

The ageing of electrical insulation materials subjected to combined voltage waves at different frequencies

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Abstract: Power quality problems are well known in low voltage grids. Over the last decade, they also become increasingly important in medium voltage grids. Closer investigation of the medium voltage in a substation confirms the existence of fast transients superimposed on the 50 Hz main voltage. Most of these fast transients are due to switching operations of vacuum circuit breakers and may affect the ageing of the electrical insulation materials used. Therefore, it become increasingly important to review the co-ordination of the electrical insulation and investigate this deterioration due to the combined effect of high and low frequency voltages at the same time. A test circuit based on a Tesla transformer is built in the laboratory to reproduce a disturbed medium voltage. First results obtained from ageing tests at cast resin confirms that the degradation of the insulation can be accelerated due to the cumulative effect of HF voltage surges without that the power frequency voltage exceeds the partial discharge inception voltage.

1. Introduction

During the last decades problems related to power quality issues as voltage dips and even more important high frequency (HF) pulses, in literature better known as fast transients, superimposed on the 50 Hz main voltage appears not only in low voltage grids but also in medium voltage (MV) grids [1]. Besides their possible influence on automated production centres, they also have a major impact on the electrical equipment itself, more specific on electrical insulation materials. Different study comities around the world have, over the last decade, reported many unusual failures of electrical machines, motors and transformers in the MV grid. Closer investigations mostly point towards the presence of fast transients in the MV grid.

The most typical example of fast transients or MV power quality problems is an overvoltage due to switching operations caused by vacuum circuit breakers or -to a lesser extend- SF₆ circuit breakers. The use of such equipment introduces resonance's resulting in extremely high voltages at a high frequency, superimposed to the 50 Hz main voltage (Figure 1) [2]. Since the electrical insulation is not developed for these voltage waves, problems like

unexpected breakdown and accelerated deterioration may occur.

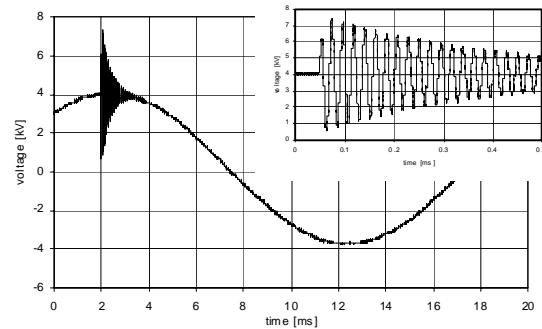


Figure 1 : Example of a fast transient superimposed to the 50 Hz main voltage - Reproduction in the laboratory

Until now, no tests are executed to evaluate the insulation for such a combined waveform (Figure 1). Therefore, a medium voltage test circuit based on a Tesla transformer is developed to produce the required waveform and to investigate the ageing effect of insulation materials. The aim is to cover the gap between the classical tests at DC or 50 Hz and the tests at higher frequencies according to the standards.

2. Test circuit

To reproduce this disturbed 50 Hz voltage wave with its HF pulses, an extended Tesla Transformer circuit is built in the laboratory. A drawing of the test circuit is shown in Figure 2. The basic element is a Tesla transformer [3]-[4]-[5], supported by 4 additional building elements: the 50 Hz main voltage and 50 Hz coupling, a measurement circuit, control unit to fire the Tesla transformer and the test object. An introduction to the concept, the operating procedure and practical relevance of the test set-up will be briefly discussed in the next paragraph, more details are available in [5].

Extended Tesla transformer: Principle

The main element of the test circuit, the Tesla transformer (TT), consists of 2 coils L_1 and L_2 , air-coupled, and 2 capacitors. Contrary to the traditional use of a TT [3], only producing a high voltage with a constant high frequency and amplitude, this circuit, designed according to the same principle, generates

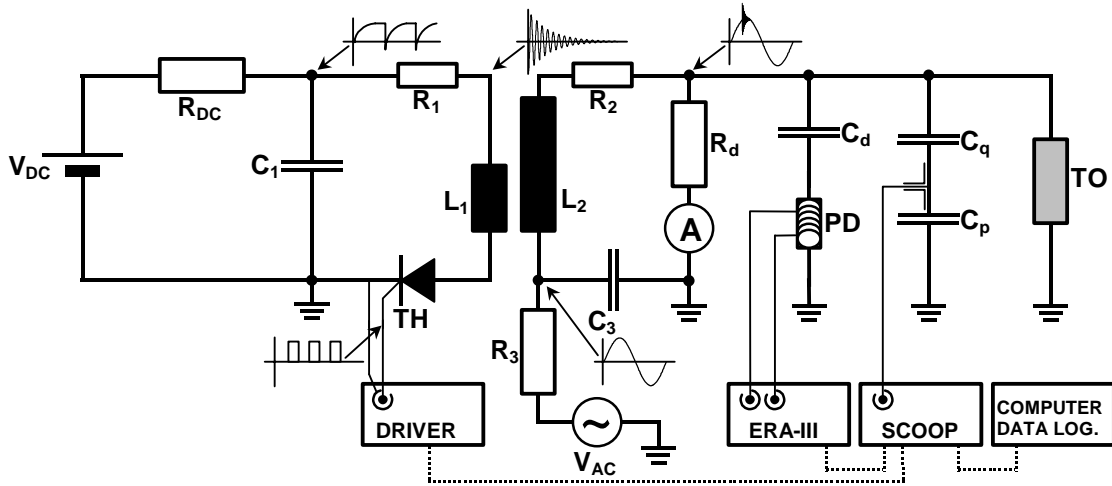


Figure 2 : Test circuit - Extended Tesla Transformer to reproduce fast transients superimposed to the 50 Hz main voltage

decaying high frequency pulse trains superimposed on the 50 Hz fundamental voltage.

The principle of the TT is based on the transfer of energy between two magnetically air coupled and perfectly tuned resonating circuits, a primary circuit C_1 - L_1 and a secondary circuit C_{tot} - L_2 . The primary capacitor C_1 acts together with the primary coil L_1 and its winding resistance R_1 as an $R_1L_1C_1$ -resonating circuit resulting in a damped oscillating wave of a given frequency f_1 . The first oscillations of this wave fire a secondary $R_2L_2C_{tot}$ resonance. The capacitor C_{tot} represents the overall capacitive value of the secondary circuit: capacitive divider C_q and C_p , the coupling capacitor of the partial discharges (PD) C_d , the 50 Hz coupling capacitor C_3 and the test object. When both circuits are perfectly tuned (1):

$$L_1 \cdot C_1 = L_2 \cdot C_{tot} \quad (1)$$

the damped oscillating voltage wave appearing at the top terminal of the secondary coil has a frequency f_2 of:

$$f_2 = \frac{1}{2\pi} \sqrt{\frac{1}{L_2 C_{tot}} - \frac{R_2^2}{4L_2^2}} \quad (2)$$

and a huge magnitude $U_{C_{tot}}$ depending of the pre-charging U_{C_1} of C_1 and the efficiency η of the energy transfer (3):

$$U_{C_{tot}} = U_{C_1} \cdot \eta \cdot \sqrt{\frac{C_1}{C_{tot}}} \quad (3)$$

A driver controls the position of the HF pulses with respect to the 50 Hz base voltage and triggers the thyristor to fire primary resonance. Measurements are performed through a partial discharge detector (ERA-III) and an oscilloscope coupled through a GPIB link and a LabVIEW program to a computer used for data logging. Since the test object is also part of the secondary resonance circuit, it can be said that the test circuit is inherent safe against open circuit failures and short circuits or electrical breakdown of the test

sample. If (1) is no longer guaranteed, the resonance disappears and the voltage across the test object collapses as there is no energy transfer.

The capabilities of the test circuit are in the order of but not strongly fixed to:

- 50 Hz voltage: adjustable from 0 V to 36 kV
- HV-HF-pulses: up to 38 kV peak to peak
- Frequency range: from 1 kHz up to 100 kHz

Practical use in the laboratory and relevance

A study on the commercially available systems generating a HF pulse train and adding them to an external voltage carrier shows that there are only a limited number of possibilities. Besides very expensive commercial systems, as burst generators, one of the better and cheaper solutions is to use a circuit containing a Tesla transformer. Developing a test circuit ourselves has several advantages. The most important one is that there are fewer restrictions regarding the generation of the required waveforms compared to commercial circuits.

Besides the use of the test circuit for accelerated ageing tests, it can also be used to inject typical power quality problems as voltage dips and HF disturbances into the grid. Important to mention is that these injections can take place up to a medium voltage scale. After all, it is possible to inject and to add a high frequency voltage of adjustable frequency and amplitude at an adjustable position against the base voltage to the base voltage carrier.

Other possible applications of a Tesla transformer can already be found in some medical systems (X-Ray) and in the movie industries (generating breakdowns in air). However a lot of other application areas are feasible. Due to the combination of high electrical and magnetical fields, the TT can have some useful applications in the food industry or in the more specialised medical sector and health care. Also the

technical application area can be very widespread: disturbing radar waves, use as triggering device for the ignition of lamps or the use as a didactical laboratory set-up for the students.

3. Material tests

Test object: Cast resin and paper-oil insulation

The HF-HV pulses as shown in Figure 1 are in first instance applied to a test object containing a needle-plane set-up cast in a commercial resin, Figure 3. The distance between needle and plane is 2 mm and the mean radius of the needle tip is $R_{\text{needle}} = 125 \mu\text{m}$.

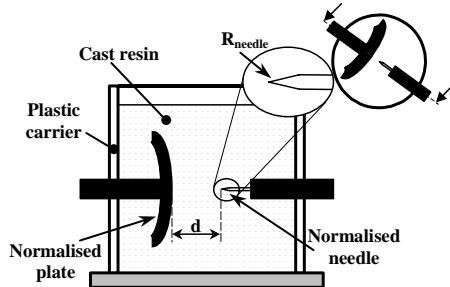


Figure 3 : Needle-plane set-up in a container cast with resin

The cast resin, STYCAST 1264, is a low viscosity transparent resin with two components: a bisphenol-A based epoxy component and an amine based hardener. The mixture can easily be manipulated under atmospheric conditions and behaves also very well under vacuum during curing. The electrical properties are according to [6] summarised in Table 1:

Table 1 : Electrical properties of STYCAST 1264

Property	Test Method	Value
Dielectric Constant @ 60 Hz	ASTM-D-150	3.7
Dissipation Factor @ 60 Hz ($\text{tg}\delta$)	ASTM-D-150	0.008
Temperature range	-	-65 to +105 °C

Using a needle-plane set-up to perform the first ageing tests has several advantages. The needle-plane set-up is very well known in the high voltage test techniques and allows to compare results with ageing characteristics obtained with only DC voltages, 50 Hz voltages and steep front voltages (lightning - and switching impulses) [7], [8], [9]. Another advantage is that it is easy to estimate the electrical field between needle and plane [10].

At the time of writing the paper, a second series test using paper-oil insulation is running. It is expected that an accelerated ageing will be seen, but as the tests are still running it is too early to draw final conclusions.

Results from ageing tests on cast resin

After initiating a pre-breakdown of less than 0.4 mm by using only a 50 Hz voltage, pulses or fast transients superimposed to a 50 Hz main voltage wave are applied to the needle. During the tests, the plane is always earthed. The high frequency voltage pulses have a peak to peak value of 38 kV at a frequency of 67 kHz and are placed at the top of a 1.5 kV voltage with a frequency of 50 Hz (Figure 1).

From time to time the partial discharge (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. Those 2 parameters are displayed in Figure 4 as function of the number of pulses. It can be derived that the PD inception voltage (bold line in Figure 4) close to breakdown is decreased to almost half of the PD inception voltage after the initiation of the pre-breakdown. Investigating the length of the tree (broken line in Figure 4) leads to the following conclusion: first, the length of the channel, result of the pre-breakdown, remains almost constant with increasing number of pulses. At a certain number of pulses (20000 pulses), the length of the channel increases in a linear way with increasing number of pulses. At about 80-85 % of the distance d , the tree is growing very fast with only a small number of pulses. Those conclusions are almost similar to those given by Zoledziowsky [11], where the ageing of cast resins is investigated under one single waveform: 1/50 μs pulses with a pulse rate of 2-2.5 pulses/s.

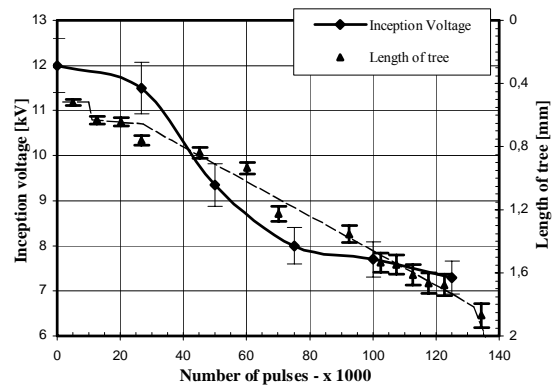


Figure 4 : Partial discharge inception voltage and length of the tree versus number of pulses (STYCAST 1264)

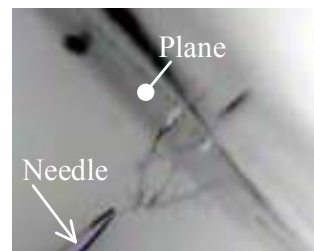


Figure 5 : Channel and breakdown between needle and plane

Finally a picture of the breakdown channel between the needle and plane is displayed in Figure 5. It can be noticed that the breakdown has developed itself following few channels starting at the needle's tip.

4. Conclusions

Measurements on different places in the grid have confirmed the existence of unusual waveforms: a combination of fast transients superimposed to the 50 Hz main voltage. The origin of this medium voltage power quality problems, is mainly found in switching operations of vacuum circuit breakers in the medium voltage electrical grid. Together with the network elements, this waveform initiates internal resonance's in the electrical equipment. Therefore, it becomes increasingly important to review the combination of the electrical insulation as a lot of research is already done in investigating the failure mechanism of insulation materials subject to DC voltage, low frequency voltages or steep front voltages. But until now, there is still a gap between the test waves at low -and high frequency. With the advancing power quality problems and politics, it is necessary to investigate the impact of a combined low -and high frequency voltage to the insulation materials.

In the laboratory, a test circuit is developed to reproduce this disturbed waveform. The circuit, based on a Tesla transformer and extended with a coupling unit to the 50 Hz base voltage, is able to add a high frequency voltage of adjustable frequency and amplitude at an adjustable position against the base voltage. Finally, the circuit is used to investigate the ageing effect of insulation materials such as cast resins and paper-oil insulation.

First results obtained from the tests to cast resin confirms that the degradation of the insulation can be accelerated due to the cumulative effect of HF voltage surges without that the power frequency voltage exceeds the PD inception voltage. The ageing effect is comparable – though not identical – to ageing under 50 Hz or steep front voltages. Second test series on paper-oil insulation are still running and not yet ready to draw final conclusions.

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