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The influence of transient parameters on the ageing of transformer turn-to-turn paper-oil insulation

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SUMMARY

The step-up transformers in the wind-farm system are prone to failure due to high-frequency repetitive transients generated by the operation of power electronics switching and circuit breaker on-off operations. The high-frequency transients can lead to the ageing of transformer turn-to-turn paper-oil insulation due to its non-linear distribution along the transformer winding. In the current study, the transformer paper-oil insulation is aged under different parameters of transient voltage viz., amplitude, and repetition frequency. The ageing experiment is done for two levels of the repetition frequency and three levels of the voltage amplitude of the transient voltage. The experiments are carried out at a temperature of 30°C and humidity of about 14%. A total of 4 treatments are considered for a two-factor experimental design. The ageing of the paper-oil insulation is measured based on two responses; the dielectric frequency response and time to failure. It was seen that the dissipation factor did not increase significantly during the ageing process due to the absence of any noticeable partial discharge activity. The time to failure for the paper-oil insulation however decreases non-linearly with an increase in voltage amplitude. The results help in understanding the ageing response of the transformer turn-to-turn paper-oil insulation for various combination of transient voltage parameters.

KEYWORDS

Wind-farm, Step-up transformer, Paper-oil insulation, Repetitive transient, Ageing, Turn-to-turn insulation.

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1. INTRODUCTION

Study operation of step-up transformers in the wind farm system is very critical for a stable supply of electric power to the grid. A wind farm unit contains a type IV generator, an AC-DC-AC converter, circuit breakers, cables, and a step-up transformer [1]. The circuit breakers disconnect the wind turbine step-up transformer during very high or very low wind speed; but the switching operation of the breakers can generate high-frequency high-voltage oscillations [2]. The AC-DC-AC converters are used to control the voltage of the wind farm unit; but the converter operation can generate high rise time, high amplitude repetitive transients [3]. Thus the converter operation along with the switching operation of the circuit breaker can introduce high dv/dt, and di/dt stresses on the transformer turn-to-turn paper-oil insulation that can lead to progressive degradation of the transformer insulation under the repeated high-frequency impression. Khanali et al. studied the relation of repetitive transient voltage parameters viz., rate of rise, and repetition frequency on the partial discharge (PD) inception voltage by detecting hydrogen gas levels during transient ageing of the paper-oil insulation [4]. They found that the partial discharge gas inception voltage, defined as the voltage level when hydrogen gas was detectable, decreased with increase in repetition frequency, and the partial discharge gas inception voltage increased for faster rise time voltages. Koltunowicz et al. obtained the influence of rise time and repetition frequency of the transient voltage on the dielectric ageing of the paper-oil insulation [5]-[6]. The authors reported that the dissipation factor increases with an increase in repetition frequency and the dissipation factor increases for the faster rise time. In [7], Koltunowicz et al. found that the breakdown voltage of paper-oil insulation under the application of a square wave repetitive voltage increased with slower rise time and the breakdown voltage increased with decrease in repetition frequency. Also, the partial discharge inception voltage (PDIV) increased with slower rise time and PDIV increased with reduction in repetition frequency. Comparing the studies carried out by Khanali [4] and Koltunowicz [7], we can see that the results contradict in terms of the influence of rise time on PDIV. Khanali obtained that the faster rise time increased PDIV, whereas Koltunowicz reports faster rise time decreased PDIV. Thus, detailed research needs to be focussed on the influence of transient parameters including rise time, repetition frequency, amplitude, and duty cycle on the repetitive transient ageing of paper-oil insulation. In the current study, the fast rise time of 100 ns is considered because a fast rise time reduces the breakdown voltage of paper-oil insulation [7]. Thus, the influence of voltage amplitude and repetition frequency of the fast rise time transient voltage on the ageing of paper-oil insulation is presented. The dielectric frequency response and time to breakdown are considered to analyse the ageing degree of paper-oil insulation under the repetitive transients.

2. EXPERIMENTAL SET-UP

2.1 Paper-oil insulation and electrode geometry

The paper-oil impregnation is carried out according to the ASTM standard D2413-16 [8]. The length and width of the square shaped paper is 5.08 cm and the thickness of the paper is 0.22 mm. The test sample (paper-oil insulation) was sandwiched between two parallel plane electrodes of diameter 2.54 cm.

2.2 Test set-up for ageing under repetitive transient voltages

The experimental set-up for ageing paper-oil insulation under repetitive transient voltage is presented in Fig. 1. The ageing is carried out in a chamber maintained at 30 °C. The applied transient voltage is measured by a high voltage probe with a voltage ratio of 1:1000. The transient current through the paper-oil insulation is measured by a current transformer with an output sensitivity of 0.1 V/A. The transient voltage and current are captured by a mixed domain oscilloscope with a bandwidth of 200

MHz and a sampling frequency of 2.5 GS/s. The repetitive transient generator produces repetitive pulse voltage of amplitude up to 4.5 kV peak-to-peak using QIS4506001-powered IGBTs [9]. A rise time greater than 100 ns and a switching frequency of up to 4 kHz are produced by the transient voltage generator. In the present study, the factors (parameters) of transient voltage that are varied are the amplitude and repetition frequency, keeping the rise time and duty cycle fixed. The levels considered for the voltage amplitude are 1 kV, 2 kV and 3 kV, and the levels for repetition frequency are 1 kHz and 3 kHz. Table I shows four treatments for two factors of the transient voltage. The transient voltage rise time is 100 ns and the duty cycle is 50 %. It has not been possible to obtain the values of the parameters (amplitude, rise time, and repetition frequency) of transient voltages from an actual step-up transformer connected to a wind farm. The paper used the values from PSCAD simulation of the high-frequency transient voltage on the wind-turbine set-up transformers by Devgan et al, [10]. A repetitive transient voltage of rate of rise from 1.1 kV/μs to 28 kV/μs, and repetition frequency ranging from 450 Hz up to 22 kHz were obtained by Devgan during switching operation of the breakers. Thus, an applied voltage (1 kV, 2 kV and 3 kV) and rise time (100 ns) were selected to match the rate of rise obtained in the simulation study.

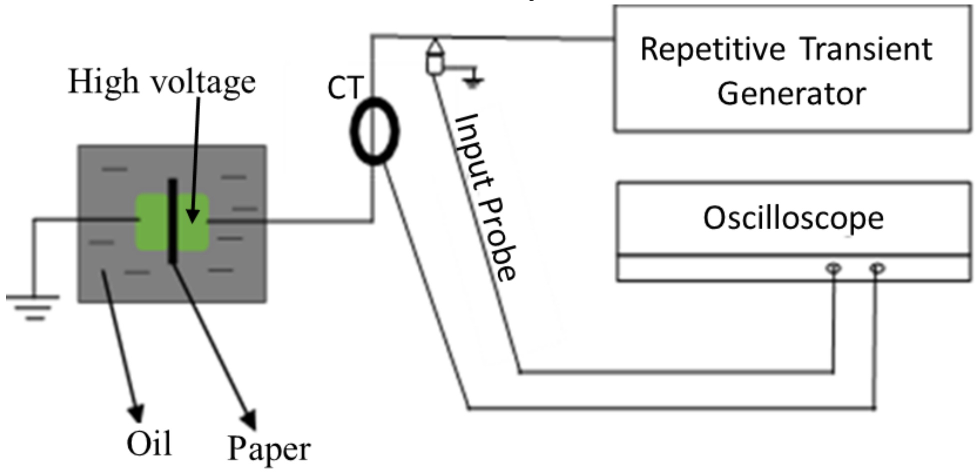

Fig. 1. Experimental set-up for ageing the paper-oil insulation under repetitive transient voltages.

TABLE I: CASES FOR TWO FACTOR/PARAMETERS OF THE TRANSIENT VOLTAGE

Cases	***Repetition Frequency (kHz)***	***Voltage amplitude (kV)***
Case 1	1	1
Case 2	1	2
Case 3	1	3
Case 4	3	3

2.3 Dielectric frequency response

The dielectric frequency response (DFR) i.e., dissipation factor as a function of frequency is used to obtain the extent of ageing for the paper-oil insulation [11]. The applied voltage for dissipation factor measurement is 140 Vrms and the frequency is varied from 0.5 mHz to 10 kHz. The dissipation factor is measured at the temperature and relative humidity of 30 ± 2 ºC and 13 ± 3% respectively. The DFR measurements were conducted before and after ageing of the paper-oil insulation without disturbing the paper-oil insulation sample.

2.4 Time to failure and partial discharge measurements

The time to failure is the time taken for paper-oil insulation to fail when aged under the repetitive transient voltage. The time to failure for each case shown in Table I is obtained. The partial discharge activity was measured according to IEC 60270 standard [12]. For the test conditions studied and uniform electrode geometry immersed in oil, no partial discharge greater than 1.3 pC was detected which confirms that the breakdown was not influenced by the partial discharge activity.

3. RESULTS AND DISCUSSION

The ac breakdown voltage for the test sample used is 9 ± 2 kV based on four readings. Fig. 2 shows the transient voltage (yellow) applied across the paper-oil insulation and the current (pink) through the insulation during the ageing process. The applied voltage is of amplitude = 3 kV, rise time = 104.6 ns, duty cycle = 50% and repetition frequency = 1 kHz. The peak-to-peak capacitive transient current through the paper-oil insulation is 2.8 A.

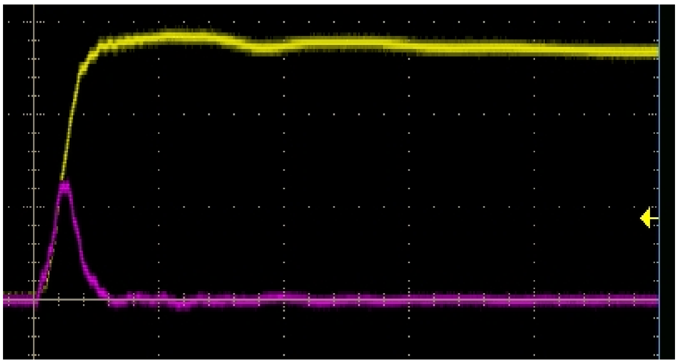

Fig. 2. The transient voltage (yellow) of amplitude = 3 kV, rise time = 104.6 ns, duty cycle = 50% and repetition frequency = 1 kHz applied across the paper-oil insulation, and the transient current (pink) through the insulation.

3.1 Time to failure

The time to failure for the paper-oil insulation under applied voltage amplitude of 1 kV, 2 kV and 3 kV for fixed rise time = 100 ns, duty cycle = 50 %, repetition frequency = 1 kHz were obtained. The paper-oil insulation sustained the applied voltage of 1 kV for a time greater than 120 hours. The time to failure for 2 kV and 3 kV were 60 hours and 21 hours respectively. The relationship between the time to failure of the paper-oil insulation and the transient voltage amplitude shown in Table II is non-linear. The time to failure was compared for two different repetition frequencies of the transient voltage i.e. 1 kHz (1000 pulses of 0.50 ms duration per second) and 3 kHz (3000 pulses of 0.17 ms duration per second). For both cases, the amplitude of the applied voltage is 3 kV, the rise time is 100 ns, and the duty cycle is 50%. It was seen that the time to failure for transient voltage with a repetition frequency of 1 kHz is 21 hours; whereas, the time to failure for transient voltage with a repetition frequency of 3 kHz is 22 hours. No difference in time to failure has been observed for the repetition frequency studied. This could be due to insignificant partial discharge activity.

TABLE II: TIME TO FAILURE AS A FUNCTION OF THE APPLIED TRANSIENT VOLTAGE

Cases	***Repetition Frequency (kHz)***	***Voltage amplitude (kV)***	***Time to failure (hours)***
Case 1	1	1	120
Case 2	1	2	60
Case 3	1	3	21

3.2 Dielectric frequency response

The dissipation factor as a function of frequency is compared between unaged and aged paper-oil insulation. The dissipation factor for the aged paper-oil insulation is measured few hours before the time to failure of the insulation. The dielectric frequency response for 2kV and 3kV is obtained at an ageing time of 52 hours and 20 hours respectively. Fig. 3 shows the dissipation factor as a function of frequency for unaged, and aged (52 hours) paper-oil insulation under repetitive transient voltage of amplitude = 2 kV, rise time = 100 ns, duty cycle = 50% and repetition frequency = 1 kHz. The aged dissipation factor measurement is taken 8 hours before the time to failure for the paper-oil insulation at a voltage amplitude of 2 kV. It can be seen that the deviation between aged and unaged paper-oil insulation occurs at frequencies below 0.1 Hz, this can be attributed to the degradation of paper and increase in oil conductivity. The deviation is not very significant because the ageing mechanism would not have involved significant partial discharge activity. At 0.5 mHz, the dissipation factor of aged paper-oil insulation is 10% higher than unaged paper-oil insulation.

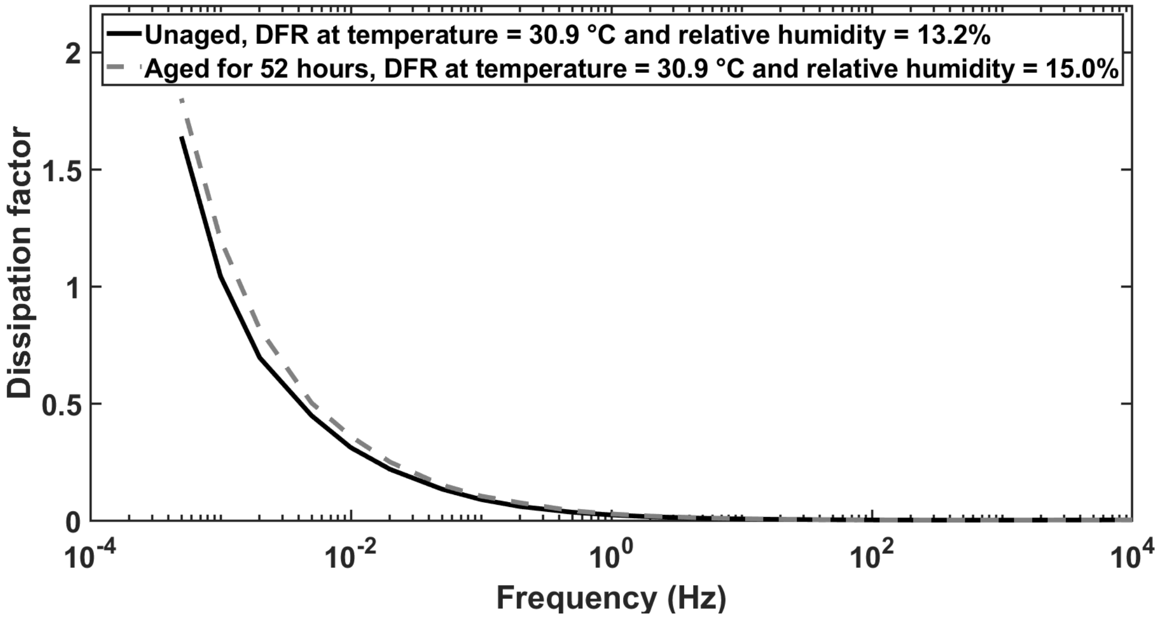

Fig. 3. Dissipation factor as a function of frequency for unaged, and aged (52 hours) paper-oil insulation under repetitive transient voltage of amplitude = 2 kV, rise time = 100 ns, duty cycle = 50% and repetition frequency = 1 kHz.

The dissipation factor as a function of frequency for unaged, and aged (20 hours) paper-oil insulation under repetitive transient voltage of amplitude = 3 kV, rise time = 100 ns, duty cycle = 50 % and repetition frequency = 3 kHz is shown in Fig. 4. The dissipation factor for aged paper-oil insulation was measured 2 hours before the time to failure. The deviation between aged and unaged paper-oil insulation DFR is seen at frequencies below 0.05 Hz. The changes in dissipation factor in this region is attributed to the degradation of paper due to ageing under repetitive transient. The dissipation factor of the aged paper-oil insulation is greater than the unaged paper-oil insulation by 8% at a frequency of 0.5 mHz. The DFR value is almost equal to ageing due to 2 kV transient voltage with a repetition frequency = 1 kHz.

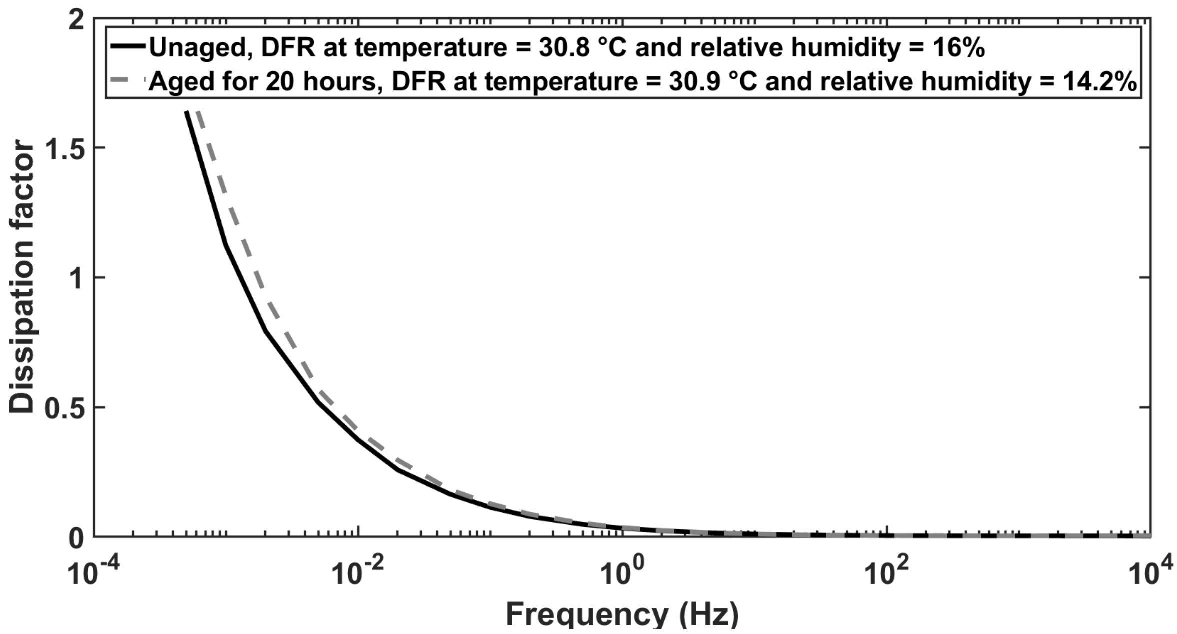

Fig. 4. Dissipation factor as a function of frequency for unaged, and aged (20 hours) paper-oil insulation under repetitive transient voltage of amplitude = 3 kV, rise time = 100 ns, duty cycle = 50% and repetition frequency = 3 kHz.

The dissipation factor of failed paper-oil insulation (time to failure = 21 hours) was compared with unaged paper-oil insulation. The paper-oil insulation failed due to the application of transient voltage of amplitude = 3 kV, rise time = 100 ns, duty cycle = 50% and repetition frequency = 1 kHz after 21 hours. Significant deviation between the failed and unaged paper-oil insulation was seen at frequencies below 0.1 Hz. Comparing failed and unaged paper-oil insulation, the dielectric frequency response for frequencies between 0.05 Hz and 0.1 Hz change due to change in oil conductivity, and the dielectric response for frequencies below 0.05 Hz change due to change in the paper material. At 0.1 Hz, the dissipation factor for failed insulation is 44% higher than unaged paper-oil insulation, thus the conductivity of oil would have been increased significantly due to the failure. The dissipation factor for failed paper-oil insulation is higher than unaged paper-oil insulation by 236% at a frequency of 0.5 mHz. So the failure has lead to the degradation of paper material significantly. It was also seen that the paper sample had undergone carbonization due to the failure of the paper-oil insulation.

4. CONCLUSION

The ageing mechanism of the paper-oil insulation is analysed for repetitive transient voltage parameters. The influence of applied voltage amplitude and repetition frequency of the transient voltage on the dielectric frequency response and time to failure were obtained. The variation of time to failure of the paper-oil insulation as a function of the applied transient voltage amplitude of 1 kV, 2 kV, and 3 kV is non-linear. The change in repetition frequency did not affect the time to failure because the ageing occurred under insignificant partial discharge activity. A slight difference between DFR of aged and unaged paper-oil insulation is observed at frequencies below 0.1 Hz for applied transient voltage of amplitude = 2 kV and 3 kV. For failed paper-oil insulation under transient voltage of 3 kV, it was seen that the failure lead to an increase in the dissipation factor at frequencies below

0.1 Hz, as expected. The current paper helps to understand the paper-oil insulation failure under fast transient voltage amplitude and repetition frequency.

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