Influence of Rise Time on the Aging of Electric Machine Windings

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Abstract- **This study examines how fast rise times, which are common in modern power electronics and drive systems, affect the aging of electric machine windings. It focuses on how to ensure these windings can last longer and work reliably in electrical systems. A twisted pair magnet wire with insulation commonly used in wound machines was used to get experimental data to understand how different voltage waveforms can influence endurance testing of motor insulation systems powered by inverters. Unlike past studies that looked at comparatively slower rise times and fewer repetitions, this research specifically addresses the challenges posed by next-generation wide bandgap (WBG)-based conversion systems. These systems operate at very high speeds, up to 100 kV/µs, and switch frequencies up to 500 kHz, where both frequency and rise time are crucial factors affecting insulation aging over time.**

I. Introduction

As traditional vehicles adapt to a rapidly changing environment, the shift from mechanical components to electrical devices is a prominent trend. This transformation is exemplified by replacing conventional internal combustion engines with electric motors, which extends to the conceptual planning of electric aircraft, all relying on electric motor technology, this is one example of shifting toward electrical alternatives [1], besides all existing electric motors applications. Achieving efficient and reliable performance from these motors now hinges significantly on advanced power electronics drivers. Historically, Variable Frequency Drives (VFDs) have long been used to control motors, particularly in various voltage ranges and low-frequency applications. However, concerns arise when applying this concept to high voltage and fast repetitive voltages, posing new challenges and considerations [2].

Advancements in power electronics, particularly the integration of wide band gap (WBG) devices, have led to higher frequencies and voltages in electrical insulation systems, impacting their longevity. Among the critical factors influencing insulation life, voltage pulse frequency and rise time play pivotal roles and are closely tied to the reliability of motor stator windings [3, 4]. Currently, to the author's best knowledge, there is no experimental data on how insulation degradation is affected when exposed to very fast and repetitive high voltage that are rated as slew rate up to 100 kV/µs and repetition rate up to 500 kHz, which is the desired limit for the US military and modern power grid applications [2].

Applying high voltage and high-frequency pulses induces partial discharges (PD) in insulators, a primary factor contributing to premature failures in inverter-powering motors [5]. Therefore, to enhance insulation reliability, it is important and urgent to conduct endurance tests early on, especially when implementing high-frequency pulses with low rise times [6]. 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 endurance 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 [7]. Another challenge is encountered when manufacturers opt for impulsive voltages to assess insulation endurance, and they consistently face difficulties controlling the practical rise time of these impulses. Factors such as specimen capacitance, circuit resistance, and inductance can easily alter the rise time, complicating efforts to maintain a constant value. In such scenarios, the rise time plays a crucial role in influencing the outcomes of endurance tests [6]. Previous literature extensively covers high-impulse voltages, typically focusing on lower frequency ranges and higher rise times. However, this paper explores the winding endurance under higher frequency and lower rise times indicative of higher slew rates and justifies these from experimental data.

II. Sample Preparation

For our experiment, a twisted pair (TP) is selected due to its resemblance to turn-to-turn insulation in motors, a critical area prone to vulnerability. The TP consists of copper wire characterized by two primary parameters: the bare copper wire's diameter (15 AWG or 1.45 mm) and its insulation's thickness (80 µm). The insulation comprises a basecoat of modified polyester and an enhanced polyamide-imide topcoat, classified under thermal class 200°C. A 24 cm length of straight wire was used to build the TP sample, with insulation removed at both ends and then twisted back onto itself. The twisting process involves twelve twists under a constant tension load. The closed end of the twisted pair loop is then cut off to maximize separation. Prior to assembly, the straight wire undergoes alcohol paper wiping to eliminate surface impurities and static electricity influence, as mentioned in [8]. Fig. 1 illustrates the sample, featuring tightly intertwined magnetic wires. One wire connects to high voltage while the other serves as ground, simulating motor operating conditions.

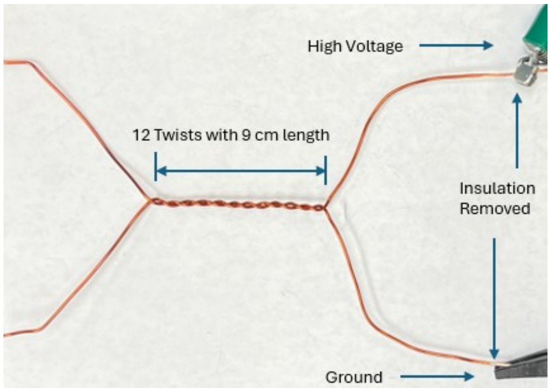

Fig. 1. Twisted pair Specimen.

III. Experimental Setup & Methodology

Fig. 2 illustrates the block diagram of the test setup. The pulse generator used in this experiment is connected to the power outlet in the high-voltage lab. The block Pulse Generator indicates the square wave voltage source (SWVS), which is a high-frequency bipolar high-voltage pulse generator. The front panel of SWVS allows one to control the parameters of the square wave and shows the current and voltage applied to the test object. In the top panel, Fig. 3, the test object is connected to the ground and pulse ports through an inductor. The inductor is used with the high capacitive test object so that the load does not affect the rise time.

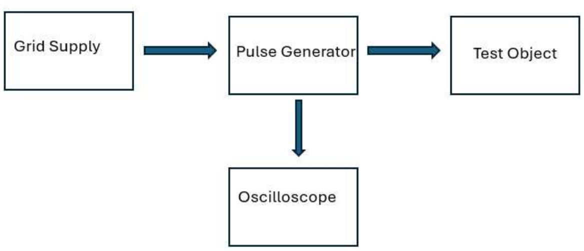

Fig. 2. The block diagram of the HV experimental test setup.

An oscilloscope is connected to the pulse source so that frequency and voltage amplitude can be calculated precisely. Tests were conducted on the twisted pair sample made according to the procedure described in Section II. The basic concept is to connect the specimen with a high voltage source at a fixed frequency and a fixed rise time and wait till the breakdown occurs. Each time a breakdown occurred, the specimen was replaced with a new one. After the breakdown occurs, time was recorded with a stopwatch and the procedure was repeated with a different rise time. This process is repeated for different frequencies, which gives the characteristics of the motor wire insulation with respect to rise time under the operation of square wave voltage. The detailed procedure of our experiment is illustrated in Fig. 4.

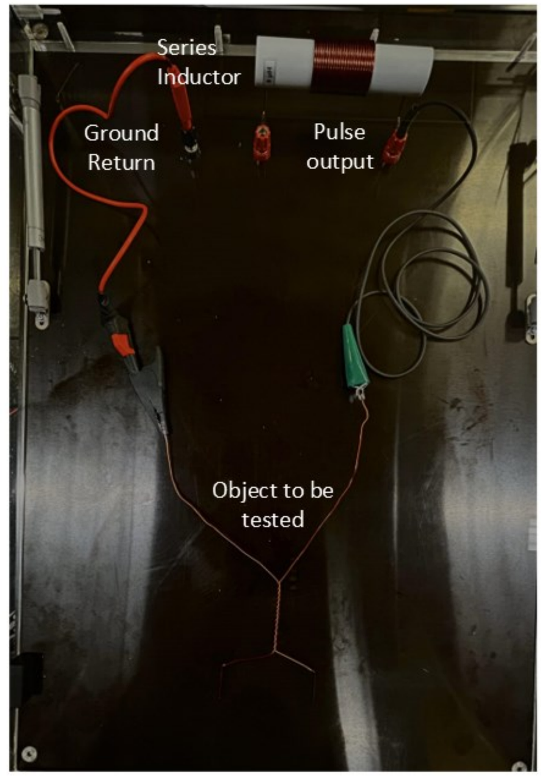

Fig. 3. Test setup.

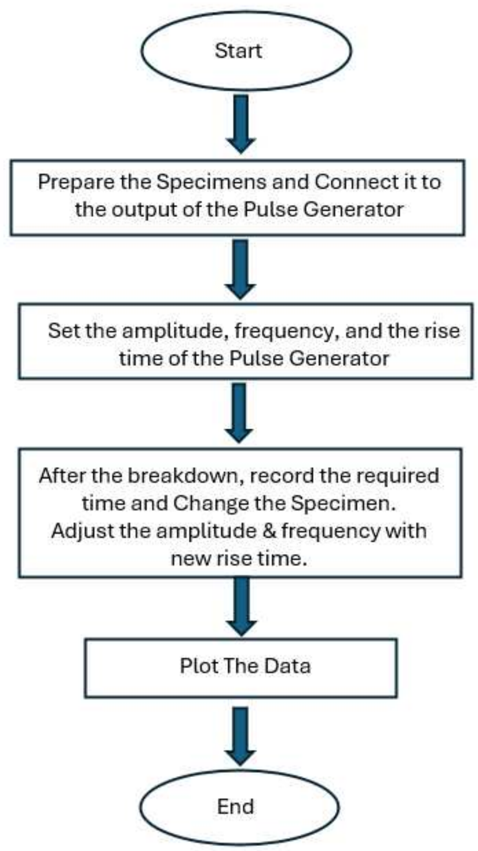

Fig. 4. Flow chart of the experimental Procedure

IV. Results And Discussion

Through the experimental setup mentioned in the previous section, we have collected the breakdown data for six different frequencies (55 kHz, 45 kHz, 35 kHz, 25 kHz, 15 kHz, and 5 kHz) and five different rise times (225 ns, 175 ns, 125 ns, 75 ns, and 50 ns). Table I consists of experimental data. Fig. 5 depicts the corresponding graph for the data mentioned below. The applied voltage for the test was a bipolar square wave with a duty cycle of 50%, and a magnitude of 1 kV which is about 1.5 times the partial discharge inception voltage (PDIV).

TABLE I

EFFECT OF RISE TIME (t_r) FOR DIFFERENT FREQUENCY

Frequencies	Endurance Time (min)				
Rise Time	t_{r1}(225 ns)	t_{r2}(175 ns)	t_{r3}(125 ns)	t_{r4}(75 ns)	t_{r5}(50 ns)
55 kHz	18	15	7	6	2.66
45 kHz	27	31	17.5	13	10
35 kHz	59	35	20	23	19
25 kHz	65	35	45	43	45
15 kHz	111	58	55	88	81
5 kHz	239	140	222	187	192

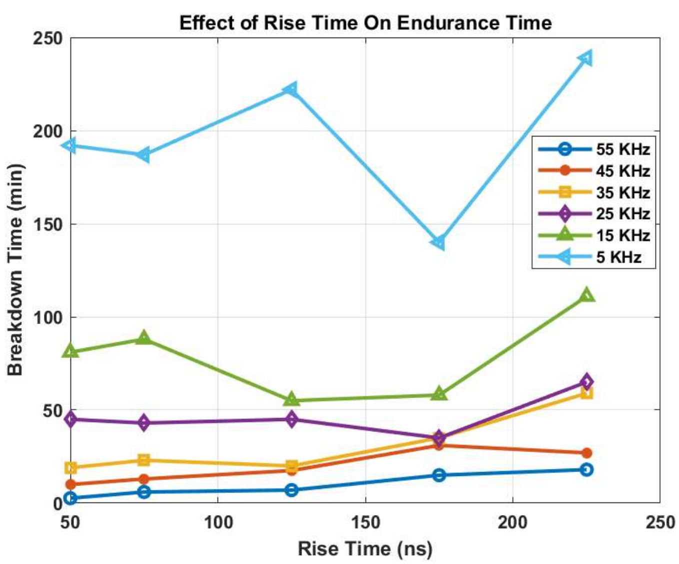

Fig. 5. Time to Breakdown for different rise times for different frequencies.

After the regression analysis, we can get a better insight into the data, and we have chosen the linear regression for this data set, see Fig. 6. As seen the breakdown is influenced by the rise time of the high-frequency square wave. Increasing the rise time at a constant frequency can extend the insulation's lifespan and vice versa. However, the rate of change in rise time varies across frequencies. The insulation's lifespan is longer for lower-frequency square waves with higher rise times. In contrast, higher-frequency square waves with lower rise times result in shorter lifespans for the magnet wire used in this experiment. The most crucial region for this specimen is to face the 50 ns rise time. This rise time drastically reduces the lifespan of the specimen for all the frequencies. The lowest rise time in this experiment has increased the slew rate so that the implied electric stress is lethal for the insulation used in the magnet wire.

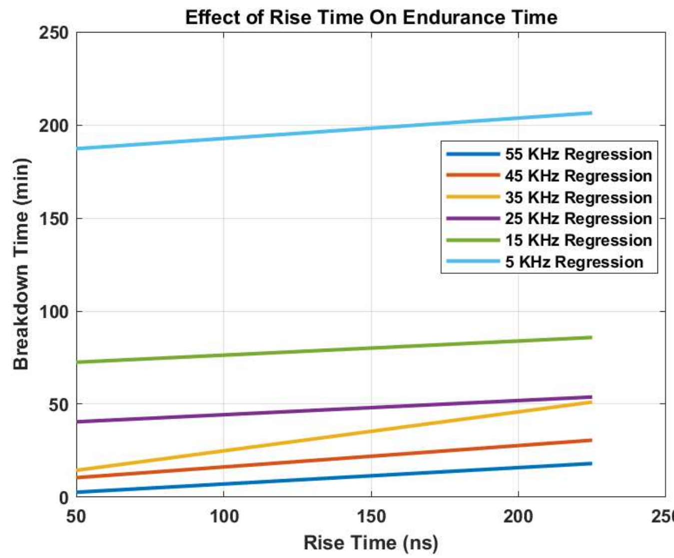

Fig. 6. Regression plot of the breakdown time variation for rise time for different frequencies.

Conclusion

In this study, we explored how the rise time of high-frequency square waves affects the insulation lifespan in electric machine windings. Our findings reveal a crucial relationship: increasing the rise time at a constant frequency extends insulation longevity, mitigating aging effects. Conversely, lower rise times, especially at higher frequencies, accelerate insulation degradation. This underscores the importance of optimizing rise times in electrical machine design to enhance component durability and reliability. Increasingly employing high voltage, high frequency U(WBG)-based drivers although resulting in increased efficiency and power density, a realm unfamiliar to current insulation materials. This experiment explores how higher frequencies with higher slew rates (lower rise times) impact the lifespan of existing insulation systems. These insights lay the groundwork for advancing insulation technologies critical for future electric machine windings.

Acknowledgment

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