REVIEW OF DIGITAL TECHNIQUES APPLIED TO HIGH-VOLTAGE TRANSFORMER IMPULSE-TEST

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Abstract: Impulse test is a usual high-voltage test on equipment of power networks. This test emulates the overvoltage that exist in lighting storms. Particularly, it applies to transformers. There are standards for performing and evaluating the result of this test, but in some cases the decision of pass/fail is not easy to do. This paper presents a review of digital techniques to help the operator decide on the setting of the generator according to the standards and whether or not the transformer passes the test.

1. INTRODUCTION

Materials and components of high-voltage power networks must withstand overvoltages caused by lightning storms. To test that, a usual laboratory technique is the impulse test. It uses a high-voltage pulse generator and a measuring system to record the response of the object under test. Figure 1 shows the waveform of the pulse defined by IEC Standard [1]. It reaches the peak in T_1=1.2 µs and decreases to half the peak value in T_2=50 µs.

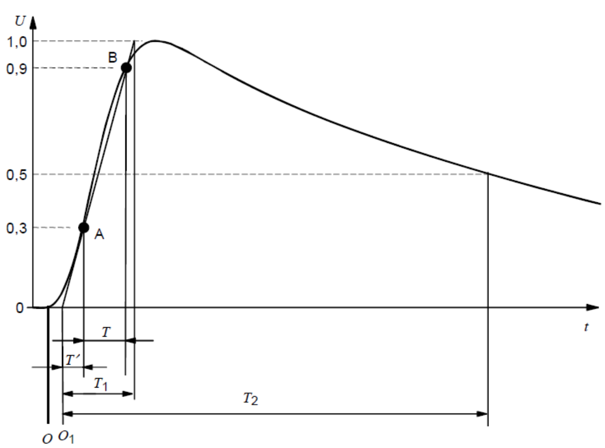


***Fig. 1**. Full lightning impulse (from [1]).*

The Standard defines the front time T_1 as 1.67 times the interval between points A and B (30 % and 90 % of the peak value), and T_2 as the time between the virtual origin O_1 and the point when the waveform decreases to 50 % of its peak value. Another waveform used in these tests is the chopped waveform. It emulates an impulse overvoltage that suddenly turns to zero because of a failure in the insulation of the power system. Figure 2 shows a typical waveform (negative polarity).

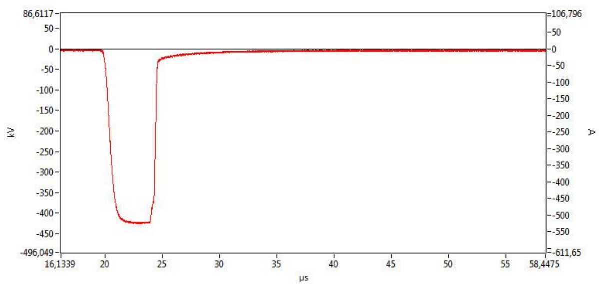


***Fig. 2.** Chopped impulse voltage waveform.*

The chopping time must be between 2 µs and 6 µs. Most impulse generators are according to Marx type that is summing several stages in a series-parallel configuration. Figure 3 shows an example for five stages. Each stage is charged in parallel and discharged in series when the sphere gaps are discharged.

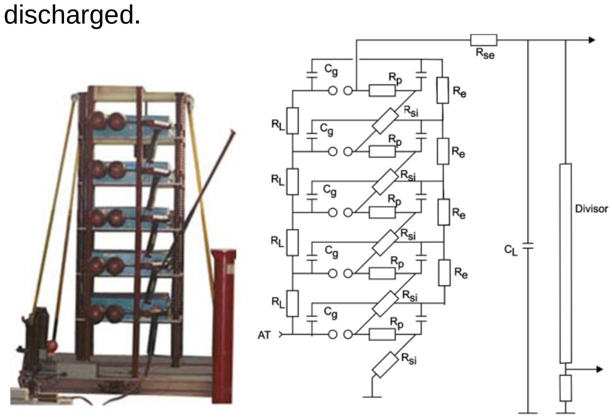


***Fig. 3.** Five-stage impulse generator according to Marx.*

The adjustment of the pulse times is done by modifying the values of the series resistors R_s and parallel resistors R_p (others, remain fixed). However, try and error method is very cumbersome with high number of stages. Each adjust implies, at least, changing all the parallel resistors, and some of the series ones. To help operators for this task, there are some assistances. One of them, is using theoretical formulas [2]. If the object under test has a capacitive model, of value *C*, the value of the resistors can be estimated from

$$T_1 = 3R_{st}\frac{C_{gt}C}{C_{gt}+C} \quad T_2 = 0.7R_{pt}(C_{gt}+C) \tag{1}$$

where $C_{gt}=C/n$, $R_{st}=R_s.n$ and $R_{pt}=R_p.n$, being *n* the number of stages. However, a problem arises when the object under test is a complex one, as a power transformer. It adds a network of inductances, capacitances and resistances that distorts the waveform. In this case, a typical assistance is performed using Recurrent Impulse Generators that produces low voltage impulses whose resistor and capacitor settings can be easily changed.

Digital help has also been proposed [3]. It is based on determining the model of the transformer by testing it with a Frequency Response Analyzer equipment. It measures the impedance against the frequency, and together with the generator circuit information, a software calculates the values of the capacitors and resistances that best fit the standard waveform.

To decide if the transformer passes the test, the voltage as well as the current through the transformer (measured using a shunt) must be recorded. The evaluation is done comparing these pairs of waveforms, between reduced (around 50 %) and full level (100 %) impulse voltages [2]. It is assumed that at reduced voltage the transformer has no failure. So, any difference between those waveforms indicates an internal failure. Large failures produce very large differences in both, voltage and current waveforms. However, minor failures, as turn-to-turn short circuits, are associated with small differences. For this last case, digital techniques are very useful to help the operator to decide on the result of the test.

2. DIGITAL RECORDERS

Impulse generators are equipment that last for many decades, which is good, but there is a problem related to applicable Standards. They change, so different requirements appear, which may not be met with the current equipment. This is the same for recorders and software. The Standard IEC 61083-1 [4] recently changed. Its last version is from 2021, and the previous one, from 2001. According to the 2001 version, the sampling rate must be, at least, 30/Tx, where Tx is the time interval to be measured. For lighting impulses, this leads to 60 MS/s of sampling frequency. Regarding resolution, at least 9 bits must be used. However, version 2021 recognizes that the resolution of modern digitizers has been improved and 14-bits resolution are currently available for impulse measurement equipment. Furthermore, this standard takes into account that a great improvement has been achieved in the A/D converters, so it stablishes new requirements. It states that this component is not the main concern of measurement accuracy and instrument reliability at the current time. In accordance, the number of type tests for evaluating the performance of A/D converters has been reduced, but new requirements for the linearity of complete system have been added. Requirements for static integral non-linearity and static differential non-linearity have been removed and requirement for impulse scale factor non-linearity has been added. Testing is necessary to verify if the current equipment complies with this new Standard version.

In this work, a dual channel digitizer of 12 bits was used (PICO ADC-212), with additional shielding and filters to reduce electromagnetic interferences. It fulfills the IEC 2001-Standard version, but it has not tested yet for the 2021 one, as most digitizer in use have not. One channel of the digital recorder is connected to the output of the high voltage divider (figure 4). It comprises a low voltage divider, low-pass filter, surge protection and an input resistance to adapt to the cable impedance, avoiding reflections. A current shunt is connected between the tested winding terminal and ground. Its voltage output is measured by the other channel of the recorder.

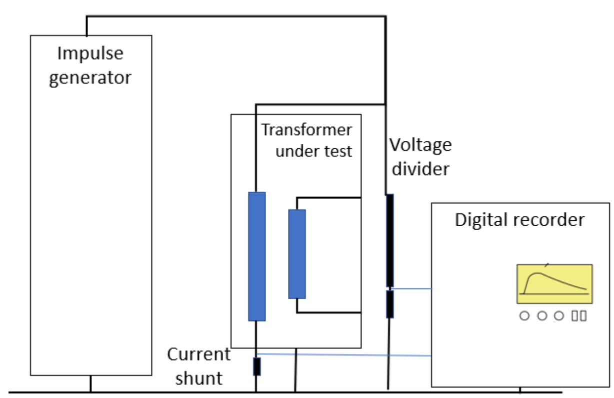


Fig. 4. *Connection of the instrumentation.*

3. SOFTWARE

The recorded data is processed by appropriate software. Many different versions are in use, designed by impulse generator manufacturers or academic researches. Despite of their differences, there have common aspects to fulfill the Standards [5]. As happens to recorders, Standards change in each revision, which leads to user problems if no software update is available. In the following paragraphs, we will concentrate on discussing general aspects of the Standard requirements on the data processing, based on a specific software developed by these authors [6].

3.1 General characteristics

As conventional oscilloscopes, the software has controls for amplitude and time ranges. Additionally, it allows to set the ratio of the high voltage divider and the value of the current shunt. Figure 5 shows the home screen of the analyzed software. Automatically, it presents the maximum voltage and current for each selected range. The trigger controls include the display of the value, directly in kilovolt, according to the high voltage divider ratio and the voltage range of the digitizer. Other possibilities of the software are smoothing and insertion of filters. The smoothing function is useful to reduce the noise of the records. This signal processing does not introduce any visible variation in the shape of the waves. A bandwidth reduction enables to reject interferences and noise produced by the impulse generator. Transformers have a cutoff frequency of few megahertz, so any part of the spectrum higher than that frequency, generally, does not come from the under-test-transformer.

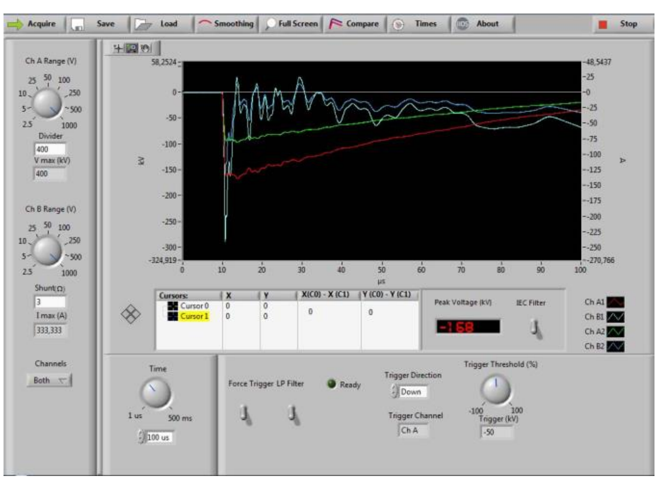


Fig. 5. *Home screen of the software.*

3.2 Peak value

The first calculation is the peak value of the applied voltage pulse. The IEC 60060-1 Standard states how to do this calculation. It defines this parameter as the real maximum value of the voltage waveform, only if there are no oscillations near the peak or if they exist, their frequencies are low. If high frequencies oscillations or overshoots are overlapped, then a mean curve must be considered for the computation of the peak value. The 1989-version of the Standard, states that if the frequency of the oscillations is higher than 0.5 MHz or the overshoot interval is less than 1 µs, the peak value is determined by the base curve (average). Otherwise, the peak value is determined by the crest value. The analyzed software includes filters to implement this criterion (IEC Filter), and to verify this calculation, standard waveforms have been analyzed with results inside the tolerances.

However, the current version of this Standard (2010) [1] changes the method of calculating the peak value. This change also affects software and involves updating them. It defines a *k*-factor, depending on the oscillation frequency *f* (in MHz) as

$$k = \frac{1}{1 + 2.2f^2} \tag{2}$$

This factor is applied to the oscillatory amplitude, that can be calculated by some methods [7], and added to the base curve. A comparison between both Standard versions was done in [8]. At 0.5 MHz, *k* value is 0.65. That means that 65 % of the amplitude of the oscillation must be added to the base curve. On the other hand, the old version of the Standard recommended 0 % or 100 %, depending on which side of that frequency limit is located. With an amplitude oscillation of 10 %, the difference in the peak voltage, between both calculations can reach 6.5 %. This shows that there is a significant difference between both Standards, and an up-date is needed in the software. Figure 6 shows a real voltage waveform example analyzed by the developed software. It has

- crest value: -168 kV,
- amplitude oscillation: 5 % of the peak voltage,
- frequency: 200 kHz.

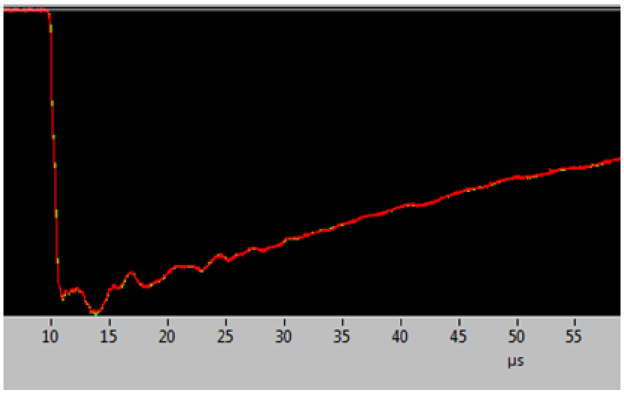


Fig. 6. *Example of lightning impulse with oscillations after the peak.*

As the oscillation frequency is lower than 0.5 MHz, according to the old Standard version, no correction must be done and the actual peak value must be used. However, according to the new version, *k*=0.92, so the oscillation must be reduced 8 %. It passes from 5 % to 4.6 %. This leads to a reduction in the peak value of 0.4 %. In this example, the difference between both methods is relatively low but, with other oscillations, the difference can be higher. The fractional ratio *r* between the new and the old Standar peak value calculations are

$$r_1 = \frac{1+\alpha k}{1+\alpha} \qquad (f < 0.5\ MHz) \tag{3}$$

$$r_2 = 1+\alpha k \qquad (f > 0{,}5\ MHz) \tag{4}$$

where r_1 is valid for low frequencies and r_2, for higher frequencies. α is the ratio between the oscillation amplitude and the base peak value. Figure 7 shows these calculations for α=0.1 (10% of oscillation amplitude). The difference can reach 6.5 % for a frequency slightly higher than 0.5 MHz. It is clear that old software needs to be updated.

3.3 Time values

Software calculates the front and tail times. Also, for this parameter differences exist according to the version of the implemented Standard. The front time of the voltage of figure 6, computed by the software from 30 % and 90 % of the peak voltage, is 3.487 µs, but this waveform has a fast slope, until 86 %.

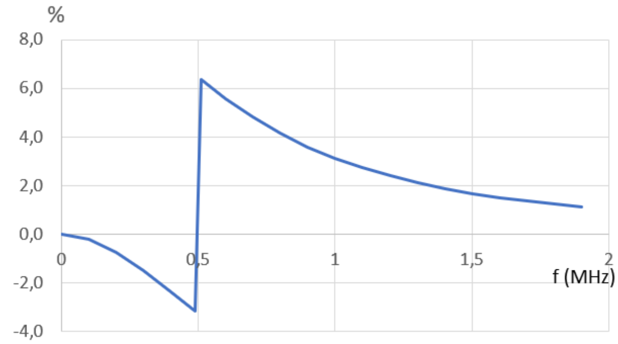


Fig. 7. *Difference in calculating peak value of oscillatory impulses, between current and old versions of IEC Standard [1].*

So, if 30 % and 86 % were taken for calculating the front time, its value will be 1.1 µs, inside the tolerance of the Standards. The new version proposes a method to avoid this problem, however there are cases that require the intervention of an expert.

3.4 Waveform comparisons

For comparing voltages and current waveforms, the analyzed software permits to select superposition or subtraction of reduced and full-level waveforms (see figure 8).

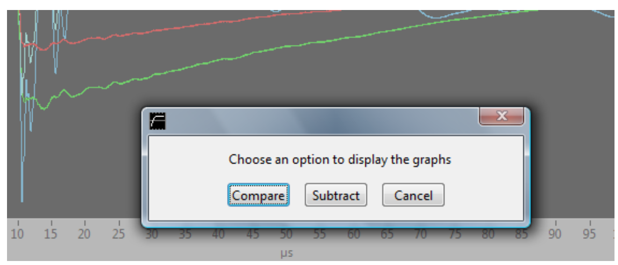


Fig. 8. *Selection of comparing method: overlapping or subtraction.*

These waveforms have large difference in amplitudes and also some time-shift. As the comparison refers only to the wave shape, the software adjusts amplitudes and time shift to get the lower differences between curves. In this way, the best adjust is obtained. Any residual difference may indicate a failure in the transformer. Figure 9 shows the superposition of the two voltages waveforms (up) and current waveforms (down).

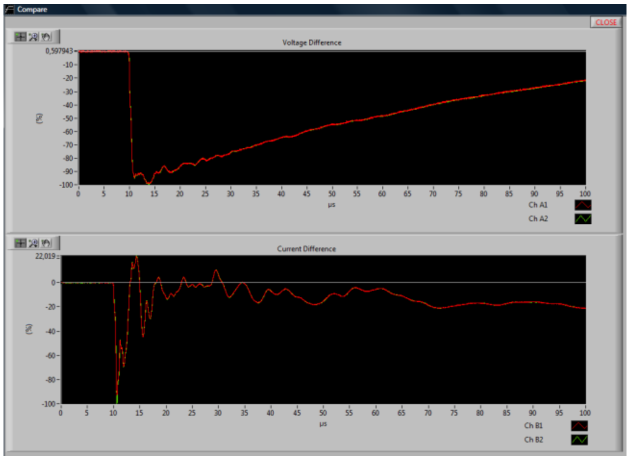


Fig. 9. *Voltage and current comparison using superposition.*

No significant difference appears in the screen. It indicates a good agreement between full and reduced amplitudes. According to these curves, the transformer passes the test.

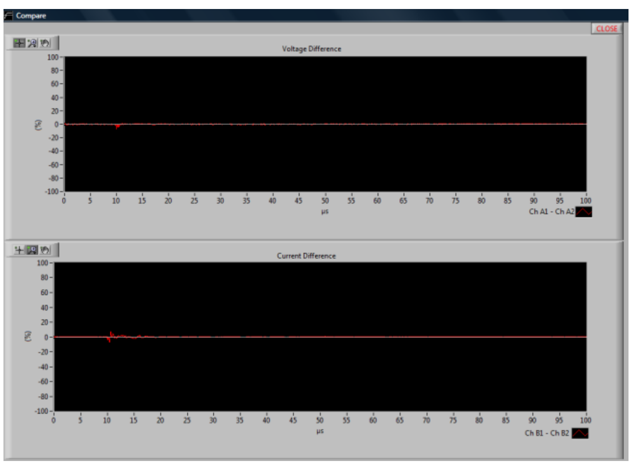


Fig. 10. *Subtraction of voltage and current waveforms.*

A better inspection can be done by subtracting the two waveforms, as figure 10 shows. The differences are presented in percentage of their maximum amplitudes. As previously, from these results most technicians will conclude that these differences are not significant, and the transformer passes the test. To observe with more details, the software has the possibility to expand these records to full screen (see figures 11 and 12). A clear difference of 5.5 % appears in voltage subtraction, that coincide with front time of the waveforms.

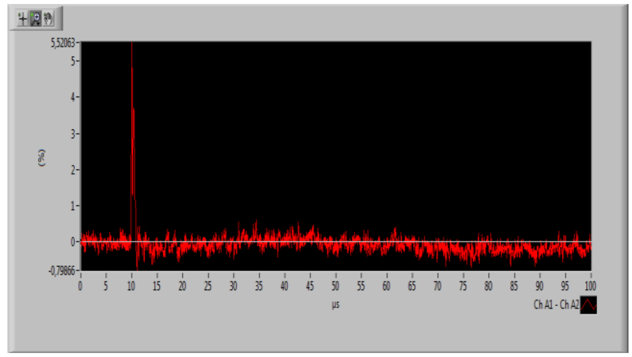


Fig. 11. *Voltage comparison expansion using the subtraction method.*

What follows, is random noise, inside 0.5 %. IEC Standards accepts that differences in the front may come from changes produced by the generator, and do not imply failures in the transformer.

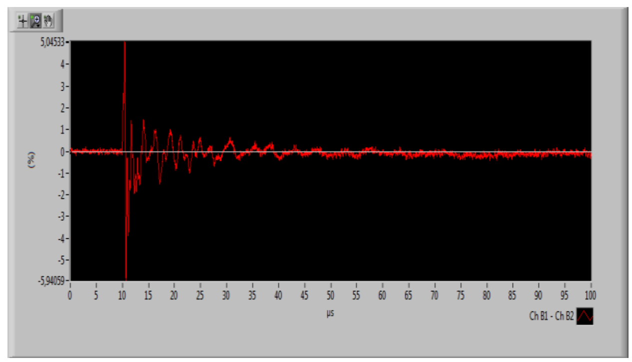


Fig. 12. *Current comparison expansion using the subtraction method.*

However, current subtraction shows oscillatory differences up to 2 % (discarding the ones in the front time). They are clearly not random noise. The question is if they came or not from failures in the tested transformer. Answer to this question cannot be decided by the software itself, but by experts. In the past, with simple cameras, or even with digital recorders with no subtraction capability, this difference could not be detected, and the conclusion would have been that the test was fulfilled. This example illustrates a risk for using powerful digital analysis. It can improve past comparative methods, but the transformer knowledge must go along with it. Otherwise, good transformers can be rejected.

3.5 Chopped waveforms

A more complex comparison is with chopped waveforms. The main problem is related with the chopping time. Impulse generators stability goes from some tenth of microsecond to few microseconds, depending on the chopping device. With this difference between reduced and full-level impulses, it is not possible to directly compare these waveforms. Even, few tenth of microseconds can produce large discrepancies in the current, after the chopping time. Figure 13 shows an example with 1.6 µs of difference in the chopping time. Voltage and current waveforms coincide before chopping, but very large differences appear in current records. This has led some Standards to avoid the comparison. However, there are some proposals to do the comparisons, even with significant differences. In [9], a method based on the transfer function of the transformer was proposed. The idea was to compute the frequency response as

$$Y(\omega)=I(\omega)/V(\omega) \qquad (5)$$

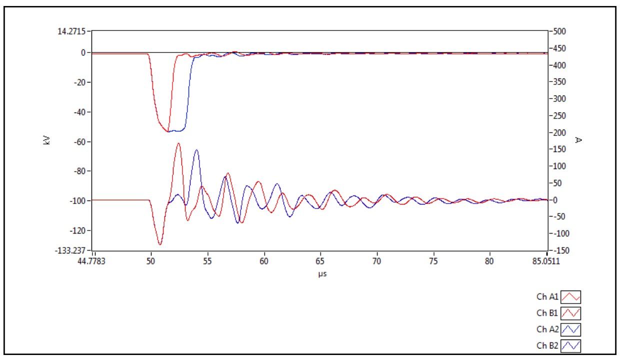
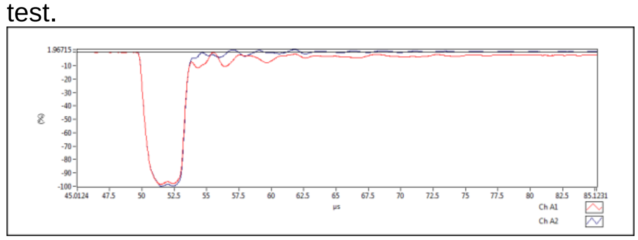


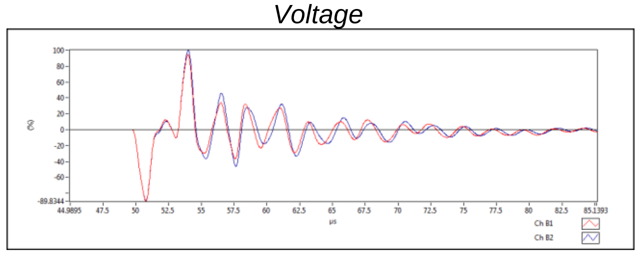
Fig. 13. *Chopped waveforms with large chopping time difference.*

I(ω) is the Fourier Transform of *i(t)* and *V(ω)* of *v(t).* In this way, the result *Y(ω)* does not depend on the impulse voltage waveform, but only on the transformer impedance. If the internal *R-L-C* network of the transformer does not change because of an internal failure, the function *Y(ω)* remains the same whatever been the voltage excitation. In principle, this solves the problem caused by differences in the chopping time. Even more, according to the authors, this method could compare chopped waveforms with full ones. However, both excitations must have similar bandwidth, and full waveforms have smaller bandwidth than chopped one. This imposes some restrictions but remains useful for comparing full and reduced level chopped impulses, which is the main goal.

Alternatively, we have proposed another comparison method, implemented digitally, that works even with large chopping time differences [10-12]. The main idea is to calculate a reduced-level chopped waveform, with the same chopping-time of the full-level chopped test. For that, a couple of reduced-level waveforms are used. One is a full-length (complete) and the other, a chopped one with any chopping time. With the last one, an algorithm computed the time response of the transformer to the voltage collapse, after the chopper acts. Then, the algorithm adds it to the reduced full-length waveform at the same time than the full-level chopped one. In this way, data vectors of voltage and current reduced-level chopped waveforms are generated with the same chopping time than the full-level chopped impulse. Figure 10 shows an example. The large time difference of figure 9 was reduced to less than 0.1 µs. Although voltage comparison shows small differences after the chopping, current waveforms superpose good enough to assure that the transformer passes the test.



Voltage



Current

Fig. 10. *Comparison between two chopped waveforms with large chopping time differences, adjusted according to the method proposed in [10].*

4. CONCLUSIONS

A review of different algorithms and calculation methods, digital implemented, for transformer impulse tests, have been analyzed. They improve the analysis of the results and reduce test time. However, some precautions should be considered. Standards change from time to time and software update is necessary. Current digital aids have limitations, and better AI-based software would be needed to avoid the requirement for experts to decide on edge cases.

REFERENCES

[1] IEC 60060-1, “High-voltage test techniques - Part 1: General definitions and test requirements,” 2010.

[2] IEC 60076-4, “Power transformers - Part 4: Guide to the lightning impulse and switching impulse testing - Power transformers and reactors,” 2002.

[3] H. R. Mirzaei, "A Simple Fast and Accurate Simulation Method for Power Transformer Lightning Impulse Test," in IEEE Transactions on Power Delivery, vol. 34, no. 3, pp. 1151-1160, June 2019.

[4] IEC 61083-1, “Instruments and software used for measurements in high-voltage impulse tests – Part 1. Requirements for instruments”. 2021.

[5] IEC 61083-2, “Digital recorders for measurements in high voltage impulse testes – Evaluation of software used for the determination of the parameters of impulse waveforms,” 2013.

[6] G. Slomovitz, D. Slomovitz, “Digital processing of impulse measurements in transformer tests,” IX SEMETRO, Natal, Brazil, 23 -30 set. 2011.

[7] N. Pattanadech, P. Yutthagowith, “Fast Curve Fitting Algorithm for Parameter Evaluation in Lightning Impulse Test Technique,” IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 22, No. 5; October 2015.

[8] A. Pfeffer, S. Tenbohlen, “Evaluation of Parameters of Lightning Impulse Voltages from Transformer Tests Using the New k-factor Approach,” IEEE Trans. on Dielectrics and Electrical Insulation Vol. 17, No. 3; June 2010.

[9] R. Malewski and B. Poulin, "Impulse testing of power transformers using the transfer function method," in IEEE Transactions on Power Delivery, vol. 3, no. 2, pp. 476-489, April 1988.

[10] D. Slomovitz, G. Slomovitz and J. Joskowicz, "New method for comparison of chopped waveforms in impulse transformer tests," VI IEEE/PES Transmission and Distribution: Latin America Conference and Exposition, 2012.

[11] D. Slomovitz, G. Slomovitz, J. Joskowicz, “Processing methods for comparing chopped waveforms in impulse transformer tests,” X-SEMETRO, Buenos Aires, Argentina, 25-27 Sep., 2013.

[12] J. Joskowicz, G. Slomovitz and D. Slomovitz, "Evaluation of comparing algorithms used in chopped impulse transformer measurements," IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 149-152, 2014.