Impact of High-Frequency Repetitive Bipolar Square Wave Voltages on the Lifetime of Turn-to-Turn Insulation

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***Abstract*- Emerging power electronic drives and converters are planned to operate at high voltages with high switching frequencies (up to a few hundred kHz), which will affect the reliability of insulation systems of windings of electrical machines. To evaluate the insulation quality under such high-frequency pulses, lifetime test is a prominent way. For simplification of test procedure, turn-to-turn insulation samples are approved by IEC 60034-18-42. In past studies, the impact of switching frequencies has been investigated under lower frequencies (up to 20 kHz), which cannot address the challenges of next-generation wide bandgap (WBG)-based power converters. In this study, the lifetimes of turn-to-turn insulations under high switching frequencies (50 kHz) are tested at four different rise times (50 ns, 100 ns, 150 ns, 200 ns), and the impact of switching frequency on the lifetime of the insulation is analyzed.**

I. Introduction

The rapid degradation of turn-to-turn winding insulation, the part of electrical machines most susceptible to failure, is mostly due to the inception of partial discharge (PD). The main factors behind PD inception are impedance mismatch at winding-cable interface, non-uniform distribution of voltage and consequently creation of uneven electric fields in the turns [1-4]. PD will most likely occur in motor insulation when the voltage is higher than partial discharge inception voltage (PDIV). To improve insulation reliability, IEC TS 60034-18-42 recommends conducting lifetime tests on new and proven models to assess their performance [5]. Technological developments in power electronics, namely the incorporation of wide band gap (WBG) devices, have resulted in increased frequencies and voltages within electrical insulation systems, hence influencing their longevity. Voltage pulse frequency and rise time are two important variables that affect insulation life and are directly related to the reliability of motor stator windings [2, 3].

PDs appear on both the rising and descending edges of the voltage waveform under recurrent surges. PD doesn't start until an initial electron is accessible. As a result, there is a statistical lag between the point at which the voltage is adequate for the PD to initiate and the actual PD inception. Larger PD magnitudes correspond with shorter rise times, resulting in a shorter lifespan [6-11]. The modern, state-of-the-art power electronic converters can create fast (50 kV/μs) and repetitive (100 kHz) voltage pulses that negatively influence the insulation systems of various power system apparatuses. As far as the author is aware, there is currently no experimental data regarding the impact of extremely high voltages that are rated for slew rate up to 100 kV/μs and repetition rate up to 500 kHz on insulation degradation. This is the desired limit for both modern power grid applications and the US military [1]. Power electronic drives of the new generation put machines under additional strain that cannot be handled by AC-fed machinery. Because of the numerous early insulation failures brought on by these extra stresses in the past, manufacturers have increased the voltage insulation rating of their machines to handle these higher stresses [12, 13]. Given the ongoing development of power semiconductor devices and their greater capacity for power and switching speed, this technique might no longer be effective [1]. Therefore, it is more important than ever to have a greater understanding of these stresses in order to be able to sustain the reliability of rotating equipment for the duration of their designated lifecycle.

Measuring PD with impulsive voltage waveforms is challenging due to generator interference [14-17]. Several methods were presented to identify PD signals with high signal-to-noise ratios (SNR), one of which is ultra-high-frequency (UHF) PD detection, which is a viable option due to its intrinsic generator disturbance rejection [14, 18]. Manufacturers encounter several challenges when conducting lifetime evaluations on insulation for inverter-fed motors. One of the challenges is that the source voltage wave shape significantly affects the lifetime of insulation. Though it is assumed that the square wave and sinusoidal wave give comparable results in the lifetime test, the study depicts different results. There are significant differences in the lifetime when the square wave voltage source is used instead of the sinusoidal wave [19]. Manufacturers also have trouble managing the practical rise time of these impulses when they want to use impulsive voltages to test insulation lifespan. It might be difficult to keep a steady value when factors such sample capacitance, circuit resistance, and inductance readily change the rising time. In these kinds of situations, the rising

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time is a critical factor that affects lifetime test results [20]. High-impulse voltages have been widely covered in previous literature, which usually focuses on lower frequency ranges and higher rise times. This work, however, investigates and validates the winding lifetime under higher frequency and lower rise times, which are suggestive of larger slew rates, using experimental data.

II. Sample Preparation

A twisted pair (TP) was chosen for our experiment since it closely resembles the turn-to-turn insulation found in motors, a crucial component that is vulnerable. The two main characteristics of the copper wire that make up the TP are the diameter of the bare copper wire (15 AWG or 1.45 mm) and the thickness of the insulation (80 µm). The insulation consists of a modified polyester basecoat and an improved polyamide-imide topcoat, both of which are categorized as thermal class 200°C. Table I presents the properties of the magnet wire.

TABLE I
Magnet Wire Properties

Parameter	Value
Copper conductor diameter	1.45 mm (15 AWG)
Insulation Thickness	80 µm
Insulation basecoat	Modified polyester
Insulation topcoat	Polyamide-imide
Thermal class	200°C

The TP sample was constructed using a 240 mm length of straight wire that had its insulation stripped at both ends and then twisted back onto itself. Twelve twists are made while the tension load is maintained. In order to optimize separation, the closed end of the twisted pair loop is then severed. As stated in [21], the straight wire is cleaned with alcohol paper before assembly to remove any surface contaminants and static electricity influence. The sample, which shows closely entwined electromagnetic wires, is shown in Fig. 1. To simulate motor operating conditions, one wire is connected to high voltage and the other to the ground.

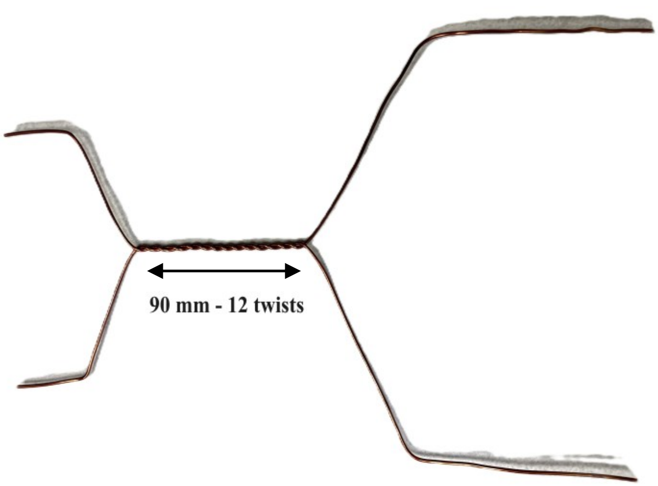

Fig. 1. Twisted pair sample for experiment

III. Experimental Setup & Procedure

The block diagram of the experimental setup is shown in Fig. 2. A high-frequency bipolar high-voltage pulse generator, having rise times ranging from 50 ns to 800 ns and frequencies from 0 to 500 kHz is used, which is capable of producing unipolar (both positive and negative) and bipolar square pulses up to ±6 kV. The square wave's parameters can be adjusted and the current and voltage supplied to the test object are displayed on the front panel of the pulse generator. The test object is connected via a series inductor in the top panel to the pulse and ground connections. To ensure that the load has no effect on the rise time, the high capacitive test object, in this case, the TP, is employed with an inductor. The pulse generator is connected to an oscilloscope in order to accurately calculate the frequency and voltage amplitude.

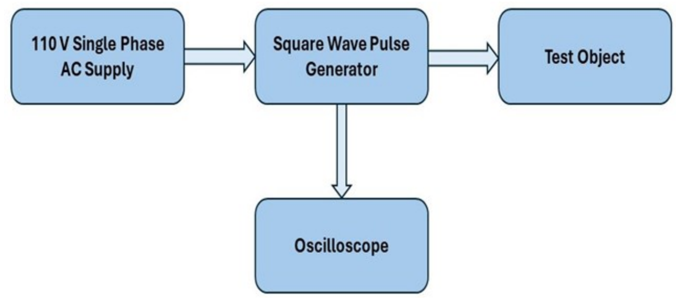

Fig. 2. The Block diagram of the HV Experimental Test setup

The twisted pair sample made in accordance with the method outlined in section II was subjected to tests. The fundamental idea is to attach the specimen to a high-voltage source at a predetermined frequency and rise time and then watch for the breakdown to happen. Every time there is a breakdown, another sample is used in its place. A stopwatch was used to record the time after the breakdown, and the process continued with a different frequency. The characteristics of the motor wire insulation with regard to switching frequency under square wave voltage operation are obtained by repeating this method for various rise times. Fig. 3 shows the test setup.

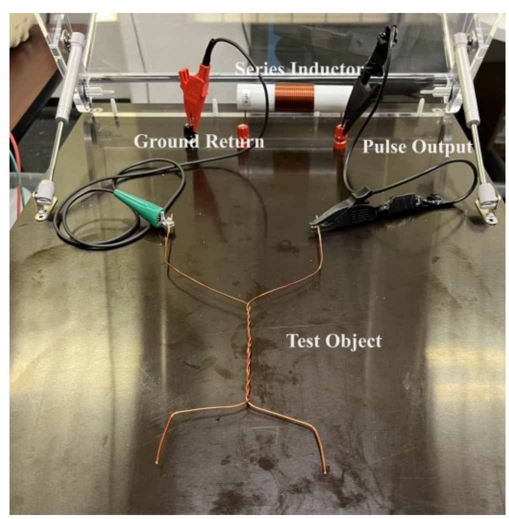

Fig. 3. Test setup.

IV. Results And Analysis

We obtained the lifetime data for five distinct frequencies (50 kHz, 40 kHz, 30 kHz, 20 kHz, and 10 kHz) and four distinct rise times (200 ns, 150 ns, 100 ns, and 50 ns) using the experimental setup described in the preceding section. The data from the experiment are presented in Table II. The relevant graph for the data mentioned above is shown in Fig. 4. It demonstrates how the high-frequency square wave's ascent time affects the lifetime. The lifetime of the insulation can be increased by increasing the rise time at a regular interval and vice versa. However, the pace at which the rising time changes differs for different frequencies. Higher-frequency square waves with lower rise times cause the magnet wire used in this experiment to have a shorter lifetime, whereas lower-frequency square waves with higher rise times result in insulation having a longer lifetime. For this particular instance, facing the 50 ns rise time is the most important part. The specimen's lifetime is significantly shortened for all frequencies by this rising time. This experiment's lowest rising time has raised the slew rate to the point where the associated electric stress is fatal for the magnet wire's insulation.

TABLE II
Impact of Switching Frequency for Different Rise Times

	Average Lifetime (min) for Different Frequencies				
Rise Time	10 kHz	20 kHz	30 kHz	40 kHz	50 kHz
50 ns	13	4	2.5	1.3	0.8
100 ns	143	70	51	55	4
150 ns	110	80	107	57	13
200 ns	194	110	91	136	78

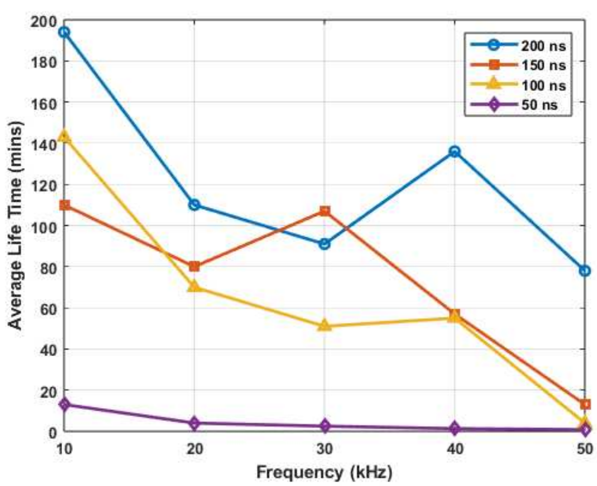

Fig. 4. Average lifetime as a function of switching frequency of repetitive square wave voltage for all rise time conditions

V. Conclusion

The impact of high switching frequency square waves on the insulating lifetime of electric machine windings was investigated in this study. Our results highlight an important relationship: increasing the frequency at a steady rise time increases the impacts of accelerated aging on insulation. On the other hand, insulation deterioration is minimized by lower frequencies, particularly at higher rise times. In order to improve component lifetime and reliability, this emphasizes how crucial it is to optimize switching frequency in electrical machine design. Managing high-frequency, high-slew rate signals is a growing challenge in WBG power electronic modules. High-voltage, high-frequency pulses are being used more frequently to use their advantages, such as higher power density and efficiency, but current insulation materials are not familiar with this field. This experiment investigates the effects of increasing frequencies on the longevity of current insulation systems with higher switching frequencies at different rise times. These findings set the framework for the advancement of future power electronic insulation technologies.

Acknowledgment

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