



## Influence of High Frequency Stress of Waveforms on Life of Polymeric Enamel Insulation

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### **Abstract:-**

Insulation breakdown in electrical motors has been observed in recent years as a result of adjustable speed drives driven by power electronic converters. These converters generate impulse waveforms with a high slew rate as a result of IGBTs' high switching frequencies. This paper focuses on high switching frequency stress in low voltage electrical motors for adjustable speeds. To examine the motor winding insulation under such stress twisted-pair samples were developed from enameled wires. A single-coated Polyester of enamel with a thickness of 40 microns is used for this work. The test results show that the insulation fails earlier for the square waveform compared to the square-spike and square-rising waveforms. In this paper the Weibull distribution and the shape parameter is analyzed for life of enamel insulation at high-frequencies, high voltages of square, and square-rising, square-spike waveforms of 10 to 30kHz.

**Keywords:** Square wave voltage, Twisted pair, High switching frequency, Shape parameter, Weibull distribution

### **1. Introduction**

Inverter-fed motors are now widely employed in numerous industries, including high-speed railways, hybrid electrical vehicles (HEVs), and many industrial applications, due to several advantages such as high efficiency and controllability [1]. In contrast to typical motors supplied by alternating current voltages, inverter-fed motors are powered by pulse width modulation (PWM) technology, which generates high-frequency pulses with a high slew rate via IGBTs [2]. As a result, the coil's enamel insulation experiences frequent surge voltages with nanosecond rise times. These surges damage both low and medium voltage



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motors, leading to reliability difficulties [3]. Furthermore, excess voltages would arise at the motor winding's phase-to-phase and turn-to-turn insulation terminals due to reflection and resonance phenomena, as well as impedance mismatching between the inverter, cable, and motor, resulting in voltages up to double the input voltage [4]-[5]. These stresses are responsible for the unexpected early breakdown of motor winding insulation [6-7]. Furthermore, there is an unequal distribution of electrical potential throughout the windings. As a result, phase-to-ground and turn-to-turn insulation experiences more electrical stress than a sinusoidal waveform [8], especially in the early turns [9]. Overvoltage and partial discharge (PD) activities can occur when voltages rise and fall quickly. This causes organic insulating materials used in winding insulation to degrade quickly [10]-[11].

The literature contains reports on the investigation of low-frequency stress. However, because the enamel insulation may be subjected to higher frequencies, this work presents a higher frequency stress of 10-30 kHz for square, square-rising, and square-spike waveforms. The reason for selecting high frequency for the test is the increased need for variable speed applications and the growing number of low voltage motors [12]. The objective of using high frequency switching in this study is to investigate the electric stress caused by high-frequency pulses with a rapid rise in voltage surge on the motor winding insulation.

The aging of enamel insulated wires was tested using five distinct waveforms with a fundamental frequency of 300 Hz in the presence of PDs, and the shape of the waveform was found to affect the life of enamel insulation [13]. V. Madonna et al [14] investigated the size factor theory and the Weibull distribution are used to predict the thermal lifespan of random wound coils. The effect of short unipolar repeating impulsive voltages with voltage durations of 200 ns on PD statistics and enameled wire insulation lifetime was investigated [15]. The life of two types of enamel wires made of organic resin and nanofilled resin was investigated, and a lifetime model was developed [16]. Though work has been done at lower frequencies up to 600 Hz and 3 kHz, the endurance of insulation subjected to higher frequency pulses caused by MOSFET or IGBT switching at up to 10-50 kHz must be known. The stator winding insulation is subjected to much higher frequency stress significantly degrading the motor winding insulation [17].

As a result, an attempt is made in this work to test the twisted pair insulation at higher frequencies ranging from 10 to 30 kHz in order to investigate the life of twisted pair enamel insulation. In the present study, the twisted-pair sample of polyester enamel is stressed by square, square-rising, and square-spike waveforms over the range of frequencies from 10-30 kHz. The tests are carried out to demonstrate that early failure of twisted pair insulation may be attributed to PD phenomena caused by higher switching frequency. The Weibull distribution and shape parameter are investigated for the life of enamel insulation from 10 to 30 kHz of square, square-rising, and square-spike waveforms.

The rest of the paper is structured as follows: Section 2 describes the experimental setup and test procedure for breakdown test. Section 3 presents the experimental results as well as the weibull distribution at different waveforms at different frequencies. Section 4 concludes



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the probability of enamel insulation breakdown is higher for square waveforms than square-rising, square-spike waveforms.

## 2. Experimental Procedure

### 2.1 Sample preparation

The twisted-pair specimens are formed of two enameled magnet wires braided into a plait in accordance with ASTM D 1676-03 requirements [18]. Testing involves using a 40  $\mu\text{m}$  thick single-coated polyester enamel insulation. The twisted-pair length ( $12\pm 6$ ) cm meets specifications. The number of twists is six, depending on the wire diameter.

### 2.2 Test setup

Figure 1 shows a block schematic of the power frequency arrangement. It is made up of a variac with an output range of 0-230 V AC, 50 Hz, and a high voltage transformer with an output range of 0-10 kV AC, 50 Hz. A sample of twisted pairs is connected to the high voltage transformer's output. An auxiliary winding with a 1000:1 voltage ratio is supplied for monitoring the output breakdown voltage of the twisted pair sample with a DSO or Voltmeter.

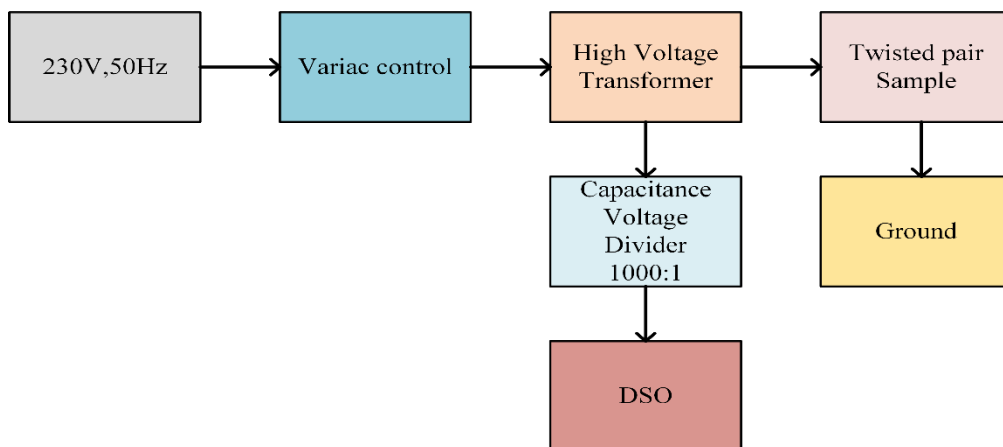


Figure 1. Block diagram of high voltage power frequency arrangement [19]

Figure 2 shows the experimental setup for square, square-rising, and square-spike waveforms with high frequencies, as well as the high voltage utilized to test the twisted pair samples. All of the waveforms utilized here are bipolar. The EMI line filter receives the 230V, 50Hz source and connects its output to the frequency and duty cycle controller. The output of the inverter is increased by using a nanocrystalline core transformer for high frequency operation, which stresses the twisted pair sample. A capacitance voltage divider of



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1000:1 is used in a digital oscilloscope to monitor peak voltage. Figure 3 shows the laboratory setup utilized to carry out the breakdown testing.

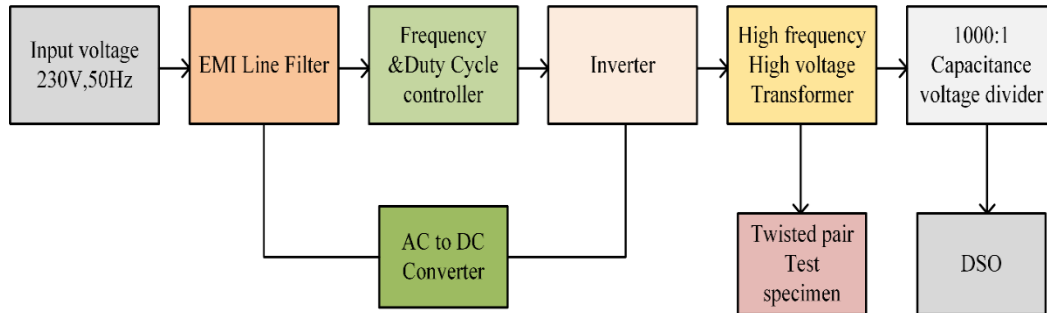


Figure 2. Block diagram of power frequency high voltage arrangement [20]

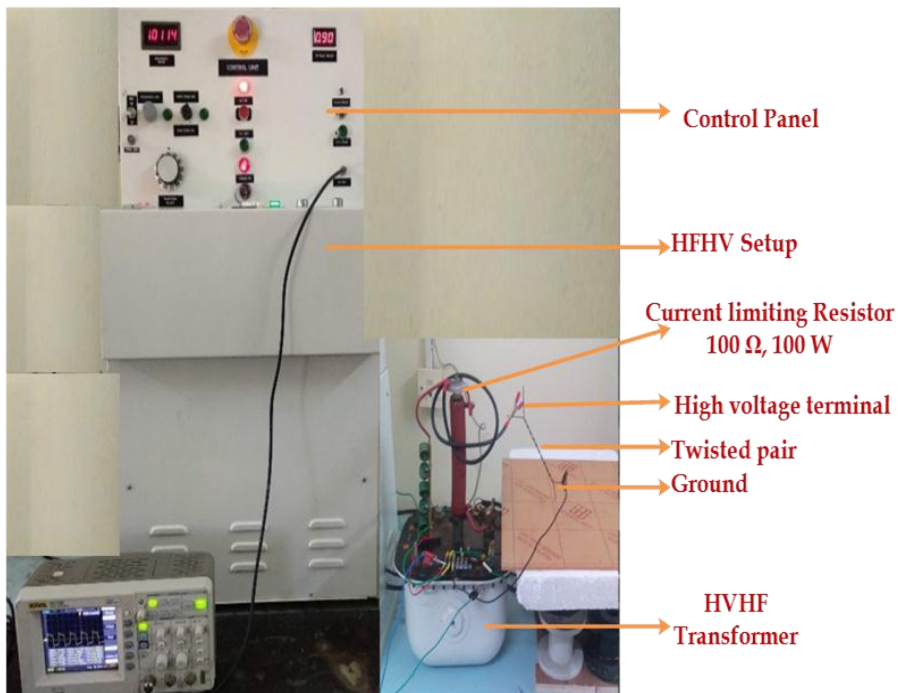


Figure 3. Laboratory setup used for breakdown tests

### 2.3 Test procedure

The breakdown voltage of a twisted-pair specimen is determined by gradually increasing the voltage at a rate of 500 V/sec [21] until power frequency breakdown occurs. The



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breakdown studies on enamel insulation were performed at room temperature with a power frequency high voltage sinusoidal waveform. The hissing noise was heard when a high voltage (3kV or more) was applied to the sample while completing the experiments at power frequency, and the breakdown was accompanied by an increase in current. This is known as the insulation breakdown. The voltage at that time was recorded as the breakdown voltage, which is reported here. During high-frequency breakdown testing, the breakdown voltage of a twisted pair is determined by raising the applied voltage magnitude at a rate of 500 V/s [21] until the breakdown occurs. The breakdown studies were performed on enamel insulation at room temperature using high frequency high voltage of sine, square, square-rising, and square-spike with frequency levels of 10 kHz, 20 kHz, and 30 kHz. The breakdown voltage is calculated by taking the average of five breakdown values. When the experiments are performed at high frequencies, the ionization effect in the gap between the twisted pairs is visible as a faint violet glow. When the applied voltage is raised, the corona discharge increases as the glow spreads across the length of the twist, enhancing current and temperature. This indicates that when the voltage increases, the insulating resistance lowers, and a spark is observed between the conductors. This is considered the beginning of high-frequency insulation breakdown. The voltage at that point is denoted as breakdown voltage and is recorded here. Table 1 shows the parameters of the test setup used for breakdown tests.

Table 1. Details of the test setup

Frequency	Duty cycle	Waveforms	Test operating voltage
0-30 kHz	0-50%	sine, square, square-rising, and square-spike	0-15 kV (P-P)

### 3. Results And Discussion

#### 3.1 Experimental results

Modified polyesters of various types are tested and found to have varying breakdown strengths [19] due to a variety of characteristics such as crystallinity, as well as other factors such as PD at low voltage, joule heating, and so on. Throughout the investigation, one sample was chosen, average of five samples were tested. Figure 4 depicts the variance in breakdown voltages as a function of frequency and waveform. The graph shows that the square, square-rising, and square-spike waveforms have two straight lines with variable slopes, as in [22], with a frequency rise ranging from 10 to 30 kHz. The graphs show that the breakdown voltage of the square-rising waveform is higher than that of the square-spike and square



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waveforms. As a result, it is described that employing a square waveform accelerates the deterioration rate of the twisted pair insulation system when compared to square-spike and square-rising waveforms.

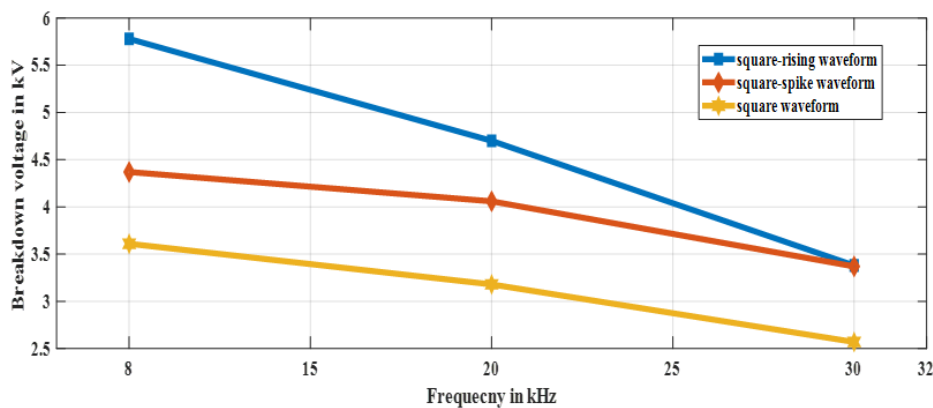


Figure 4. Breakdown voltage variations for square, square-rising, and square-spike Waveforms range from 10 to 30 kHz

### Weibull distribution

Weibull distribution is the most commonly used distribution in the reliability studies and in the breakdown voltage testing of breakdown of insulation. Weibull distribution parameters  $\gamma$  and  $\beta$  are estimated using maximum likelihood estimation method. Two-parameter Weibull distribution analysis was performed at each frequency since the dielectric breakdown is a stochastic process. The Weibull reliability function is described by [23]

$$F(t) = 1 - \exp[-(t-\gamma)^\beta / \eta] \quad (1)$$

Where  $\gamma$  is the scale parameter shows the voltage at which, for a particular thickness, the probability of breakdown is 63.2%, the parameter  $\beta$  is a dimensionless factor known as the shape parameter and  $t$  is the time to failure. These parameters (i.e.  $\gamma$  and  $\beta$ ) are determined via a graphical method based on the linear regression approach. Table 2 shows the scale and shape parameters at power frequency and high frequency of sine waveform. As seen from the table, the scale parameter decreases as frequency increases, which indicates that breakdown strength decreases as frequency increases. Table 3 shows the scale and shape parameters of square-rising, square-spike, and square waveforms at different frequency levels from 10 to 30 kHz. From the



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table the scale parameter for the sine waveform is the highest at each frequency, while it is the lowest for the square waveform, the scale and shape parameter also varies on the type of waveforms.

Table 2. Weibull distribution parameters of sine waveform

Parameter	50 Hz	10 kHz	20 kHz	30 kHz
Scale parameter (kV)	9.71	6.56	6.3	6.37
Shape parameter	43.65	31.57	25.96	13.34

Table 3. Weibull distribution parameters of Square-Rising, Square-Spike, and Square, Waveforms

Parameter	Scale parameter (kV)			Shape parameter		
	10 kHz	20 kHz	30 kHz	10 kHz	20 kHz	30 kHz
Square-Rising waveform	5.78	4.7	3.38	23.94	31.68	17.7
Square-Spike waveform	4.37	4.06	3.37	104.36	32.45	80.37
Square waveform	3.61	3.18	2.57	20.32	63.38	61.17

Figure 5 shows the probability of breakdown of sine waveform at power frequency and high frequency. It is seen from the graph shows that the probability of insulation failure at higher frequencies is compared to the power frequency of a sine wave. Figure 6, 7 and 8 show the Weibull distribution of square-rising, square-spike and square waveforms from 10 kHz to 30 kHz. It is seen from the graphs that the probability of enamel insulation breakdown is higher for square waveforms than square-rising, square-spike waveforms from 10 kHz to 30 kHz. As a result, it is stated that using a square waveform enhances the deterioration rate of the twisted pair insulation system in comparison to square-spike and square-rising waveforms.



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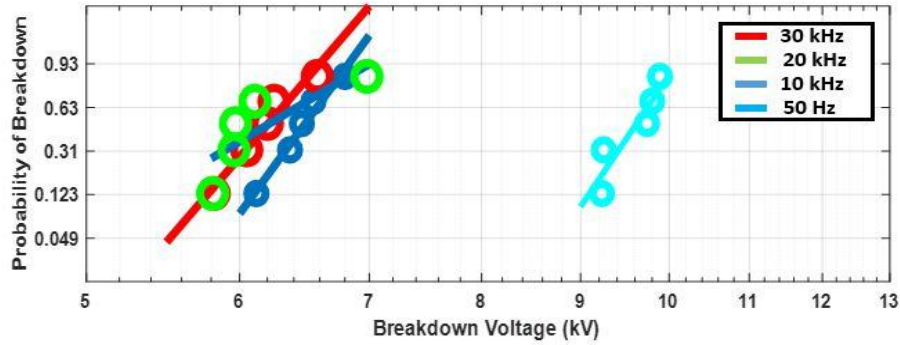


Figure 5. Probability of breakdown of sine waveform at power frequency and high frequency

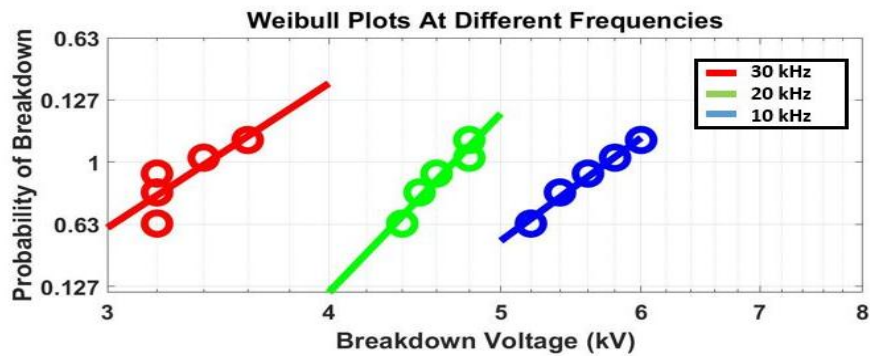


Figure 6. Probability of breakdown of square-rising waveform from 10-30 kHz

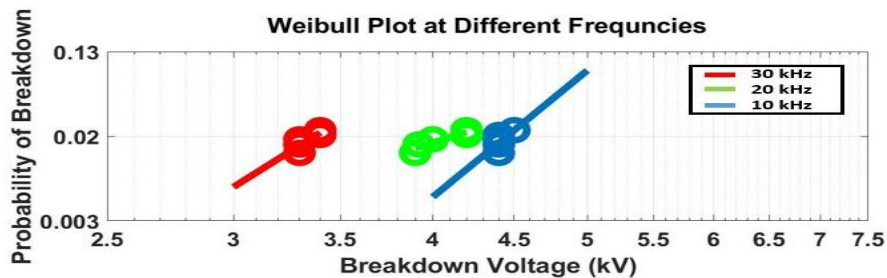


Figure 7. Probability of breakdown of square-spike waveform from 10-30 kHz



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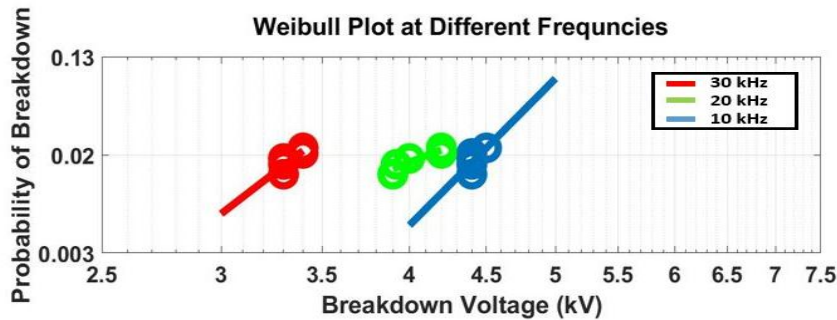


Figure 8. Probability of breakdown of square waveform from 10-30 kHz

#### 4. Conclusion

The high switching frequency is a predominant factor that causes reliability problems in insulation. After investigating the experimental results it is found that the breakdown voltage of power frequency is higher than that of high frequency. The breakdown voltage of the square waveform is lower compared to breakdown voltage of square-rising waveform and square-spike waveforms. It is also observed that using a square waveform the rate of deterioration of the insulation system is faster when compared with square-spike and square-rising waveforms. When the test voltage frequency is increased from 10-30 kHz, the lifetime of square-rising and square-spike waveforms are two straight lines with higher slopes followed by lower slopes for all frequencies. From the weibull distribution, the scale parameter decreases as frequency increases, which indicates that breakdown strength decreases as frequency increases. The scale parameter for the sine waveform is the highest at each frequency, while it is the lowest for the square waveform. It is seen from the graphs that the probability of enamel insulation breakdown is higher for square waveforms than square-rising, square-spike waveforms from 10 kHz to 30 kHz. As a result, it is stated that using a square waveform enhances the deterioration rate of the twisted pair insulation system in comparison to square-spike and square-rising waveforms. It is noticed that the influence of PD for the square waveform on enamel insulation is so significant at higher switching frequencies that the twisted-pair sample breaks prematurely.

#### References

1. P. Wang, C. Zheng, Y. Li, Y. Lei, A. Cavallini, "The PD and Endurance Features of Enameled Wires at Short Repetitive Impulsive Voltages," IEEE Electrical Insulation Conference EIC, pp. 572-576, June 2018, doi: 10.1109/EIC.2018.8481043.



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2. V. N. Höpner, V. E. Wihelm, "Insulation Life Span of Low Voltage Electric Motors-A Survey," *Journal of Energies*, vol. 14, pp .1-32, March 2021, doi:1996-1073/14/6/1738.
3. M. Florkowski, "Magnetic Field Effects on Partial Discharges in Electrical Insulation Subjected to PWM Excitation," *IEEE Transactions on Power Electronics*, vol. 39, no. 2, pp. 2741-2750, Feb. 2024, doi: 10.1109/TPEL.2023.3334011.
4. Lusuardi, A. Cavallini, M. G. de la Calle, J. M. Martínez-Tarifa, G. Robles, "Insulation design of low voltage electrical motors fed by PWM inverters," *IEEE Electrical Insulation Magazine*, vol. 35, no. 3, pp. 7-15, June 2019, doi: 10.1109/MEI.2019.8689431
5. Y. Xie, J. Zhang, F. Leonardi, A. R. Munoz, M. W. Degner, F. Liang, "Voltage Stress Modeling and Measurement for Random-Wound Windings Driven by Inverters," *IEEE International Electric Machines & Drives Conference (IEMDC)*, August 2020, pp 1917-1924, doi: 10.1109/TIA.2020.2986184.
6. R. Leuzzi, V. G. Monopoli, F. Cupertino, P. Zanchetta, "Active Ageing Control of Winding Insulation in High Frequency Electric Drives," *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018, pp. 1-7, doi: 10.1109/ECCE.2018.8558257
7. Z. Wei, H. You, B. Hu, R. Na, J. Wang, "Partial Discharge Behavior on Twisted Pair under Ultra-short Rise Time Square-wave Excitations," *IEEE Electrical Insulation Conference EIC*, 2019, pp. 493-496, doi: 10.1109/EIC43217.2019.9046624.
8. A. Caprara and G. Ciotti, "Investigation about the effect of the voltage profile on RPDIV and time to failure for insulation materials subjected to impulsive stress conditions," *IEEE Electrical Insulation Conference (EIC)*, 2022, pp. 98-101, doi: 10.1109/EIC51169.2022.9833191.
9. L. Lusardi, et al., "The Effect of Inverter Characteristics on Partial Discharge and Life Behavior of Wire Insulation," *IEEE Electrical Insulation Magazine*, vol. 34, no. 2, pp. 32-39, April 2018, doi: 10.1109/MEI.2018.8300442.
10. F. Guastavino, E. Torello, L. D. Giovanna and I. Khan, "Study of the Partial Discharge Inception Voltage Variation Over Time on Enameled Wires Subjected to Thermal-Electrical Stress," *IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, 2023, pp. 1-3, doi: 10.1109/CEIDP51414.2023.10410540.



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*Revised: 15-11-2024*

*Accepted: 10-12-2024*

11. M. Kozako et al., "Prediction of Lifetime in Surge Resistant Enamel Twisted Pair by Partial Discharge Degradation under Repetitive Impulse Voltage Application," IEEE 4th International Conference on Dielectrics (ICD), 2022, pp. 261-264, doi: 10.1109/ICD53806.2022.9863577.
12. K. Hameyer, A. Ruf, F. Pauli, "Influence of fast switching semiconductors on the winding insulation system of electrical machines," International Power Electronics Conference (IPEC), 2018, pp. 740- 745, doi: 10.23919/IPEC.2018.8507972.
13. F. Guastavino, A. Dardano, "Life tests on twisted pairs in presence of partial discharges: influence of the voltage waveform," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, no. 1, pp. 45-52, February 2012, doi: 10.1109/TDEI.2012.6148501.
14. V. Madonna et al., "Weibull Distribution and Geometrical Size Factor for Evaluating the Thermal Life of Electrical Machines Insulation," IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, Singapore, 2020, pp. 1114-1119, doi: 10.1109/IECON43393.2020.9255227.
15. P. Wang, C. Zheng, Y. Li, Y. Lei, A. Cavallini, "The PD and Endurance Features of Enameled Wires at Short Repetitive Impulsive Voltages," IEEE Electrical Insulation Conference EIC, 2018, pp. 572-576, doi: 10.1109/EIC.2018.8481043.
16. F. Guastavino, L. Briano, F. Gallesi, E. Torello, "Corona resistant insulating systems characterization for low voltage rotating machine," IEEE Conference on Electrical Insulation and Dielectric Phenomena CEIDP, 2019, pp. 694-697, doi: 10.1109/CEIDP47102.2019.9009901.
17. S. Matsumoto, Nguyen Nhat Nam, D. Nagaba and T. Ogiya, "Partial discharge characteristics of twisted magnet wire under high frequency AC voltage," International Symposium on Electrical Insulating Materials, 2014, pp. 57-60, doi: 10.1109/ISEIM.2014.6870719.
18. ASTM D1676 - 17 Standard Test Methods for Film-Insulated Magnet Wire, Annual book of ASTM standards, 2017.
19. S.Narasimha Rao, Elanseralathan. K "Influence of square waveform on life of twisted pairs due to power electronics converter" Journal of CPRI, Vol. 13, No. 1, Marchr 2017, pp. 135-139.
20. S.Narasimha Rao, Elanseralathan. K "Modeling of high frequency high voltage of waveforms on the life of enamel insulation" Indonesian Journal of Electrical



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Engineering and Computer Science (IJEECS), Vol. 23, No. 3, September 2021, pp. 1331-1339, doi: 10.11591/ijeecs.v23.i3.pp1331-1339.

21. IS 13778 (Part 5): 2012, IEC 60851-5: 2008 winding wires- test methods-part-5- electrical properties.
22. S. N. Rao, K. Elanseralathan, "Influence of PWM technique on breakdown in twisted pairs," 3rd International Conference on Condition Assessment Techniques in Electrical Systems CATCON, 2017, pp. 427-431, doi: 10.1109/CATCON.2017.8280258.
23. G. C. Stone, and R.G. Van Heeswijk, "Parameter Estimation for Weibull Distribution", IEEE Trans. on Elect. Insul., Vol. EI-12, No. 4, pp. 253- 261, August 1997 CESS.2022.3208258