# New Method for Comparison of Chopped Waveforms in Impulse Transformer Tests

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*Abstract*—Power transformers must be evaluated under impulse tests. For that, it is necessary to compare voltage and current waveforms corresponding to reduced-level and full-level voltages. Any difference may correspond to a failure in the transformer under test. This test is based on the principle that there is no change in the generation of the impulse voltage. However, with chopped waveforms, many impulse generators have significant differences in the time of chopping that make difficult to get a conclusion on the test result. This paper presents a new algorithm that generates reduced-level chopped voltage and current waveforms, with arbitrary chopping time, from a couple of reduced voltage of full and chopped waveforms. In this way, it is possible to compare full-level voltage chopped waveforms with reduced-level ones with different chopping times.

*Index Terms*—Impulse test, transformer, chopped waveform, comparison, standard, transfer function, high voltage, dielectric, arc, sphere gap, rod-rod gap, multiple chopping gap.

## I. INTRODUCTION

RANSFOMERS are tested under different requirements to prove that fulfill international standards [1]. During their operation, they will be exposed to lighting overvoltages and must withstand them. To test this condition, an impulse test is described in the standards. Basically, it consists in applying impulses with two waveforms: a full-length high voltage impulse that reaches its peak value at 1.2 µs and then decays slowly, reaching the 50% of the peak value at 50 µs, and a chopped one with similar waveform but chopped in a time between 2 µs and 6 µs (see Fig. 1). This last waveform occurs during lighting storms if a flashover is produced in a device near the transformer. In the test, the impulse is applied to one terminal of the transformer, while the others are connected to ground or a shunt for current measurement. Different voltages are applied as stated in the standards; some full-level (100% to 110% of the nominal peak voltage) and some reduced-level impulses (between 50% and 75%). The sequence is:

a. One reduced-level full-length impulse.

- b. One full-level full-length impulse.
- c. One or more reduced-level chopped impulses.
- d. Two full-level chopped impulses.
- e. Two full-levels full-length impulses.



Fig. 1. Typical waveforms in impulse transformer tests, full-length (up) and chopped (down). Red: voltage, Blue: current.

The test consists in comparing full-level and reduced-level voltages and current waveforms, in both, the full-length and chopped waveforms. The main assumption is that the unit under test (UUT) is a linear device and its response is the same with different impulse voltage levels. Full and reducedlevel waveforms are compared and any significant difference in their shapes, in voltage or in current, can be considered as a failure. A main assumption is that the generator must produce the same waveforms when the voltage is changed between reduced and full levels. This is generally true for full-length waveforms, but for chopped ones it is difficult to get exactly the same chopping time between the full-level and the reducedlevel waveforms. Differences of tenths of microseconds may cause significant differences between full

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and reduced-level current waveforms that can be interpreted as a failure in the transformer. This behavior is very well known, and it is referred in many standards [2], [3]. These time differences are due to the chopping device. The simplest one is a rod-rod gap. Its chopping time depends on the gap length and the peak voltage level, and is based on an intrinsically statistical process, letting to large dispersion in the chopping time [4]. Different impulses, with the same peak voltage, can have different chopping times, due to the arc generation process between the rods. Moreover, as reduced and full level tests have large difference in the peak voltage, it is very difficult to adjust the rods in order to maintain the same chopping time.

A better and more stable device is a sphere gap controlled by a trigger device [5]. This device has a small spark gap excited by an auxiliary high voltage generator. For peak voltages up to 300 kV this device has a response time not depending on the voltage, and a low dispersion in the chopping time. However, for higher voltages the phenomenon of generation of the arc between the spheres changes, and delays as large as 1  $\mu$ s appear from the triggered time to the effective arc generation. In addition, the time dispersion increases [5]. To avoid these problems, a multiple chopping device was proposed [6]. It has several sphere gaps, connected in series, to reduce the voltage and the gap distance between each pair of spheres. The dispersion is relatively low, around

 $0.15 \ \mu$ s, even at high voltages. The problem is its high cost, so that, not all laboratories have one. In conclusion, the difficulty for generating reduced and full-level chopped waveforms with the same chopping time remains as a practical issue for many laboratories that perform impulse tests on transformers. This leads to difficulties in the comparison process between the reduced and full level chopped waveforms. In the following sections, a new idea for the comparison technique, when the reduced and full-level waveforms have differences in the chopping time, is proposed. It only uses mathematical processing on the acquired test data for the reduced-level waveforms, not affecting in any way the full-level waveforms.

The main idea of the proposal is to compute a reduced-level chopped waveform, with the required chopping time, equal to the chopping time obtained in the full-level chopped tests. These two waveforms (the obtained in the full-level chopped test and the computed for the reduced-level) can then be directly compared, with any usual method used to wave comparison in impulse tests.

The computed reduced-level chopped waveform can be calculated based on a couple of reduced-level waveforms: a full-length and a chopped one with any chopping time between 2  $\mu$ s and 6  $\mu$ s [1]. For this, it is necessary to compute the response of the transformer to the voltage collapse, when the chopper acts, and add it to the full-length waveform at the appropriate time. In this way, a reduced-level chopped waveform is generated with the required chopping time, according to the actual chopping time obtained in the full-level chopped impulse. To get the collapse response, we propose to subtract the full-length response from the chopped one in the reduced-level waveforms. If  $v_i(t)$ ,  $i_i(t)$  are the acquired full

length waves, and  $v_c(t)$ ,  $i_c(t)$  the chopped ones, the first task is to normalize them. Although  $v_j(t)$  and  $v_c(t)$  would have nearly the same peak voltages, because both were generated at the same reduced level voltage, it is important for the processing that the peak voltages are exactly the same. This is easy to get, multiplying one of the couples by an appropriate scaling factor. A second adjust shifts the starting point of one of the couples to coincide with the other. This adjust is necessary because the sampling process may have time differences in the starting point. Both adjustments are usual tools of impulse processing programs for comparison between full and reducedlevel waveforms [7]. Being  $v_{fa}(t)$ ,  $i_{fa}(t)$  and  $v_{ca}(t)$ ,  $i_{ca}(t)$  the adjusted waveforms (scaled, and starting at the same time), the response to the breakdown,  $v_b(t)$ ,  $i_b(t)$ , will be

$$v_b(t) = v_{ca}(t) - v_{fa}(t) \tag{1}$$

$$i_b(t) = i_{ca}(t) - i_{fa}(t)$$
 (2)

Once we have  $v_b(t)$ ,  $i_b(t)$ , the next step is to add them to the reduced-level full-length waves at the selected chopping time. Once again, their amplitudes must be normalized because they depend on the chopping time. As the voltage waveform decreases in time, the larger the chopping time, the smaller the amplitude. A constant *a* must be calculated for this adjustment.

$$a = v_f(t_2) / v_f(t_1)$$
 (3)

Where  $t_1$  is the chopping time of the original waveform and  $t_2$  is the desired chopping time. The reconstructed chopped waves will be

$$v_{cr}(t) = v_{fa}(t) + av_b(t - \Delta t) \tag{4}$$

$$i_{cr}(t) = i_{fa}(t) + ai_b(t - \Delta t)$$
(5)

where  $\Delta t$  is the time difference between the new chopping time ( $t_2$ ) and the original one ( $t_1$ )

$$\Delta t = t_2 - t_1 \tag{6}$$

Rigorously, for doing this process it is necessary that the mathematical representation of the curve  $v_j(t)$  fulfills the property

$$v_f(t + Lt) = f(\Delta t)v_f(t) \tag{7}$$

That is, the shifted voltage full waveform must be the same than the original, multiplied by a constant  $f(\Delta t)$  that depends on the time shift. It is easy to see that exponential waveforms according to (8) fulfill this property.

$$v_f(t) = V e^{-t/\tau} \tag{8}$$

In this case,  $f(\Delta t)$  can be expressed as

$$f(\Delta t) = e^{-\Delta t/\tau} \tag{9}$$

Fortunately, the basic function that represents the impulse tail is of the form of (8), generated by the discharge of the impulse

generator capacitors on the tail generator resistors [8].

### II. VALIDATION OF THE METHOD

A program that performs the proposed algorithm was designed and developed. It uses two recorded couples of reduced-level waveforms: one full-length and other chopped, as described previously. From them, a new chopped waveform is computed, with a new arbitrary chopping time, selected equal to the chopped time obtained in the full level waveform.

The program receives the original reduced-level waveforms: one full-length and one chopped. In order to adjust the waves in time, it calculates the cross correlation between them taking into account only the samples before the chopping time. Then, it calculates the average of the modulus of the waves around the peak to determine the coefficient for using in the amplitude adjustment. After applying that factor to the waves, the program subtracts the chopped waveform from the full-length one, obtaining the system response to the chopping. Finally, the response is adjusted in amplitude to the new desired chopped time and it is subtracted from the original full-length waveform. The obtained waveform can then be directly compared with the full-level chopped waveform.

Results on a 30 kV transformer are shown in Fig. 2. Figures 2a to 2c show reduced-level chopped waveforms, with different chopping times, from 2.2 µs to 4.8 µs. Fig. 2d shows the reduced-level full-length waveform corresponding to the same transformer.







Fig. 2b. Chopped waveform at 3.6 µs.



Fig. 2c. Chopped waveform at 5.0 µs.



Fig. 2d. Full waveform.

In order to show the performance and accuracy of the proposed method, we used the 2.3 µs reduced-level chopped waveform to generate a new chopped waveform with 3.6 µs chopped time. Fig. 3 shows the superposition of the reconstructed waveform (blue) and the original one (red). Fig. 3a shows the voltage comparison and Fig. 3b the current comparison. No significant differences are detected between both couples, which confirm the validity of the proposed method.





Fig. 3b. Comparison between reconstructed and original current waveforms.

### III. DISCUSSION

The proposed method, as previously mentioned, is based on the hypothesis of exponential shape in the voltage waveform. Although this is the standard waveform generated by the impulse generation equipment, in some cases, this waveform can be distorted due to the transformer load, producing some oscillations after the peak value (see Fig. 4).



Fig. 4. Result of an impulse test with oscillations in the voltage waveform, after the peak.

Theses oscillations may lead to errors in the reconstructed waveform. Fig. 5a shows two chopped impulses with 2.2  $\mu$ s and 3.7  $\mu$ s chopping times. The voltage and current waveforms are exactly the same, up to the first chopping time (2.2  $\mu$ s). After this time, the currents (at the bottom) are totally different so that it is not possible to decide on the result of the test.

Using the proposed algorithm, the 3.7  $\mu$ s waveform was reconstructed from the full waveform and the 2.1  $\mu$ s waveform. Fig. 5b and 5c show the comparison between the original and reconstructed waveforms (voltage and current, respectively), both with 3.7  $\mu$ s of chopping time. Adjusts between both couples of waveforms are much better than those of Fig. 5a, however, some differences remain. If the time difference is smaller, the adjust is better.

Variations in the proposed algorithm to improve the comparison of this type of waveforms is under development.



Fig. 5a. Impulses with 1.4  $\mu$ s of chopping time difference.



Fig. 5b. Comparison between reconstructed and original impulses (voltages).



Fig. 5c. Comparison between reconstructed and original impulses (current).

## IV. CONCLUSIONS

A new method for waveform comparison in chopped impulse tests, on power transformer, was presented. It reduces the comparison errors due to the usual problem of differences in the chopping time between full and reduced-level waveforms. For that, the proposed algorithm generates a new reduced-level chopped waveform with arbitrary chopping time, to use as reference in the comparison to the full-level waveform. Tests on real power transformers corroborate the theoretical proposal, showing good results.

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