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ANALYSIS OF FULL AND CHOPPED LIGHTNING IMPULSE VOLTAGES FROM TRANSFORMER TESTS USING THE NEW K-FACTOR APPROACH

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Abstract: The analysis of the lightning impulses is made graphical according to IEC 60060-1: 1989. A new algorithm has been proposed to analyse the parameters, front time, time to half, peak value, of full and chopped lightning impulses. The algorithm provides a procedure for obtaining the parameters of the impulse voltages from waveforms with varying degrees of distortions in the front part of the impulse. Oscillations or overshoot in the peak region of the impulse are such distortions. The new algorithm was tested in different laboratories with different program languages and the results were compared to the IEC 60060-1: 1989 evaluation. Investigations with the new k-factor approach are already made with 52 TDG test data but the scientific view of real test data is missing. Therefore, full and chopped lightning impulses of transformer tests from manufacturers were investigated with the global and the residual filtering methods and were compared to the IEC 60060-1: 1989 evaluation.

1. INTRODUCTION

The standard IEC 60060-1: 1989 [1] is dealing with high voltage test techniques, general specifications and test requirements, and therefore with the analysis of full and chopped lightning impulse voltage.

The lightning impulse voltages of transformer tests with physically given inductances and capacities shows impulse shapes with superimposed oscillations or overshoots. The standard defines that oscillations on lightning impulses with frequencies above 500 kHz should be disregarded and the peak value is defined with the help of a drawn mean curve. This definition is against the physical characteristics due to its sharp definition to disregard oscillations. A European Project was carried out to remove the ambiguity in the evaluation of the impulse voltages when oscillations or an overshoot appear [6].

Breakdown tests were performed on different materials, e.g. oil, air, SF_6, to study the influence of oscillations on lightning impulses. With the results a frequency dependent k-factor function was defined [7]:

$$k = \frac{1}{1+af^2} \quad \text{with a = 2.2, value of f in MHz} \qquad (1)$$

Therefore, the k-factor function was used for a new algorithm to analyse the parameters, front time, time to half and peak voltage of full and chopped lightning impulses and to reach more reliability with the actual breakdown behaviour of the devices under test.

The evaluation of the so-called test voltage $U_t(t)$ out of the recorded lightning impulse U(t) is the crucial factor of the new evaluation. The peak value of the test voltage, U_t, lies between the extreme value of the lightning impulse with superimposed oscillations, U_e, and the peak value of the base curve of the impulse, U_{mp}. The k-factor varies from 1 to 0 depending on the oscillation frequency. The test voltage which is the basis for the determination of peak value U_t, front time T_1 and time to half value T_2 is defined as:

$$U_t(t) = U_m(t) + k(f) * \big(U(t) - U_m(t)\big) \qquad (2)$$

This algorithm was tested with artificial impulse voltages in different high voltage laboratories [3]. In this work data of full and chopped lightning impulse voltages from different transformer test bays were analysed with the new k-factor function and were compared to the results of the IEC 60060-1: 1989 evaluation.

2. NEW PARAMETER EVALUATION WITH THE NEW K-FACTOR DEFINITION

The implementation of equation (2) is the important task for the new k-factor evaluation. Investigations of global filtering methods were made, that means the filtering of the complete recorded impulse and the evaluation of the parameters from this test curve. But the differences of the global filtering method with the old evaluation were large. Therefore, a new approach was suggested with a fitted base curve and a residual filtering.

The recorded curve is fitted with a double exponential curve with four free parameters A, B, C and D and gives the so-called base curve $U_m(t)$:

$$U_m(t) = A\left(e^{-\frac{(t-D)}{B}} - e^{-\frac{(t-D)}{C}}\right) \qquad (3)$$

The fitting takes the Levenberg-Marquardt algorithm and its derivatives as a basis for finding the best least

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square estimation. The uncertainty of a freehand base curve drawing is eliminated with this fitting.

The k-factor function is included in the new approach as FIR or IIR filter. The linear phase FIR filter design is available in many programming languages (e.g. MATLAB – fir2). A typical number of coefficients in the range from 500 to 4000 are needed to get a linear-phase response.

For the IIR filter design a dual pass filtering approach has been implemented to get a linear phase response [4]. In this case the data has to be filtered twice, first forward and then in reverse:

$$y(i) = b_0 x(i) + b_1 x(i-1) + a_1\, y(i-1) \tag{4}$$

The filter coefficients are simply calculated - 'a' is the -3dB point of the k-factor filter and T_s the sampling interval of the recorded impulse voltage:

$$x = tan\left(\frac{\pi T_s}{\sqrt{a}}\right), \tag{5}$$

$$b_0 = b_1 = \frac{x}{1+x}, \text{ and} \tag{6}$$

$$a_1 = \frac{1-x}{1+x}. \tag{7}$$

2.1. Residual filtering method for full lightning impulse voltages

The procedure for parameter evaluations of full lightning impulse voltages (LI) differs from chopped impulses. Parameters - front time, time to half, peak voltage - of full lightning impulse voltages are evaluated by the so-called residual filtering method shown in Figure 1. First the base curve is fitted with the Levenberg-Marquardt algorithm. Then the recorded impulse subtracted with the base curve built the residual curve. The FIR or IIR filtering is applied to the residual curve and the test voltage impulse for parameters evaluation is the summation of the filtered residual curve and the base curve. The parameters of the test voltage T'_1, T'_2, peak voltage U_t and overshoot magnitude β' characterise the impulse voltage.

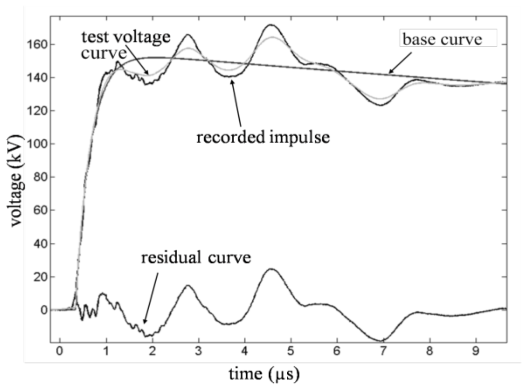

Figure 1: Evaluation of full lightning impulses with the residual filtering method.

2.2. Chopped lightning impulse voltages

For tail chopped lightning impulse voltages (LIC) two different methods are investigated for the parameter evaluation. The first method is the voltage reduction ratio method and the second one the residual curve method. The analysis of front chopped lightning impulses will not be discussed.

Voltage Reduction ratio method: As the name implies the ratio of voltages is calculated to evaluate the peak value of the test voltage, U_t. The voltage ratio is obtained with the peak values of the corresponding full LI and test voltage impulse, U_t, and U_e:

$$R_V = \frac{U_t}{U_e} \tag{8}$$

The peak value U_{eLIC} and time to chopping T_c is built with the original LIC. The peak value U_t is defined as:

$$U_t = R_V \cdot U_{eLIC} \tag{9}$$

The time parameter T'_1 and overshoot magnitude β' are taken from the results of the corresponding LI.

Residual curve method: The residual curve method for LIC uses the base curve of the corresponding full LI and the recorded LIC. The different applied voltage of LI and LIC requires an adjustment of the peak values. Therefore, the base curve and the peak value U_e of the LI are assessed. For scaling the base curve to the peak value of the LIC U_{eLIC} the equation is defined as:

$$u_{bLIC}(t) = \frac{U_{eLIC}}{U_e} \cdot u_{bLI}(t) \tag{10}$$

The residual curve method works like the LI residual filtering method. The scaled base curve and the recorded LIC built the residual curve for filtering and the test voltage is used to get the front time parameter T'_1, peak value U_{tLIC} and the overshoot magnitude β'. The recorded LIC is used to get the parameter T_c. This method is more complex and the results of both methods are insignificant small. In this work the differences of both methods will be discussed.

3. RESULTS

The new k-factor evaluation of the impulse voltages from transformer manufactures varies from the results of the IEC 60060-1: 1989. The differences of the evaluation results serve as basis for the comparison and rating of the new k-factor approach. For this purpose differences of both methods are built by subtracting parameters of the new k-factor evaluation (T'_1, T'_2, U_t) with the old IEC 60060-1: 1989 (T_1, T_2, U_e) method related to the old evaluation.

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$$\Delta U_t = \frac{(U_t - U_e)}{U_e} \cdot 100\% \qquad (11)$$

$$\Delta T_1 = \frac{(T'_1 - T_1)}{T_1} \cdot 100\% \qquad (12)$$

$$\Delta T_2 = \frac{(T'_2 - T_2)}{T_2} \cdot 100\% \qquad (13)$$

3.1. Full lightning impulses

The full lightning impulses were analysed with the new k-factor approach with the FIR and IIR filtering. In this work only the results of the FIR filtering method are presented because investigations showed that the maximum differences of the two filtering method are small [4].

Matters of particular interests are lightning impulses with superimposed oscillation frequencies between 300 and 800 kHz and parameters close to the limit range. Conforming to the IEC standard the front time of a lightning impulse lies in the range of 1.2 µs ± 30% and the time to half by 50 µs ± 20%.

In this contribution lightning impulses of real transformer tests were evaluated, which are close to the ranges because of test circuit limitations. The parameters of these lightning impulses lie almost close to the upper limit range of the standard tolerance for the front time.

Figure 2 shows the parameter differences calculated with the equations (11), (12), (13) of the old evaluation and the results of the residual FIR filtering method against the oscillation frequency. If the difference results in a positive value than the LI parameter of the new evaluation is higher and the opposite way around if the difference is negative.

In table 1 the comparison of the parameters between both evaluations are shown against different frequency ranges. Peak voltage and front time show the same characteristics. For small frequencies the k-factor has the value of '1' and the parameters are almost the same. In the frequency range between 300 and 500 kHz the old evaluation of peak voltage and front time results the higher value. The new k-factor parameter evaluation of front time and peak voltage shows the higher value by 500 – 800 kHz. The time to half shows the oppositional characteristic. For frequencies higher than 800 kHz an approximation of both methods is expected because of the run of the k-factor curve.

Table 1: Comparison of the LI parameters of the new (T'_1, T'_2, U_t) and old evaluation (T_1, T_2, U_e) against three frequency ranges

Frequency (kHz)	U_t to U_e	T'_1 to T_1	T'_2 to T_2
0 - 300	$U_t \approx U_e$	$T'_1 \approx T_1$	$T'_2 \approx T_2$
300 – 500	$U_t < U_e$	$T'_1 < T_1$	$T'_2 > T_2$
500 - 800	$U_t > U_e$	$T'_1 > T_1$	$T'_2 < T_2$

To show advantages and disadvantages of the new k-factor analysis the front and the time to half were investigated more closely. Therefore, a closer look was taken at impulse voltages with front and time to half close to the upper and lower tolerance limits.

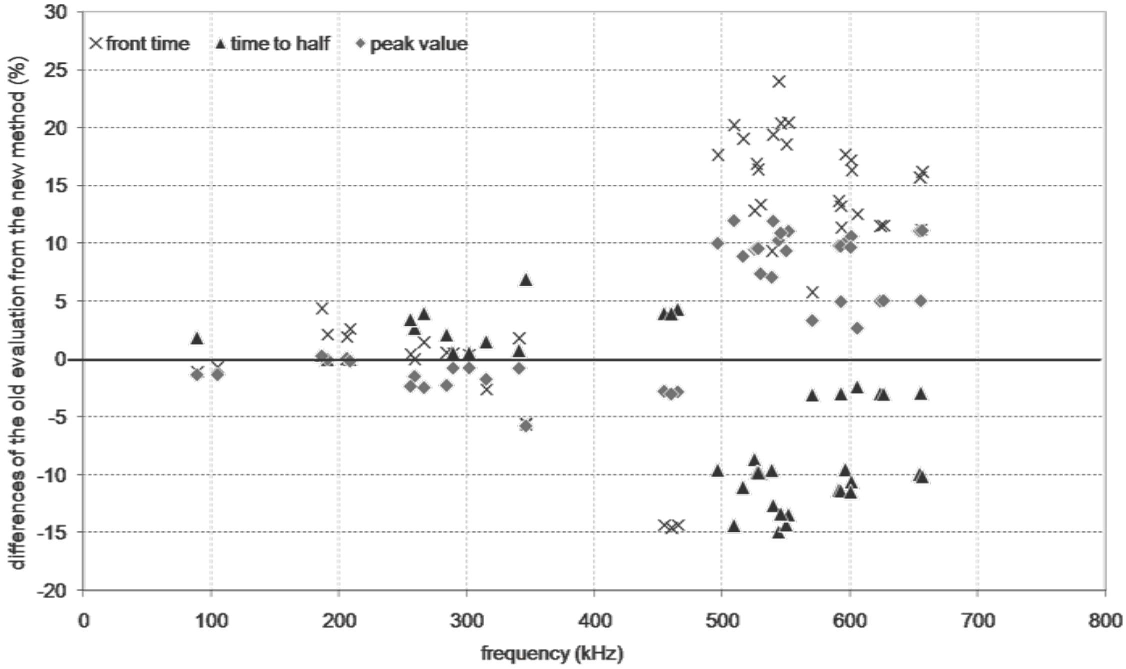

Figure 2: Differences of ΔT_1, ΔT_2 and ΔU_t of the old evaluation from the new method

Figure 3 and Figure 4 shows the front time and the time to half values of the new k-factor approach and the old evaluation against the frequency range.

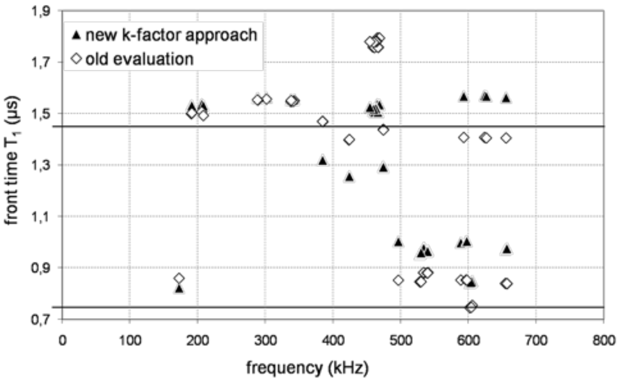

Figure 3: Comparison of front time T_1 and T'_1 of LI considering the tolerance limits

In Table 2 the differences between upper and lower tolerance limit are listed and the effect of a LI conforming to IEC standard is rated. In the frequency range of 300 – 500 kHz in the upper front time limit the front time T'_1 evaluated with the new method has a smaller value. For higher frequency ranges (500 – 800 kHz) the old front time T_1 is smaller as T'_1. Thus the new method results in exceeding the upper tolerance limit for the evaluated lightning impulses.

Table 2: Results of the front time parameters

Frequency (kHz)	T'_1 to T_1	tolerance limit	T'_1 conforming to standard
300 - 500	$T'_1 < T_1$	upper	✓
500 - 800	$T'_1 > T_1$	upper	-
300 - 500	$T'_1 < T_1$	lower	-
500 - 800	$T'_1 > T_1$	lower	✓

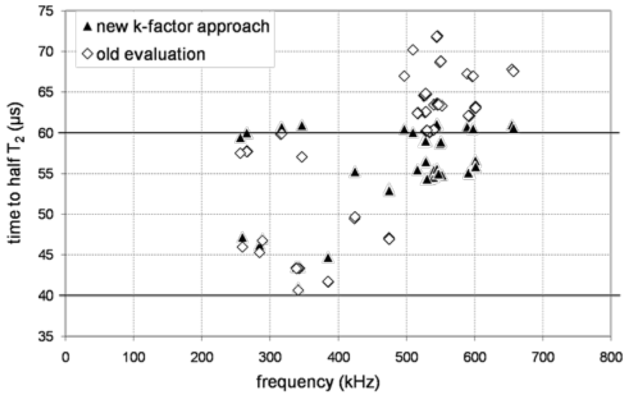

Figure 4: Comparison of time to half T_2 and T'_2 of LI considering of the tolerance limits

In Figure 4 the time to half values are shown. In the frequency range of 300 – 500 kHz the time to half T'_2 evaluated with the new method has higher values. For higher frequency ranges (500 – 800 kHz) the effect is reverse, but there are no severe differences between both methods.

3.2. Tail chopped lightning impulses

The tail chopped lightning impulses were analysed with both methods explained in chapter 2.2. The differences to compare the new evaluations with the IEC 60060-1: 1989 are built with the equations (11) and (12) and are shown in Figure 5 and 6 against the oscillation frequency.

The differences from the old IEC evaluation in the frequency range of 500 to 800 kHz are positive, i.e. T'_1 is longer than T_1 and U_t is higher than U_e. In the frequency range between 400 and 500 kHz the results vary from -13 % to 5 %. The analysis of LIC by frequencies of 600 to 900 kHz show differences in the front time from 20 - 35 % and in the peak voltage of 10 – 20%.

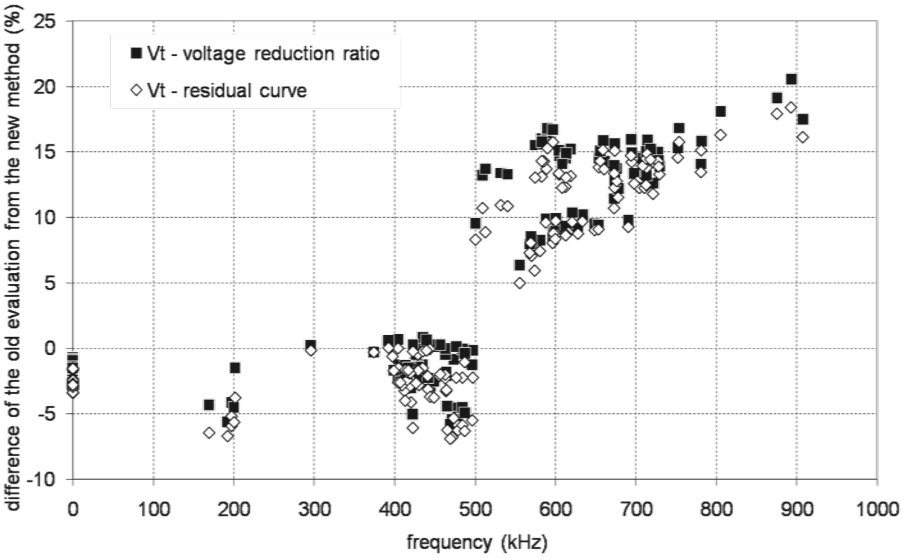

Figure 5: Differences of ΔU_t of the old IEC evaluation from both new LIC evaluations

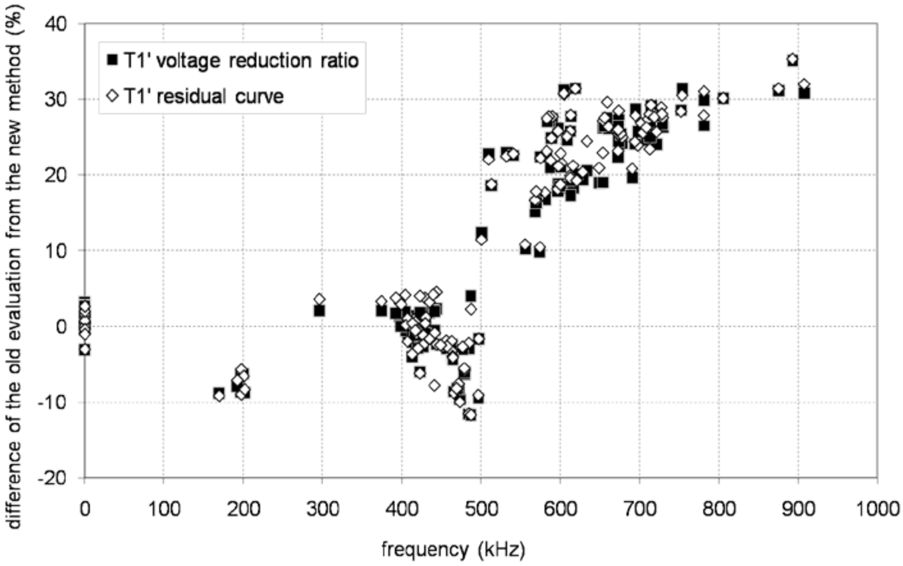

Figure 6: Differences of $\Delta T'_1$ of the old IEC evaluation from both new LIC evaluations

In Figure 7 the time of chopping T_c shows that the difference of -1.4 % to 0.3 % is a negligible characteristic between the old evaluation and residual curve method.

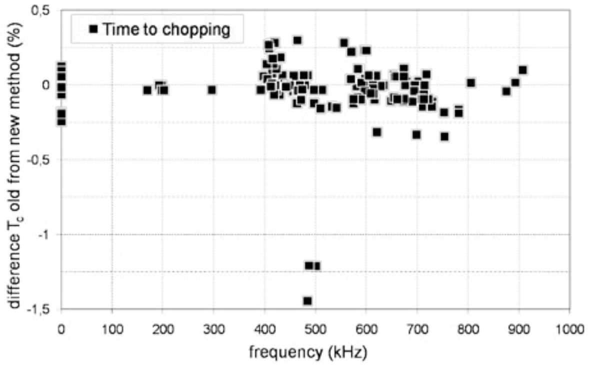

Figure 7: T_c difference between old and new evaluation (residual curve method)

The maximal difference between the voltage reduction ratio and residual curve method is 3%. For further investigations the voltage reduction ratio is recommended because of the simpler analysis.

4. OVERSHOOT MAGNITUDE B' OF LI

According to the IEC 60060-1 the relative overshoot magnitude β can be calculated as the difference between the extreme value of recorded and mean curve related to the extreme value of the recorded curve:

$$\beta = \frac{(U_e - U_{mp})}{U_e} \cdot 100\% \qquad (14)$$

According to the IEC 60060-1: 1989 standard an overshoot of β = 5 % is accepted. Several IEC apparatus standards accept higher overshoot level. The current overshoot definition β does not take into account the superimposed oscillation frequencies or the duration of an overshoot which are important values for the development of a discharge.

The new proposal for the relative overshoot magnitude is defined as the relative difference between extreme values of recorded and base curve [9]:

$$\beta' = \frac{(U_e - U_{mp})}{U_e} \cdot 100\% \qquad (15)$$

Because in this case the overshoot is based on the recorded curve it takes only the magnitude of the impulse into account. To consider the importance of the overshoot for the physical discharge characteristics also the duration of the overshoot has to be taken into account. This is achieved by the following proposal which uses the test voltage curve and considers therefore magnitude and duration of the overshoot:

$$\beta^* = \frac{(U_t - U_{mp})}{U_t} \cdot 100\% \qquad (16)$$

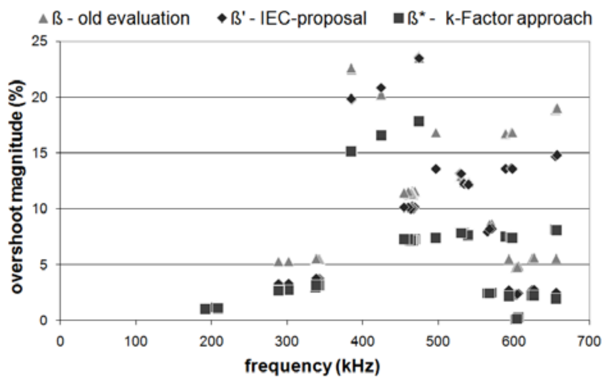

Figure 8: Overshoot magnitude β of the old IEC evaluation and the new k-factor proposal

In Figure 8 the overshoot magnitude of the different definitions (14), (15) and (16) are shown against the frequency range between 0 to 700 kHz. With higher frequencies the overshoot magnitude β' and β^* gets lower because of the influence of the new k-factor function. The highest value of the overshoot magnitudes of the analysed lightning impulses are less than 25% which is higher than the IEC standard allows.

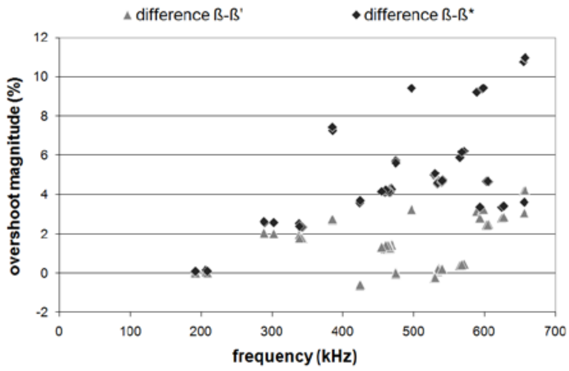

Figure 8: Differences of the overshoot magnitudes of the old evaluation and the IEC proposal β-β’ and β-β*

In Figure 9 the differences between the three overshoot magnitude definitions (14)-(15) and (14)-(16) are shown. The level of the old overshoot magnitude β equals the new defined overshoot magnitude β’ and β* but in most cases β differ 3 – 5 %. In the frequency range between 0 – 200 kHz old and new k-factor curves are similar. The differences in the higher frequency range (300 - 700 kHz) between β and β* are up to 12 %. The overshoot magnitudes β’, β* of LIC are the same for the voltage reduction ratio method because the parameters of the LI analysis are used.

In test circuits for transformer tests high inductances and capacities cause high overshoot magnitudes. The level of the accepted overshoot magnitude is still under discussion.

5. CONCLUSION

Principally the new k-factor evaluation is working and the results from laboratories around the world showed comparable results in spite of different programming languages. For chopped lightning impulses the methods has to be adapted because of the missing possibility to fit the base curve directly from the recorded impulse.

The differences of the parameter values between IEC 60060-1: 1989 and new k-factor approach for lightning impulses can be up to 25 %. For tail chopped lightning impulses the differences are even higher. The frequency range between 400 to 600 kHz shows the most changes because of the influence of the new k-factor function. Figure 3 clarifies the consequences of the new evaluation for LI close to the parameter tolerance limits. A change of the oscillation frequency of a few Hz in the range of 500 kHz can influence the value of the front time enormously. This effect can be found again for the time to half with the contrarian characteristic of the front time and the analysis of the impulse voltages are more difficult.

For the chopped lightning impulse the full recorded impulse is used for analysing. The disadvantage is the non-direct filtering method of the recorded impulses. The differences between old and new evaluation are up to 35 %. This fact has to be considered for the development of transformers. Further the voltage reduction ratio method is recommended to analyse LIC because of the easier handling.

The overshoot magnitude is still in discussion because of the allowed level. With the new definition of β’ the k-factor function is considered. For transformer test curves overshoot magnitudes of 30 % are possible.

The analysis from impulse tests from transformers are principal possible. The manufacturers have to keep in mind that the parameters are changing in the frequency range between 300 to 800 kHz with the influence of the k-factor function.

6. ACKNOWLEGDEMENTS

Evaluation methods of chopped lightning impulse voltages results from discussions of the Cigré D1.33 working group “High Voltage and high current test and measurement techniques”.

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