THE IMPACT OF REPETITIVE COMBINED VOLTAGES WITH LOW AND HIGH FUNDAMENTAL FREQUENCIES ON THE AGEING OF CAST RESIN

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SUMMARY

Due to the increased unbalanced loading of electrical grids, the penetration of power electronics and an increased number of switching phenomena in low and medium voltage grids, it is obvious that electrical insulation systems are no longer subjected to only a 50 Hz, purely sinusoidal voltage. The existence of fast transients, switching impulses or in general combined voltages with at least two clearly distinguishable frequencies affects the ageing mechanisms and expected lifetime of electrical insulation systems.

Some typical fast transients superimposed on the main 50 Hz voltage are generated in the laboratory by using a Tesla transformer and supplied to a commonly used cast resin insulated system. One of the most important conclusions confirms an accelerated accumulated ageing mechanism of the resin due to the combined fast transient pulses. This specific ageing is also modelled by an equivalent ageing effect using only a 50 Hz sinusoidal voltage having a crest value of 127 % of the highest peak value ever measured for the superimposed fast transients.

INTRODUCTION

During the last decades problems related to power quality issues as voltage dips and swells, and even more high frequency (HF) pulses, fast transients superimposed on the 50 Hz main voltage, Figure 1, appears in both the low and medium (MV) or high (HV) voltage grids [1].

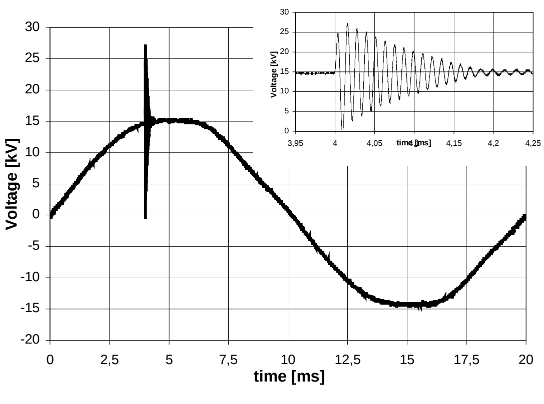

Figure 1 : Fast transient superimposed to the 50 Hz main voltage - Reproduction in the laboratory

These transients not only have a major impact on for instance automated production centres, but also affects the electrical equipment itself, more specifically the electrical insulation materials. This statement is reinforced by several reports of different study committees: many unusual failures of electrical machines, motors and transformer in the MV-grid were reported. Closer investigation mostly points towards the presence of fast transients in these grids.

Overvoltages due to switching operations mainly caused by vacuum circuit breakers and –to a lesser extent– SF_6-circuit breakers are typical examples of fast transient MV power quality problems. The use of those circuit breakers may introduce resonance's in the MV-grid, resulting in extremely high voltages at a high frequency superimposed on the 50 Hz main voltage (Figure 1). Since the major part of electrical insulation is not developed for this voltage waves, unexpected problems like dielectric breakdown and accelerated deterioration may occur.

Until now, no tests are executed to evaluate the insulation subject to such combined HF-HV waveforms. Therefore, a MV test circuit is developed in the laboratory to generate the combined voltage shape and to investigate the ageing effect on insulation materials. The aim is to give a first move in covering the gap between the classical standardized tests at DC or 50 Hz and the impulse tests at higher frequencies. The effect of such kind of waveforms on the development and growing speed of partial discharges in a typical cast resin is already reported in [2]. This paper focuses mainly to the comparison of the ageing mechanism under the combined HF-HV pulses and the 50 Hz ageing of the same cast resin.

TEST CIRCUIT & TEST SAMPLES

Extended Tesla-Transformer

To produce the required waveform of Figure 1 in order to investigate the ageing effect on insulation materials subject to combined HF-HV voltages, an extended Tesla transformer is developed and built in the laboratory [2]. A simplified drawing is shown in Figure 2. The basic element of the circuit is a Tesla transformer TT [3] supported by 4 additional blocks: the 50 Hz main voltage U_{50Hz} and its coupling capacitor C_C to the Tesla circuit (TT), a measuring unit and the test sample C_T. A detailed description of the test circuit is given in [2].

Test Samples

In order to get a general test object, which can act as a reference through all the measurement, a typical needle-plate set-up is chosen, Figure 3. To avoid unwanted discharges and disruptions of the electric field between needle and plate, the plate is manufactured as a well-shaped aluminium electrode with smoothed surface and rounded corners. The position of the needle is perpendicular pointing to the middle of the plate at a distance d = 2 mm from the plate. This needle of polished steel has also a hyperbolically-shaped tip.

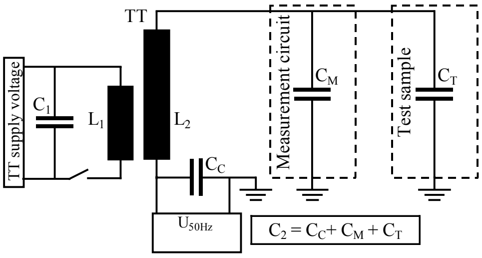

Figure 2 : Extended Tesla transformer circuit

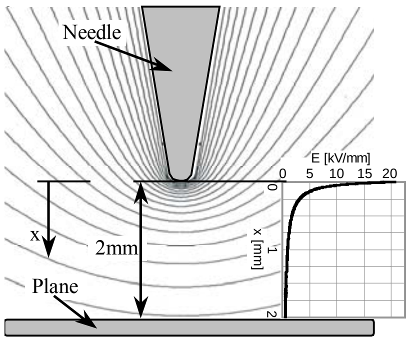

Figure 3 : Test sample - set-up

Through all the tests, the needle is connected to the test voltages, the plate to earth. Fulfilling the conditions given in [4], the electric field E vertically between the tip of the needle and plate can analytically be calculated from [4]:

$$E(x) = \frac{2 \cdot U}{\ln\left(4 \cdot \frac{d}{R_p}\right) \cdot \left(2 \cdot x + R_p - \frac{x^2}{d}\right)} \; [kV/mm] \qquad (1)$$

In (1) is R_p the radius of curvature of the tip of the needle and has a value of R_p = 0.125 mm.

A simplified view of the equipotential lines around needle tip and (1) are also given in Figure 3. A 50 Hz voltage of 5 kV was applied.

The former set-up is cast under vacuum using a common used, transparent resin STYCAST 1264 A/B [5]. Table 1 summarizes the most important electrical parameters. Those parameters are more or less comparable to the parameters of carbonates and polymers, but the resin is less efficient compared to ceramics [6]. As seen at the field distribution of Figure 3, applying a small voltage of 5 kV is sufficient to exceed the critical field strength of 14.76 kV/mm in the neighbourhood of the needle tip. This advantage enables to perform the required tests at a relatively low voltage when introducing a controlled ageing phenomenon in the cast resin starting at the tip of the needle and growing to the plate [2].

Table 1 : Electrical properties of STYCAST 1264 A/B

Electrical Property	Test method	Value	
Dielectric constant ε_r			
@ 60 Hz	ASTM-D-150	3.7	-
@ 1 mHz		3.3	-
Dissipation factor $\varepsilon_r tg\delta$			
@ 60 Hz	ASTM-D-15	0.008	-
@ 1 mHz		0.030	-
Resistivity ρ @ 25°C	ASTM-D-257	10^{15}	Ω-cm
Critical field strength E_{max}	-	14.76	kV/mm

AGEING RESULTS : PRACTICAL TESTS

Ageing at 50 Hz Sinusoidal Voltage

In order to have a reference to draw conclusions on the ageing of the used resin under the combined HF-HV impulses of Figure 1, similar tests are conducted on the same test object by applying a pure sinusoidal 50 Hz voltage. A brief summary of applied voltages and their number of periods until breakdown are given in Table 2.

Table 2 : Ageing @ 50 Hz voltage

Voltage [kV_{RMS}]	Voltage [kV_{PEAK}]	# 50 Hz periods
48.33	68.35	1
24.78	35.04	47 150
15.01	21.23	191 300

To compare the effect of several waveforms with a slightly different wave shape, it is important to use for all waveforms the same and most significant ageing parameter. As concluded in [7] and [8], this parameter is the highest peak value of the applied voltage. The peak values of the applied 50 Hz voltages are displayed against the number of 50 Hz periods until breakdown (ageing characteristic) in Figure 4 (solid line).

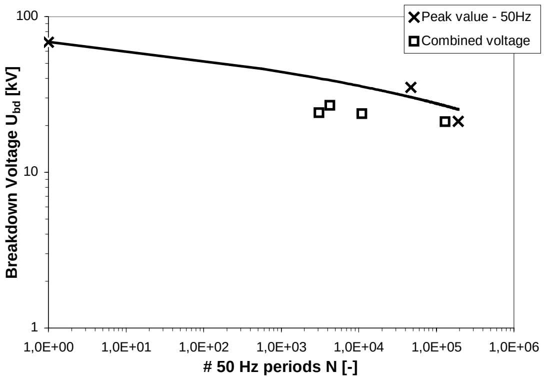

Figure 4 : Ageing model under 50 Hz voltage (x) and combined HF-HV pulses (□)

A possible analytical approach of this ageing effect is generally given by [9]:

$$n = \left[\frac{U_0}{U}\right]^{k_1} \Rightarrow \frac{1}{n}(\%) = \left[\frac{U}{U_0}\right]^{k_1} \cdot 100 \qquad (2)$$

In (2), n is the number of applied 50 Hz periods, U_0 the critical breakdown voltage, U the applied voltage and k_1 an empiric constant (depending on material properties, test conditions etc.). In this specific case the value of $k_1 = 19.25$ and $U_0 = 68.35$ kV.
The interpretation of (2) can also be that the cumulative ageing effect of a 50 Hz voltage with a peak value of U kV and a duration of a single period, can be expressed as 1/n (%) of the total ageing time or effect [9]. This interpretation is used further on in the paper.

Ageing at Combined LF/HF Voltage

To investigate the ageing effect of the pulses of Figure 1, a number of combined voltages is applied to the test object in the same manner as in the 50 Hz tests. Some combinations are briefly summarized in Table 3:

Table 3 : Different combinations for the combined HF-HV pulses

$U_{50\,Hz}$ [kV_{RMS}]	U_{FT} [kV_{PP}]	# pulses n to breakdown	$U_{peak,\,comb}$ [kV_{PEAK}]
1.50	38.00	129 337	21.12 †
7.50	29.6	3 071	24.15 †
10.00	29.81	4 237	26.90
10.00	20.28	10 974	23.80

† Initiation of pre-breakdown with 50 Hz voltage

Note that the 50 Hz RMS-value U_{50Hz} and the peak-to-peak value U_{FT} of the superimposed transient voltages are displayed in the table above. The FT-pulses are always superimposed to the positive top of the 50 Hz main voltage. According to previous research [10], a positive (peak) voltage applies a more severe condition to the system under test than an equivalent negative one. Taking this in consideration, it is sufficient to do the remaining calculations and comparisons only for the positive peak voltage. However, if partial discharges are involved in the channelling mechanism, peak-to-peak values should be taken. The time between two consecutive HF-HV pulses is always 1 s. Considering this, clearly the number of pulses n until breakdown equals the time until breakdown in seconds.

The maximum peak value $U_{peak,\,comb}$ of the combined HF-HV pulses are also displayed in Figure 4 by boxes '□'. Comparing the 2 ageing characteristics points towards an accelerated ageing when supplying combined HF-HV pulses. However, it is important to note that the former conclusion may not be drawn so easily. The definition for the time until breakdown is for both ageing mechanisms totally different. For the 50 Hz ageing, the number of applied *PERIODS* is used, while for the combined HF-HV pulses the number of applied *PULSES* is key. A closer view to one 'period' of a combined HF-HV pulse shows that the voltage combination includes 49 consecutive 50 Hz peaks at 20 ms (Figure 5: $U_{C,16}$-$U_{C,64}$), preceded by 15 peaks included in the HF-HV pulse superimposed to the first period of the 50 Hz main voltage (Figure 6: $U_{C,1}$-$U_{C,15}$). Remark that the assumption is made that only the first 15 peak values of the HF-HV pulse have a noticeable ageing effect (within the measurement accuracy) on the material. So only the first 15 peaks will be taken in to account for the total ageing effect.

Due to the huge difference in wave shape of both voltages, it is important to recalculate the time base of for instance the combined HF-HV pulses. Only after this modification that correct conclusions can be drawn.

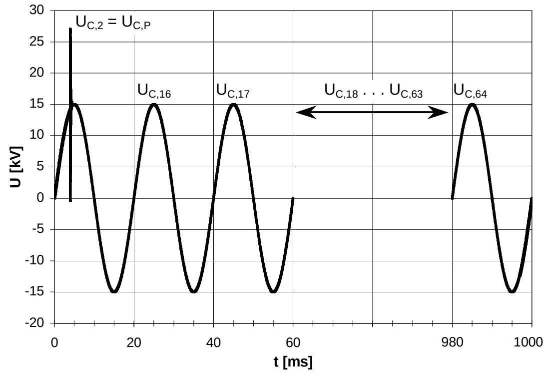

Figure 5 : One 'period' of a combined HF-HV pulse

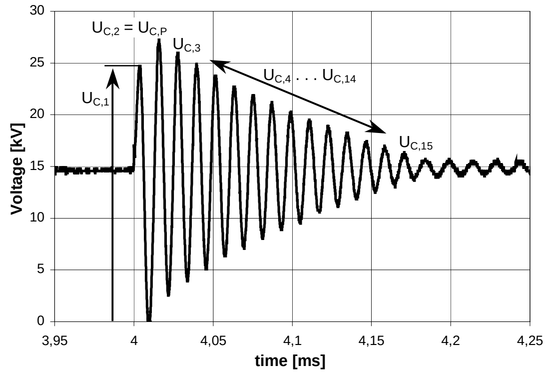

Figure 6 : HF transient pulse superimposed on main voltage

First suppose that every peak value $U_{C,1}$ to $U_{C,64}$ of the combined voltage is part of a continuous and purely sinusoidal voltage with the same peak value. Then the relative removed lifetime of the test sample by a single application of only one period of this voltage of magnitude $U_{S,i}$ is expressed as $1/N_{S,i}$:

$$N_{S,i} = \left[\frac{U_{S,0}}{U_{S,i}}\right]^{k_2} \Rightarrow \frac{1}{N_{S,i}}(\%) = \left[\frac{U_{S,i}}{U_{S,0}}\right]^{k_2} \cdot 100 \qquad (3)$$

This equation is valid for every peak voltage $U_{S,i} = U_{C,i}$ for I = 1…64 of the combined HF-HV pulse. With the assumption that the ageing for consecutive pulses is in first instance independent of the frequency of the applied voltage [11] and secondly has a cumulative nature [9], then, the total relative removed lifetime $1/N_{S,T}$ of the test object by applying one 'period' of this voltage (Figure 5) is expressed as (m = 64):

$$\frac{1}{N_{S,T}} = \sum_{i=1}^{m} \frac{1}{N_{S,i}} = \sum_{i=1}^{m} \left[\frac{U_{S,i}}{U_{S,0}}\right]^{k_2} \qquad (4)$$

The values for parameters k_2 and $U_{S,0}$ are the same as calculated for the 50 Hz ageing characteristic: $k_2 = 19.25$ and $U_{S,0} = 68.35$ kV.

Taking the highest peak value $U_{C,P}$ of the combined HF-HV pulse as reference for all the single peak values $U_{S,i}$ within this pulse, (4) becomes:

$$\frac{1}{N_{S,T}} = \sum_{i=1}^{m} \frac{1}{N_{S,i}} = \sum_{i=1}^{m} \left[\frac{U_{S,i}}{U_{S,0}}\right]^{k_2} \quad (5)$$

In the same way as for the 50 Hz sinusoidal voltages, it can be said that the degradation of the test sample increases with 1/n when applying one combined HF-HV pulse with highest peak value $U_{C,P}$:

$$\frac{1}{n} = \left(\frac{U_{C,P}}{U_{C,0}}\right)^{k_1} \quad (6)$$

Since (5) and (6) describes the same ageing characteristics, but with a different view to the waveform, clearly (7) is also valid:

$$\frac{1}{n} = \frac{1}{N_{S,T}} \Rightarrow \left[\frac{U_{C,P}}{U_{C,0}}\right]^{k_1} = \left[\frac{U_{C,P}}{U_{E,0}}\right]^{k_2} \cdot \sum_{i=1}^{m} \left[\frac{U_{S,i}}{U_{C,P}}\right]^{k_2} \quad (7)$$

The ageing effect of the combined HF-HV pulse is after all independent of the mathematical approximation. Writing $U_{S,0}$ as function of $U_{C,0}$ finally gives:

$$U_{S,0} = U_{C,0} \cdot \left(U_{C,0}\right)^{(k_1/k_2)-1} \cdot \left(U_{C,P}\right)^{(k_2-k_1)/k_2} \cdot \left(\sum_{i=1}^{m} \left[\frac{U_{S,i}}{U_{C,P}}\right]^{k_2}\right)^{1/k_2} \quad (8)$$

The interpretation of (8) is as follows: to simulate (in other words to compare) the ageing effect of a combined HF-HV pulse by using only a purely sinusoidal 50 Hz voltage, it is necessary that the latter voltage has a peak value U_S being λ times the highest peak value U_C measured for the combined HF-HV pulse. The multiplier λ is defined as:

$$\lambda = \frac{U_{S,0}}{U_{C,0}} = \left(U_{C,0}\right)^{(k_1/k_2)-1} \cdot \left(U_{C,P}\right)^{(k_2-k_1)/k_2} \cdot \left(\sum_{i=1}^{m} \left[\frac{U_{S,i}}{U_{C,P}}\right]^{k_2}\right)^{1/k_2} \quad (9)$$

Supposing that k_1 equals k_2 [9], (9) can be simplified to:

$$\lambda = \left(\sum_{i=1}^{m} \left[\frac{U_{S,i}}{U_{C,P}}\right]^{k_2}\right)^{1/k_2} \quad (10)$$

Using (10) to calculate the correction factor for the tests of Table 3 gives a mean value λ = 1.27. This suggests that the combination of a long term (1 s) 50 Hz sinusoidal voltage and the oscillating nature of the high frequency transient superimposed on the 50 Hz voltage, may have a significant effect on the accelerated ageing of the cast resin under test. Moreover, the decrease in lifetime associated with this combined ringing-50 Hz voltage is comparable to the decrease in lifetime of only one period of a pure 50 Hz sinusoidal pulse having a crest value being 27 % larger.

The peak values of the different tests $U_{peak, comb}$ (Table 3) are recalculated to the equivalent 50 Hz sinusoidal crest value $\lambda^* U_{peak, comb}$, Table 4.

Table 4 : Corrected peak values with reference to 50 Hz crest value

$U_{50 Hz}$ [kV_{RMS}]	U_{FT} [kV_{PP}]	$U_{peak, comb}$ [kV_{PEAK}]	$\lambda^* U_{peak, comb}$ [kV_{PEAK}]
1.50	38.00	21.12 †	-
7.50	29.6	24.15 †	31.88
10.00	29.81	26.90	33.69
10.00	20.28	23.80	30.87

† Initiation of pre-breakdown with 50 Hz voltage

Doing this recalculation is in fact the same as adjusting the time base of the two tests to each other. Plotting the modified peak values of the combined HF-HV pulses to Figure 4 is graphically the same as shifting the boxes '□' of the real peak values. This is done in Figure 7 where the modified peak values are shown by triangles 'Δ'.

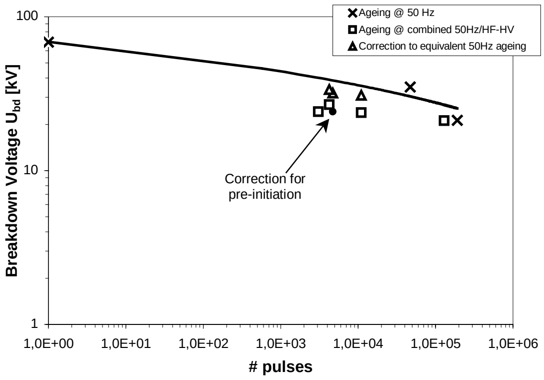

Figure 7 : Corrected ageing characteristic for HF-HV pulses

The filled circle in Figure 7 is a modification made to the first set of tests and measurements in order to adjust the time base of the combined HF-HV pulse for the initiation of a pre-breakdown channel in the resin using a 50 Hz voltage. For doing this, the above theory is used from bottom to top.

From Figure 7 it is also seen that the corrected ageing characteristic of the combined HF-HV pulses is close to the characteristic for power frequency conditions. This is the same conclusion as mentioned in [9]. The oscillations appearing at the first 50 Hz period of the combined HF-HV pulse have indeed a significant effect on the ageing of the examined cast resin.

The same technique was used earlier by Toth [12] and Nelson [9]. However Nelson uses it to investigate the influence of only steep front voltages with ringing on the ageing of a certain insulation material while Toth uses switching and lightning impulses. Comparing with the combined HF-HV pulses as defined in this paper, it can be said that the voltage waves used by Nelson and Toth are restricted to one single waveform. Therefore, the results obtained by this investigation shows that the same technique is also applicable to combined waveforms such as HF-HV pulses superimposed to a carrier wave, in this case a 50 Hz voltage.

Nelson calculates a correction factor λ = 1.72 for steep front voltages with a pulse width of 100 µs. Using the same technique to the surge voltages used by Toth, gives a correction factor λ = 2.44. Comparing with the λ = 1.27 obtained for the combined HF-HV pulses as described in the first section, concludes that the voltage endurance for the superimposed transient voltages is lesser than the endurance for steep front voltages and voltage surges in general. Since electric equipment situated in the medium voltage grid is more and more exposed to switching phenomena producing HF-transient voltages nowadays, the significance of some prescribed, standardized tests can be highly doubtful. The influence of HF-transients is more critical to the ageing of insulation materials than for instance lightning impulses. The former statement can be justified by the release of a final draft version of a new IEC standard 60664-4 covering the coordination of the insulation system at low voltage equipment including high frequent overvoltages [13].

CONCLUSIONS

Due to the accumulated ageing effect, it has been shown that the accelerated ageing of the cast resin subject to repetitive combined HF-HV pulses can easily be modelled by an equivalent ageing of the same resin under a purely 50 Hz sinusoidal voltage. The technique, already used in the past for steep front-waves and switching impulses, is validated in the laboratory by practical measurements. To get this equivalent ageing effect, the 50 Hz voltage needs a peak value of λ = 127 % of the highest peak value measured from the combined HF-HV pulse. In relation with steep front voltages or standard switching and lightning impulses, the fast transients superimposed to the 50 Hz main voltage are much worse for the degradation of electrical insulation materials. The λ-values for the former voltage waves are respectively 1.72 and 2.44.

The development of an accurate model towards standardisation of the typical waveform, can only be satisfied by using an extensive set of measurements, spread over a broad range of relative phase angles of the fast transient pulse and relative peak values against the 50 Hz main voltage, and tested for several insulation materials. However, it is shown that the test circuit and modelling techniques are useful to perform more tests in future. The development of a new standardised waveform for medium voltage insulation materials can be of more practical result for the industry.

ACKNOWLEDGMENTS

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