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Lifetime of oil-impregnated paper under pulse stress at different frequencies

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Abstract

With the increasing penetration of power electronic interfaces in the power grid, insulation materials will begin to experience stresses at higher frequencies than the conventional 50 Hz AC. This article studies the lifetime curves of oil-impregnated paper (OIP) under pulsed stresses and compares them at 10 kHz and 50 kHz. A pulse modulator is constructed consisting of a rectified DC supply feeding an H-bridge pulse driver connected to a 4:200 pulse transformer. The modulator is used to apply medium voltage pulse waveforms with rise-times of $T_r \approx$ 1.8 µs across single-layer OIP samples. The results clearly show that an increase in pulse frequency significantly accelerates insulation ageing. However, it is also observed that below a certain threshold of field strength, the slope of the lifeline decreases dramatically thereby indicating decelerated ageing. Possible reasons for this phenomenon are also discussed in this article.

1. Introduction

High voltage (10-15 kV) Silicon Carbide (SiC) power MOSFETs with reasonable current capabilities (10-20 A) are under development and will be introduced into the market in the coming years [2]. These switches have much smaller switching losses compared to commercially available 6.5 kV IGBTs even when they are switched at 2-3x higher voltage. They can therefore be used for hard switching at much higher switching frequencies. By means of such switches, multilevel converters made of cascaded H-bridge or Modular Multilevel Converters MMC can be simplified to two levels converter or at least the number of levels can be decreased considerably which in-turn reduces the complexity of control system and increase overall reliability by reducing number of parts.

However due to high frequency and fast switching (short turn-on and turn-off time) of the SiC MOSFETs, a very high dv/dt is created which accelerates insulation ageing thereby reducing the average lifetime of components connected to such type of SiC MOSFETs. For example a medium frequency transformer (MFT) together with H-bridges (e.g. in a Dual Active Bridge DAP configuration [3]) made of these new SiC MOSFETs can be used to step-down/step-up medium voltage to low voltage level. However, the insulation of such transformer undergo severe electric stress due to the high voltage high frequency stress created by the switches.

The results presented in this article were produced by the authors in the form of the MSc thesis from Delft University of Technology [1].

To have a reliable converter it is necessary to ensure reliable operation of its insulation system under actual in-service electric stress experienced over its lifetime. For this, it is needed to obtain the lifetime curves of possible candidate materials under actual or very similar in-service electric stress. Based on such lifetime curves, it can be decided which insulation material is most suitable for a particular application and design guidelines for minimum insulation thicknesses necessary for a desired lifetime can be extracted from the lifetime curves and can be implemented in the design. While a significant amount of work has been done on lifetime of different insulation material at 50 Hz AC, experimental data available in the literatures for insulation lifetime under pulse stress at high frequencies is limited to several kHz [4-6]. Different factors such as magnitude of the electric stress, frequency, temperature, rise time of the waveform, ON period of the waveform, presence of partial discharges, environment, etc. can play a role in insulation aging. Each of these factors can have different impacts on the insulation lifetime. In reality almost of these factors are present at the same time resulting in a combined ageing effect on the insulation system. Among these factors it is well known that magnitude of electric field has the most severe impact on insulation aging. Cavallani *et. al.* [7] proposed equation (1) which relates the lifetime to the voltage peak, voltage rms and harmonics content.

$$L = L_0 {K_p}^{-n_p} {K_{rms}}^{-n_{rms}} {K_s}^{-n_s} \quad (1)$$

Faster rise time can cause a reduction of lifetime and longer pulse duty cycle increases the aging [8-9]. There is a common consensus that the lifetime decreases with an increase of frequency. This is expressed as an inverse exponential as shown in (2).

$$T_{failure} \propto f^{-k} \quad (2)$$

Different values for k is proposed by different researchers, with k=1 [3] and k between 0.6-0.7 [5]. Presence of PD and increase of temperature can both accelerate aging and reduces the lifetime [8].

For high voltage applications, liquid immersed MFT is the most practical and reliable choice. OIP is hence an obvious insulation material candidate for an oil immersed MFT. In this paper lifetime curves of OIP samples are obtained at 10 kHz and 50 kHz and parameters of the curves (slope and y-intercept) are compared and the trend present in the lifetime curves is analyzed.

2. Experimental setup

Fig.1 shows OIP samples after impregnation and during experimentation. Sample preparation procedure is explained with details in [6]. Fig. 2 shows schematics of the experimental setup. An H-bridge made of 1200 SiC MOSFETs is constructed and used to excite the primary winding of a pulse transformer with bipolar pulses. Pulse frequency is adjusted by an Arduino microcontroller. Pulse duty cycle is kept at 50% throughout the experiments. Due to leakage inductance and capacitance of the pulse transformer as well as presence of a capacitive load, the output pulses have an overshoot as shown in Fig. 3. As was explained before, magnitude of applied voltage has major impact on the lifetime of insulation material. Since the goal of this research was to identify impact of frequency of pulses, it was decided to damp the overshoots so that a clean pulse waveform is applied over the samples. This is achieve using an RC circuit between the pulse transformer and the test cell [1]. A variable HV capacitor and a variable bank of high power resistors were used to control the rise time and overshoot of the pulses as shown in Fig 4. The pulse transformer has an E-core made of 8 U93/104/30 N87 material ferrite core. On the primary side it has 4 turns made of 20 kV isolated silicone wire. Transformer turn ratio is 50 and the HV winding is made of 200 turns of 1 layer enameled copper wire of 0.3 mm diameter. A picture of the pulse transformer is provided in Fig. 6.

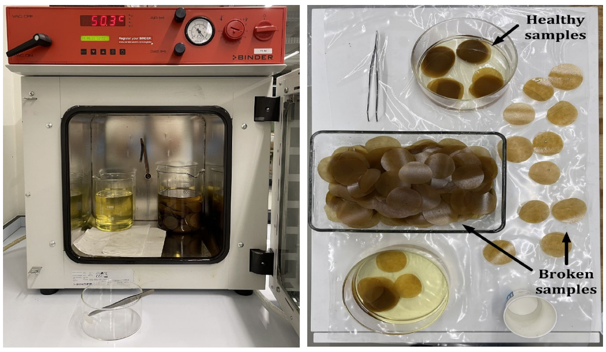


Fig. 1 left: OIP samples after preparation inside a BINDER VD vacuum oven, right: Sample table during experiments

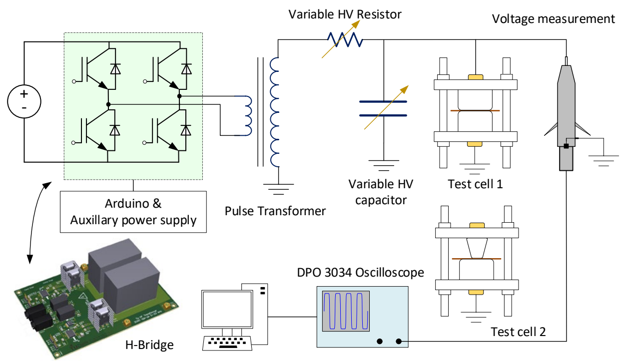


Fig. 2. Experimental setup used to measure lifetime curves and breakdown strength of OIP samples.

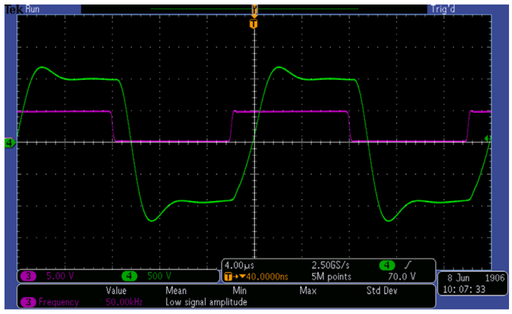


Fig. 3. Output pulse waveform without variable capacitor

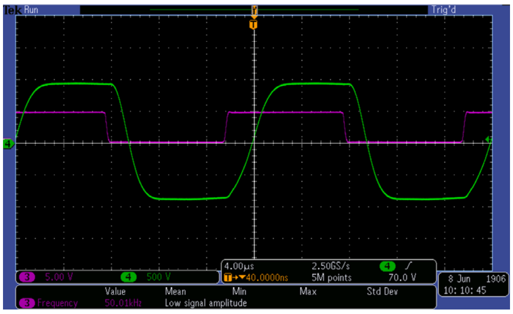


Fig. 3. Output pulse waveform with variable capacitor tunes for zero overshoot

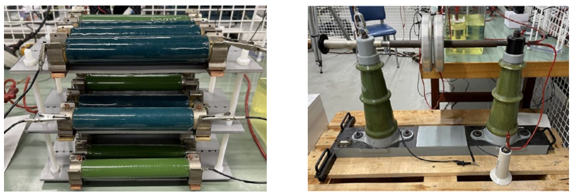


Fig. 4. Left: resistor bank for damping the output voltage waveform, right: variable capacitor for tuning the overshoots.

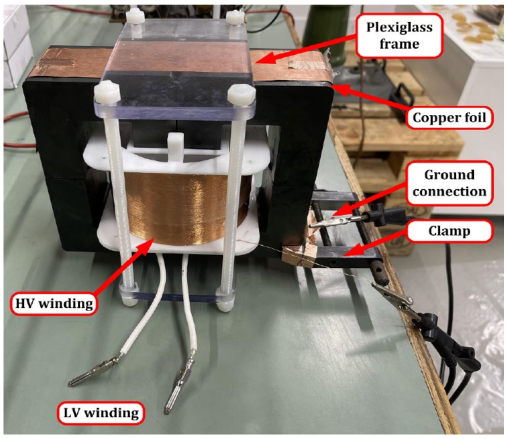


Fig. 5. Pulse transformer

3. Ramp breakdown test at 50 kHz

In order to determine breakdown strength of the samples, ramp tests with slope 1 kV_{pk}/s were carried out at 50 kHz for cylindrical and conical electrodes. The electrodes are shown in Fig. 6. The data is plotted on a special Weibull probability graph. This graph linearizes the cumulative probability of failure $F(E)$ on the y-axis across the breakdown strengths E_{break} on the x-axis. This is expressed in the form of (3).

$$F(E) = 1 - e^{-\left(\frac{E_{break}}{\alpha}\right)^{\beta}} \quad (3)$$

The constant β is called the shape parameter and represents the slope of the line. The constant α is called the scale parameter and is determined as the E_{break} corresponding to a *F(E)* = 63.2% on the graph. The result is in Fig. 7. The cylindrical electrode applies the electric field across more area of the sample thereby lowering its breakdown strength. The obtained Weibull parameters are summarized in Table 1. From the results of this experiment, it was decided to go ahead with cylindrical electrodes since a lower effective voltage would be needed to breakdown the samples. Also based on these results, a set of 6 electric field values were selected for the accelerated ageing tests. The highest of these values were selected to be smaller than the lowest recorded value i.e. E $\approx$25 kV/mm. This is to ensure that the samples take a reasonable amount of time to break down.

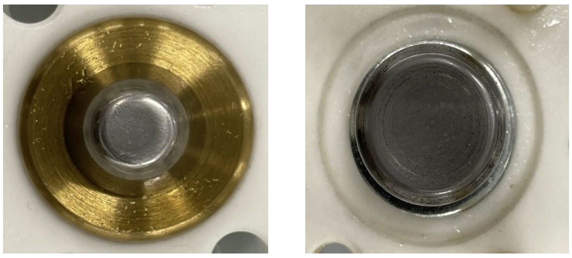


Fig. 7. Left: conical top electrode (d=12 mm), Right: cylindrical top electrode (d=25mm). In both cases the bottom electrode is a cylindrical electrode (d=25mm)

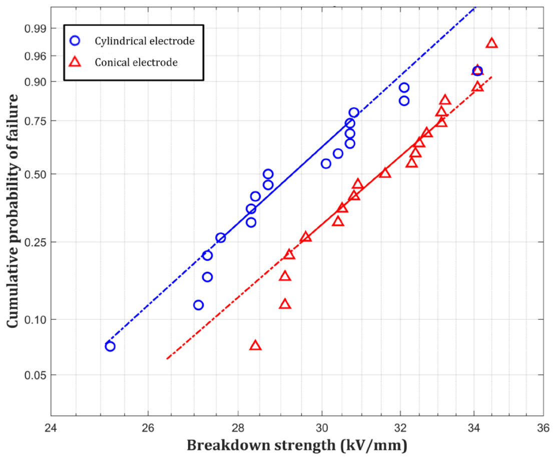


Fig. 8. Weibull plots with cylindrical and conical electrodes

Table 1. Obtained Weibull distribution parameters

Study case	β	$\alpha\ [kV_p/mm]$	ρ
Conical electrode	32.3	18.1	0.90
Cylindrical electrode	31.3	17.8	0.99

4. Lifetime test

To estimate the remaining lifetime of an insulation, accelerated ageing tests are conducted at field levels that are much higher than the nominal operational level. Several tests are carried out at a few selected field levels and the median at each level is used to extrapolate a lifeline on a log-log scale. If this method procedure results in a straight-line then the life of the insulation is said to fit an inverse power law model. Such a model predicts that the remaining lifetime T_{life} of a sample is inversely proportional to the nth power of the applied field E (kV/mm). This is expressed in the form of (4).

$$T_{life} = k\left(\frac{E}{E_0}\right)^{-n} \qquad (4)$$

The constant k has a unit of time and varies with test conditions like number of layers while E0 has a unit of electric field (1 V/mm). The constant n is the slope of the lifeline indicating the sensitivity of a given insulation to a change in field. To obtain 50 kHz lifetime curve, values of $E = 24, 23, 22, 21, 20, 19$ kV/mm were selected which correspond to $V_{p-p} = 7.2, 6.9, 6.6, 6.3, 6.0, 5.7$ kV considering a $d_{sample} = 150\ \mu m$ consist of 1 layer of OIP. To obtain 10 kHz lifetime curve values of $E = 30, 29, 28, 27$ kV/mm were selected. At each electric field around 21-41 tests (red points) were performed to obtain healthy statistics. The frequency was set and the rise-time recorded to be $T_r = \frac{3.68}{2}\ \mu s$ for both 50 kHz and 10 kHz. Each data point is plotted on a log-log scales as shown in Fig. 9. The medians (blue points) at each field were connected with a best-fit line to produce the lifetime line of the insulation. An interesting observation is that below E = 21 kV/mm the slope of the line drastically increased. This indicates that there is a transition in insulation ageing mechanism below this point. The obtained lifetime parameters for each curve are summarized in Table 2.

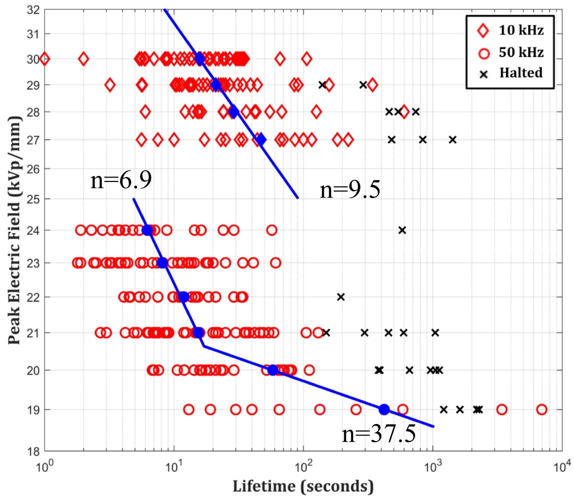
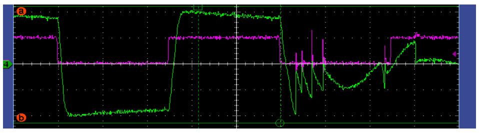


Fig. 9. The lifetime curves obtained at 10 kHz (red diamonds) and 50 kHz (red circles). The blue points are the median values for each electric field set. The black crosses are halted experiments. The slope of the lifetime at 50 kHz "bends" further away below E = 21 kV/mm indicating a shift in ageing mechanism below this point.

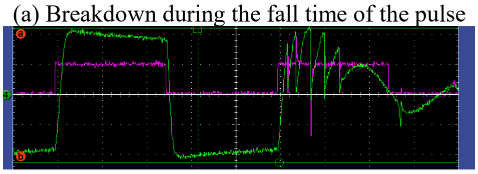
Table 2. Obtained lifetime curve parameters

Study case	n	k
10 kHz (above transition)	9.5	1.7×10^{15}
50 kHz (above transition)	6.9	2.1×10^{10}
10 kHz (below transition)	37.5	3.6×10^{50}

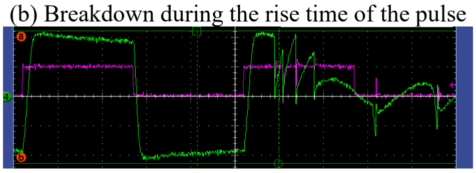
A fast short circuit detector circuitry was installed on the ground side of the test cell, which trips the input voltage as soon as the current through the OIP is above a certain threshold. Even so, after every test the electrodes were polished to ensure removal of black spots and surface inhomogeneity caused by the previous breakdown. Additionally, the breakdown instants were analyzed. Breakdowns during the fall time as in Fig. 10 (a) are the most common, but can also occur during the rise-time and at both pulse tops, albeit with less likelihood.



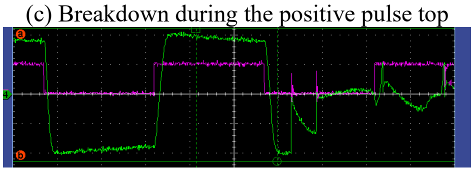
(a) Breakdown during the fall time of the pulse



(b) Breakdown during the rise time of the pulse



(c) Breakdown during the positive pulse top



(d) Breakdown during the negative pulse top

Fig. 10. Breakdown instants observed during the tests

5. Discussion

Two possible hypotheses can explain the observed ageing "transition" phenomenon:

- It is possible that a field enhancement occurs at the edge of the electrodes, which exceeds the PDIV of oil at that point. This could accelerate the breakdown of the paper itself. If true, the breakdown marks on the sample would tend to be on the extreme outer rim of the electrode. However by observing the breakdown marks of all broken samples, this was concluded to not be the case.
- It is possible that there exists oil-filled voids within the paper between its individual fibers. Above a certain field, the field enhancement within these cavities could then exceed the local PDIV thereby causing partial discharges to occur. This would then accelerate the ageing of the insulation, very similar to [10]. Although the second hypothesis could explain the observed phenomenon, it still requires further verification and analysis.

7. Conclusion

The results from the ageing experiments provide necessary insights into the ageing of oil-paper and in-turn its suitability for medium-frequency applications. The suitability of oil-impregnated paper as an insulation in MFTs is unlikely, at least in its current form. The increase in frequency causes a severe reduction in lifetime of OIP which can only be countered by designing thicker insulation systems or by combining plastic/paper insulation such as polypropylene paper laminated PPL. The slope of the lifetime curve becomes sharper with an increase in frequency. A transition point was clearly observed indicating a shift in ageing mechanism at lower fields. This could not be observed in ageing tests at lower frequencies. Testing at higher frequencies, however, allows us to lower the field while also ensuring the test does not take several months to complete.

Acknowledgement

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