EFFECT OF FAST TRANSIENTS ON DISTRIBUTION TRANSFORMER INSULATION : SWITCHING TRANSIENTS MODELLING AND MATERIAL RESEARCH

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Summary: *Worldwide many transformer insulation failures have been reported caused by switching operations, while those transformers had previously passed all the standard tests and complied with all quality requirements. The problem is mostly associated with high-frequency overvoltages generated during opening or closing of a switching device. Therefore, a numerical model of a transformer and a circuit breaker are first of all combined and weighted against laboratory measurements. To improve the accuracy of the overall model, the transformer model is extended with a frequency dependent loss model. Secondly, it is important to know the sensitivity of the electrical insulation against these high frequency disturbances superimposed on the 50 Hz main voltage. To investigate this, material tests using an extended Tesla transformer are performed on 2 types of insulation materials: cast resin and paper-oil insulation.*

INTRODUCTION

During the last decade, many unexpected transformer failures have been worldwide reported. While first examinations may point to an unknown overvoltage phenomenon, closer investigations of the voltage waveform in a medium voltage (MV) substation often reveal the presence of fast transient overvoltages [1].

In MV networks the most typical example of fast transients is a switching transient caused by vacuum circuit breakers or - to a lesser extend - SF_6 circuit breakers. Due to their well-known pre- and re-striking effects, they are easily recognizable as potentially harmful sources of overvoltages. Therefore, extensive series of switching tests were performed in the laboratory [2] in order to measure switching transients in a test set-up, combining a test transformer and vacuum circuit-breaker. The measurements confirmed once again that these switching transients produce steep pulse trains within a wide range of frequencies. If these frequencies coincide with natural frequencies of the transformer windings, they may cause harmful voltage amplifications inside the transformer by exciting internal resonances. A picture of the re-striking process during the opening of a vacuum circuit breaker is shown in Figure 1. The voltage wave is measured at the high voltage terminals of the test transformer during the opening of the circuit breaker approximately at the instant of maximum current: the primary source voltage was 5 kV rms, while the maximum measured overvoltage was 35 kV peak. During an interval of 1.2 ms numerous re-strikes can be observed.

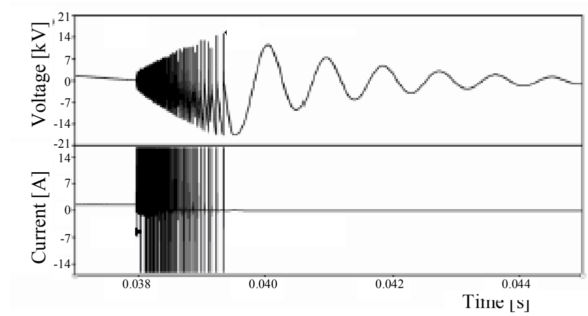

Figure 1 : Re-striking process at opening of vacuum circuit breaker

A numerical model of a circuit breaker as implemented in [2], is added to an existing distribution transformer model in order to simulate such switching tests. Finally, the transformer model is extended by a frequency dependent loss model, improving the accuracy of the simulations.

To verify the sensitivity of the electrical insulation material, used in a transformer, to such kinds of (over)voltages, laboratory tests are carried out for 2 types of materials. The materials are subjected to a disturbed voltage wave similar comparable to the one measured in a MV substation [1].

FREQUENCY DEPENDENT LOSS MODEL

To simulate the high-frequency behavior of a transformer in its electrical environment a dedicated transformer model is required. While general high-frequency models are usually too large to be incorporated in a general system model, appropriate reduction techniques allow these models to be reduced to a more convenient size. For efficiency reasons, a reduced model was built [1], aiming for a compromise between calculation time, flexibility and accuracy in the prediction of the first resonance frequencies, as they are typically excited by transient network disturbances.

The duality based model represents the leakage fluxes by an inductive polygon [3]. The elements of this polygon can be derived from the corresponding short-circuit inductances, that can be obtained both numerically as well as experimentally. This approach was chosen because it's reasonably simple and has already proven to represent the essential transformer resonances. The high voltage layer winding is broken up into smaller segments. Depending on the required accuracy, this can be done on a per turn basis, on a per layer basis, or with any segmentation in between. Figure 2 shows the principle of the model structure. For sake of clarity the high voltage winding in this figure is only broken up in 3 segments, which is of course inadequate for practical calculations.

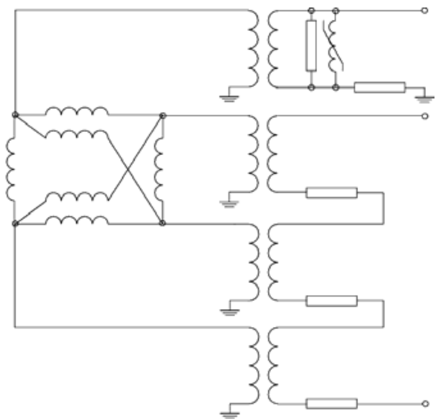

Figure 2 : Transient model with 4 winding segments

The model is built on a leakage inductance polygon, describing the leakage field of the transformer. The actual winding segments are connected to this polygon by means of ideal transformers, allowing the inductive elements to be on a common voltage level, preferable the voltage level of the reference-winding segment. The leakage inductances are calculated in a four-step process:

- The first step consists in the calculation of the short-circuit reactances X_{ij}. These are calculated using a modified Rabin's procedure.
- In a second step the bus impedance matrix Z_{BUS} is determined.
- The corresponding admittance matrix Y_{BUS} is then obtained by inversion.
- Finally the leakage inductances are calculated.

The non-linear magnetizing inductance is connected at the terminals of the inner low voltage winding, by analogy with the traditional equivalent circuits of a transformer. A parallel resistance is included here as well, in order to represent the frequency-dependent core losses. The model is finally completed with a series resistance, to account for the copper losses in each winding segment, with series capacitances for each winding segment, and with shunt capacitances between neighboring winding segments.

The influence of core losses is now investigated and compared to the realistic data measured in the laboratory. The description of eddy currents is a very complex problem. Basically the core losses are calculated based on the Dowel's theory [4], [5]. As a result of the calculations we obtain an equation of the core losses. It's of course frequency dependent and in this way it cannot used in EMTP. To be able to incorporate it to EMTP calculations, we must find an equivalent circuit with lumped parameters. The useful solution for this task is a circuit build from Foster sections [6]. Most accurate approach we got from Cauer sections Figure 3. The model obtained in this way reproduces exactly the impedance at all frequency.

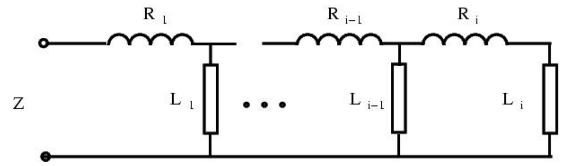

Figure 3 : Subsitute Z schema for EMTP calculation

The whole modeling process has been integrated in an EMTP pre-processing program. The inputs are the geometric and material properties of the transformer; the output is an EMTP-input file to be used in transient runs or frequency scans. Extra options are available to investigate the influence of connected cables and surge protection devices. The results of the modeling made by EMTP are shown on Figure 4. At 62 kHz, the simulation shows that there is a very marked danger for resonances.

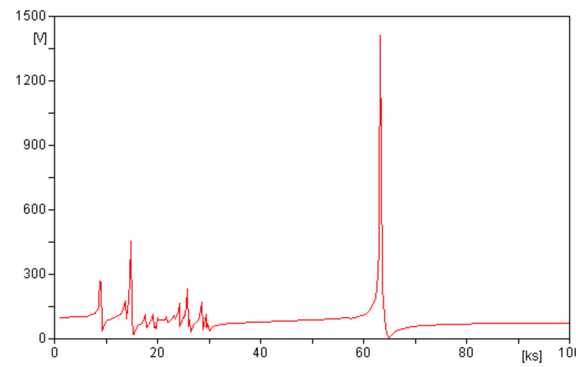

Figure 4 : Frequency scan for testing transformer 0..100 kHz

MATERIAL TESTS

General Test Setup

All the material tests are carried out using a disturbed 50 Hz high voltage (HV) waveform consisting of two sub-waves: a high frequency (HF) disturbance, representing a fast transient, is superimposed on the 50 Hz mains voltage. The existence of such voltages in the medium voltage grid was proven by a long-term measurement campaign [1]-[7]. The disturbances can reach a peak to peak value of more than 50 % of the 50 Hz voltage amplitude and usually have a dominant frequency between 20 kHz and 100 kHz. Almost all of the fast transients occur near the peaks of the mains voltage. An example of such HF-HV waveform is displayed in Figure 5.

To reproduce these HF pulses superimposed on the rated 50 Hz base voltage and to check their combined effect on the distribution transformer's insulation, an extended Tesla Transformer circuit was built in the laboratory. A simplified drawing of the test circuit is shown in Figure 6. The basic element is a Tesla transformer [8]-[9] supported by four additional building elements:

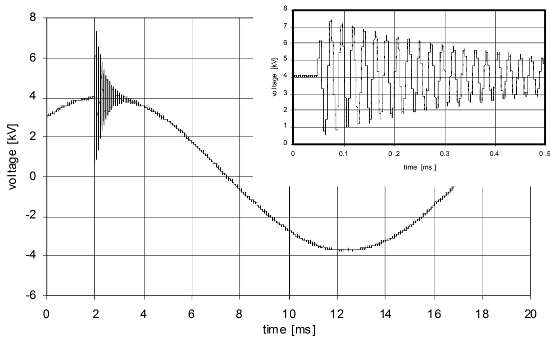

Figure 5 : Reproduction of one HV-HF disturbance

- the 50 Hz main voltage and 50 Hz coupling,
- a measurement circuit,
- a control unit to fire the Tesla transformer,
- the test object.

A detailed description and operating procedure of the circuit can be found in [10]-[11].

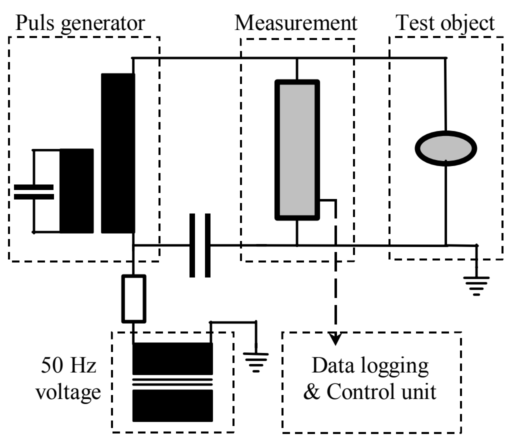

Figure 6 : Simplified laboratory set-up

The superimposed HF-pulses are applied to two different test objects: the first test object consist of a traditional needle-plane set-up cast in a commercially used resin for in electrical apparatus. The second test object uses a small winding configuration impregnated in standard transformer oil. Both tests will be discussed briefly.

Cast Resin: Needle-Plane Setup

The needle-plane set-up accounts for the following observations: the plane is a normalized aluminum plate electrode with a smooth surface and rounded corners to eliminate disturbing edge effects. The needle has a sharp point cut in 1 direction with a top radius of less then 0.12 mm and is placed in a aluminum carrier. The distance of the needle's shaft is according to [12] more than 10 times the length of the needle's point. This is necessary to ensure that the carrier to which the HV is applied does not disturb the electrical field between needle and plane. The distance between needle and plane is frozen to 2 mm. The set-up is placed in a cylindrical plastic container filled with a cast resin in a controlled atmosphere. A technical drawing is shown in Figure 7.

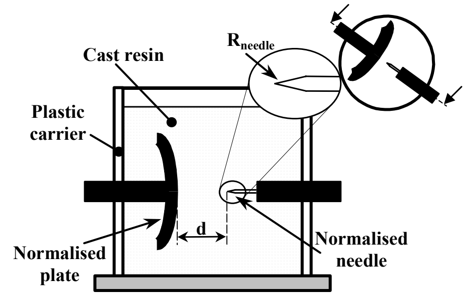

Figure 7 : Needle-plane set-up in cast resin

The resin used is STYCAST 1264. It is a low viscosity transparent resin with 2 components. The epoxy component is based on a bisphenol-A while the hardener is based on an amine. The mixture can easily be manipulated under atmospheric conditions and behaves also very well under vacuum, which is important during curing to evacuate all air inclusions and voids. Some electrical properties are summarized in TABLE 1 [13].

TABLE 1 : Electrical properties of STYCAST 1264

Property	Test Method	Value
Dielectric Constant @ 60 Hz	ASTM-D-150	3.7
Dissipation Factor @ 60 Hz (tgδ)	ASTM-D-150	0.008
Temperature range	-	-65 to +105 °C

During the tests, the voltage is applied to the needle's carrier while the plane is connected to earth. The test procedure is divided into two sub-cycles. A first cycle initiates a small tree or pre-breakdown using only a 50 Hz voltage. This can be justified as follows: in general it is not required to initiate a tree with the HF pulses because by examining a real situation it is clearly that there are a lot of possibilities to trigger a tree by only a pure 50 Hz voltage. For instance, the triggering can be done during the routine partial discharge (PD) tests in the factory. When the initiated treeing is small, it is possible that the measured PD stay below the standard limits and that this small tree does not affect the transformer in service when he is only subjected to its rated 50 Hz voltage. The key knowledge is whether or not there is a further development of this treeing under influence of HF disturbances. Therefore, to investigate this last statement, a second test cycle applies a combined voltage with a wave shape like Figure 5 to the test object.

Several test cases are carried out on the cast resin test samples. During the first test case, only a 50 Hz voltage is applied to explore the limits of the test object and to search a safe 'PD-free' voltage. Since the voltage is PD-free, there will be no further development of the pre-breakdown when applied. This voltage can then be used as 50 Hz base voltage for the HF pulses. It is essential to apply a 'safe' base voltage because the aim of the research is to investigate the accelerated ageing of the insulation material subjected to a number of HF pulses superimposed on the base voltage and not the progress of the treeing under the 50 Hz voltage. A second series of tests applies the combined waveform with a fixed time interval of 0.8 s between two consecutive HF pulses. The HF pulses are added to the positive top of the 50 Hz sine wave. The last test case is carried out with only pulses separated by the same time interval of 0.8 s. The three tests cases are summarized in TABLE 2.

TABLE 2 : Summary of 3 test cases

50 Hz base voltage	HF-pulses Peak to peak value	HF-pulses Frequency	Number of pulses to breakdown
Test case 1			
32.7 kV	-	-	75000 cycles
Test case 2			
1.5 kV	38 kV	67 kHz	129337
Test case 3			
-	38 kV	67 kHz	134425

To initiate a tree, a voltage of 15 kV (50 Hz) is applied during 5 min. In general this voltage seems to be sufficient to exceed the intrinsic dielectric strength of the epoxy resin to initiate and propagate the pre-breakdown channels in a controlled way. The length of the pre-breakdown is in all three cases between 0.45 and 0.52 mm. Further investigations show that a voltage of 5 kV (50 Hz) (during more then 10 h) does not process the tree of the pre-breakdown.

Comparing the initiation with test case 2, it can be noted that during both cases a voltage with the same amplitude positive peak value is applied to the test object (1):

$$\begin{aligned} &\text{Test case 2}: 1.5\,\text{kV}\cdot\sqrt{2}+38\,\text{kV}/2=21.12\,\text{kV} \\ &\text{Initiation}: 15\,\text{kV}\cdot\sqrt{2}=21.21\,\text{kV} \end{aligned} \qquad (1)$$

However, the physical effect of both voltages is different. The initiating voltage is a continuous AC-voltage while the combined voltage of test case 2 has a more pulsed nature (in relation to the resin). Treeing under a continuous voltage will be the result of a combined electrical (overvoltage) and thermal effects. Contrary, when using the combined waveform, the development of the tree is only the result of an overvoltage effect since the time between 2 consecutive pulses can be considered as thermally infinite.

Observations of the development of the channel in cases 2 and 3 result in similar conclusions: visual inspection of the channel show that after a number of pulses the pre-breakdown becomes thicker and the number of channels is increasing. Some pulses later, a number of thin channels in the direction of the plane are developed. After thickening those channels, additional thin channels are developed near the plane electrode until an accelerated and fast branching of these channels initiates a breakdown in only one channel. It has to be noticed that in test case 2 the presence of the 50 Hz voltage can still influence the accelerated branching and final breakdown. Therefore, no base voltage is applied in test case 3. However the results are almost similar: there is a breakdown in only one channel and the number of pulses until breakdown is almost the same, but the tree shows less branching.

From time to time the PD inception voltage and the length of the channel in the shortest direction of the plane, from the tip of the needle perpendicular to the plane is measured. Both parameters are displayed in Figure 8 respectively in Figure 9 as function of the number of HF pulses.

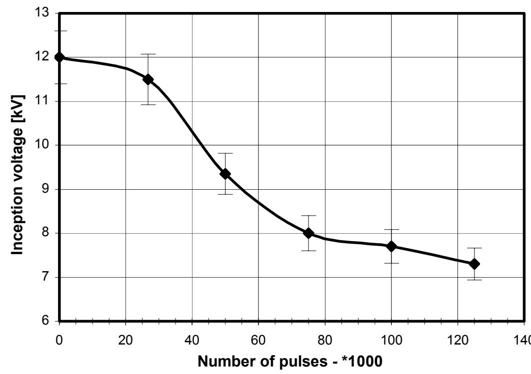

Figure 8 : PD inception voltage as funtion of the number of HF pulses

From Figure 8 it can be derived that the PD inception voltage close to breakdown is decreased to almost half of the initial PD inception voltage after the initiation of the pre-breakdown. Investigating the length of the tree, Figure 9, yields the following conclusion: in first instance, the length of the channel, resulting from the pre-breakdown, remains almost constant with increasing number of pulses. At a certain moment (20000 pulses), the channel grows in a linear way with the number of pulses. At about 80-85 % of the distance d, the tree is growing very fast with only a small number of pulses. This is approximated in Figure 9 with a broken line. Those conclusions are almost similar to those given by Zoledziowsky [14], where the ageing of cast resins is investigated under one single waveform of 1/50 µs pulses with a pulse rate of 2-2.5 pulses/s.

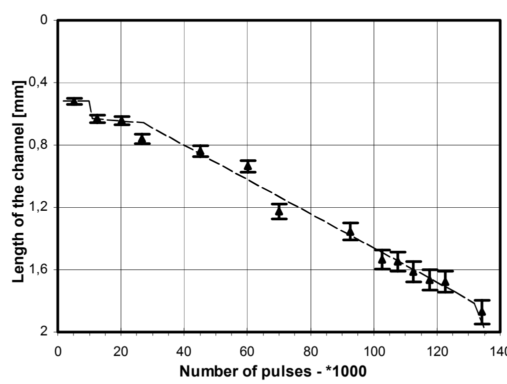

Figure 9 : Lenght of the treeing channel as a funtion of the number of pulses

Finally a picture of the breakdown channel between the needle and plane is displayed in Figure 10 (case 2).

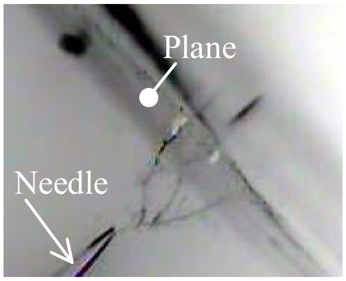

Figure 10 : Channel and breakdown between needle and plane

Paper-Oil: Equivalent Winding Configuration

A second test series is performed using a small winding configuration equivalent to a double layer of a transformer. The set-up is schematically drawn in Figure 11. A number of Copper windings are attached and electrically connected to an Aluminum electrode, earthed during the tests. The separate windings are insulated with two paper layers. Opposite to the wires is a normalized plane electrode, connected to the high voltage. Between plane electrode and wires, there are few layers of orpoxy paper insulation as used in a double layer of transformers. The winding configuration is placed in a cylindrical plastic container and impregnated under vacuum by standard transformer oil.

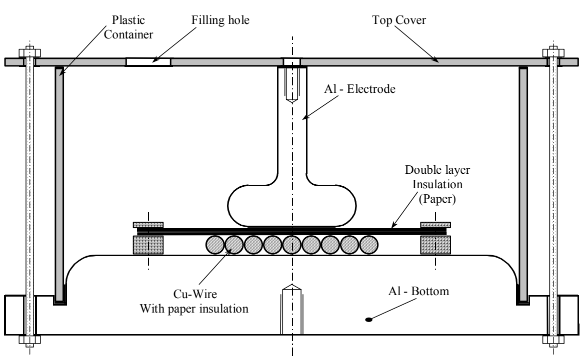

Figure 11 : Paper-Oil set-up - winding configuration

By doing this, the electrical field generated between the wires and the plane electrode of the test set-up is almost similar to the electrical field between 2 opposite windings of a double layer of a transformer winding. In the end, it is also easy to integrate a small perturbation, such as sharp point or voids, between the plane electrode and the wires to investigate their effect.

The test procedure is the same as with the cast resin test samples: a number of pulses superimposed to a 50 Hz base voltage is applied to the sample. However, due to the small distance between plane and wires, the visualization of the treeing is no longer possible. Therefore, in order to have an idea of the ageing of the insulation materials, an antenna is introduced in the test sample. This antenna is used together with a spectrum analyzer to pick up and accumulate the produced PD's. As the tests are still running, it is too early to draw conclusions at this time.

CONCLUSIONS

To simulate the high-frequency behavior of a transformer in its electrical environment a dedicated transformer model is required. Therefore, a numerical model of a vacuum circuit breaker is add to an existing distribution transformer model in order to simulate switching tests. The results are compared to measurements in the lab. Finally, in order to improve the accuracy of the simulations, the transformer model is extended with a frequency dependent loss model.

The real lifetime characteristics of two types of commercially used electrical insulation materials, such as cast resin and paper-oil insulation, are investigated. The insulation materials are subjected to a combined voltage wave constructed of HF-pulses superimposed on a 50 Hz voltage carrier. The cast resin is tested using a typical needle-plane set-up, while for the tests with paper-oil insulation, a winding sample configuration is built equivalent to a transformer's double layer. First results obtained from the cast resin tests show that the degradation of the insulation can be accelerated due to the cumulative effect of these HF voltage surges, even when the power frequency voltage does not exceed the PD inception voltage. The ageing effect is comparable – though not identical – to ageing under 50 Hz or steep front voltages. Further tests with paper-oil insulation are still running and at this time it is not possible to draw final conclusions.

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