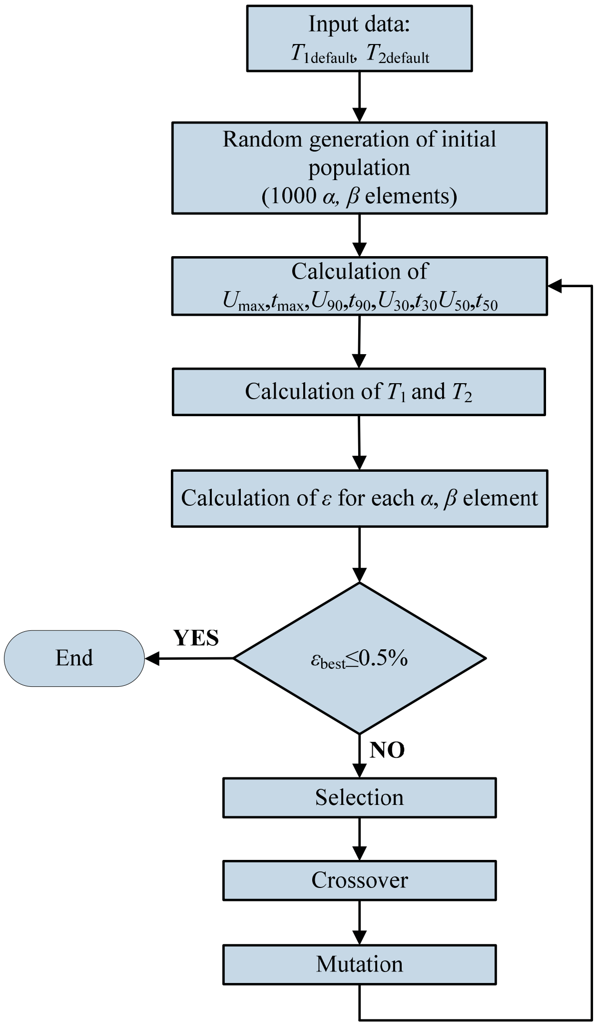

Fig. 16. Flowchart of the algorithm for determination of parameters α and β of the double exponential function

The selection function chooses the parents for the next generation based on fitness results [12].

The elite count specifies the number of individuals that are guaranteed to survive to the next generation (in this case 10). Crossover fraction specifies the fraction of the next generation, other than elite individuals, that are produced by crossover (80 %). The remaining individuals are produced by mutation.

The scattered crossover function creates a random binary vector. It then selects the genes for which the vector value is a 1 from the first parent, and the genes for which the vector value is a 0 from the second parent, and combines the genes to form the child.

Mutation functions create small random changes in individuals from a population, and they provide genetic diversity and enable the GA to search a broader space. Mutation function based on the Gaussian distribution with a mean value of 0 adds a random number to each vector entry of an individual. The stopping criteria determine what causes the algorithm to terminate. If the best fitness value ε_{best} is less than or equal to the value of the fitness limit, the algorithm stops. In this case, the fitness limit was set to 0.5 %.

For lightning impulse voltage waveform 0.84/60 µs, parameters α=-11936.54 and β=-3641900.427 were obtained after 23 generations. Best fitness value was equal to 0.42 %. The change of the fitness value throughout the generations is shown in Fig. 17.

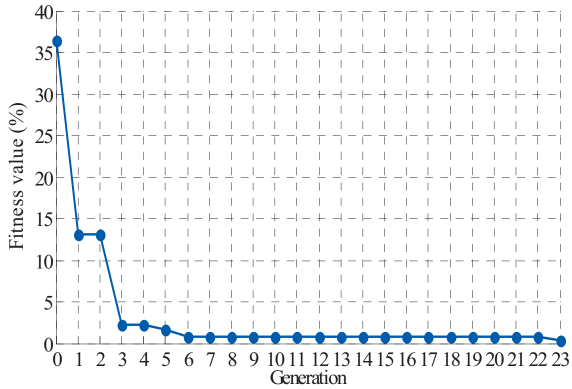

Fig. 17. Change of fitness value throughout generations

VI. Method for Calculation of CFO

Method for calculation of CFO is shown in Fig. 18.

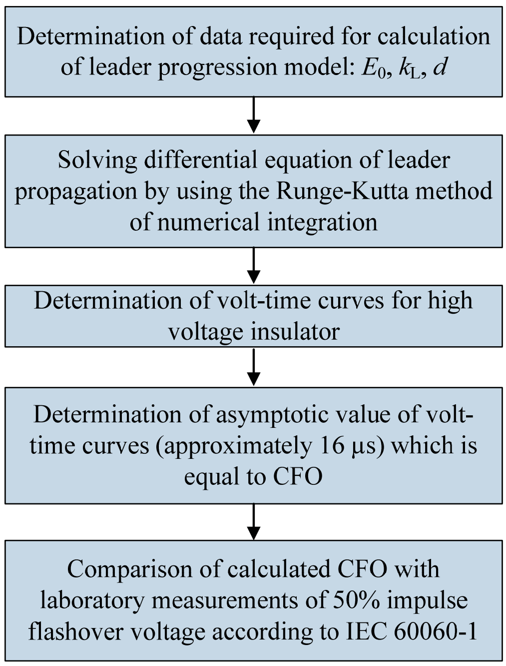

Fig. 18. Method for calculation of CFO

The method is based on LPM and determination of volt-time curves of high voltage insulators. Calculation results were compared with laboratory measurements for different constants k_L and E_0 of the LPM. The percentage error for each calculated CFO is determined by using the expression (6):

$$\varepsilon = \left(\frac{CFO_{calculated} - CFO_{measured}}{CFO_{measured}} \right) \cdot 100\% \quad (6)$$

VII. Comparison of Calculation Results and Laboratory Measurements

Volt-time curves and CFOs of the insulator strings were determined by applying previously described method. Figs. 19-20. show calculated volt-time curves and CFOs for standard lightning impulse voltage waveform 1.2/50 µs.

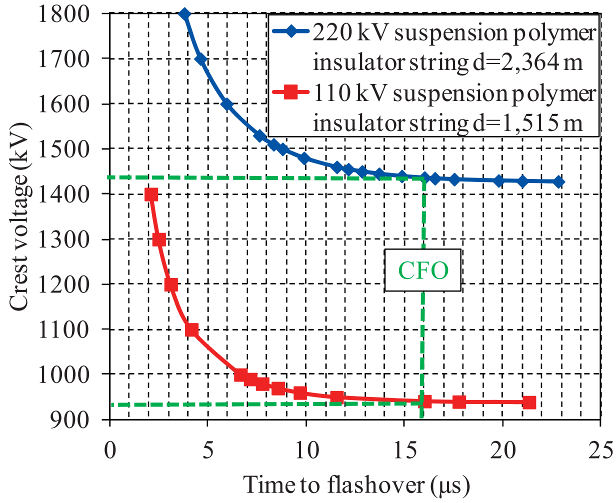

Fig. 19. Calculated volt-time curves of the 110 kV and 220 kV insulator strings (for 1.2/50 µs waveform)

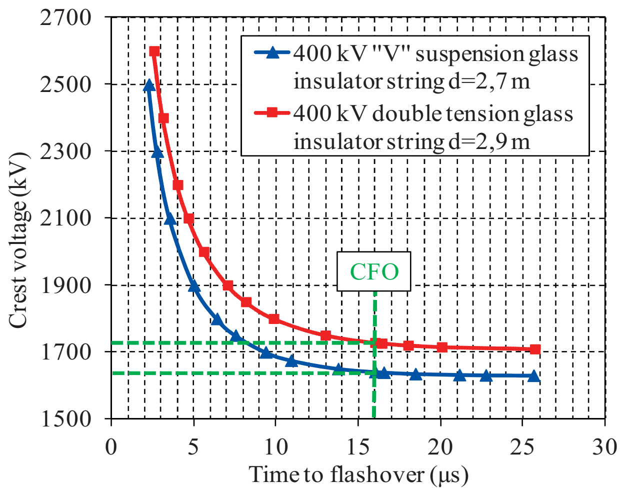

Fig. 20. Calculated volt-time curves of the 400 kV insulator strings (for 1.2/50 µs waveform)

In general the specifications [3] permit a tolerance of up to ±30 % (0.84 µs - 1.56 µs) for T_1 and ±20 % (40 µs - 60 µs) for T_2. Therefore, influence of front time T_1 and time to half T_2 on CFO was analyzed for 220 kV suspension polymer insulator string. Parameters α and β were determined by applying genetic algorithm. Results are shown in Table III and Figs. 21-22.

TABLE III
Influence Of T_1 And T_2 On CFO For 220 Kv Suspension Polymer Insulator String

T_1/T_2 (µs)	α	β	CFO (kV)
0.84/40	-18108.43	-3564728.0342	1457.0
0.84/50	-14442.93	-3610213.6489	1443.0
0.84/60	-11936.54	-3641900.4270	1433.0
1.56/40	-18733.85	-1824057.4041	1450.0
1.56/50	-14781.47	-1857538.8203	1438.0
1.56/60	-12167.64	-1897815.4983	1429.5
1.2/40	-18469.09	-2414130.1572	1453.0
1.2/50	-14598.54	-2741703.8114	1441.0
1.2/60	-12039.59	-2500103.9749	1431.0

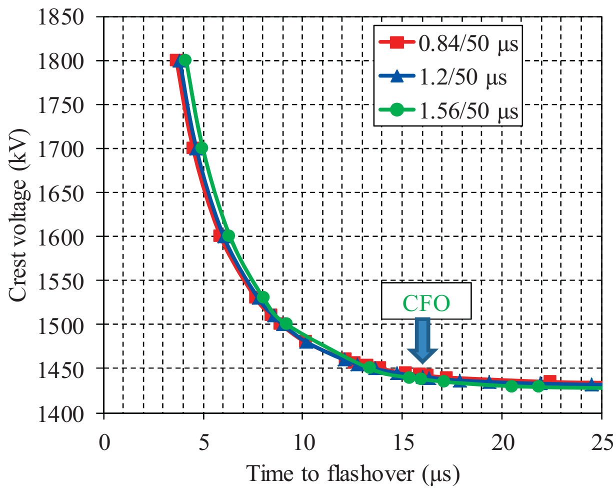

Fig. 21. Calculated volt-time curves for 220 kV suspension polymer insulator string – influence of front time T_1 on CFO

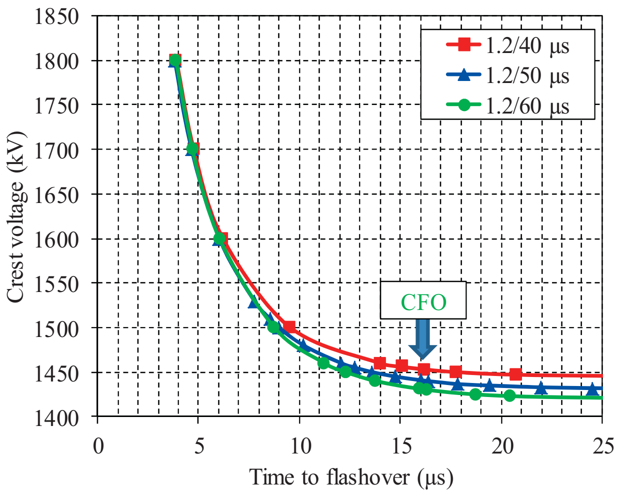

Fig. 22. Calculated volt-time curves for 220 kV suspension polymer insulator string – influence of time to half T_2 on CFO

Time to half T_2 has a greater impact (less than ±1 %) on CFO than the front time T_1 (less than ±0.2 %). CFO was calculated for standard 1.2/50 μs waveform and for measured waveforms shown in Table IV.

TABLE IV
PARAMETERS A AND B OF A DOUBLE EXPONENTIAL FUNCTION FOR MEASURED LIGHTNING IMPULSE VOLTAGES DETERMINED BY APPLYING GENETIC ALGORITHM

Insulator string	Measured T_1/T_2 (μs)	α	β
A	1.139/59.900	-12068.541	-2645505.844
B	1.141/59.955	-12031.332	-2632795.134
C	1.127/59.800	-12021.168	-2667214.857
D	1.153/59.850	-12046.261	-2611164.943
E	1.306/48.376	-15176.752	-2251398.400
F	1.239/47.492	-15426.583	-2375859.162

Comparison of calculated and measured CFO is shown in Tables V-VI. for different constants k_L and E_0 of the LPM. Percentage error ε between calculated and measured CFO of the 110 kV insulator strings A and B was lower than 1 % when constants of the LPM from [9] were used in calculations. ε was lower than 1 % for the insulator strings C-E and equal to 2.55 % for the insulator string F, when constants of the LPM from [6] were used in calculations.

TABLE V
COMPARISON OF CALCULATED AND MEASURED CFO (CONSTANTS FROM [9], A-D: k_L=0.8·10^{-6} m^2/V^2/s, E_0=600 kV/m; E-F: k_L=1.2·10^{-6} m^2/V^2/s, E_0=520 kV/m)

Insulator string	Measured (kV)	Calculated			
		1.2/50 (kV)	ε (%)	Table IV (kV)	ε (%)
A	942.4	944.2	0.19	938.85	-0.38
B	932.8		1.22	938.85	0.65
C	1428.5	1473.5	3.15	1465	2.56
D	1437.8		2.48	1464.95	1.89
E	1638.0	1450.0	-11.48	1449.84	-11.49
F	1726.0	1557.5	-9.76	1558.5	-9.71

TABLE VI
COMPARISON OF CALCULATED AND MEASURED CFO (CONSTANTS FROM [6], k_L=0.6747·10^{-6} m^2/V^2/s and E_0=578 kV/m)

Insulator string	Measured (kV)	Calculated			
		1.2/50 (kV)	ε (%)	Table IV (kV)	ε (%)
A	942.4	923.5	-2.01	917.3	-2.66
B	932.8		-1.00	917.2	-1.67
C	1428.5	1441	0.88	1431	0.18
D	1437.8		0.22	1432	-0.40
E	1638.0	1646	0.49	1646.02	0.49
F	1726.0	1768	2.43	1770	2.55

Figs. 23-24. show comparison between measured and calculated voltage on 110 kV single suspension polymer insulator string for U_{max}=922.311 kV. Parameters of double exponential function were determined for measured lightning impulse voltage (T_1/T_2= 1.144/59.84 μs): α=-12087, β=-2629200. Flashover on the insulator string occurs at t_{fl}=12.4 μs. Constants [9] k_L=0.8·10^{-6} m^2/V^2/s and E_0=600 kV/m were used in calculations. Measured and calculated voltage and time to flashover show a good agreement.

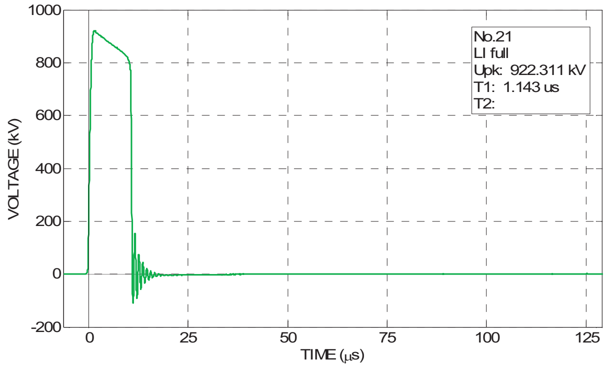

Fig. 23. Measured voltage on 110 kV single suspension polymer insulator string for U_{max}=922.311 kV

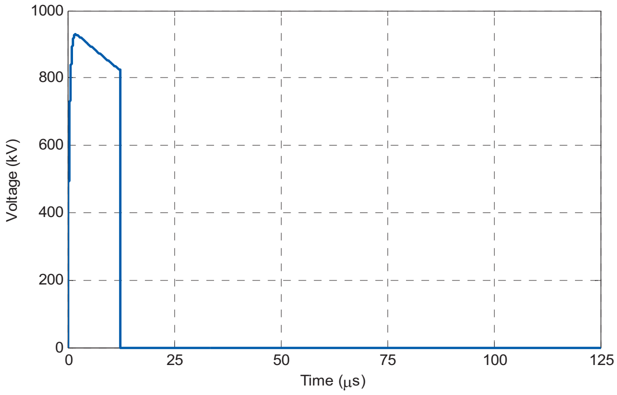

Fig. 24. Calculated voltage on 110 kV single suspension polymer insulator string for U_{max}=922.311 kV

VIII. Conclusion

This paper presents the method for calculation of lightning critical flashover (CFO) voltage of high voltage insulators, which is based on the application of leader progression model (LPM). CFO was calculated and compared to laboratory measurements for high voltage polymer and glass insulator strings with different arcing horns and grading rings fittings, used on transmission lines in 110 kV, 220 kV and 400 kV networks.

CFO was calculated for standard 1.2/50 μs waveform and for waveforms measured in laboratory conditions. The parameters α and β of double exponential function were determined using genetic algorithm. The influence of front time T_1 and time to half T_2 on CFO was analyzed.

It was verified that presented method predicts CFO with good accuracy.

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