

SOP TRANSACTIONS ON POWER TRANSMISSION AND SMART GRID

Analysis of Evaluating Methods for Transformer Chopped Impulse Tests

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Abstract:

Power transformers must be tested under high voltage impulse tests with full-length and chopped waveforms. This paper compares different evaluation methods used for lighting impulse chopped tests, showing the advantages and drawbacks of them. The evaluation technique compares voltage and current waveforms corresponding to reduced-level and full-level voltages. Any difference between the waveforms may correspond to a failure in the transformer under test. However, with chopped waveforms, impulse generators may have significant differences in the time of chopping, so that low-level and full-level waveforms are different, making difficult to get a conclusion on the test result. Typical evaluating methods and a new recently proposed algorithm are compared using different power transformers and chopping times.

Keywords:

Impulse Test; Transformer; Chopped Waveform; Comparison; Standard; Transfer Function; High Voltage; Dielectric; Arc; Sphere Gap; Rod-rod Gap; Multiple Chopping Gap

1. INTRODUCTION

Transformers are tested under different requirements to prove that fulfill international standards [1–3]. During their operation, they are exposed to lighting overvoltages and must withstand them. To test this condition, high voltage impulse tests are described in the standards. Basically, they consist in applying impulses of high voltages to one terminal measuring the response current at other terminal. Lighting impulse test has two types of waveforms: full-length impulse that reaches its peak value at 1.2 μ s and then decays slowly reaching 50% of the peak value at 50 μ s (see **Figure 1**), and chopped one (LIC) with similar waveform but chopped in a time between 2 μ s and 6 μ s (see **Figure 2**). This last waveform occurs during lighting storms if a flashover is produced in a device near the transformer. The impulse polarity may be positive, as in **Figure 1**, or negative, as in **Figure 2**, according to the transformer under test (TUT) type and the considered standard.

To analyze the result of the test, the applied voltages and the response currents must be recorded. One channel of a digital oscilloscope or digital recording system (DRS) with a high voltage divider is connected to the input terminal of the transformer to get the applied voltage. The response current, generally the current to ground of the opposite terminal of the excited winding, is connected to the other channel of the DRS using a current shunt, as **Figure 3** shows. All other terminals must be grounded.

The sampling rate of the DRS must be, at least, 60 MS/s and the resolution must be 9 bits or better according to [4].



Figure 1. Full length impulse voltage waveform.



Figure 2. Chopped impulse voltage waveform.



Figure 3. Transformer connection to impulse generator and Digital Recording System.

When signal processing is needed, higher resolution is preferred because of the small differences that are necessary to detect in this type of measurement. Digitizers up to 12 bits are usually used in industry laboratories. Once the test is

performed, the digitalized voltages and currents are processed with specific or generic software programs in order to evaluate the results.

During the test, different voltages are applied as stated in the standards; some full-level impulses (100% to 110% of the required peak voltage) and some reduced-level impulses (between 50% and 75%). The sequence is [1]:

One reduced-level full-length impulse.

One full-level full-length impulse.

One or more reduced-level chopped impulses.

Two full-level chopped impulses.

Two full-levels full-length impulses.

The evaluation of the test consists in comparing full-level and reduced-level voltages and current waveforms. One pair of the curves (voltage and current) is scaled in order to fit the other. Any significant difference in their shapes, in voltage or in current, can be considered as a failure. Even for LIC tests, standards state that the detection of faults depends essentially on wave comparison [1].

There are two main assumptions when performing this test. The first one is that the TUT is a linear device and its response is the same with different impulse voltage levels. This assumption is true if there are no failures in the TUT. On the contrary, if any failure is produced under full-level impulses, this non-linear difference will affect the voltage and current waveforms. The second assumption is that the generator produces exactly the same waveforms when the voltage is changed between reduced and full levels. This is generally true for full-length waveforms, but not for chopped waveforms because it is very difficult to get exactly the same chopping time between the full-level and the reduced-level waveforms. Different chopping devices are allowed by standards. Although it is accepted to use simple rod-rod gaps [1], standards recommend electronic controlled chopping devices. Using rod gaps, when the voltage exceeds a certain trigger value the discharge is initiated. It takes few microseconds for the leader discharge to arrive to the opposite electrode, so that a small delay allows getting the chopped voltage waveform [5]. Different impulses with the same peak voltage can have different chopping times due to the random arc generation process. Moreover, as reduced and full level tests have large voltage difference, it is very difficult to adjust the rods distance in order to maintain the same chopping time [5]. It is accepted that when using these gaps, the chopping time can vary some microseconds.

A better and more stable device is a sphere gap controlled by an electronic trigger device [6, 7]. 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 with low dispersion in the chopping time. However, for higher voltages the phenomenon of arc generation changes and delays as large as some microseconds appear from the triggered time to the effective arc generation. In addition, the time dispersion increases [6]. To avoid these problems, a multiple chopping gap device was proposed [8]. 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, but it is expensive so that not all laboratories have one. In any case, even differences of tenths of microseconds may cause significant differences between full and reduced-level current waveforms that can be interpreted as a failure in the transformer, as we will show in the next sections.

In conclusion, the difficulty for generating reduced and full-level chopped waveforms with the same chopping time remains as a practical issue for laboratories that perform LIC tests on transformers. This leads to difficulties in the comparison process between the reduced and full level chopped waveforms. In [9] a first attempt to evaluate different comparing method was shown. In section 2 a review of the typical methods used for chopped waveforms comparison is presented. The limitation of these methods is discussed. A recently proposal [10, 11] by these authors for the comparison technique is shown in section 3. Different comparison methods between curves are discussed in section 4 and experimental results, comparing the goodness of each method, are presented in section 5. Finally,

conclusions are remarked in section 6.

2. TYPICAL METHODS USED FOR WAVEFORMS COMPARISON

2.1 Direct Comparison

The simplest and most used comparing method is the direct comparison between curves [3]. The only needed processing is the amplitude adjustment of the voltage and current waveforms. Using the same adjustment coefficient for both quantities, the goal is to get the same amplitude for both pairs of curves. For chopped waveforms, if they have exactly the same chopping time, this method is enough to decide on the pass/fail result. However, if there are chopping time differences the direct comparison can be done only up to the first chopping time. After this point, even small time differences in the chopping time may lead to confuse results. Figure 4 shows a test on 31 kV, 10 MVA transformer with 0.05 μ s of time difference in the chopping time (a time difference that can exist even using multiple chopping gap devices). The test was done at very low voltage, so that, there was not any failure in the TUT. The time difference is so small that it is not easy to see it in the voltage waveforms. Both voltage curves are superposed. Only amplifying the time scale the voltage difference turns visible. However, significant current differences appear that may lead to an erroneous interpretation as a failure result.



Figure 4. Test with 0.05 μ s of chopping time difference.

2.2 Time Shift Method

With significant time differences in the chopping time, one method of comparison is to shift in time one of the curve pairs (voltage and current) to coincide with the other at the collapse time. Up to the first chopping time, the direct comparison works well. After that time, the voltage and current pair with the smallest chopping time is shifted in time to coincide with the largest one. **Figure 5** and **Figure 6** show an example of this method for a 31 kV, 200 kVA transformer with 0.6 μ s difference in the chopping time. **Figure 5** shows the actual records and **Figure 6** the shifted ones. In this way, waveforms after chopping are more similar and can be better compared.

Although the comparison after the chopping time is much better using the shifted curves than the originals, this example shows that current curves do not superpose (see **Figure 6**) and a wrong conclusion on the test result will be got.



Figure 5. Recorded waveforms with 0.6 μ s in chopping time.



Figure 6. Shifted waveforms for better comparison after chopping.

2.3 Transfer Function

In the context of this test, the transformer can be modeled as a linear quadrupole (four-terminal network). As a linear device, the quadrupole will have a unique transfer function H(t)

$$v(t) * H(t) = i(t) \tag{1}$$

where v(t) is the applied voltage, i(t) the response current, and * the convolution function. This relation can be also represented in the frequency domain as

$$V(w)H(w) = I(w) \tag{2}$$

where $V(\omega)$ and $I(\omega)$ are the Fourier transform of v(t) and i(t), and $H(\omega)$ the transfer function in the frequency domain. Knowing $V(\omega)$ and $I(\omega)$, $H(\omega)$ can be directly calculated as

$$H(w) = \frac{I(w)}{V(w)} \tag{3}$$

In [12] the Transfer Function (TF) has been proposed to be used in impulse tests. In theory, the TF should not depend on the shape of the input voltage waveform, so that differences in the chopping time should not affect the

results. In practice, the TF is calculated using Fast Fourier Transform (FFT) of the voltage and the current records, using a finite number of voltage and current samples and a limited resolution. Voltage and current Fourier transform amplitudes decays quickly at high frequencies, so that the ratio $I(\omega)/V(\omega)$ has high uncertainties at high frequencies because it approximates to 0/0 division. In any point where the FFT of the voltage has low value, the uncertainty is large. This drawback makes difficult to decide, in some cases, if the TUT passes or fails the test. **Figure 7** and **Figure 8** show the TF (magnitude and phase angle) up to 1.2 MHz, for the same 31 kV, 200 kVA transformer shown in previous section, calculated with two different pair of voltage and current curves, with 0.6 μ s difference in the chopping time.

Another example is presented in Figure 9 and Figure 10. In this case, a 31 kV, 10 MVA transformer was used, and the difference in chopping time was 0.04 μ s.



Figure 7. Modulus of the Transfer Function for waveforms with 0.6 μ s differences in chopping time in a 31 kV, 200 kVA transformer.

Even with this very small difference in the chopping time, appreciable differences can be seen in both, the magnitude and phase of the calculated TF.



Figure 8. Phase angle of the Transfer Function for waveforms with 0.6 μ s differences in chopping time in a 31 kV, 200 kVA transformer.

Looking at the first example (Figure 7 and Figure 8), the graphs are very similar up to 500 kHz, but are different for higher frequencies. In the second example (Figure 9 and Figure 10), there are differences starting at 850 kHz.



Figure 9. Modulus of the Transfer Function for waveforms with 0.04 μ s differences in chopping time in a 31 kV, 10 MVA transformer.



Figure 10. Phase angle of the Transfer Function for waveforms with 0.04 μ s differences in chopping time in a 31 kV, 10 MVA transformer.

The frequency bandwidth of most power transformers are between 1 MHz and 2 MHz [3], so that the differences previously shown are significant, and could be erroneously considered as transformer failures. In [2] a "reliability indicator" is proposed for the TF. This indicator is equal to 1 when the TF is reliable and less than 1 for if it is not reliable. This requires to define a specific "reliability function" and a threshold value for $V(\omega)$, but there is no standard criterion on how to define these parameters. The differences seen in the previous figures can be due to low values of $V(\omega)$, but there is no way to avoid it because the chopped voltage approximates to a rectangular pulse, so its Fourier transform approximates to the a SINC function with multiple zeros. Even, using the "reliability indicator" this method can lead to erroneous conclusion.

None of the three classic methods discussed works perfect for chopped impulse tests when the chopping time of the reduced-level waveform is different to the chopping time of the full-level waveform.

3. RECONSTRUCTED CHOPPED RESPONSE

In [11] we have proposed a new method for comparison of full and reduced-level waveforms with different chopping times. 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 can then be directly compared, with any usual method used to wave comparison in impulse tests. The reconstructed reduced-level chopped waveform is calculated based on a couple of reduced-level waveforms: a full-length and a chopped one. 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. To get the collapse response, we proposed to subtract the full-length response from the chopped one in the reduced-level waveforms. If $v_f(t)$, $i_f(t)$ are the acquired full length waves, and $v_c(t)$, $i_c(t)$ the chopped ones, the response to the breakdown, $v_b(t)$, $i_b(t)$, will be

$$v_b(t) = v_c(t) - v_f(t) \tag{4}$$

$$i_b(t) = i_c(t) - i_f(t) \tag{5}$$

Once we have $v_b(t)$, $i_b(t)$, the next step is to add them at the selected chopping time to the reduced-level full-length waves. 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.

$$a = \frac{v_f(t_2)}{v_f(t_1)} \tag{6}$$

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

$$v_{cr}(t) = v_f(t) + av_b(t - \Delta t) \tag{7}$$

$$i_{cr}(t) = i_f(t) + ai_b(t - \Delta t) \tag{8}$$

where Δt is the time difference between the new chopping time (t_2) and the original one (t_1)

$$\Delta t = t_2 - t_1 \tag{9}$$

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

$$v_f(t + \Delta t) = f(\Delta t)v_f(t) \tag{10}$$

That is, the shifted voltage-full-waveform must be the same than the original, multiplied by a constant $f(\Delta t)$ that depends only on the time shift. It is easy to see that exponential waveforms fulfill this property, and fortunately the basic function that represents the impulse tail has this shape as it is generated by the discharge of the impulse

generator capacitors on the tail generator resistors [11]. This requirement is needed because the method uses the superposition principle. In fact, the collapse can be seen as the application of a second voltage impulse source with a waveform equal to the first one, but with opposite polarity. **Figure 11** shows a graphical explanation. The upper voltage waveform (a) is the full-length impulse, the medium waveform (b) is the chopped one at t_1 , and the lower waveform (c) was calculated subtracting the previous ones. In this way, the chopped waveform (b) is the superposition of two voltage sources (a) and (c). As the transformer is assumed as a linear device for impulse tests, the response current will be also the superposition of the two partial responses.

This method shifts in time waveform (c) and adjusts its amplitude resulting in waveform (d). To get the new chopped waveform at time t_2 , this method superposes sources (a) and (d), resulting in waveform (e). It is necessary that the voltage has an exponential behavior. If oscillations exist close to the peak, curve (d) will contain these oscillations, which are not present in (a) at time t_2 . This will result in voltage differences with the actual chopped waveform of time t_2 , leading to differences in currents.

4. COMPARISON METHODS

As shown in previous sections, when there are differences in chopping times, differences in voltage and current waveforms appear, even when there are no failures in the transformers. For comparison in time domain, both voltage and current curves must be compared. However, in this analysis we focus in the current curves because they have more sensitivity for detecting failures in the transformer [3]. The curve comparisons were performed taking into account up to 35 μ s after the latest chopping time. Differences exist in the time domain and also in the frequency domain. The main risk is to decide that the transformer did not pass the test because of the differences between the waveforms, when these differences were not produced by an internal failure but just for comparing curves with different chopping time.

Although the criterion to decide if a transformer passes or not the test is nowadays based on the experience and opinion of experts, some objective parameters can be defined. To evaluate the degree of similarity between curves, we propose to use two metrics, one based on the root mean square (rms) value (C_{rms}) and the other on the Pearson Correlation Coefficient (*PCC*). For the first one, the curves to be compared must be previously normalized, that is adjusted in amplitude. Both must have the same amplitude. After that, in the time domain, the relative rms value of the difference is computed according to

$$C_{rms} = \sqrt{\frac{\int_{t_1}^{t_2} (i_1 - i_2)^2 dt}{\int_{t_1}^{t_2} (i_1)^2 dt}}$$
(11)

where i_1 and i_2 are the two currents to be compared over a period of time t_1 to t_2 . The smaller the value of C_{rms} is, the more similar the curves are. The second metric, *PCC*, is defined in the time domain according to

$$PCC = \frac{\sigma_{i_1 i_2}}{\sigma_{i_1} \sigma_{i_2}} \tag{12}$$

Where $\sigma_{i_1i_2}$ is the covariance of i_1 and i_2 , σ_{i_1} is the standard deviation of i_1 and σ_{i_2} is the standard deviation of i_2 . *PCC* ranges from -1 to 1. A value of 1 implies that a positive linear relationship describes the relationship between both curves perfectly. There is no need to normalize the curves in order to compare them with this proposed second metric. For most impulse currents, *PCC* values are close to one, so that for improving the comparison the Pearsons distance *1-PCC* is calculated to enlarge the differences. The smaller the value of *1-PCC* is, the more similar the curves are.



Figure 11. Graphical explanation of the reconstructed method.

5. EXPERIMENTAL EVALUATION

Four transformers with different nominal power and voltage were tested. A 12 bits, 100 MHz digitizer was used with a sample time of 20 ns. All impulses, full length and chopped, were generated by a recurrent low voltage impulse generator. The chopping time was varied from 2 μ s to 8 μ s. As the test was performed with low voltages, any difference between the obtained waveforms is produced by the difference in the chopping time, but not due to failures in the transformer.

The simplest direct comparison was not included in this analysis because it has very large errors even with small chopping time differences. Then, the "Time Shift" method was compared agaist the "Reconstructed Chopped Response" method in time domain. For each transformer, we have chosen the curves obtained with the lowest chopping time as the reference ones. For the "Time Shift" method, these curves were shifted in time up to the chopping time of each other curve. For the "Reconstructed Chopped Response" method, a new pair of current and voltage curves were calculated at each chopping time, using the reference curves (at the lowest chopping time) and a pair of voltage and current full-length curves. The resulting current waveforms obtained with each method were compared with the actual waveform at each chopping time. **Table 1** shows results for a 6.3 kV, 630 kVA transformer. One curve is used as the reference (chopped at 2.4 μ s) and the others, at different chopping times, are compared to it. Column one shows the chopping time, columns two and three show the *C_{rms}* and Pearsons distance for the time-shifted current is. Similarly, columns four and five show the results for the reconstructed current *i*_r. **Table 2**

refers to a 200 kVA, 31 kV transformer, using as reference a chopping time of 2.3 μ s. **Table 3** refers to a 10 MVA, 31 kV transformer, using as reference a chopping time of 2.6 μ s. Finally, **Table 4** refers to a 10 kVA, 15 kV transformer using as reference a chopping time of 2.2 μ s.

	Method: Shifting in time the chopped curve with the smallest chopping time		Method: Computing the chopping response from a 2.4 μ s chopped waveform	
Chopping time	C _{rms}	1-PCC	C _{rms}	1-PCC
(μ s)	$(i-i_s)/i$	$(i-i_s)$	$(i-i_r)/i$	(<i>i</i>- <i>i</i> _{<i>r</i>})
3.84	0.54	0.183	0.15	0.014
4.35	1.00	0.075	0.11	0.006
4.49	0.96	0.051	0.10	0.005
6.08	1.00	0.188	0.13	0.010

Table 1. Transformer: 6.3 kV, 630 kVA. Reference: 2.4 µs.

Table 2. Transformer: 200 kVA, 31 kV. Reference: 2.3 µs.

	Method: Shifting in time the chopped curve with the smallest chopping time		Method: Computing the chopping response from a 2.4 µs chopped waveform	
Chopping time	C _{rms}	1-PCC	C _{rms}	1-PCC
(μ s)	$(i-i_s)/i$	$(i-i_s)$	(<i>i</i>-i _r)/ <i>i</i>	(<i>i</i> - <i>i</i> _{<i>r</i>})
2.51	0.11	0.005	0.07	0.002
3.03	0.32	0.051	0.10	0.005
3.63	0.45	0.111	0.14	0.009
3.70	0.45	0.111	0.12	0.007
4.05	0.52	0.148	0.14	0.010
5.32	0.60	0.211	0.11	0.007
5.90	0.59	0.202	0.10	0.005

Table 3. Transformer: 10 MVA, 31 kV. Reference: 2.6 µs.

	Method: Shifting in time the chopped curve with the smallest chopping time		Method: Computing the chopping response from a 2.4 μ s chopped waveform	
Chopping time (µs)	C_{rms} $(i-i_s)/i$	1-PCC (i-i _s)	C_{rms} $(i - i_r)/i$	<i>1-PCC</i> (<i>i</i> - <i>i</i> _{<i>r</i>})
3.47	1.00	1.118	0.57	0.151
3.43	1.89	1.118	0.63	0.200
5.05	0.43	0.095	0.17	0.006
5.09	0.43	0.095	0.19	0.009
7.75	0.54	0.130	0.22	0.019
7.99	0.70	0.144	0.29	0.061

The evaluating metric based on rms shows average improvements between 2.4 and 6.4 times when using the "Reconstructed Chopped Response" method instead of the "Time Shift" method. The average reduction of the relative rms difference is 6.4 times for the transformer of **Table 1**, 3.8 times for **Table 2**, 2.4 times for **Table 3** and 2.7 times for **Table 4**. If Pearsons distance metric is used, the average reduction is 14 times for **Table 1**, 18 times for **Table 2** and 8 times for **Table 3** and **Table 4**. These results show that the "Reconstructed Chopped Response" method is better than "Time Shift" method in all analyzed cases. It is not easy to compare to the "Transfer Function" method because

	Method: Shifting in time the chopped curve with the smallest chopping time		Method: Computing the chopping response from a 2.4 μ s chopped waveform	
Chopping time (µs)	C_{rms} $(i-i_s)/i$	1-PCC (i-i _s)	C _{rms} (i-i _r)/i	<i>1-PCC</i> (<i>i</i> - <i>i</i> _r)
2.24	0.31	0.048	0.13	0.008
2.46	0.44	0.103	0.17	0.015
3.17	0.41	0.101	0.13	0.008
3.55	0.41	0.088	0.13	0.008
5.40	0.36	0.065	0.14	0.010
6.37	0.31	0.048	0.13	0.008

Table 4. Transformer: 10 kVA, 15 kV. Reference: 2.2 μ s.

it mainly depends on the definition of the reliability function, which eliminates zones where there are large differences between the compared curves. Additionally, there is no a direct comparison technique because the "Reconstructed Chopped Response" and "Time Shift" methods are time based, but "Transfer Function" method is frequency based.

6. CONCLUSIONS

A discussion on different proposed methods for evaluating chopped impulse test on power transformers was presented. The simple current and voltage curve superposition criterion is the worst for this test because of differences in the chopping time between full and reduced levels waveforms. The "Time Shift" method (consisting in shifting one of the curve pairs to coincide with the other at the collapse time) and the "Reconstructed Chopped Response" method (consisting in computing a reduced-level chopped waveform with the required chopping time) were compared in four power transformers, showing that the second method is better. The rms relative differences between current curves are between 3 and 6 times lower with the "Reconstructed Chopped Response" method than the "Time Shift" method.

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