A Physical Approach of the Test Voltage Function for Evaluation of the Impulse Parameters in Lightning Impulse Voltages with Superimposed Oscillations and Overshoots

Ricardo R. Diaz
National University of Tucuman
1800 Av. Independencia
SM Tucuman, 4000, Argentina

and **Adan A. Segovia**
National University of Tucuman
1800 Av. Independencia
SM Tucuman, 4000, Argentina

ABSTRACT

The introduction of the test voltage function or k-factor in IEC 60060-1 Ed. 3 has been an important step to ensure reproducibility and traceability in high voltage tests techniques for lightning impulses with superposed oscillations and overshoots. The standard recommends computed fitting methods to extract a base curve from the oscillating recorded voltage curve and, applying the test voltage function, it is possible to calculate the impulse parameters. Testing external insulations with positive polarity lightning impulses at 50% breakdown voltage or lower level, the disruptive discharge usually arrives after ten microseconds. For these cases the test voltage function and procedures for calculating impulse parameters proposed by the standard may lead to divergent results. In this paper a new approach is proposed for fitting the base curve for metric air gaps based on the relevance of the leader propagation phase, highlighting the influence of the instantaneous voltage between the impulse crest and the time-to-breakdown. A comparison of three calculation methods for test curves with long time-to-breakdown is discussed and a new test voltage function obtained by measurements on a 1 m rod-plane air gap is proposed. Compared to the standard test voltage factor, this approach evidences a negligible influence of oscillations and the relevancy of the impulse tail voltage for testing external insulations with moderately distorted lightning impulses. Finally, a generalization of the voltage test function is proposed for several types of insulation considering mainly the average breakdown times.

Index Terms - **Dielectric breakdown, insulation, lightning impulse, test voltage function, overshoot, base curve, test voltage.**

1 INTRODUCTION

DISTORTED lightning impulses are a subject of marked interest in high voltage techniques due to the fact that generating standard lightning impulses in a laboratory is not always possible. Voltage oscillations and superimposed overshoots frequently appear in high-voltage lightning impulse (LI) tests on large apparatus by the influence of the physically distributed inductances of circuits. The calculation of the parameters of an equivalent two-exponential LI with equal probability of discharge as the distorted impulse is therefore of the utmost importance. In the past, a simple convention was adopted in high-voltage standards [1] for relative overshoots or oscillations lower than 5%: if the frequency of oscillation was lower than a reference value (500 kHz), the crest voltage considered for testing (test voltage value) was the maximum of the impulse voltage. If the frequency was higher than the reference value, the test voltage was calculated by interpolation of the oscillations with a "mean" base curve. For much damped voltage oscillations without a clear frequency, the criterion was to assimilate the low frequency case to the overshoot duration lower than one microsecond. This method presented the disadvantage of attributing an arbitrary stress influence to voltage oscillations incorporating a sharp frequency transition, and inserting a quota of subjectivity to the test analysis.

Manuscript received on 10 October 2015, in final form 12 May 2016, accepted 16 July 2016.

DOI: 10.1109/TDEI.2016.005676

New h-v standards [2, 3] introduced the test voltage function, or k-factor, for LI, which provides a gradual transition in the frequency dependence of the overshoot magnitude on the dielectric strength. A relative overshoot of up to 10 % is accepted in the current standards. The experiments carried out in order to determine the k-factor in [2, 3] are described in [4], but concerning non uniform air gaps it is worth emphasizing that LI voltages were not higher than 100 kV and that the relative overshoots were around 15%. In [4] the tests for evaluating the k-factor were made by using two high voltage generators. In the actual test there is only one voltage source and the determination of a "smooth" base curve is critical in order to apply the standard procedures [2, 3] for evaluating parameters of LI with superimposed overshoot or oscillations. Significant efforts were devoted to implementing efficient fitting for base curves from the recorded voltage curves [5, 6, 7, 8, 9, 10] because the methods proposed in [2, 3] are suitable for insulations with uniform or quasi uniform electric fields, with time-to-breakdown not greater than ten microseconds. For a 1 m rod-plane air gap submitted to standard LI of positive polarity with $U_{50\%}$ level, the measured individual breakdown time for each shot ranges from 10 to 30 µs [11] depending on humidity, and the time grows slightly with air gap distances [25]. For a 3 m air gap, consisting of a ring shield and a plane ground, the times-to-breakdown reported for each shot in [18] were concentrated from 10 µs to 33 µs. Instead, for negative polarity, the times-to-breakdown are shorter than in positive polarity [19]. In a previous experimental study [12] with a 2 m rod-plane air gap, the individual breakdown times occurred between 12 and 31 µs for standard LI of positive polarity at $U_{50\%}$ level and between 5 and 10 µs for negative polarity. Furthermore, the experimental study [12] regarding the influence of overshoots and tail times has shown that, with positive polarity, the first parameter is less significant on the breakdown voltage than the second one, but the opposite happens with negative polarity. In other words, the overshoot effect decreases when the time-to-breakdown is much greater than the crest time. This effect is related to the leader propagation whose velocity can be considered proportional to the excess field along the streamer zone [13, 14]. Under positive LI voltages it can be assumed that the leader phase starts when streamers have reached the grounded electrode. In this paper, positive polarity is mainly analyzed because it is generally associated to lower breakdown voltages in external insulations. Furthermore, the long time-to-breakdown observed in large air gaps is on the basis of the new method (MC) proposed in Section 2.2 for fitting the base curve for external insulations.

The breakdown times are a function of the applied overvoltage, as shown in volt-time curves [14, 26, 27] and predicted in certain cases by the disruptive effect [28, 29]. However, the test voltage function is calculated at the $U_{50\%}$ level [4, 20] because is applied to tests with low and mean disruptive-discharge probabilities [2, 3].

2 TEST VOLTAGE FACTOR AND OVERSHOOT IMPULSE EVALUATION

The first part of this section describes the application of the k-factor in order to calculate the LI parameters while the second part explains how the k-factor was experimentally calculated for a 1 m length air gap.

2.1 IMPULSE PARAMETER EVALUATION

A brief description of the standard method to calculate the parameters of test voltages [2, 3] on oscillating LI is presented below.

The effect of superimposed oscillation (identified by the β overshoot of frequency *f*) is reduced by factor *k(f)*. The k-factor function *k(f)* takes zero value when the stress caused by the β overshoot on the insulation is negligible, and assumes a unit value when the β overshoot fully affects the insulation. This procedure would allow the calculation of an equivalent LI with the same disruptive discharge probability as a standard impulse, with a crest value equal to U_t and time parameters calculated from the base curve, with the same disruptive discharge probability as such a standard impulse. See Figure 1.

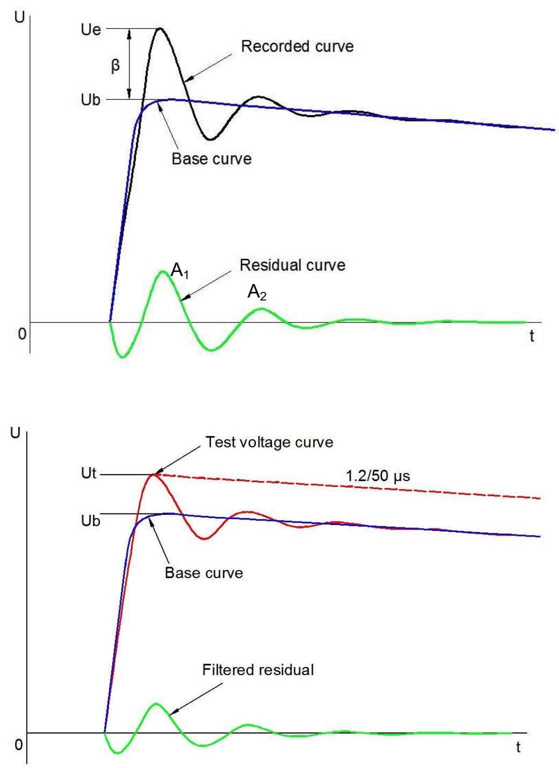


Figure 1. Recorded, base, residual, test voltage curves and equivalent standard LI.

The equivalent impulse value U_t (test value) is equal to the peak value of the applied smooth impulse U_b (base curve) plus *k(f)* times the overshoot magnitude β. The experimentally determined values of *k(f)* plotted against frequency are shown in Figure 2 and are valid for different dielectric media [4].

$$U_t = U_b + k(f) \cdot \beta \tag{1}$$

where: $\beta = U_e - U_b$

U_t is the test voltage to be determined.

U_b is the maximum value of the fitted base curve.

U_e is the maximum value of the recorded curve.

The k-factor function is given by the following formula [2, 3], with frequency expressed in (MHz):

$$k(f)=\frac{1}{1+2{,}2f^{2}} \tag{2}$$

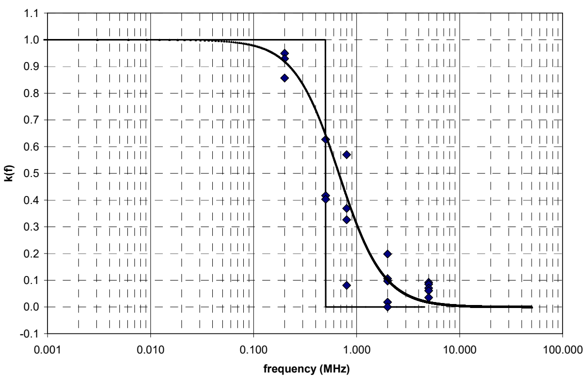


Figure 2. Current test voltage factor *k(f)* [2, 3] and former sharp transition [1].

2.2 K-FACTOR EVALUATION PROCEDURE

This section describes the methods applied to calculate the k-factor experimentally for different frequencies and overshoots, as presented in Table 1. The eight waveforms are identified by a number, the measured front times T_1 and average breakdown times T_B in the distorted impulses are accompanied by the front time T_{1MB} of the smooth impulses for the experimental method. The k-factor value *k(f)* was calculated for the 50% of disruptive-discharge probability level for a specific oscillation frequency f and a specific relative overvoltage β' [2]. The k-factor was calculated from two test groups under identical atmospheric conditions: the first test for smooth lightning impulses 1.2/50 μs to determine U_t and the other for oscillating lightning impulses to determine U_e and U_b. The up-and-down method [2] was applied to determine *k(f)* with 23 shots, in order to obtain at least ten discharges to calculate the average breakdown time T_B. Then the k-factor was derived for the 50% probability level as follows:

$$k(f)=\left(\frac{U_t-U_b}{U_e-U_b}\right) \tag{3}$$

where:

U_t is the maximum value of the test voltage.

U_b is the maximum value of the base curve.

U_e is the maximum value of the recorded curve.

The determination of the base curve was carried out by using three different methods:

1) MA or standard method: The four parameters of the two-exponential function (8) are fitted with the Levenberg-Marquart algorithm (from Matlab code), as recommended by the standard [2].

2) MB or experimental method: Fitting the recorded curve with the normalized smooth experimental impulse obtained in the laboratory by short-circuiting the inductances in the h-v circuit that produces the oscillating impulse. Normalization is made fitting on the tail.

3) MC or tail method: The four parameters of the two-exponential function (8) are calculated by fitting the recorded curve following the sequence:

3.1) a virtual extreme value U_α of the first exponential function and the time constant α of the tail is calculated by fitting the recorded tail values between 90 % and 50 % of the maximum value, by the method of least squares:

$$u(t)=U_{\alpha}.e^{-\alpha.t} \tag{4}$$

3.2) a virtual U_γ value and the time constant γ of the front is calculated by fitting the recorded curve between 30% and 90% of the maximum value, by the method of least squares.

$$v(t)=U_{\gamma}.e^{-\gamma.t} \tag{5}$$

3.3) the virtual origin t_d of the curve is calculated by matching both exponential functions:

$$t_d=\frac{\ln(U_{\alpha}/U_{\gamma})}{(\alpha-\gamma)} \tag{6}$$

3.4) the exponential extreme value U_0 is calculated from (4) for $t = t_d$:

$$U_0=U_{\alpha}.e^{-\alpha.t_d} \tag{7}$$

3.5) the fitted two-exponential base curve is obtained with:

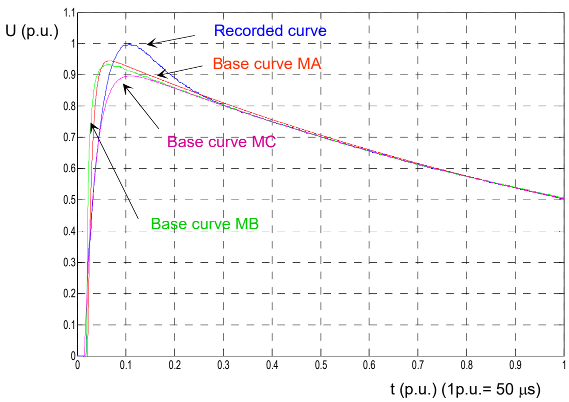
$$U(t)=U_0.(e^{-\alpha.(t-t_d)}-e^{-\gamma.(t-t_d)}) \tag{8}$$

Figure 3 shows the application of the referred methods to calculate the base curve for two different recorded curves obtained in the laboratory. Method MA in Figure 3 gives slightly greater voltage values for base curves than for recorded curves on the tail after the overshoot and until 30 μs. This method emphasizes the weight of the first oscillation on the base curve, but appears to be physically inappropriate when the discharge occurs at a much longer time than the crest, as explained in Section 3.

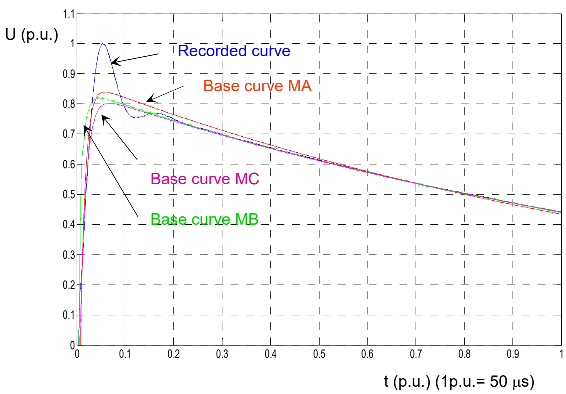
The application of the three methods leads to different values of overshoot, frequency and k-factor. The oscillating damping ratio between the second A_2 and first A_1 oscillation, see Figure 1, was lower than 10 % for all impulses presented in Table 1.

3 PHYSICAL CHARACTERISTICS OF THE DISCHARGE

To assess the relationship between the long time-to-breakdown observed in laboratory and the k-factor for rod-plane gaps, further analysis using a physical approach was performed. Experiments were carried out with a 1 m rod-plane air gap and LI of positive polarity. Eight different oscillations and overshoots on voltage wave-shapes were obtained introducing various inductances and resistances in the h-v generator. The discharge-disruptive voltage U_{50} at the 50% probability level was determined by using the up-and-down method and an approved measuring system [2, 3].



a)



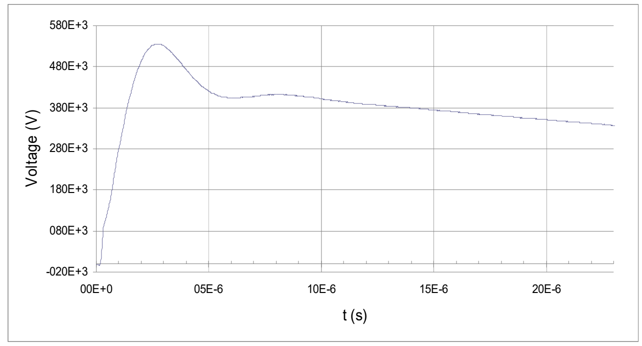
b)

Figure 3. Oscillating and overshooting impulses. Recorded curve and base curves calculated with methods MA, MB and MC. Waveforms No. 1 (a) and No. 6 (b).

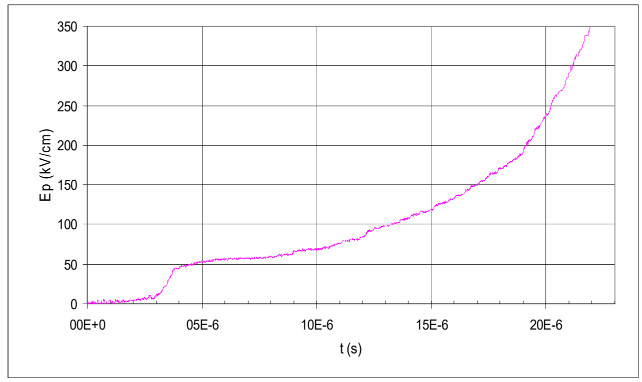
Table 1. Comparison between over-voltages, frequency and k-factors calculated with methods MA, MB and MC.

Waveform			MA			MB			MC		
No.	T_1/T_{1MB} [µs]	T_B [µs]	β′ [%]	f [MHz]	k [p.u.]	β′ [%]	f [MHz]	k [p.u.]	β′ [%]	f [MHz]	k [p.u.]
1	3.6/1.1	24	5.5	0.059	0.49	6.6	0.044	0.58	10.4	0.041	0.73
2	1.4/1.2	20	8.0	0.215	-0.12	9.3	0.210	0.04	9.4	0.203	0.05
3	5.4/6.2	21	7.5	0.051	0.03	12.4	0.056	0.41	11.5	0.061	0.37
4	1.95/2.5	20	7.9	0.177	-0.21	10.5	0.136	0.09	9.9	0.150	0.03
5	1.35/1.3	14.5	12.9	0.234	-0.01	14.1	0.236	0.07	14.5	0.226	0.10
6	2.1/1.1	17	16.1	0.153	0.08	18.0	0.158	0.18	19.7	0.150	0.25
7	1.85/1.7	17	15.6	0.185	-0.08	18.5	0.181	0.09	18.6	0.181	0.09
8	0.75/0.7	17.5	14.7	0.348	0.00	16.0	0.352	0.08	15.0	0.367	0.02

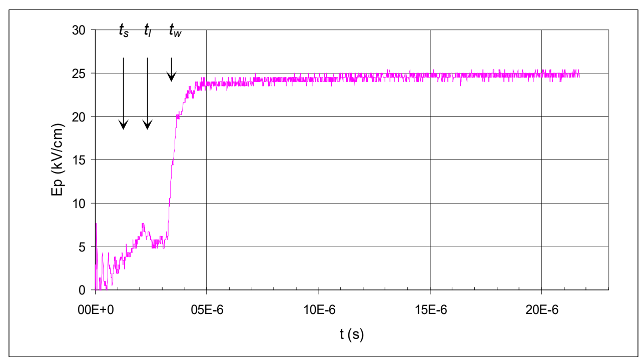
For each voltage waveform, the tests were repeated with standard LI under identical atmospheric conditions. In both cases U_{50}, T_B (time-to-breakdown) and the electric field at the plane E_p were measured. The electric field was measured with a field probe which allows an evaluation of the leader progression. Figure 4 shows an example for the recorded voltage of waveform No. 6. Two records of electric field measurements on the ground plane are presented in Figure 4b) for breakdown and 4c) for withstand, where t_s is the time of streamer arrival at the plane, t_l the time of leader inception and t_w the time of leader stop in the gap for withstand. At time t_s the streamers arrive at the ground plane with a field of about 6-7 kV/cm. The probe is perturbed and a slight field reduction is observed until t_l when the leader is launched increasing the measured field. It has been experimentally observed that the time difference (t_l - t_s) is a function of humidity and voltage that decreases when humidity grows.



a)



b)



c)

Figure 4. Applied voltage a), measured electric field at ground b) and c).

Figure 5 represents the typical behavior of a lightning discharge in air gap [13, 21].

Models of leader advancement have been previously proposed considering some expressions for leader velocity, which allow the computation of the time needed for a leader to traverse the whole gap length d. A useful expression for leader velocity proposed in [13] is:

$$v_l(t) = a\,(E_s(t)-E_0)+b\,dU(t)/dt \qquad (9)$$

where E_0 is the minimum field for streamer propagation, $E_s(t)$ is the excess field along the streamer zone (d-l_l), $U(t)$ is the instantaneous voltage, a and b are parameters of field intensity and voltage derivative which control the speed sensitivity to actual voltage shapes.

For high field and overvoltage, in [14] other formulas have been proposed, such as:

$$v_l(t)=170\,d\,e^{(0.0015\,U(t)/d)}((U(t)/(d-l_l))-E_0) \qquad (10)$$

Nevertheless this formula was not tested in this work because the study was performed with $U_{50\%}$.

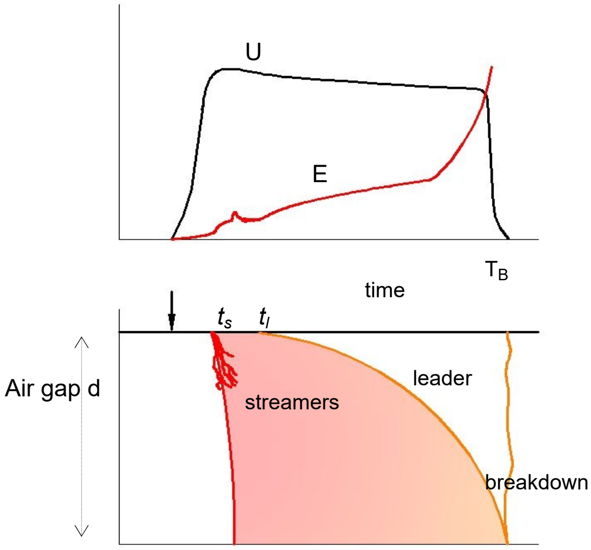
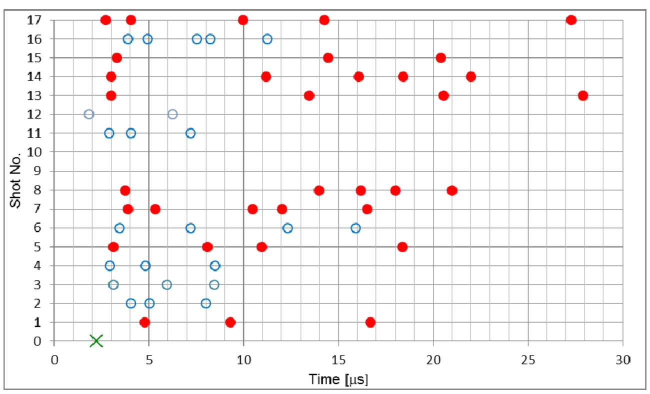
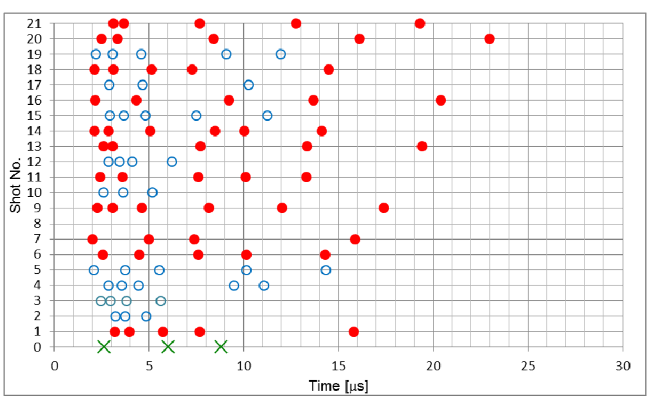


Figure 5. Sketch of the lightning discharge showing voltage, field, streamers and leader propagation.



a)



b)

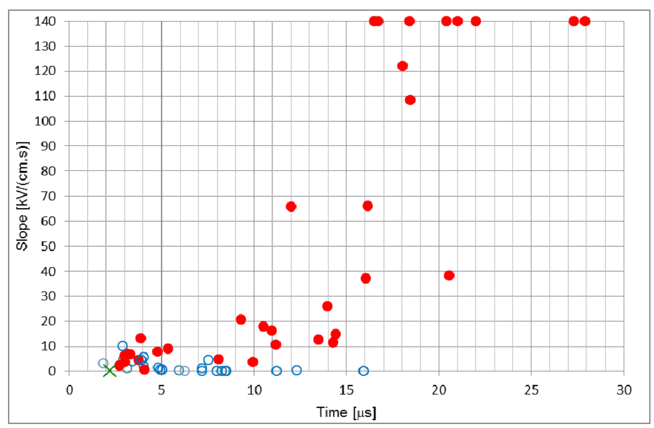
Figure 6. Measured time of change in the electric field (leader progression) as a function of time. Full and empty dots correspond to breakdown and withstand, respectively. Crosses show the relative extremes of the recorded curve voltages. a) Smooth and b) Oscillating impulses. Waveform No. 6.

The leader elongation l_l can be iteratively calculated by integration of equation (9) at any time, and this progression "provokes" the breakdown when the leader length l_l equals the insulation distance d.

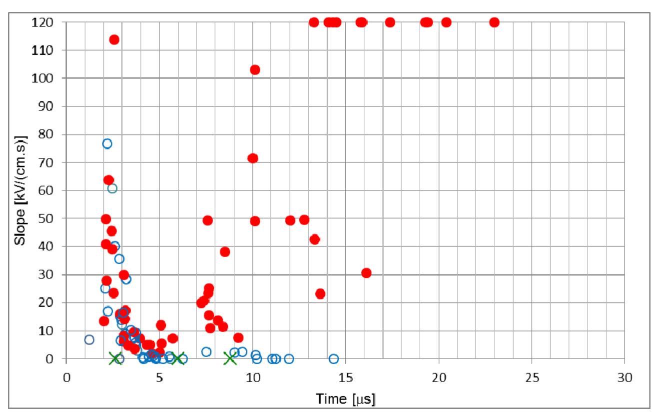
When measuring the electric field at plane, for each shot it was possible to determine the field slope changes in the time. Figures 6 and 7 show parameters associated to the leader progression during the up-and-down procedure obtained from field measurements for waveforms No. 6.

Figures 6 and 7 identify the behavior of the leader velocity for each shot. The field slopes depend on the leader speed because the measured field is a function of the leader length. The correlation with the applied voltage derivative may be used to verify the voltage slope influence and justify adopting equation (9) for simulation. Figure 7 shows growing slopes, i.e. increasing in the speed of the leader, which are important after 5 µs only for breakdown impulses. It is as if the breakdown were not "decided" before the initial five microseconds.

As demonstrated in [11] U_{50} and T_B depend on moisture. Figure 8 shows this dependency for a rod-plane gap of 1 m.



a)



b)

Figure 7. Slope of the measured electric field showing acceleration of the leader progression. Full and empty dots correspond to breakdown and withstand, respectively. Crosses show the relative extremes of the recorded curve voltages. a) Smooth and b) Oscillating impulses.

For the calculation of the test voltage function as well as for simulation no atmospheric corrections were performed on voltage impulses, because the standard procedures [2] are verified only for smooth impulses but not for distorted waveforms. Furthermore, a t_l time reduction was observed experimentally with increasing humidity. A simplifying assumption to overcome this dependency consists of making t_l equal to t_s and calculating the a parameter as a function of atmospheric moisture. The values of a and b have been calculated by matching simulations with measured values of U_{50} and T_B for smooth standard LI.

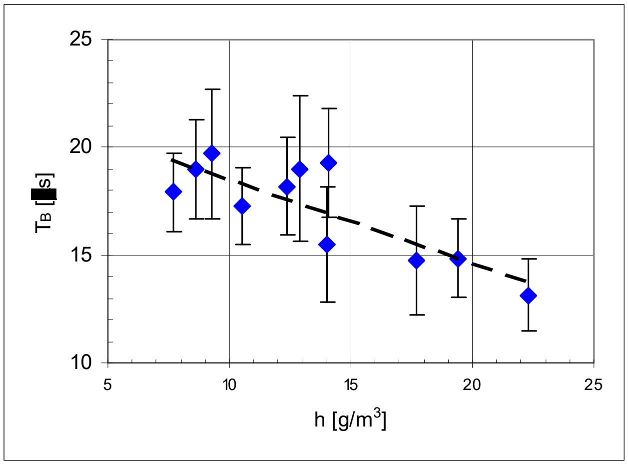


Figure 8. Measured time-to-breakdown (average value) as a function of humidity for standard LI [11]. The bars show the standard deviation.

Figure 9 shows the values of parameters a and b calculated from smooth impulses for actual atmospheric conditions (humidity h between 7 and 15 g/m^3, relative air density δ, between 0.93 and 0.99 p.u.).

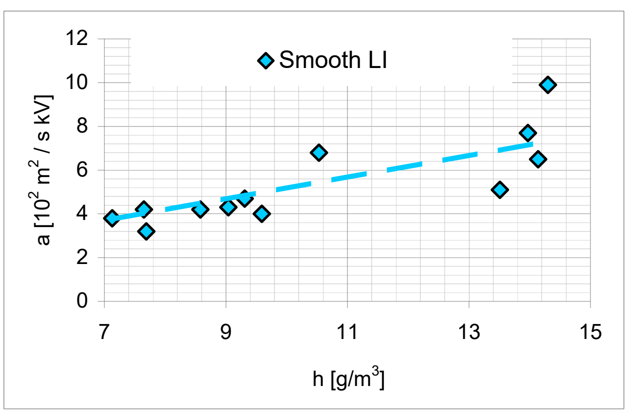


Figure 9. Calculated parameter a of equation (9) as a function of humidity, with b = 1.5 10^{-4} m/kV.

The average value of the minimum gradient for positive streamer propagation E_0 in e equation (9) was calculated with the expression obtained from data provided by [15]:

$$E_0 = 400\ \delta^{1.5} + (h\ (4+5\ \delta)) \qquad [\text{kV/m; g/m}^3] \qquad (11)$$

Considering the mechanism of breakdown proposed in [13] as a reference, a simulation of the up-and-down method has been made to evaluate measured U_{50} and T_B on distorted LI with oscillations and overshoot. The algorithm is shown in Figure 10.

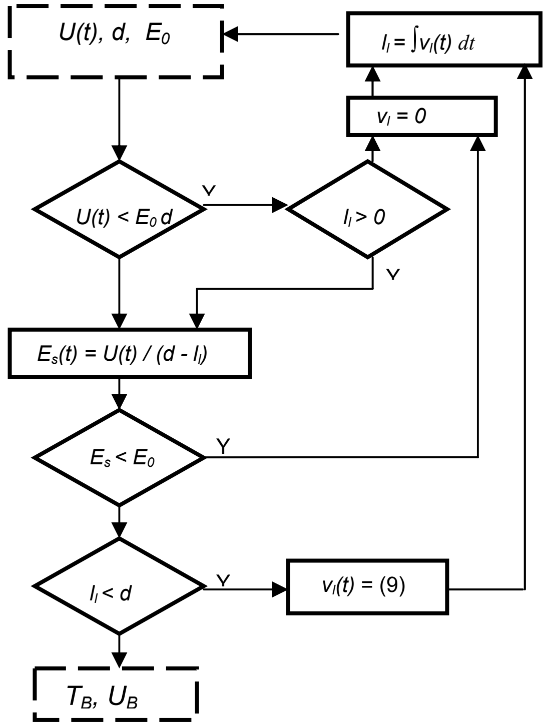


Figure 10. Simulation algorithm.

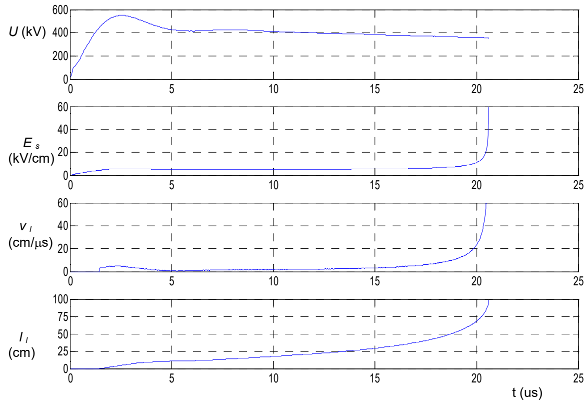
Figure 11 gives two examples of simulation considering the values of U_{50} and T_B (raw atmospheric conditions), which shows reasonable agreement with such measurements for impulses with overshoot. Similar agreement was obtained for the other waveforms.

The result of simulation highlights the relevancy of the instantaneous voltages during the whole leader propagation phase and enhances the validity of the new method MC proposed in Section 2.2, which pays major attention to tail voltages.

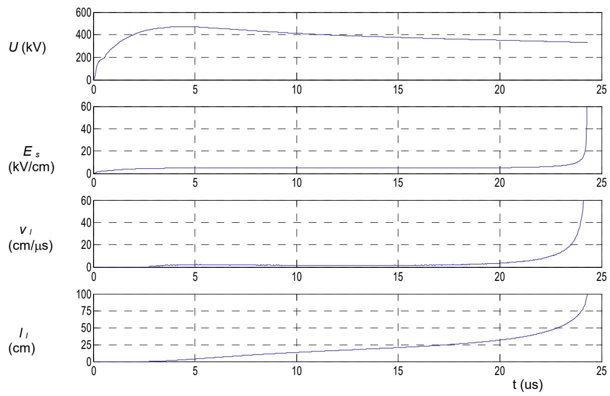
This model provides significant information for assessing the importance of the tail voltages on the disruptive discharge. Even more, the simulation shows that the influence of damped overshoots can be neglected and consequently the method to determine the k-factor, i.e. the base curve, should consider these particular physical characteristics for dielectric stress with voltages of positive polarity on external insulations. $E_s(t)$ of Figure 11 is the average electric field in the streamer zone calculated neglecting the voltage drops in the leader channel. This field is only a rough approximation of the measured value at the ground plane because the space charge fields of the streamers and the leader stem formation [30] are disregarded.

4 K-FACTOR CALCULATIONS FOR A 1 M AIR GAP

As explained in Section 2.2, the k-factor was calculated in laboratory for eight different frequencies and overshoots. Figure 12 gives test results for the three methods. It is noteworthy that for impulses with strongly damped oscillations, the IEC method to calculate the base curve gives negative k-factor values because the base curve results greater than the test curve. However, the methods MB and MC always give positive k-factor values.



a)



b)

Figure 11. Applied voltage and simulation of electric field, leader velocity and leader length. a) Waveform No. 6 b) Waveform No. 1.

It is possible to consider a new expression for the k-factor in metric air gaps by interpolating experimental values:

$$k(f) = \frac{1}{1+330f^2} \qquad (12)$$

This function, shifted to lower frequencies than the standard equation, would indicate that overshoots do not seem to have a significant effect on the breakdown mechanism of long air gaps submitted to voltage impulses of positive polarity. In fact, the field excess during the leader phase has a more significant effect on the leader progression, which is launched after the front time. Thus, leader elongation or its arrest may occur before reaching the ground electrode.

The results calculated with methods MB and MC are in agreement with recently published experiments [9, 16]. In addition, this work points out the physical background of the new method to calculate the test voltage function for large air gaps submitted to impulse voltages of positive polarity and its relationship with the time-to-breakdown.

5 ENLARGEMENT OF THE TEST VOLTAGE FUNCTION

Several results published in [4, 16, 17, 18, 19, 20, 21, 23, 24] are analyzed in this section. Such articles present different test voltage functions for air gaps between 0.2 and 3 m, with uniform and non-uniform electric fields identified by air-gap factors [22] between 1 and 1.5. Some cases of negative polarity voltages were included from [19]. The authors of the present article obtained two additional test values besides those of Figure 12, one for rod-plane with negative polarity (T_B=5 μs) and the other for rod-rod with air gap-factor equal to 1.22 (T_B=13 μs) with positive polarity, both cases for 1 m gap and waveform No. 2. Moreover, several results for other insulating materials, like oil and SF6 [17, 23], were also included in the analysis.

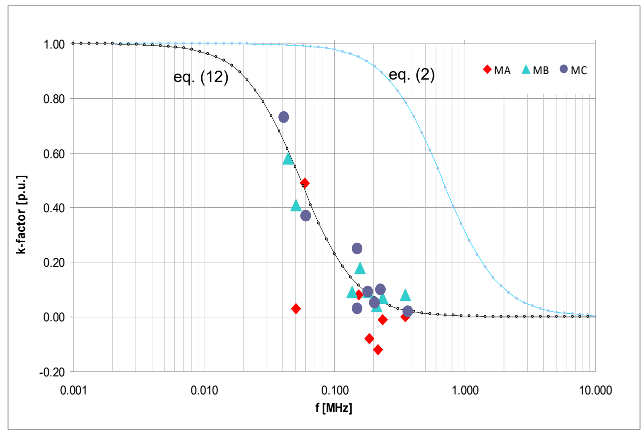


Figure 12. k-factors calculated with the methods described in Section 2.2. Air gap: 1 m rod-plane.

In [16, 20] the authors did not provide the measured times-to-breakdown for each k-factor, but for the configurations with gap-factors (1 and 1.45) the breakdown times were estimated from the literature [14, 25]. In order to obtain a generic expression for the test voltage function, depending only on the oscillation frequency and average breakdown time, the available data were drawn in Figure 13. This figure shows the behavior of the function τ (T_B) with the average time-to-breakdown T_B for $U_{50\%}$ expressed in μs.

The analysis of the situations previously mentioned is interesting because it confirms the physical approach adopted for the k-factor, showing that it is a relative parameter that depends fundamentally on the time-to-breakdown for overshoots lower than 20%.

Figure 13 was drawn using the k-factors published by some authors [4, 16, 17, 18 19, 23, 24]. The data were interpolated with the family of test voltage functions shown in Figure 14.

It should be remarked that the values of τ (T_B) lower than 6 correspond to small gaps of different insulating materials, as shown in [4, 23], and to metric air gaps and negative polarity voltage [19]. Intermediate τ (T_B) values between 6 and 150 are related to metric gaps and air-gap factors greater than 1. The highest τ (T_B) values correspond to rod-plane and large air-gaps with positive voltage. The saturation effect observed matches the experimental limit of T_B noted in [14].

Consequently, the voltage test factor for several insulations can be generalized by a single equation as:

$$k(f) = \frac{1}{1+\tau(T_B).f^2} \quad (13)$$

This function, linking T_B with τ, was calculated by fitting the values of Figure 13 with the hyperbolic tangent function (14).

$$\tau(T_B) = \frac{1}{(-0.235.\tanh(0.3.T_B - 2.2) + 0.238)} \quad (14)$$

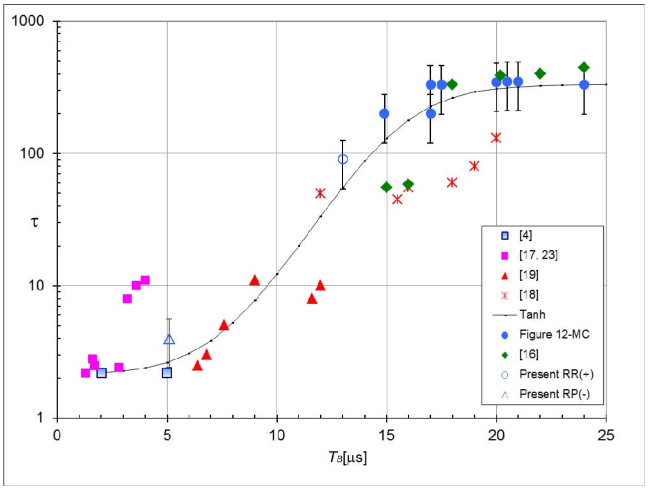


Figure 13. Experimental data and proposed τ *(T_B)* function.

Consequently, if the time-to-breakdown of any insulation submitted to distorted lightning impulses is known, it should be possible to calculate the $\tau(T_B)$ value and the corresponding test voltage function in order to evaluate the parameters of the equivalent lightning impulse in h-v test techniques.

Note that the application of method C or A for calculating the base curve leads to differences in the overshoot evaluation lower than 40%. If the relative overshoot β´ is lower than 10%, the affectation of the test voltage crest will be less than 4%. Considering this reduced effect, method C could be adopted for all cases, i.e. for all breakdown times.

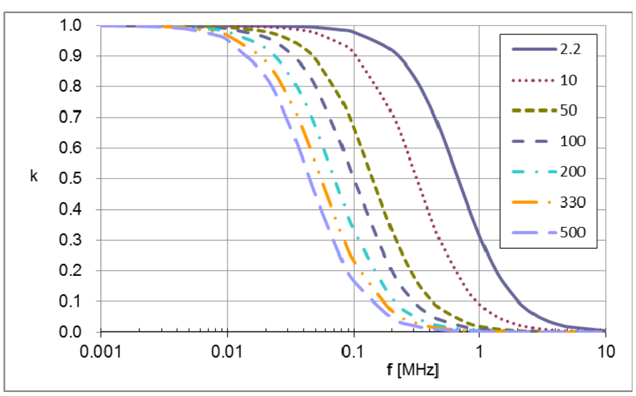


Figure 14. Calculated test voltage functions with $\tau(T_B)$ as a parameter.

6 CONCLUSIONS

In rod-plane air gaps submitted to lightning impulses of positive polarity at $U_{50\%}$ level the individual times-to-breakdown lie between 10 and 30 µs and so, the influence of tail voltages on discharge is greater than the overshoot values. Breakdown or withstand depends on leader progression controlled by the tail voltage and the excess field in the streamer zone.

External insulations of metric distances with non-uniform electric fields and gap factors [14] close to unity, present long times-to-breakdown. Thus the evaluation of lightning impulse parameters with oscillations or overshoots should include a new k-factor, as expressed by equation (12). This function differs from that proposed in [2, 3] because the effects of oscillations and overshoots on the dielectric stress are lower than those prescribed by standards.

The opposite happens in external insulations submitted to LI of negative polarity. The times-to-breakdown are shorter (< 10 µs) and the influence of overshoots is higher than that of tail voltage. In this case, the k-factor proposed by standards [2, 3] seems satisfactory. The same situation occurs in insulations with prevalence of convergent fields, i.e. with gap factors approaching 1.5 and short times-to-breakdown.

A general expression for the test voltage function has been proposed considering the mechanism of breakdown. This expression is a function only of the time-to-breakdown and the equivalent frequency of oscillation. This k-factor could be applied to any gap configuration and voltage polarity. In principle, comparing the experimental results published by other authors, the generalized test voltage function works well with various insulating materials, such as air, oil and SF6.

A disadvantage of the proposed approach is its limitation when applied onto non self-recoverable insulations by the need for previous knowledge or estimation of the time-to-breakdown. But this type of insulation is often associated with short times-to-breakdown (<10 µs) and the standard test voltage function seems to be satisfactory.

The potential extension of this approach to non-conventional lightning impulses of very short tail times (e.g. 1/5 µs), also considering overstressed insulations and short gaps would be very useful, but additional investigations are required.

ACKNOWLEDGMENT

This work was supported in part by the National Scientific and Technical Research Council (CONICET) of Argentina.

REFERENCES

[1] IEC 60060-1 Ed.2, "High-voltage test techniques-Part 1: General definitions and test requirements", 1989.

[2] IEC 60060-1 Ed.3, "High-voltage test techniques-Part 1: General definitions and test requirements", 2010.

[3] IEEE Std. 4, IEEE Standard Techniques for High-Voltage Testing, 2013.

[4] F. Garnacho, E. Gockenbach, S. Benda, P. Simón, K. Hackemack and P. Werle, "New proposal for evaluation of lightning impulses based on experimental research. Revision of the IEC60060-1 and IEC 61083-2", Electra Paper, No. 204, pp. 30-39, 2002.

[5] J. Hällström, A. Bergman, Ding, F. Garnacho, R. Gobbo, T. Kato, Y. Li, A. Nilsson, G. Pesavento, S. Sato and A. X. Yu, "International comparison of software for calculation of lightning impulse parameters based on a new processing algorithm", 15th Int'l. Sympos. High Voltage, Paper No. T10-539, 2007.

[6] M. Hinow, W. Hauschild and E. Gockenbach, "Lightning Impulse Voltage and Overshoot Evaluation Proposed in Drafts of IEC 60060-1

and Future UHV Testing", IEEE Trans. Dielectr. Electr. Insul., Vol. 17, No. 5, pp. 1628-1634, 2010.

[7] S. Okabe, T. Tsuboi, G. Ueta, J. Takami and H. Hirose, "Basic Study of Fitting Method for Base Curve Extraction in Lightning Impulse Test Techniques", IEEE, Trans. Dielectr. Electr. Insul., Vol. 17, pp. 2-4, 2010.

[8] G. Ueta, T. Tsuboi and S. Okabe, "Evaluation of Overshoot Rate of Lightning Impulse Withstand Voltage Test Waveform Based on New Base Curve Fitting Methods - Study on Overshoot Waveform in an Actual Test Circuit". IEEE Trans. Dielectr. Electr. Insul., Vol. 18, No. 3, pp.783-791, 2011.

[9] G. Ueta, T. Tsuboi and S. Okabe, "Evaluation of Overshoot Rate of Lightning Impulse Withstand Voltage Test Waveform Based on New Base Curve Fitting Methods- Application to Practical Diverse Waveforms", IEEE Trans. Dielectr. Electr. Insul., Vol. 19, No. 1, pp. 352-362, 2012.

[10] A. Segovia and R. Diaz, "Calculating Experimental Values of the Test Voltage Factor in Non-Uniform Air-Gap", IWD 391, CIGRE WG D1.35/36 Meeting, Kista, Sept. 2012.

[11] R. Diaz and A. Segovia, "Humidity corrections and front time tolerance for lightning impulse voltages in metric air gap", 18th Int'l. Sympos. High-Voltage Eng., paper PC-02, Korea, 2013.

[12] B. Hutzler and J. Gibert, "Breakdown characteristics of air insulations exposed to short tailed lightning impulses", Int´l. Conf. on Lightning and Power Systems, IEE Conf., London, UK, Pub. No. 236, pp.158-162, 1984.

[13] G. Baldo and G. Pesavento, "Leader propagation under lightning overvoltages with different gap lengths". 4th Int'l. Sympos. High-Voltage Eng., Paper No. 42.05, Athens, 1983.

[14] A. Pigini, G. Rizzi, E. Garbagnati, A. Porrino, G. Baldo and G. Pesavento, "Performance of large air gaps under lightning overvoltages: experimental study and analysis of accuracy of predetermination methods", IEEE Trans. Power Delivery, Vol. 4, No. 2, pp. 1379-1392, 1989.

[15] B. Phelps and R. Griffiths, "Dependence of positive streamer propagation on air pressure and water vapor content", J. Appl. Phys. vol. 47, No.7, pp. 2929-2934, 1976.

[16] F. Garnacho, A. Khamlichi, A. Valladolid, P. Simon and M. Valcarcel, "k-factor Test Voltage Function for Oscillating Lightning Impulses in Nonhomogenous Air Gaps", IEEE Trans. Power Delivery, Vol. 29, No. 5, pp. 2554-2260, 2014.

[17] S. Okabe, T. Tsuboi and G. Ueta,"Comprehensive Evaluation of the K-factor Values in the Lightning Impulse Voltage Test Techniques for UHV-class Electric Power Equipment", IEEE Trans. Dielectr. Electr. Insul., Vol. 19, No. 3, pp. 812-820, 2012.

[18] G. Ueta, T. Tsuboi, S. Okabe, Y. Shimizu and E. Hino, "K-factor Value and Front Time Related Characteristics of UHV-class Air Insulation for Positive Polarity Lightning Impulse Test", IEEE Trans. Dielectr. Electr. Insul., Vol. 19, No. 3, pp. 877-885, 2012.

[19] T. Tsuboi, G. Ueta, S. Okabe, Y. Shimizu, T. Ishikura and E. Hino, "K-Factor Value and Front-Time-Related Characteristics in Negative Polarity Lightning Impulse Test for UHV-Class Air Insulation", IEEE Trans. Power Delivery, Vol. 28, No. 2, pp. 1148-1155, 2013.

[20] F. Garnacho, A. Khamlichi, A. Valladolid, P. Simon and R. Guirado, "Procedures to Determine k-Factor Function for Air Gaps", IEEE Trans. Power Delivery, Vol. 28, No. 2, pp. 686-692, 2013.

[21] R. Gobbo and G. Pesavento, "Application of the k-Factor Approach to Laboratory Tests", 16th Int'l. Sympos. High-Voltage Eng., Paper A9, Johannesburg, 2009.

[22] L. Paris, "Influence of air gaps characteristics on line to ground switching surges", IEEE Trans. Power App. Syst., Vol. 86, No. 8, pp. 936-947, 1967.

[23] T. Tsuboi, G. Ueta, S. Okabe, Y. Shimizu and K. Inami, "K-factor Value of SF6 Gas Gap under Non-homogeneous Electric Field for UHV-class Gas-Insulated Switchgear", IEEE Tran. Dielectr. Electr. Insul., Vol. 21, No. 3, pp. 988- 994, 2014.

[24] A. Segovia and R. Diaz, "Contribution to evaluating lightning-impulse voltage parameters with superimposed overshoot in air gaps", 19th Int'l. Sympos. High-Voltage Eng., Paper 109, Pilsen, 2015.

[25] T. Suzuki and K. Miyake, "Experimental study of breakdown voltage-time characteristics of large air gaps with lightning impulses", IEEE Trans. Power App. Syst., Vol. 96, No. 1, pp. 227-233, 1977.

[26] A.F. Rohlfs and H.E. Fiegel, "Impulse Flashover Characteristics or Long Strings of Suspension Insulators", Trans. AIEE, Vol. 76, pp. 1321-1329, 1957.

[27] M. Darveniza, F. Popolansky and E.Whitehead, "Lightning Protection of UHV Transmission Lines", Electra, No. 41, pp. 39-68, 1975.

[28] R. L. Witzke and T. J. Bliss, "Surge protection of cable connected equipment". Trans. Amer. Inst. Electr. Eng., Vol. 69, pt. I, pp. 527-542, 1950.

[29] M. Darveniza and A.E. Vlastos, "The Generalized Integration Method for Predicting Impulse Volt-Time Characteristics for non- Standard Wave Shapes - a Theoretical Basis", IEEE Trans. Electr. Insul., Vol. 23, No. 3, pp. 373-381, 1988.

[30] I. Gallimberti, "The mechanism of the long spark formation", J. de Physique, Supp. No.7,T No.40, pp. C7 193, 1979.

Ricardo R. Diaz (M'88–SM'02) was born in Argentina in 1955. He received the engineer degree in electrical engineering from the National University of Tucuman, Argentina, and the doctorate degree in high voltage engineering from the University of Padua, Italy. He was with the Direction des Etudes et Recherches of Electricité de France and Les Renardières Group between 1983 and 1985, and with the University of Pau, France, between 1986 and 1988. He is with the National Scientific and Technical Research Council (CONICET) of Argentina since 1991 and a member of CIGRE and IEEE. Currently, he is full professor at the National University of Tucuman and director of the Institute of High Voltage and Power Transmission at this university. His main research activities are electrical discharges, electrical insulations, h-v measurements and testing.

Adan A. Segovia was born in Argentina in 1982. He received the engineering degree in electrical engineering from the National University of Tucuman, Argentina, in 2010. Between 2010 and 2014 he was with the Institute of high voltage and power transmission of Tucuman University as a graduate student with a grant of CONICET. Currently, he is with Ledesma S.A.A.I., an agro-industrial company in Jujuy, Argentina, where he is mainly engaged with the supply of electric power. His main fields of interest are electrical measurements and testing in power systems.