Dielectric Fundaments of k-Factor Function to Determine the Test Voltage of Lightning Impulses with Overshoot Used in the IEC 60060-1 and IEEE 4 Standards

Tomás García, Abderrahim Khamlichi, Fernando Garnacho, and Fernando Álvarez

***Abstract*--The IEC 60060-1 (2010) and IEEE 4 (2013) Standards establish the k-factor function to determine the test voltage value of lightning impulses (LI) with superimposed oscillations. The test voltage function is included in these Standards to enable a more accurate and consistent determination of the test voltage and the time parameters, of LI with superimposed oscillations of any frequency content. The experimental k-factor function was determined by five research European institutes, but no dielectric fundaments were given to justify the k-factor function. This paper presents a specific study that was performed to validate the k-factor approach by checking its compatibility with the disruptive physic phenomenon. The same testing data used for determining the k-factor function for the air dielectric medium were used to determine the disruptive effect area model proposed by Kind in 1958. The results obtained ratify the compatibility between the k-factor function and the disruptive effect area model. The results presented in this paper are considered a valuable information for future research related to the test voltage k-factor function to improve the current International Standards.**

***Index Terms*--High-voltage techniques, impulse testing, lightning protection, insulation testing, electric breakdown, flashover, breakdown voltage, disruptive effect.**

I. INTRODUCTION

THE current IEEE 4 2013 [1] and IEC 60060-1 2010 [2] Standards include the k-factor function that was determined by experimental results obtained in a European Project [3]. The tests were carried out mainly by five research institutes (Schering, KEMA, NGC, Graz University and LCOE). The k-factor function (1) determines the peak value of the equivalent 1.2/50 µs smooth LI, that provokes the same dielectric stress as a LI with overshoot (see "Fig. 1"). The test voltage function takes the following form.

$$k(f) = \frac{1}{1 + 2.2f^2} \qquad (1)$$

where *k* is the k-factor and *f* the oscillation frequency. This equation is used to calculate the effective peak voltage of the lightning impulse as a function of the frequency of the overshoot, where *f* is the frequency in MHz.

The introduction of this voltage function in the last edition of the standards [4] removes the drawbacks related to the stepwise change of 500 kHz frequency introduced in old IEC 60060-1 Standard edition (1989), by using a smooth transition through the mathematic function shown above (1).

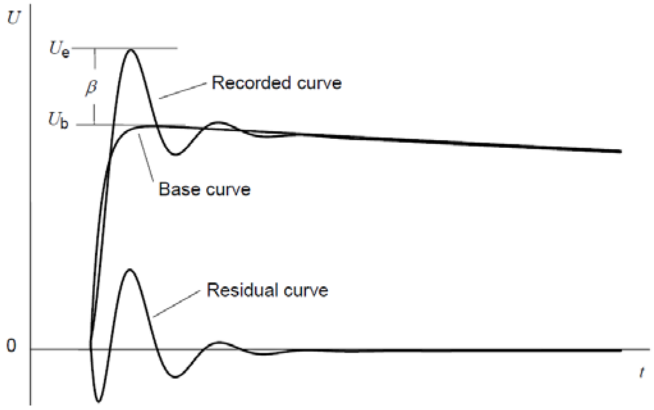

Fig. 1. Base curve, recorded curve, and residual curve. Parameters V_e, V_{mp} and β associated with a *LI* with superimposed oscillations stated in IEC 60060-1 and IEEE 4 Standards.

The defined test voltage function and the standardized procedure allow the determination of test voltage of LIs with an overshoot amplitude up to 10%.

In the current research a specific study of the compatibility between the k-factor approach and the disruptive effect area model is performed. In section II the k-factor method and its basic concepts are described. Section III is dedicated to the study of the compatibility between the k-factor method and the disruptive effect area model in air media. Finally, in section IV the conclusions are presented.

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Further lightning impulse research as the one published in [5] to extend the conclusions to higher voltage levels are recommended.

II. K-FACTOR METHOD AND BASIC CONCEPTS

The test voltage k-factor function of an electrical configuration is the empirical function that best represents the insulation behavior when LI with superimposed oscillations on the crest are applied to different insulation media (see Figure 1). By means of the k-factor function, the dielectric equivalence between the actual LI applied and a smooth LI 1.2/50 µs composed by two exponential functions is established.

Annex A of IEEE 4 [1] and Annex B of IEC 60060-1 [2] standards include the procedure for calculating the main parameters of a LI voltage with a superimposed oscillation on the peak.

$$U_t = U_b + k \times \beta \qquad (2)$$

where β is the overshoot magnitude, U_e the peak value of the recorded LI and U_b the peak value of the base curve.

Equation (2) describes an effective test voltage value, Ut, that the insulation would be subjected, under a LI voltage with an overshoot magnitude, β. This test voltage value is used to determine the impulse parameters.

A base curve $U_m(t)$ is first constructed from the part of the recorded curve above the 20% of peak value U_e on the impulse front and 40% of U_e on the impulse tail, by fitting a mathematic model composed by the subtraction of two exponential functions. The resulting curve obtained as the subtraction between the original applied lightning impulse $u(t)$ and the base curve $U_m(t)$ is called residual curve $R(t)$.

The oscillatory components, the residual curve $R(t)$, is then filtered by a frequency filter with a transfer function $H(f)$ equal to that defined by the test voltage function $k(f)$ to become $R_f(t)$, before being added back to the base curve $\mathrm{U_m(t)}$ to achieve the test voltage curve $U_t(t)$.

The procedure for calculation from the digital waveforms included in the Standards, allows the determination of the test voltage value U_t and the values of the front time T_1 and the time to half-value T_2 from the processed waveform $U_t(t)$.

The relative overshoot amplitude expressed as a percentage, β' (%), is determined from the relative difference between the peak value U_e of the recorded curve and the peak value of the base curve U_m.

The IEC 60060-1 Standard [2] assumes that the test voltage k-factor function depends mainly on the frequency of the oscillations.

In "Fig. 2" it is shown the standard k-factor function, as a unique curve that represents the average behavior for four dielectric media: air, SF6, XLPE and oil [6]. In this figure the experimental points corresponding to each dielectric medium and homogeneous or non-homogeneous field are marked with a different color.

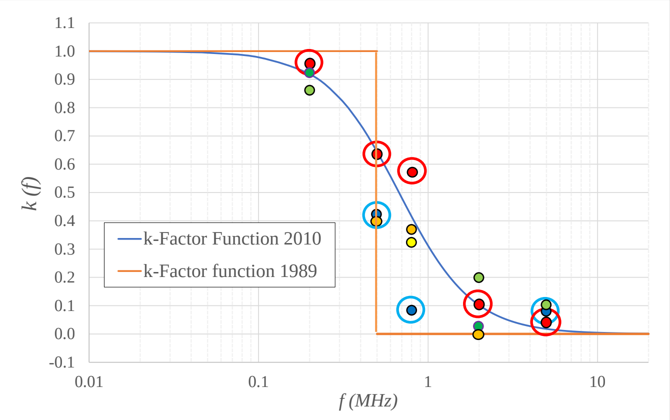


Fig. 2. Standard k-factor function. Representative experimental points obtained in the European Project [3].

The red points show the results for air in homogeneous field, the blue points for air in non-homogeneous field, the green points for SF6 in non-homogeneous and homogeneous field, the yellow points for XLPE and the orange points for oil. Current test voltage function of IEC 60060-1 2010 [2] comparing with effective test voltage function of IEC 60060-1:1989.

For impulses without overshoot, the test voltage is directly the peak value of the recorded voltage curve, that has the form of a smooth lightning impulse without any superimposed oscillation.

Such curves are unaffected by the residual filter function and yield impulse parameters that are unaffected by the test voltage function. Different influencing parameters shall be considered when the experimental k-factor values are researched:

1) The dielectric medium, gap space and uniformity of the electric field which is defined by means of the air gap K factor.

2) The LI parameters (maximum voltage, polarity, oscillation damping, oscillation frequency and overvoltage amplitude).

3) The atmospheric local conditions as temperature, pressure, and relative humidity.

III. COMPATIBILITY BETWEEN THE K-FACTOR METHOD AND THE DISRUPTIVE EFFECT AREA MODEL FOR AIR MEDIA

The results of the disruptive effect (DE) area theory [7], corresponding to the data of the tests used to determine the k-factor curves for the air dielectric medium are presented in this section. The experimental data corresponding to air medium tests cells used in [6] are checked to verify if they meet the disruptive effect area model.

The scope is to analyze the physic phenomenon and the compatibility between the k-factor approach and the disruptive effect area model has been studied.

A. *The disruptive effect area model*

The disruptive model introduced by Kind in 1958 [7] was used in the research literature [8] to analyze the physic phenomenon of disruptive discharge. The disruptive effect is related to the time lag, t_{lag}, versus the overvoltage curves experimentally obtained for gases [9]. According to the DE model, applicable to all chopped wave impulses (chopped on the front or chopped on the tail), the breakdown instant is assumed to take place when the integral, DE, reaches a fixed value depending on the waveform and voltage polarity for a specific air gap. The DE is defined by means of the following equation (3).

$$DE = \int_{t_1}^{t_1+t_{lag}} [U(t) - U_s]^n \, dt \qquad (3)$$

Where if $n = 1$, *DE* is the area of the impulse over the U_s level (see “Fig. 3”). If the voltage *U(t)* does not overcome the U_s, the breakdown never occurs. The main practical problem for applying this criterion is to determine the U_s level, because this level is a characteristic value of each insulation configuration depending on the air gap and electric field.

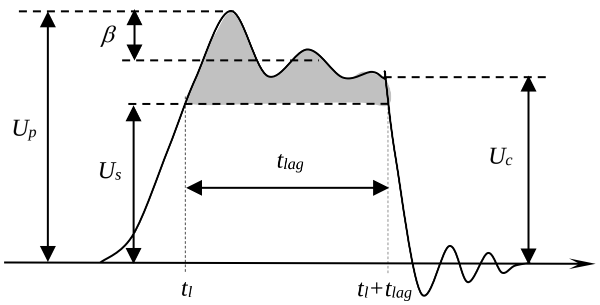


Fig. 3. Disruptive effect calculation. *DE* area over U_s voltage level.

The disruptive effect method should not change when the LI waveform changes in a specific range even when the peak value is too high, and the impulse is chopped at the front or at the crest zone, (see “Fig. 4”). Disruptive effect area has been checked for smooth LI and for LI with different overshoot amplitudes β and oscillation frequencies *f* as it will explain in section C.

B. Method to determine the U_s level

The U_s level can be determined for each test object with air insulation (homogenous and non-homogeneous field), by performing tests with chopped LI of different waveforms as showed in “Fig. 4”.

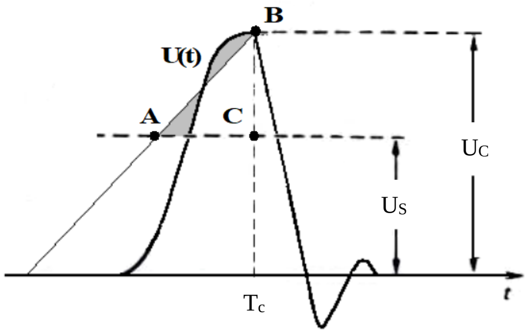


Fig. 4. Example of an impulse chopped on the peak. Equal areas criteria.

For chopped impulses, the straight line that satisfies the two following conditions can be defined.

- It must pass through the chopping instant B.
- The two shadowed areas in “Fig. 4” must be equal.

If the two previous conditions are satisfied, the disruptive area of the actual chopped impulse is the same as the area of the triangle *ABC*.

Assuming that the equal area model is satisfied (n=1), the following formula (4) can be established for the slope *S* of the straight line associated to each chopped impulse.

$$Area_{ABC} = \phi = \frac{(U_c - U_s)^2}{2S} \qquad (4)$$

Considering the area as a constant value for a specific test object or test setup, the previous equation can be expressed as:

$$U_c = U_s + C \cdot \sqrt{S} \qquad (5)$$

Where:

$$C = \sqrt{2\phi} \qquad (6)$$

By means of several points ($\sqrt{S}$, U_c) calculated by chopped impulses of different slopes, a regression straight line is calculated to determine the U_s level where U_s is the value of U_c for $S=0$.

This is an iterative procedure (see “Fig. 5”) because to determine the value of $\sqrt{S}$ it is necessary to choose an estimated U_s level and verify if the regression straight line cuts the U_c axis at the estimated U_s level. Sections C, D and E show two practical examples about this procedure.

In the first step of the iterative method, it is necessary to choose an initial estimated value for U_s to determine a set of pairs ($\sqrt{S_i}$, U_{ci}). A regression straight line using the ($\sqrt{S_i}$, U_{ci}) points is determined, which slope *C* is related to the best average area for the estimated value of U_s. The voltage U_c for S=0 is used as the new value of U_s’ in the next iteration.

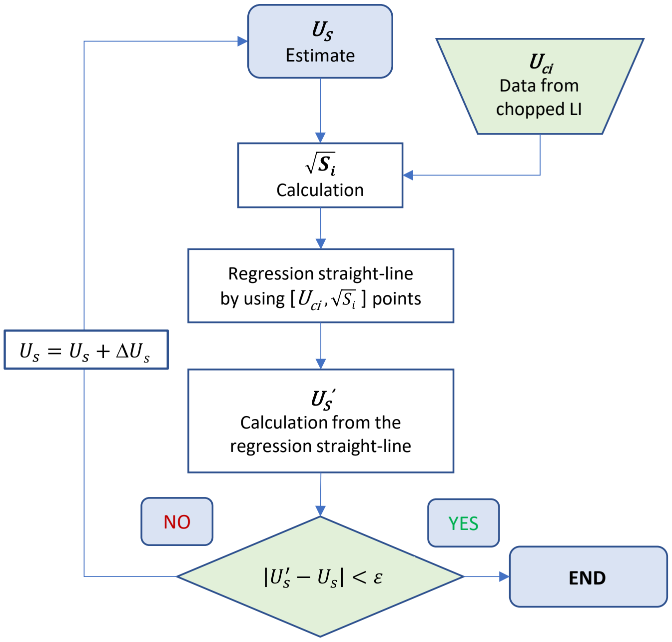


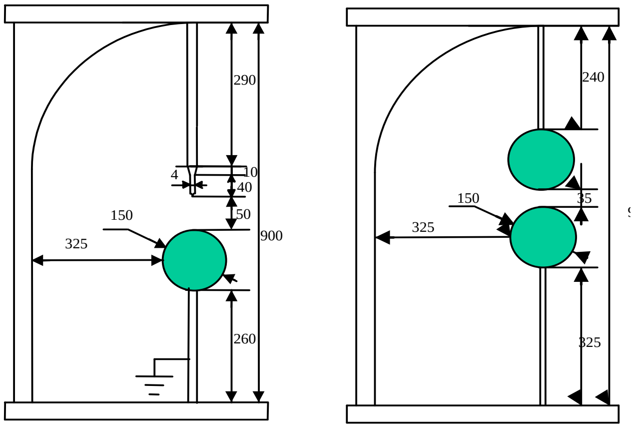
Fig. 5. Flowchart to determine the U_s level.

C. *Calculation of the Us level and the disruptive areas for four air gaps used in the standardized k-factor approach*

Four test cells of air dielectric medium were used to demonstrate the compatibility between the k-factor approach and the disruptive effect area. Two objects named medium voltage (MV) test cells with small air gaps (see “Fig. 6” and “Fig. 7”) were used. Two additional samples, named high voltage (HV) test cells, with bigger air gaps were also used for the analysis (see “Fig. 9” and “Fig. 10”). In both cases one test cell was designed for quasi-homogeneous field and the other one for non-homogeneous field.

For each test cell, different LI waveforms were applied.

- Front chopped LI from smooth impulses 1,2/50 µs.
- And full LI with superimposed oscillations of the following frequencies: 200 kHz, 500 kHz, 800 kHz, 2 MHz and 5 MHz and overshoot amplitudes of 5% and 20%.



(a) Non-homogeneous (b) Quasi-homogeneuos

Fig. 6. MV test cells for non-homogeneous field (a) and for quasi-homogeneous field (b). Drawings and dimensions.

The U_s level and the disruptive area were determined for the four test cells. For the quasi-homogeneous test cells the chopping instants were close to the peak value and for the non-homogeneous test cells the chopping instants occurred after the peak value. In the following development the equal disruptive effect area is determined for each test cell.

Fig. 7. Picture of the MV test cell for the quasi-homogeneous field.

D. *Test results for MV test cells*

For both MV test cells of “Fig. 6”, few hundreds of lightning impulses (LI) with oscillations were applied, 243 for non-homogeneous field and 310 for quasi-homogeneous field test cell and additionally 50 front chopped impulses 1.2 / 50 µs were applied, ten impulses per voltage level at five different voltage levels. Table I shows the number of applied impulses series for each MV test cell.

TABLE I

Applied Impulses on MV Test Cells

Cell	Field type	Impulses with oscillations	Front chopped impulses
MV	Quasi-homogeneous field +	310	10 × 5 series
	Non-homogeneous field +	243	10 × 5 series

Based on the set of points (T_c, U_c) corresponding to the front chopped LI and LI with superimposed oscillations, the associated U_s level of each MV test cell was determined by means of the iterative process described in the flowchart shown in “Fig. 5”.

Using the first estimated Us value, the real area enclosed by each LI of the test up to the instant *t* equal to *Tc* is determined by means of the following equation (7).

$$\phi = \int_{t(U_s)}^{T_c} [u(t) - U_s] \cdot dt \qquad (7)$$

In practice the area is determined applying the trapezoidal rule using the recording samples of each LI that are above the Us level up to the instant *t*=*Tc*. The average value of the disruptive areas ϕ_i of each test is then determined and the $\sqrt{S_i}$ value for this test is calculated by means formula (8) using the average values U_{ci} and ϕ_i of the tests.

$$\sqrt{S_i} = \frac{(U_{ci} - U_s)}{\sqrt{2 \cdot \emptyset_i}} \qquad (8)$$

Points ($\sqrt{S_i}$, U_{ci}) related to all performed tests, smooth LI and LI with superimposed oscillations, are calculated applying the same procedure.

The straight line is then fitted applying the least squares method to all points ($\sqrt{S}$, U_c). The intersection of the straight line with the “*y axis*” is determined to obtain a new value of U_s'. This procedure is repeated up to the difference between the initial value of U_s and U_s' is lower than 1 %.

The straight lines showed in “Fig. 8” fitted to the set of experimental points ($\sqrt{S}$, U_c) derived from the performed tests gave a very good concordance with the equal disruptive area model.

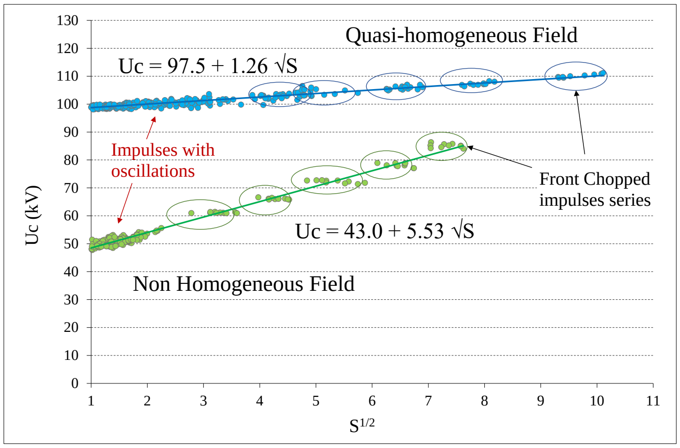


Fig. 8. Applied impulses and determination of the Us level for the MV cells of quasi-homogenous field and non–homogenous field with positive polarity.

Using the U_s level, the equal disruptive effect area was verified for the applied smooth LI of 1.2/50 µs with different slopes and for several LI with superimposed oscillations of 200 kHz, 500 kHz, 800 kHz, 2 MHz and 5 MHz frequencies and overshoot amplitudes of 5% and 20%. Test results are shown in Table II, obtaining U_s voltage level of 100 kV for quasi-homogeneous field and around 45 kV for non-homogeneous field test setup and in Table III, showing the calculated disruptive area for LI with superimposed oscillations.

TABLE II
Disruptive Area Calculation for MV Test Cells

Cell	Field type	Gap (mm)	U_S (kV)	ϕ (kV·µs)
MV	Quasi-homogeneous field +	35	97.5	0.80
	Non-homogeneous field +	50	43.0	15.28

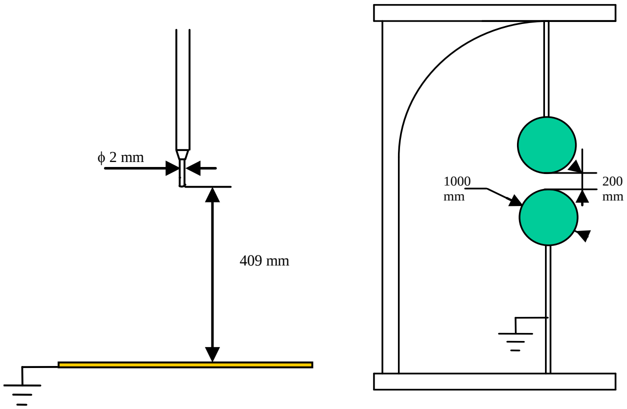
TABLE III
Disruptive Area Calculation for LI with oscillations

U_S (kV)	Field type	f (MHz)	ϕ (kV·µs)
97.5	Quasi-homogeneous field + Gap = 35 mm	0.2	0.45 ± 0.13
		0.5	0.67 ± 0.28
		0.8	0.73 ± 0.18
		2.0	0.88 ± 0.21
		5.0	1.19 ± 0.41
43.0	Non-homogeneous field + Gap = 50 mm	0.2	12.15 ± 2.7
		0.5	15.27 ± 3.0
		0.8	18.66 ± 6.9
		2.0	16.38 ± 3.0
		5.0	17.04 ± 4.3

E. Test results for HV test cells

A similar testing procedure was applied for the HV test cells corresponding to the 500 kV setup for quasi-homogenous field (air gap 200 mm) and 170 kV setup non-homogenous field (air gap 409 mm) (see “Fig. 9”).

Smooth impulses and impulses with different oscillation frequencies, 200 kHz and 800 kHz for quasi-homogenous field, and 200 kHz with two different damping oscillations for non-homogenous field were applied. In both cases overvoltage amplitudes β up to around 20 % were achieved.



(a) Non-homogeneous (b) Quasi-homogeneuos

Fig. 9. HV test cells for non-homogeneous field (a) and for quasi-homogeneous field (b). Drawings and dimensions.

For the quasi-homogenous field and non-homogenous~~-~~field, more than 120 impulses were applied to determine the U_s level. The straight lines fitting to the set of points ($\sqrt{S}$, U_c) for the high voltage test cells are shown in “Fig. 10” and “Fig. 11”.

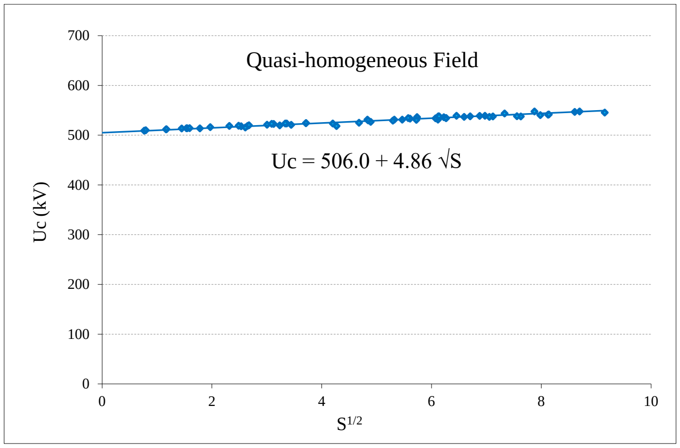


Fig. 10. Applied impulses and determination of the Us level for the HV cell of quasi-homogenous field and positive polarity.

The test results carried out for the k-factor approach on the studied high voltage tests cells for quasi-homogenous and non-homogenous fields up to voltages of 170 kV and 500 kV, were analyzed considering the disruptive effect area criteria.

The calculated disruptive area ϕ ($Area_{ABC}$) for each test cell is shown in Table IV and it was determined from the slope C of each fitted straight line, according to (5) and (6).

TABLE IV
Disruptive Area Calculation for HV Test Cells

Cell	Field type	Gap (mm)	U_S (kV)	ϕ (kV·µs)
HV	Quasi-homogeneous field +	200	506.0	11.82
	Non-homogeneous field +	409	170.0	370.3

A good fitting to the disruptive effect model was found for the used LI waveforms to determine the k-factor approach on both HV test cells.

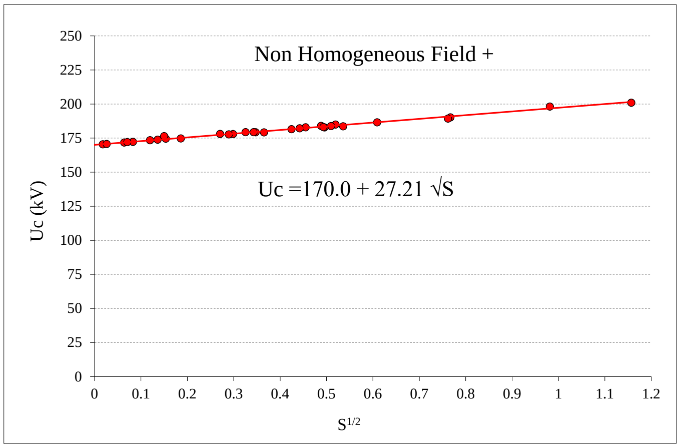


Fig. 11. Applied impulses and determination of the Us level for the HV cell of non–homogenous field and positive polarity.

IV. Discussion

An iterative procedure to determine the disruptive effect area is presented in this paper using booth smooth LI chopped on the peak and the set of LI used for the k-factor approach.

The physical phenomena of the dielectric breakdown behavior of various tests cells with air dielectric medium was analyzed comparing the tests used to determine the k-factor function with the disruptive effect area model.

A very good fitting to the disruptive effect model was found for the LI waveforms used to determine the k-factor function on both medium-voltage and high-voltage test cells for quasi-homogeneous and non-homogeneous fields.

For the oscillation frequency range from 200 kHz to 2 MHz and overshoot amplitudes β up to 20 %, test voltages up to 500 kV in homogenous field and up to 170 kV in non-homogenous field, the disruptive effect model was satisfied for the test cells used to determine the k-factor function.

V. Conclusions

The results of the research carried out demonstrate that the k-factor function introduced in the International Standards IEEE 4 and IEC 60060-1 and determined by the experimental results of the European Project is fully compatible with the disruptive effect model for the dielectric medium air and lightning impulses with oscillations for air gaps up to 200 mm for quasi-homogeneous field and air gaps up to 400 mm for non-homogeneous field.

The procedure presented in this paper to check the compatibility between the k-factor approach and the disruptive effect area model should be used for next research. MV test cells were more extensively analyzed than HV cells and further research as the ones published in [10] are recommended to extend the conclusions to higher voltage levels.

VI. References

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VII. Biographies

Tomás García was born in Madrid, Spain on November 2, 1981. He received the Industrial Engineering degree from the Polytechnic University of Madrid (UPM), Madrid, Spain, in 2007. Currently, he is the technical responsible for testing and calibration of the high voltage laboratory of LCOE High Voltage Technological Center from the Foundation of the Industrial Promotion FFII. Mr. García is a member of the Technical Committees TC42 "High Voltage Testing Techniques" and TC38 "Instrument Transformers" of the Spanish Standardization Institute AENOR, member of several IEC working groups for high voltage products and is a member of the technical committee of AELP "Asociación Española de Laboratorios de Potencia".

Abderrahim Khamlichi received the electrical engineering degree from the Polytechnic University of Madrid (UPM), Madrid, Spain, in 1999. Currently, he is the manager of R&D department and technical responsible of current impulses laboratory of LCOE High Voltage Technological Center from the Foundation of the Industrial Promotion FFII. He is also an Educator in the Electrical Department, Technical High School of Engineering and Industrial Design, UPM.

Fernando Garnacho received the Ph.D. degree in electrical engineering from the Polytechnic University of Madrid (UPM), Madrid, Spain, in 1986. Currently, he is Professor of the Electrical Department, Technical High School of Engineering and Industrial Design, belonging to the Polytechnic University of Madrid, Madrid. He has been the Director of High Voltage Technological Center of Laboratorio Central Oficial Electrotecnia (LCOE) from the Foundation of the Industrial Promotion (FFII) from 1984 to 2019. Dr. Garnacho is Chairman of the Technical Committee 42 “High Voltage Testing Techniques” of the Spanish Standardization Institute AENOR.

Fernando Álvarez received the M.Sc. degree in technical electrical engineering and in industrial electrical engineering from the Polytechnic University of Madrid (UPM), Madrid, Spain, and from the University Carlos III of Madrid, Madrid, Spain in 1999 and 2008, respectively. In 2015, he received the Ph.D. degree in electrical engineering from the UPM. His doctoral thesis was developed in the High-Voltage Test Laboratory LAT-UPM. Since 2004, he has been an Associate Professor with the Department of Electrical Engineering, UPM. He has participated in several research projects related with HV electrical insulation diagnosis. His main research interests include high voltage insulating materials and partial discharge measurements.