MODEL OF TRANSFORMERS WINDING FOR LIGHTNING

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ABSTRACT

The aim of the impulse tests on distribution transformers is to evaluate the winding insulation performance during lightning occurrence. Thus, the transformer is considered perfect if the acquired wave shapes do not present distortions associated with failure evidences. The key point on these cases is that some measurement equipments rarely show failure signals, mainly due to high frequency oscillations, considering as perfect a failed transformer. This paper discusses some mathematical modeling and testing results that shows that some high frequency oscillations are related to turn-to-turn failures.

INTRODUCTION

The experience with Brazilian manufacturers shows that the analysis of the wave shapes from transformer impulse tests must consider the performance of measurement equipments. Some of them are not able to show specific failures as for instance small turn-to-turn short-circuits. In other cases, concerning equipments able to show these failures, the usual scaling adopted during the testing do not permit a clear visualization of the failure. In some cases, small "noise" signals are considered as failure of the measurement system i.e. induced pulses noises, and not the testing apparatus failure. The idea of this paper is to show, aided by ATP simulations, that some measurements evaluations permit that small failures pass without being noticed, and that the current signal of the chopped impulses must be considered on the analysis adding one more evidence that the high frequency oscillations on the current of full waves are real failure evidences.

MODEL PARAMETERS

The approach used in this paper considers power frequency capacitances, the winding self-capacitance and the impulse inductance, connected in a suitable way to represent the transformer during impulse tests as shown by Figure 1.

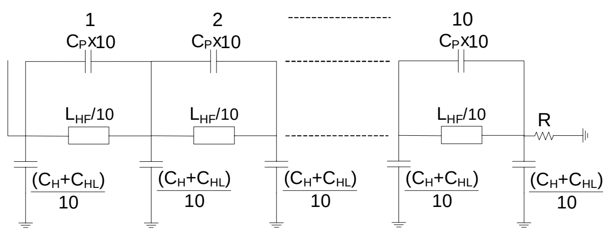
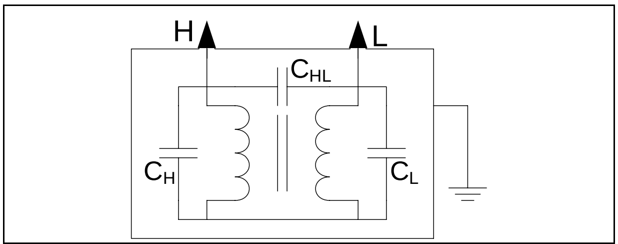


Figure 1 – Used transformer winding model

Figure 1 Shows the transformer winding divided in ten equal parts with its correspondent values of capacitances and inductances [1].

Capacitance Measurements

The power frequency capacitances are obtained according to the traditional Schering Bridge approach as shown by Figure 2.



Source	measurement	grounding	Result
H	L	-	$C_{HL} + \frac{1}{\frac{1}{C_H} + \frac{1}{C_L}}$
H	L	L	$C_{HL} + C_H$
L	H	H	$C_{HL} + C_L$

Figure 2 – Transformer capacitance measurement model

As long as the voltage impulse test is carried out in the HV bushing, the high voltage capacitance to the ground and between high and low voltage are taken into account.

Winding Self-Capacitance (Sc) and Inductance (L_{HF})

From the simulation of the circuit shown in Figure 3 it is possible to obtain the maximum current (I_{MAX}), for the voltage zero-crossing time. This permits to construct current amplitude surfaces matching the variation of the maximum current, voltage zero-crossing time with the winding surge impedance, and the coil length as shown in Figure 4.

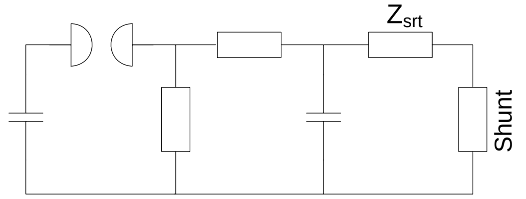


Figure 3 – Circuit used to determine the winding inductance

The shape of these surfaces depends on the configuration of the impulse generator. The present impulse generator has a load capacitance of 47 nF per stage.

Therefore, from a lightning impulse oscillogram, considering the voltage zero-crossing time, the maximum current amplitude and surfaces similar to that one shown by Figure 4 it is possible to get the winding surge impedance (Z_{STR}) and length (L_{WTR}). With the values of C_H, C_{HL}, power frequency capacitances and Equation 1 it is obtained the winding high frequency inductance – L_{HF}.

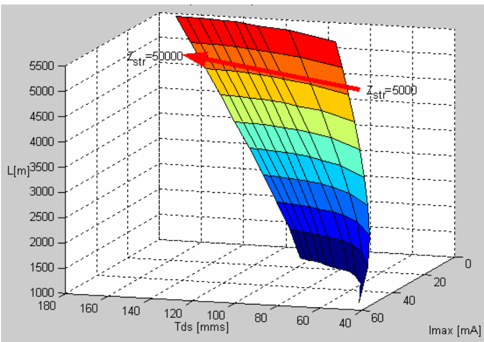


Figure 4 – Maximum Current according to coil length, voltage zero-crossing time and transformer surge impedance

$$L_{HF} = Z_{STR}^{\ 2} \times (C_H + C_{HL}) \qquad (1)$$

Likewise the inductance determination, from the simulation of the circuit shown in Figure 5 it is obtained the matching of the peak current (I_P) and the winding self-capacitance, shown for a specific connection of the impulse generator, in Figure 6.

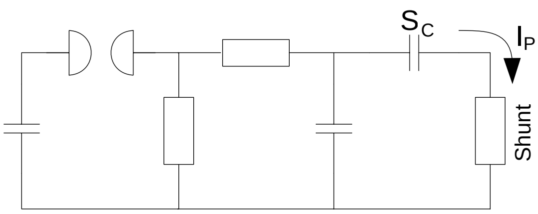


Figure 5 - Circuit used to obtain the curve from Figure 6

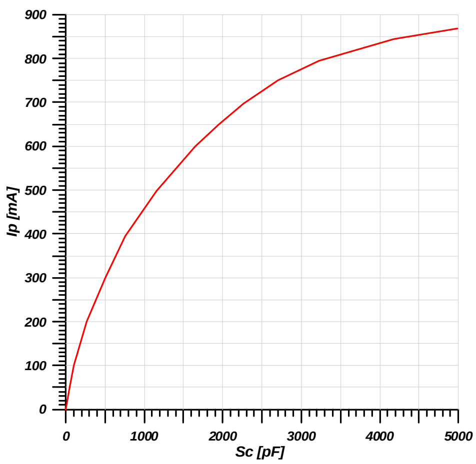


Figure 6 – Peak-Current versus Winding Self-Capacitance

From the first current peak of a lightning impulse oscillogram and curves similar to that shown in Figure 6 it is possible to get the S_C.

Model Parameters Composition

Applying the real parameter values to the model of Figure 1, it is possible to find results as shown by Figure 7.

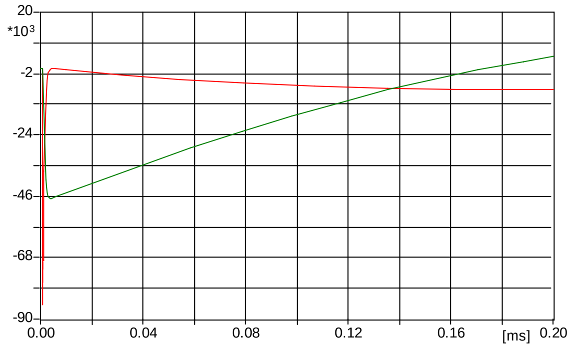


Figure 7 – Composition of the winding model simulated in ATP program – voltage and current waves

THE MODEL ACCURACY

To verify the model accuracy it was applied a voltage impulse to an actual 15 kVA, 95 kV BIL single-phase transformer. Figure.8 shows the reduced full-impulse and the first full-impulse [3]-[4]. These oscillograms show the shape of the total current ground [4]. Figure 9 shows the testing and the simulated current attachment.

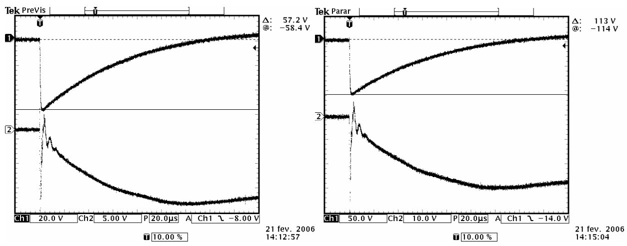


Figure 8 – Applied voltage impulse in an approved transformer

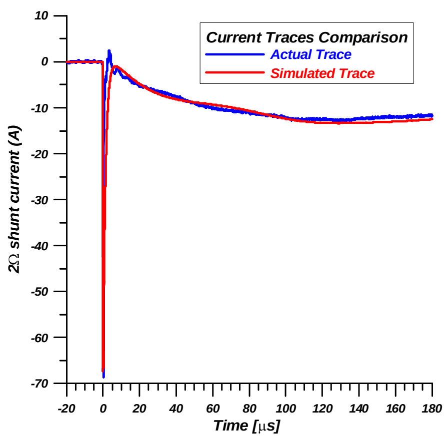


Figure 9 – Comparison between testing and simulating results

FAILURE SIMULATIONS

The ATP failure simulations consider the circuit of Figure 10 where each short-circuit is modeled by the closing of the switches in each part of the divided winding. R_{CC} is dimensioned according the ATP simulation convenience and R is the value of the used shunt during the actual test.

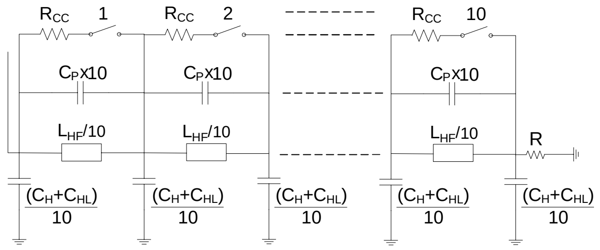


Figure 10 – Winding model to the failure simulations

To the comparison between the actual and the simulated results it was considered a 15 kVA, 150 kV BIL single-phase transformer.

Full-wave failure simulations

Figure 11 shows the comparison between the actual and simulated current for the first full-impulse [2]-[4]. The observed difference in the end of the wave can be addressed to the difference in the transformer internal construction, or to difference between the actual number of turns in short-circuit and the number considered by the simulation.

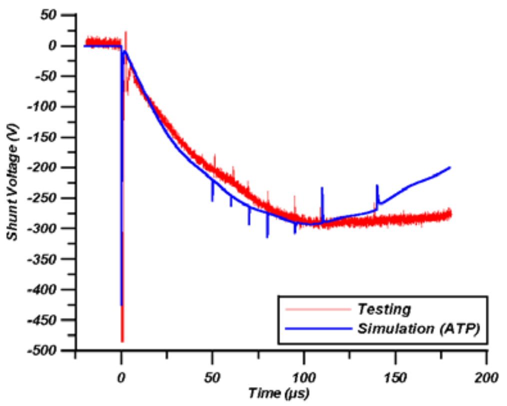


Figure 11 – Comparison between Testing and Simulation Results

Chopped-wave failure simulations

Figure 12 shows the comparison between the actual and simulated chopped impulses. Voltage traces at left and current traces at right side.

The failure signal on the voltage trace was amplified in the current trace. It is possible to show with several impulse test results that for an approved transformer there is no distortion at the beginning of the current wave of the chopped impulse. This simulation, as others suggest that the use of chopped wave current trace must be considered on evaluation of a transformer.

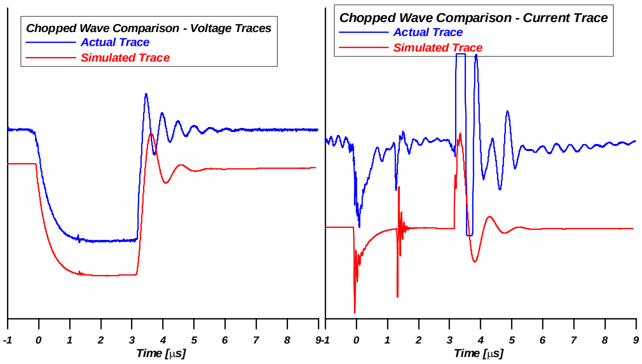


Figure 12 – Reduced chopped Impulse – actual and simulated traces comparison

Figure 13 shows, respectively, the first and the second chopped-wave [2] - [4] applied to a 75 kVA, 150 kV BIL three-phase transformer. There is not any failure signal in the voltage wave, and beside the difference in the chopp-time, there is no distortion in the current wave.

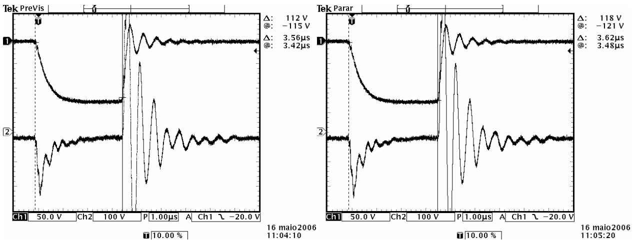


Figure 13 – First and second chopped-wave applied to an approved transformer

SCALES OF DIGITAL RECORDERS AND OSCILLOSCOPES

Figure 14 shows the oscillograms of a reduced impulse applied to a 15 kVA, 150 kV BIL single phase transformer acquired simultaneously by a standard digital oscilloscope of 9 bits 2.5Gs/s per channel and a prototype 12 bits 50Ms/s per channel digital recorder of internal development.

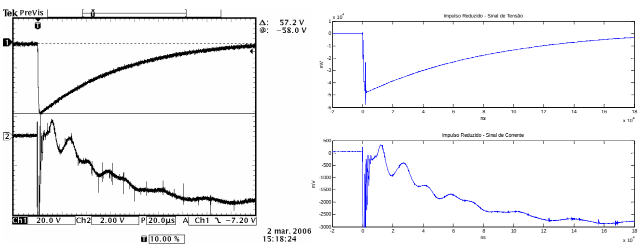


Figure 14 – Reduced impulse in a transformer with turn-to-turn short-circuit

In this case, the digital oscilloscope – at left – could not register the insulation failure in the voltage wave – channel 1 – as did the prototype digital recorder. This can be attached just to the time scale as it will be possible to see. The current wave – channel 2 – shows some failure signals

due to corona or arc extinction from some insulation failure at the beginning of the winding. These signals are not so visible in the prototype digital recorder because the used probe attenuation.
By other side, closing the time scale from de 20 µs/Div in Figure 14 to 1 µs/Div in Figure 15, the failure visualization becomes so clear.

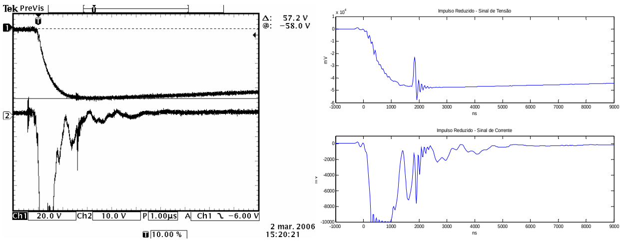


Figure 15 – Reduced full impulse with time scale 1µs/Div

The short-circuit signal at the beginning of the winding is showed in the voltage and current waves in both cases. It is possible to see that the sensitivity of the digital oscilloscope to the current wave is larger as to the voltage wave.
The most interesting point is that the used sweep time in this case is the same of the chopped waves [3], [4] and [5].

CONCLUSIONS

The model used in this paper does not take into account the construction characteristics of the transformers, and at certain point, the number of short-circuited turns. The parameters are simply obtained from the voltage impulse tests and from capacitance measurement. As it can be observed even without considering the construction characteristics the model presented a good attachment with the testing behaviour.
The recommendations on testing transformers according [2], [3] and [4] are clear for analogue oscilloscopes, but there is no mention about possibilities offered by the digital oscilloscopes and recorders. The same can be stated regarding some previous IEC equivalent standards.
It was possible to observe – added to ATP simulations – that some signals attributed to high frequency noise can be actual failures evidence as well as shunt flashover. Figure 12 and 13 show the possibility of considering the current of chopped waves in a transformer evaluation. The Brazilian Standards are not so clear about this point. But there is a mention in [5] about the use of the chopped-wave tests not suitable with the ground current method.
By anyway, the evaluation of the current of chopped wave or even the use of time scaling factors, common in some scopes and digital recorders can confirm that some signals in the full-wave current can be arc extinction signals of a turn-to-turn failure at the beginning of winding.

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