Evaluation of Lightning Impulse Voltages Superimposed with Oscillations and Overshoot using the Test Voltage Function

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Abstract*: *The frequency and amplitude of the superimposed oscillations or overshoot near the peak in Lighting Impulse (LI) voltage have an influence on the 50% Break-Down Voltage (BDV). The evaluation of test voltage incorporating frequency dependent test voltage function known as k-factor which takes the physical breakdown behaviour of the different dielectric materials. The paper presents two methods for implementation of k-factor and the complete procedure to evaluate the test voltage magnitude and time parameters of lightning impulse voltage waveform. The first method is based on mean curve approach using Double Exponential (DE) function whereas second method uses Single Exponential (SE) function fitting on the tail of the measured impulse. The standard IEC 61083-2 Test Data Generator (TDG) waveforms are used for evaluation and comparison of these methods.

***Keywords*: Lightning Impulse, Test voltage function, k-factor, mean curve, oscillations, and overshoot.**

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I. Introduction

High voltage power apparatus used in power system are designed for withstanding the different dielectric stresses viz. power frequency over voltage, very fast transients due to lightning impulse, and switching impulse etc. International standards like IEC 60060-1 [1, 2] and IEEE–4 [3] describes testing techniques to check the insulation dielectric design of high voltage power apparatus. The Lightning Impulse (LI) voltage test is one of the important type and routine test which normally done using typical 1.2/50μ*s* impulse waveform. It is necessary to check the shape and parameters of the measured lightning impulse before it is applied to the test object. The parameters of LI can be determined as per IEC-60060-1 [1] and IEC-61083-2 [4] standards if the measured impulse waveform is smooth. However, the difficulties arise when the oscillations or overshoot are superimposed on the peak of impulse voltage waveform. In such cases, the standards require to draw the mean curve to evaluate the test voltage (U_{test}) through the calculation the amplitude of overshoot (β) and frequency of the superimposed oscillation (f) or the corresponding duration of overshoot (τ). According to the standard, the amplitude of superimposed oscillations/ overshoot (β) should be less than 5% of peak of measured impulse. The estimated test voltage has dependency on frequency of oscillations (f) or the duration of overshoot (τ) of the superimposed impulses. If $f < 0.5MHz$ or $\tau > 1\mu s$, then the test voltage is the peak of measured impulse otherwise the test voltage is the peak value of the drawn mean curve. The standard IEC 60060-1:1989 do not contain the exact definitions for an automated construction of the mean curve. In this regards, many researchers have proposed and implemented different alternative methods for determination of the mean curve during recent years [5-10]. In addition, the stringent frequency limit of 0.5 MHz in the standards might cause deviations in the test results [11, 12]. This necessitates introducing the frequency dependent test voltage factor function called as *k*-factor for evaluation of measured impulse voltage [13]. The test voltage function is derived based on the breakdown behaviour of different dielectric media and type of field configurations [14]. A generalized expression for the test voltage function for the non-uniform air gap field configurations is also proposed [15]. The new *k*-factor function in LI test for UHV-class equipment has been proposed [16]. Since the evaluation procedure of lightning impulse employs the base curve and test voltage function [17] many researchers are involved for implementation of test voltage function.

In this paper, two methods using Double Exponential (DE) and Single Exponential (SE) functions for implementation of the test voltage factor to evaluate test voltage during lightning impulse tests are extensively analyzed and discussed. This paper is organized as follows. The basic principle, determination and implementation of *k*-factor are explained in section II. The evaluation procedure using DE and SE functions are detailed in section III and IV respectively. The

Section V gives the results and discussion with IEC 61083:1996 TDG waveforms. Finally the section VI concludes the paper.

II. Test Voltage Factor

A. Basic Principle

The experimental investigation [11,12] has shown that 50% breakdown voltage (BDV) of LI on different dielectrics materials i.e., air, oil, SF_6, PE and oil/paper depends on the frequency of superimposed oscillations or the corresponding duration of overshoot near the peak. Fig. 1 shows the influence of frequency of superimposed oscillations on the BDV [11]. The superimposed oscillations/overshoot with low frequencies have a strong influence on the BDV and in this case the test voltage is the peak of the measured curve called extreme value U_{extr}. The superimposed oscillations or overshoot with high frequencies have no strong influence on the BDV and in this case the test voltage is the peak of the mean curve U_{pmc} . Between the two extreme cases, the influence of superimposed oscillations/overshoot near the peak was found to be decreasing continuously with increasing frequency. Hence, the test voltage factor (k) is incorporated to evaluate BDV for these two extreme cases.

B. Determination of the test voltage factor

The evaluation criteria in the standard IEC-60060-1 for impulses with oscillation or an overshoot is expressed using the test voltage factor (k) which changes from 1 to 0 at a frequency 0.5MHz as shown by the dotted line in Fig. 2. The frequency behaviour of the test voltage factor *(k)* is not the same for all dielectrics. Taking into account this as well as the measurement uncertainty a reasonable fit of the *k*-factor is described as the linear regression line on a logarithmic scale as shown in Fig. 2. Mathematically, it is described by equation (1). The *k*-factor varies as smoother transition between the values 1 and 0 for frequency between 0.3MHz to 1.6MHz.

$$k = 1.0, f \le f_1$$
$$k = \frac{(\log f_2 - \log f)}{(\log f_2 - \log f_1)}, f_1 < f < f_2 \qquad (1)$$
$$k = 0, f \ge f_2$$

where $f_1 = 0.3MHz, f_2 = 1.6MHz$

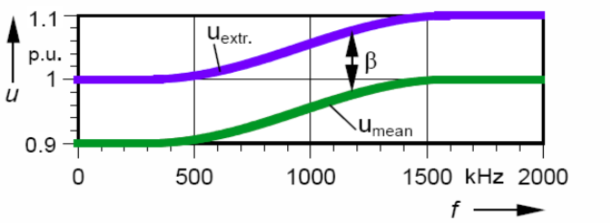

Fig. 1. Influence of the frequency of superimposed oscillations on the breakdown voltage [11].

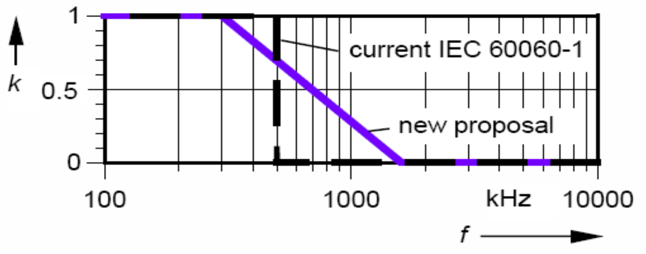

Fig. 2. Test voltage factor k as function of frequency [12].

C. Calculation of the test voltage

The actual test voltage can be evaluated using test voltage factor *k* and its value lies in between the extreme value of the measured impulse U_{extr} and the peak value of the mean curve U_{pmc} [12]. The test voltage using *k*-factor is calculated using the following equation (2) or (3).

$$U_{test} = U_{extr} - (1-k).\beta \qquad (2)$$

$$U_{test} = U_{pmc} + k.\beta \qquad (3)$$

$$\beta = U_{extr} - U_{pmc} \qquad (4)$$

where β is the amplitude of superimposed oscillations or an overshoot near peak of LI voltage waveform.

D. Implementation of the k-Factor

The method for determining the test voltage using k factor can be implemented in different ways [12-14]. The two important methods are '*global filtering approach'* and '*mean curve approach'*.

1) Global filtering approach

A moving window FIR filter is applied directly to the measured curve and filter transfer function is adjusted to equation (1). Then the test voltage is given by extreme value U_{extr} of the filtered curve. While applying this method the permitted value of $\beta < 10\%$ of $U_{extr.}$ However filtering the original impulses introduces unpredictable errors in the calculated test voltage. The front of the waveform gets heavily distorted, especially for fast front impulses. When the parameters are determined from the filtered waveform, this effect will lead to large increase of front time values compared with those evaluated from the original waveform. In addition to that this method needs to predetermine whether an overshoot exist or not.

2) Mean Curve approach

First a double exponential curve is fitted to the measured impulse and its peak value is calculated. Then the amplitude as well as frequency of the oscillations/ the corresponding overshoot is obtained. Finally the test voltage factor is calculated using equation (1). Alternatively only remaining residual is filtered and then filtered residual curve is superimposed back to the fitted DE curve. This method is complicated to implement, but in principle this matches better with the approach used in experimental study [13].

III. Evaluation Using Double Exponential Function

The determination of amplitude of oscillations or the corresponding overshoot β value require the mean curve and the mean curve should be calculated using model-based curve fitting [5]. The mean curve should follow a DE model because the empirical test voltage factor-*k* has been obtained by using DE function. The DE function should allow fitting around the crest from a fixed amplitude in the front to few microseconds after extreme value. Based on the experimental results, the maximum accepted β value should be 10% of the U_{extr} [12].

A. Determination of the mean curve

The standard LI voltage waveform using double exponential functions is represented by (5).

$$U(t) = A.(e^{-\alpha.t} - e^{-\beta.t}) \tag{5}$$

For normalized standard LI (1.2μs/50μs) characterized parameter values are:

$A = 1.0372$ p.u, $\alpha = 14659\ s^{-1}$, $\beta = 2468000\ s^{-1}$

Experiences from HV laboratories have shown that the initial rate of rise of a standard lightning impulse front is substantially lower than would be expected from the above equation. The slope of the analytical function has a finite and rather high value at the starting point. In physical circuits, however, the initial rate of rise of voltages is normally close to zero and an initial delay of the rising front section will usually occur. On the front and close to the peak value rather large deviations between the mean curve and measured data may occur. Hence the following DE function (6) describes a lightning impulse with a smoother start with start time t_0 used for determining the mean curve.

$$U(t) = A.(e^{-\alpha.(t-t_0)} - e^{-\beta.(t-t_0)}) \tag{6}$$

where $U(t)$ is the dependent function, A, α, β and t_0 are independent variables. The initial t_0 value is determined by extrapolating the line between 30% and 10% points to the measured impulse.

The Least Mean Square (LMS) error is used as quality criterion for fitting DE function and Levenberg-Marquardt iterative algorithm is used for solving non-linear equations [5, 9, 18]. Let the measured impulse data points be (t_i, x_i) for $i=1, 2, 3 \ldots n$, and the problem of fitting a model $U(t, y)$ is considered to the measured data where y is a vector of unknown parameters. The problem is to compute estimates of those parameters, which minimize the object function 'F' and is given by (7)

$$F = \sum_{i=1}^{n} [U(t)_{measured} - A.(e^{-\alpha.(t-t_0)} - e^{-\beta.(t-t_0)})]^2 = Min! \tag{7}$$

Minimization of F (α, β, t_0, A), was done by finding values of A, α, β and t_0. Take the partial derivatives of 'F' with respect to all the four parameters and equate them to zero. These nonlinear equations are solved using Levenberg-Marquardt iterative algorithm.

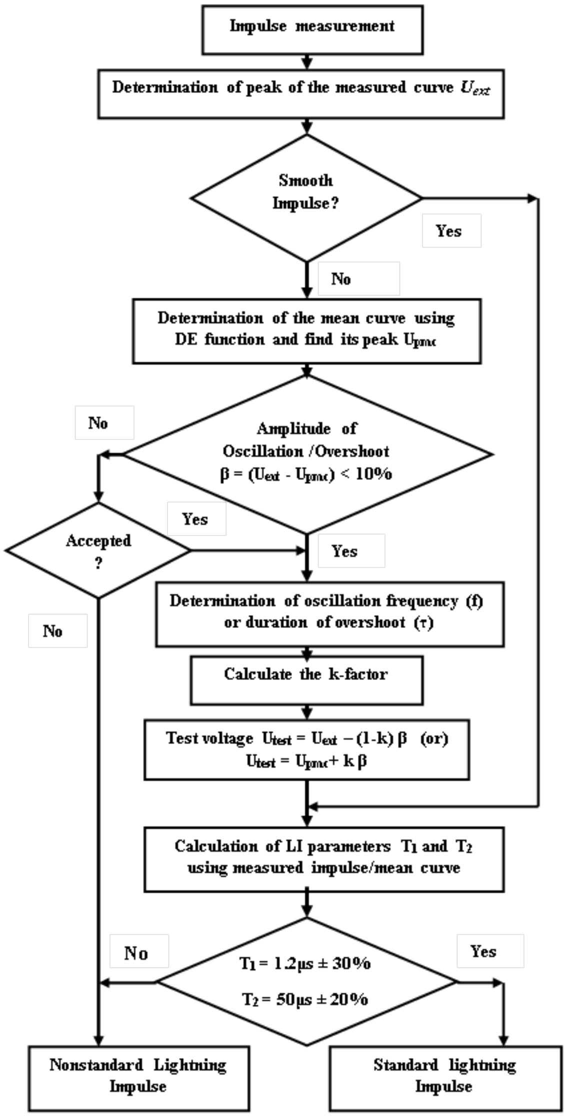

Fig.3. Evaluating of lightning impulses incorporating the test voltage factor using DE function

B. Determination of 'β', 'f' and 'τ'

The amplitude of superimposed oscillations or an overshoot near peak is calculated by (8). When the impulse has a unique frequency it can be determined manually as the time difference between two consecutive oscillations peak on the crest of the impulse waveform. The overshoot duration (τ) is determined from the point of intersection between the recorded impulse and the DE mean curve. Alternatively the frequency can be evaluated by applying FFT or FIR filter to the residual curve [8, 11-13].

$$\beta = U_{extr} - U_{pmc} \tag{8}$$

C. Determination of k-factor

Using the amplitude of the oscillation or the corresponding overshoot β and the extreme value of the measured impulse or the peak value of the mean curve, the test voltage factor is calculated using (1). Alternatively test voltage factor k is calculated by filtering residual curve using digital FIR filter [13].

D. Evaluation of U_{test}, T_1, T_2

The test voltage U_{test} is evaluated by using (2) or (3). The front time and tail time are calculated by using (9) and (10) respectively by considering the extreme value of a recorded impulse U_{extr} as 100% reference value or the calculated test voltage.

$$T_1 = 1.67.(t_{90} - t_{30}) \tag{9}$$

$$T_2 = (t_{50} - t_0) \tag{10}$$

where $t_0 = (t_{30} - 0.3T_1)$, It is the time at virtual zero and t_{90} and t_{30} are the times when the impulse first reaches 30% and 90% of its peak value. The t_{50} is the time when the impulse decays to 50% of its peak value. The complete procedure for evaluating of LI incorporating the test voltage factor using DE function is given in Fig.3.

IV. Evaluation Using Single Exponential Function

The calculation of test voltage using (2) or (3) is still require the mean curve for the determination of the oscillation amplitude β value. In order to avoid problems with the uncertain construction of a mean curve, an alternative methods were tested and compared. The method of single exponential function fitting on the tail [19, 20] can increase the test reproducibility. It is also possible to use this procedure for manual as well as for automated evaluation. Single exponential function that fits tail on the measured LI voltage is given by (11). The evaluation with SE function for the case # 9 of IEC 1083-2 waveform is illustrated in Fig.4.

$$U_t = A.(e^{(-\beta.(t-t_0))}) \tag{11}$$

$$\Delta U = (U_{extr} - U_{pvir}) \tag{12}$$

The virtual peak value is the intersection point (IP) between the single exponential function that fits the tail of the wave and the vertical straight line that passes through the extreme value of measured impulse. The amplitude of ΔU value is not an identical with the amplitude of β value but the deviation is found to be small. Also, the multiplication with the *k*-factor there are nearly no differences between the results evaluated with double exponential fitting of the tail.

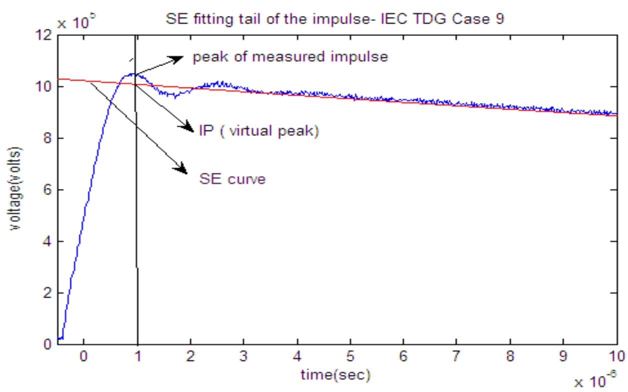

Fig. 4. Illustrates the evaluation with SE function fitting of the tail of impulse curve- Case No.9 -IEC 1083-2

A. Procedure for calculation of test voltage

1. By drawing or calculation of the tail exponential function and make decision if the impulse has an oscillation or overshoot.
2. Determination of the peak value of the measured impulse $U_{extr.}$
3. If there is no oscillation or overshoot exist the test voltage is equal to extreme value $U_{extr..}$
4. Determination of the voltage difference ΔU between the extreme value U_{extr} and virtual peak value $U_{p(vir)}$. If the difference ΔU is greater than 5% of U_{extr} then the LI is a non-standard impulse and the evaluation should be agreed upon between relevant parties.
5. Determination of the frequency of the oscillation or the corresponding duration of the overshoot.
6. Determination of the test voltage factor k value.
7. Calculation of the test voltage using following equation

$$U_{test} = U_{extr} - (1-k).\Delta U \tag{13}$$

B. Calculation of Time parameters T_1 and T_2

The basic level used for the calculation of 30%, 90% and 50% levels are based on the chosen value of U_{extr} or U_{test}. The front time (T_1) and tail time (T_2) are evaluated the equations (9) and (10) respectively.

V. Results and Discussion

The selected waveforms from IEC 61083-2:1996 Test Data Generator (TDG) used for analysis. The waveform specification and parameters i.e. test voltage, front time and tail time ranges are listed in Table 1.

TABLE I. IMPULSE PARAMETER RANGES QUOTED IN IEC 61083-2 :1996 WAVEFORMS

Case No. & Description	Peak Value U_P (MV)	Front Time T_1 (µs)	Tail Time T_2 (µs)
#3/8: LISO	1.04- 1.06	1.6 - 1.7	45 -49
#4/9: LIFA	0.96- 0.99	1.0 - 1.1	48- 49
#11: LIFO	0.94 - 0.96	1.07-1.19	82 - 91
#13: LILDO	-1.08 - -1.06	3.40 - 3.76	56-62
#14: LISDO	-0.97 - -0.95	1.85- 2.05	43- 47

LISO - LI with slow oscillations,
LIFA - LI with fast oscillations,
LIFO - LI with front oscillations,
LILDO - LI with long duration overshoot,
LISDO - LI with short duration overshoot

The procedure as given in Fig.3 is used for evaluation and analysis for DE function method. For all the case studies the

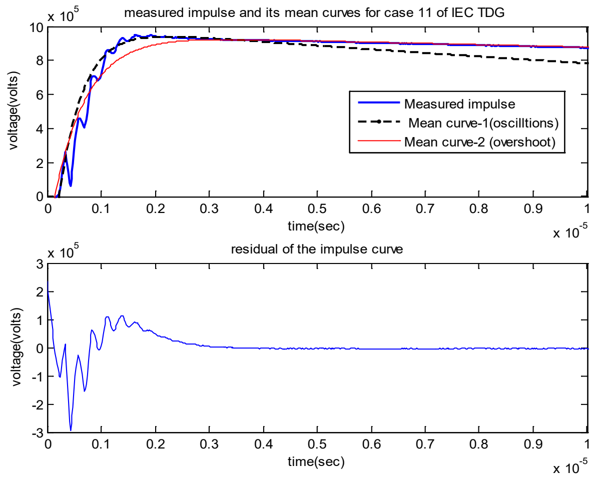

Fig. 5. Mean curve and residual curve of case No.11 of IEC 1083-2 using DE function

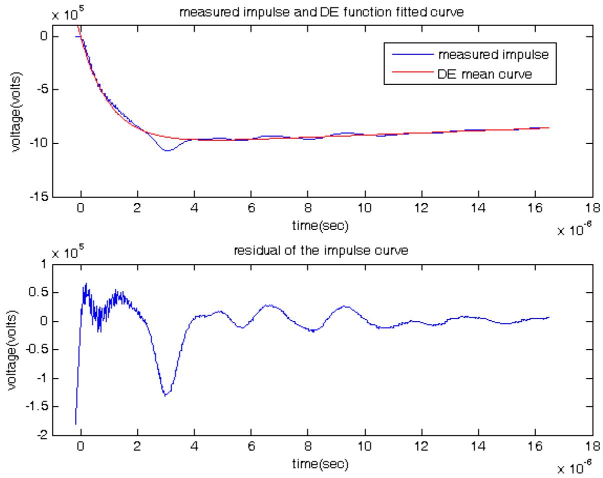

Fig. 6. Mean curve and residual curve of case No.13 of IEC 1083-2 using DE function

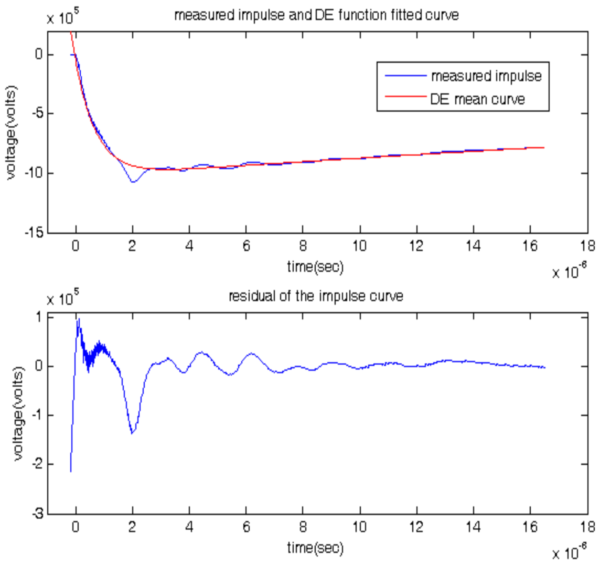

Fig. 7. Mean curve and residual curve of case No.14 of IEC 1083-2 using DE function

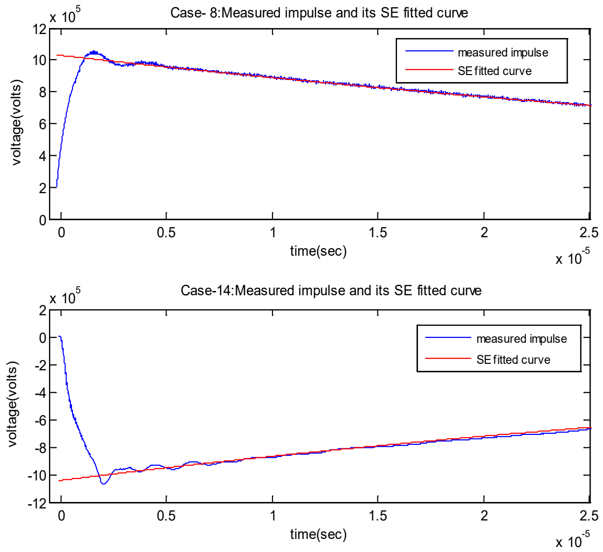

Fig. 8. Single exponential fitting on the tail of impulse waveform of case No.8 and No.14 of IEC 1083-2

standard impulse waveform constant 'α' and 'β' and the approximate peak voltage values are used as initial parameters. It is observed that 'α' and 't_0' have more influence for obtaining DE mean curve. Also 't_0' should not exceed 0.1μs otherwise it might cause distortion in the front region of the impulse especially in case #11 due to front oscillations. For LISDO of case #14, all the initial parameters have more deviations with respect to the values of standard one.

In SE function method, the peak voltage is found to have more influence in getting fitted curve. The peak values for all the considered cases are closer to the extreme value of measured impulse $U_{extr.}$. Especially, for case #13 peak voltage is very sensitive. The start time 't_0' is around 0.001μs. If the time t_0 is increased then the virtual peak decreases.

The obtained results for various cases of IEC TDG 1083-2 using DE and SE functions are given in Figs. 5 - 7 and Fig.8 respectively. Table II and Table III give the results of obtained parameters for different cases using DE and SE function respectively. It is observed that, the calculated LI impulse test voltage using test voltage factor is within the range of the specified limits of the Table I. The deviation exists between the test voltage obtained by test voltage factor and standard IEC values, when the oscillation frequency/overshoot is greater than 500 kHz as in the case #9 and #14**.** The reason is that according to standard reference values, the oscillation/overshoot must be completely removed before evaluation of the test voltage.

The case #11 has oscillations superimposed on the overshoot and therefore the mean curve method using DE function needs two mean curves as shown in Fig.5. One of the factor '$k1$' is for oscillations and the other one '$k2$' is for

TABLE II. IMPULSE PARAMETER CALCULATION USING K - FACTOR METHOD WITH DE FUNCTION

Case No.	U_{pextr} (kV)	U_{pmc} (kV)	β (KV)	β %	*f* (MHz)	*k* VALUE	U_{TEST} (KV)	Using U_{test} T_1 (μs)	Using U_{test} T_2 (μs)	using U_{extr} T_1 (μs)	using U_{extr} T_2(μs)
#8	1060	995.3	64.657	6%	0.44248	0.7679	1045.0	1.6763	47.314	1.7	47.109
#9	1050	990.13	59.87	5.7%	0.63291	0.5540	1023.3	1.061	50.553	1.1585	48.916
#11	U_{ext1} = 949 U_{ext2} = 941	923.0	β1 = 26 β2 = 18	2.734% 1.912%	f1 = 3.703/ f2 = 0.4951	k1 = 0.0/ k2 = 0.66	937	2.07	85.679	2.14	84.88
#13	-1070	-967.67	-102.53	9.582%	0.38610	0.8493	-1054.5	3.5221	59.562	3.5998	58.569
#14	-1070	-967.94	-102.06	9.538%	0.57803	0.6082	-1030.0	2.2655	41.609	2.40	38.945

TABLE III. IMPULSE PARAMETER CALCULATION USING K - FACTOR METHOD WITH SE FUNCTION

Case No.	U_{pextr} (kV)	U_{pmc} (kV)	ΔU (kV)	ΔU %	*f* (MHz)	*k* VALUE	U_{TEST} (kV)	using U_{test} T_1 (μs)	using U_{test} T_2 (μs)	using U_{virt} T_1 (μs)	using U_{virt} T_2(μs)
#8	1060	1005.7	54.251	5.118%	0.44248	0.7679	1047.4	1.678	47.71	1.57	48.907
#9	1050	1006.6	43.351	4.128%	0.63291	0.5540	1030.7	1.1229	50.21	1.02	49.292
#11	949	942.43	6.5710	0.692%	0.45045	0.7572	947.40	2.1288	85.08	1.67	81.38
#13	-1070	-988.90	-81.104	7.579%	0.3861	0.8493	-1057.8	3.5456	59.649	3.18	60.312
#14	-1070	-1002.5	-67.530	6.311%	0.57803	0.6082	-1043.5	2.3181	40.823	2.12	39.726

overshoot. The given value in Table I for this case, U_{pmc} is the peak value of the mean curve that removes only the oscillations but not overshoot. When the impulse having superimposed front oscillations between 30% and 90% of U_{extr} as in case #11, the smooth curve is necessary to calculate the time parameters. While implementing DE function some difficulties arise when the measured impulse having more than one frequency of oscillations/ overshoot and in that case residual filtering using digital filter is helpful.

TABLE IV. TEST VOLATGE COMPARISON BETWEEN DE AND SE FUNCTIONS

Case No.	%U_{test}
#8	+0.23%
#9	+0.723%
#11	+0.5%
#13	+0.3%
#14	+1.3%

Test voltage calculation using *k*-factor can permit an overshoot magnitude of 10% than existing 5% limit. It can be observed from tables that when the overshoot /oscillation amplitude β increases, the frequency decreases in all the cases considered. Table IV gives the comparison of %U_{test} between DE and SE function. The test voltage obtained by using SE function is more than the value obtained from DE function. There is no significant deviation in the obtained time parameters using both DE and SE methods by considering calculated test voltage as 100% reference and it is closer to the calculated time parameters obtained by considering extreme value of measured curve as 100% reference. In SE function method, the more variation is obtained when considering U_{pvir} as 100% reference value compared with U_{extr} in the cases #13 and #14.

VI. CONCLUSION

The extreme value and the rate of rise of applied impulse voltage determines the stress distribution in HV power apparatus especially in transformer winding during LI tests. When an oscillations/overshoot superimposes on the impulse, the actual test voltage lies in between the extreme value of measured impulse and the peak value of mean curve. Any variations in the test voltage have serious influence on the test result and for the calculation of mean steepness, 30% and 90% value of extreme of the measured impulse to be used. By incorporating the frequency dependency test voltage *k*-factor for evaluation of the test voltage during lightning impulse test gives better reliability which improves the test results.

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