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Effect of Voltage Rise Time on Time-to-Failure of Form-Wound Stator Coil Enamelled Turn Insulation

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Abstract— **The paper presents the results of aging of medium voltage stator coil enamelled turn insulation under square waves having rise times of 270 ns and 4.5 µs. Unipolar square waves having a peak voltage of 2.5 kV and a switching frequency of 3 kHz were applied to enamelled wire samples while measuring online partial discharge. A two-parameter Weibull distribution was employed for analysis of the effect of rise time on insulation life. The tests were repeated at 6 kV peak with duty cycles of 15% and 50% for both rise times. The analysis indicates that insulation life is dependent on voltage rise time only when the DC component of the wave is short.**

Keywords—Turn Insulation; Form-Wound; Square wave; Rise Time; Aging; Time-to-Failure

I. INTRODUCTION

The application of medium voltage motors fed by converters is now common place in industry. However, there is still concern about insulation life that is reduced by stresses arising from fast transients emanating from the converter. As such, there are still issues that need to be addressed on the effects of various parameters of voltage waveforms, such as rise time, on insulation life.

IEC 60034-18-42 standard has identified stress grading of ground wall insulation and turn insulation as two insulations that can experience enhanced stress due to the fast voltage rise times imposed by converters [1]. Furthermore, the current trend in the development of solid state switches indicates that switches with higher voltage and jump capabilities will soon be commercially available resulting in even faster rise time transients. Various studies addressing the issues associated with the stress grading system of form-wound insulation have been reported [2, 3], however to date, there is very little reported on the effects of fast rise time waves on the turn insulation of form wound machines.

The focus of the present research is on the effect of rise time on enamelled turn insulation of form-wound machines fed by converters. In this context, Gao et al. compared the space charge accumulation in form-wound turn samples under both 10 kHz square pulses and 50 Hz sinusoidal AC and concluded space charge accumulation is higher under square wave stress. It was also reported that tan δ increases with aging [4]. Manns et al. studied the life of form-wound epoxy-mica insulation samples under both 10 kHz PWM pulses and 60 Hz sinusoidal stress [5]. The life of the samples was reported to be independent of applied frequency or rise time.

Many researchers have focused on the issues of turn insulation in low voltage random-wound machines fed by converters; some of which may be applicable to form-wound insulation as well. Fabiani et al. presented the effect of space charge accumulation under square pulses with different switching frequencies [6]. It was reported that partial discharge (PD) magnitude is higher at higher switching frequencies and it also increases with aging time which seems to demonstrate the importance of space charge accumulation. In addition, it was shown that PD inception voltage is neither a function of switching frequency nor the shape of waveform; and it is only governed by the peak-to-peak voltage. Wang et al. investigated the effect of rise time on PD under square wave stress for twisted wire samples [7]. Square waves with a peak of 2.5 kV, frequency of 50 Hz, and rise time ranging between 0.2 to 5000 µs were used. It was reported that faster rise times contribute to higher PD magnitude leading to a faster failure. Moreover, they concluded the PD instantaneous inception voltage is higher for faster rise times. Florkowska et al. [8] conducted similar research on cable insulation samples using similar rise time and frequency and reported contradictory results to those reported by Wang et al. [7]. PD inception was observed to be lower at faster rise times and higher switching rates. However, their results agrees with [7] on having higher PD amplitude at faster rise times. Yin [9] showed that twisted wire turn insulation samples fail faster under square wave stress with faster rise times. Bipolar square waves of 20 kHz with a peak-to-peak voltage of 4 kV and 0.04 to 0.1 µs rise times was used to conduct this study.

In this research, the effect of unipolar square waves having rise times of 270 ns and 4.5 µs on the time-to-failure of turn insulation samples of form-wound medium voltage machines is investigated. The duty cycle of the square pulse was also varied to observe the effect of square wave DC component on the life of the insulation while all other parameters including the number of cycles applied to the samples was kept constant.

II. MATERIALS AND METHODS

A. Sample Preparation

The turn insulation samples used in this study were prepared according to the recommendations in IEC 60034-18-42. The samples, shown in Fig. 1, comprised of two rectangular enamelled wires with their ends spread apart and held together with mica-glass tape and vacuum pressure impregnated (VPI). By following the procedure, it was found that failures generally took place in the region where the wires are bent apart, or “crotch”. In order to prevent failures from taking place in the crotch, the samples required three VPI applications to minimize air pockets in the crotch. This finding indicates a shortfall in the IEC sample preparation procedure which needs to be addressed in order to perform aging studies on the turn insulation. For these studies, five samples in each group were prepared for Weibull life time analysis. Table I summarizes the test parameters for each group.

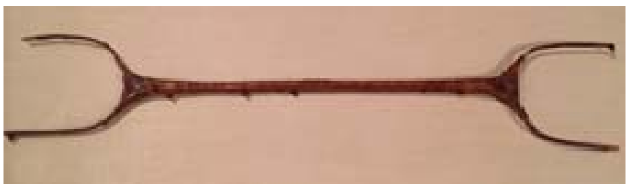


Fig. 1. Modified form-wound enamel turn insulation sample.

TABLE I. TEST PARAMETERS FOR EACH GROUP OF SAMPLES.

Group Name	Peak Voltage	Rise Time	Duty Cycle	Switching Frequency
A	2.5 kV	0.27 µs	50 %	3 kHz
B	2.5 kV	4.50 µs	50 %	3 kHz
C	6.0 kV	0.27 µs	50 %	3 kHz
D	6.0 kV	4.50 µs	50 %	3 kHz
E	6.0 kV	0.27 µs	15 %	3 kHz
F	6.0 kV	4.50 µs	15 %	3 kHz

B. High Voltage Square Wave Generator

A custom designed high voltage unipolar square wave generator based on IGBTs was used to conduct the research (Fig. 2). Adjustable peak voltage, switching frequency, rise time and duty cycle provided the possibility of investigating the effect of rise time on turn insulation life on five samples that were aged at once. Fig. 3 shows a sample output waveform of the generator. On breakdown of a sample, a fast protection system was implemented to disconnect the generator from the samples and the time to failure was recorded.

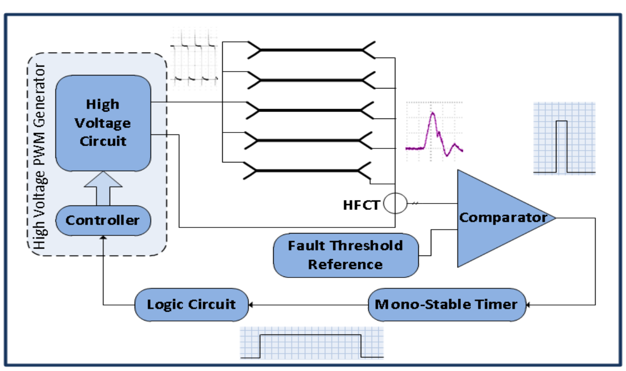


Fig. 2. Block diagram of the high voltage square wave generator.

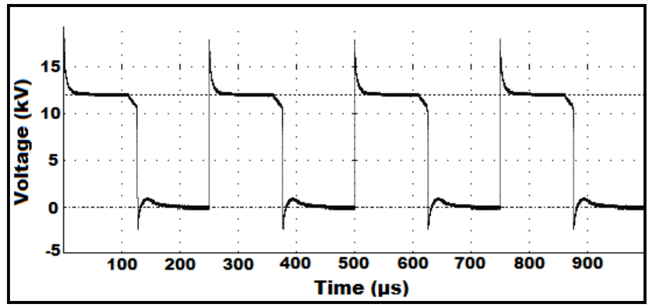


Fig. 3. Typical output voltage waveform of the generator.

C. On-line PD Detection System Under Square Wave Pulses

PD was measured using a RF antenna attached to a sample and a 7-pole Chebyshev high pass filter was used to filter the voltage pulse from the generator allowing only the PD signal to pass. A Rohde & Schwarz RTO1024 oscilloscope with 2 GHz bandwidth and 10 Gsa/sec sampling rate was used to capture and record the PD.

III. RESULTS AND DISCUSSION

Two sets of samples were aged at a peak voltage of 2.5 kV and at a switching frequency of 3 kHz; and rise times of 270 ns for group A and 4.5µs for group B. Before aging, PDIV was measured at 1.7 kV peak. The times to failure were recorded and the Weibull results are shown in Fig. 4. The shape parameters for groups A and B were found to be 1.5 and 1.4 respectively which is greater than 1.0; hence the failure is due to aging [10]. On the other, the overlapped confidence bands of these two groups suggest that rise time may not play a significant role in aging.

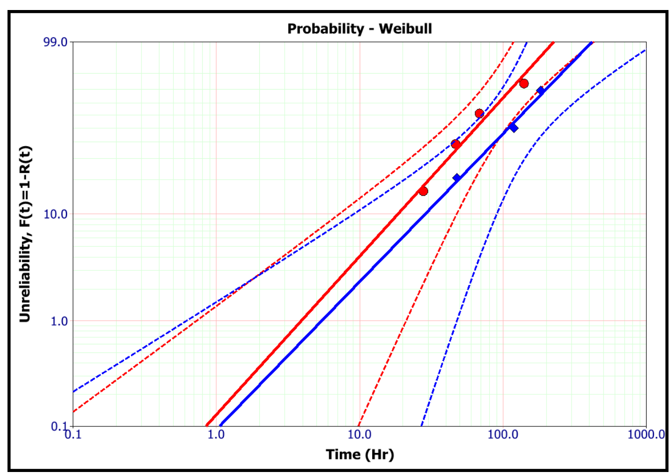


Fig. 4. Weibull times-to-failure with 50% duty cycle square waves at 3 kHz switching frequency and 2.5 kV peak; group A with 270 ns rise time (●) and group B with 4.5µs (♦) considering 80% confidence bands.

During aging, online PD measurements were taken every 5 minutes and stored using the persistent mode of the oscilloscope (Fig. 5). PD signals occurring multiple times at the same location are shown using colour spectrum; white indicating the highest number of pulses while red represents low concentration of pulses. The results show increased PD with higher magnitudes on the front of the square wave.

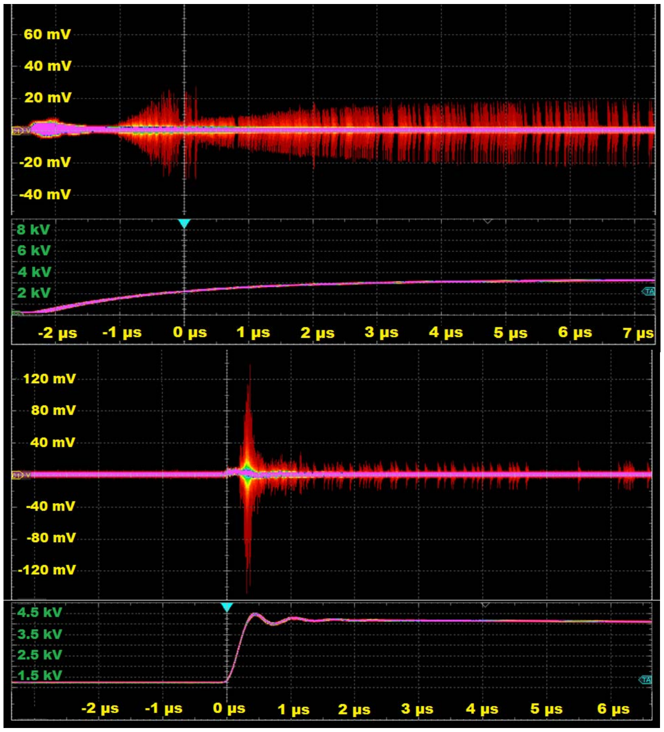


Fig. 5. Accumulative PD using antenna. Upper trace is for a pulse rise time of 4.5 µs with 20 mv/div of PD and 1 kV/div of voltage. Lower trace for a pulse of 270 ns rise time with 40 mv/div of PD and 500 V/div of voltage; both 1µs/div of time.

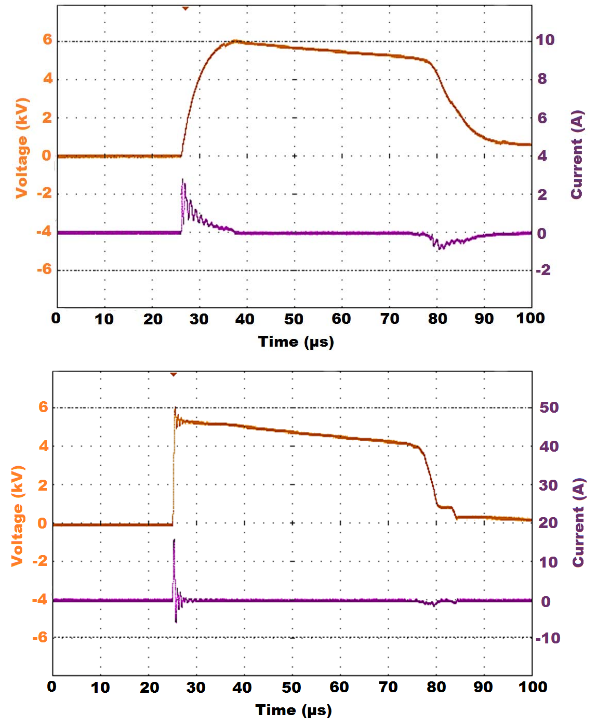


Fig. 6. Square pulses with reduced duty cycles to less than 50 µs having 6 kV peak and 4.5 µs rise time (top) and 270 ns rise time (bottom).

Fig. 5 also shows PD of about six times higher magnitude for 270 ns rise time waves than for 4.5 µs rise time waves. Therefore, due to the higher PD pulses, one may speculate that the faster rise time pulses should age the insulation faster than the slower rise time pulses.

However, from Fig. 4, both rise times show little, if any difference, in the times-to-failure. This anomaly may be explained by examining the occurrence of PD on the DC portion of the pulses which suggests that regardless of the difference in PD severity on the rise time, the characteristic life is governed by the PD on the DC portion of the wave. The DC portion is considerably longer in duration than the rise time section of the wave. PD occurring during the DC section may be due to accumulation of space charge in the insulation, which needs further investigation.

The aging tests were repeated on two additional sets of samples with 6 kV pulses; group C subjected to 270 ns and Group D to 4.5 µs rise time pulses. Shorter times-to-failure were observed but the effect of rise time was similar to those found at the lower test voltage (2.5kV). Accordingly, rest of the tests have been carried out using 6 kV pulses in order to have accelerated failures.

In order to examine the effect of the pulse DC component on the Weibull time-to-failures, the DC component was reduced from 150 µs to less than 50 µs for both rise times pulses as shown in Fig. 6. The aging tests were repeated with 6 kV peak for group E samples with 270ns rise time and group F samples with 4.5 µs rise time pulses.

Table II shows the times-to-failure for Groups C, D, E and F comparing the effect of rise time on voltage endurance life for square waves with duty cycles of 50% and reduced duty cycle of 15%. For all groups, the Weibull shape parameter was higher than 1 indicating failures due to aging. As it can be seen, the effect of rise time cannot be noticed for 50 % duty cycle for Groups C and D while a difference can be observed when duty cycle was 15% for Groups E and F.

TABLE II. TIMES-TO-FAILURE IN HOURS OF TURN INSULATION SAMPLES UNDER 6 KV PEAK SQUARE WAVE WITH DIFFERENT RISE TIMES AND DUTY CYCLES.

Duty Cycle →	**50% Duty Cycle**		**15% Duty Cycle**	
Rise Time →	***0.27µs***	***4.5 µs***	***0.27 µs***	***4.5 µs***
Group Name → **Sample No. ↓**	***Group C***	***Group D***	***Group E***	***Group F***
1	4.5	4.0	5.5	9.0
2	6.0	5.0	7.0	13.0
3	6.5	6.0	10.0	22.5
4	6.5	8.0	10.5	23.0
5	7.0	-	-	-

This can be confirmed by plotting Weibull plots for groups E and F as illustrated in Fig. 7. The confidence bands of 80% show more separation compared to that shown in Fig. 4. This means that it is possible to observe the effect of rise time on aging when the DC portion of the waves is reduced. These results confirm that faster rise time leads to faster degradation in actual insulation by imposing PDs with higher amplitudes. This is in agreement with [7], [8] and [9]. However, the location of PD, or instantaneous PDIV, is observed to be higher with faster rise times which support the results of [7] and contradict those in [8].

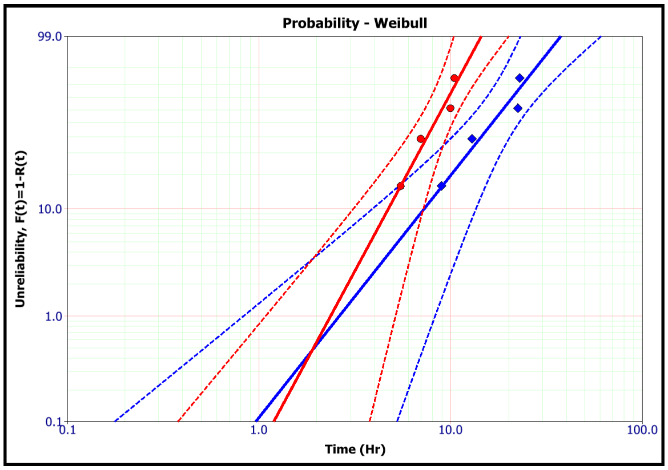
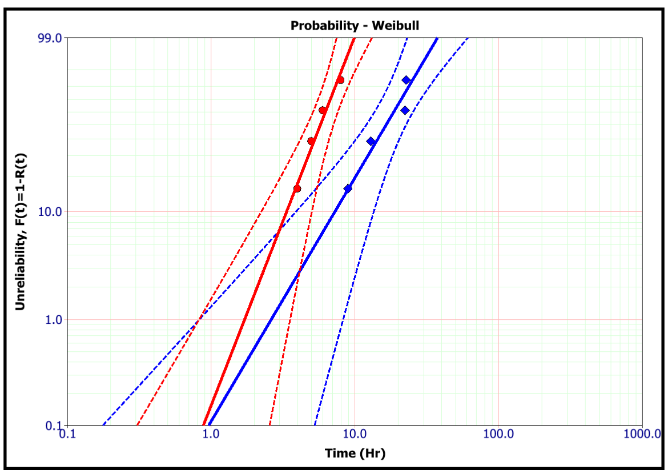


Fig. 7. Weibull times-to-failure of insulation groups with rise times of 270 ns (●) and 4.5 µs (♦) under square wave with 15% duty cycle and 6 kV peak.

Reference [9] reported reduced life of insulation under different rise times with PWM stress without reducing the DC section, which can be due to considering faster rise times ranging between 0.04 to 0.1 µs compared to the present research. The contradiction of this result with that of [5] where the life of insulation was reported to be independent of the rise time, could be either due to the use of a slow range of rise times as well as the use of different type of insulation samples.



Fi.g. 8. Weibull times-to-failure of insulation groups with rise time of 4.5 µs under square wave with duty cycles of 50% (●) and 15% (♦) at 6 kV peak.

Another interesting result can be drawn when the time-to-failure of samples with 50% and 15% duty cycles for a specific rise time, switching frequency and peak voltage are compared. Fig. 8 illustrates Weibull plots for groups D and F. Both groups aged under peak voltage of 6 kV and rise time of 4.5 µs while groups D and F were stressed by square waves with 50% and 15% duty cycles, respectively. The results show that two groups are statistically different which confirms the occurrence of PD on the DC section of the wave which causes reduction in the endurance life of the insulation. This suggests that voltages higher than the PD inception voltage, the discharges on the DC section can be the dominant factor of aging compared to the rise time.

With 50% duty cycle, the persistent occurrence of PD over the DC section of the pulse, which is about 150 µs for a 3 kHz square wave, dominates aging process compared to the PD activities during the rise time. Hence, the effects of PD activities during the rise time were observed by reducing the duty cycle to 15%. Under this test the effect of rise time on failure as indicated in Fig. 7 is found. This is because of domination of aging by high amplitude PD during the rise of 270ns fast pulse over the sustained low amplitude PD on DC section of the slow rise time wave (4.5 µs).

IV. Conclusions

The times-to-failure of form-wound turn insulation samples prepared according to IEC 60034-18-42 were measured with application of square pulses considering peak voltages of 2.5 kV and 6 kV with a switching frequency of 3 kHz while varying rise time and duty cycle of the applied waveform.

- The results show that there is no noticeable difference in life of the insulation with respect to the rise time when 50% duty cycle is used irrespective of the voltage level considered. It can be due to the presence of PD in DC section of the wave.
- A shorter insulation life was observed with faster rise time with reduced duty cycle of 15%. These results were supported by higher magnitude of PD that were observed with faster rise times, contributing to a faster degradation of the insulation.

Future work will examine a larger duty cycle range and will consider a greater number of samples for statistical analysis.

Acknowledgment

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