International Journal of Multidisciplinary Research and Technological Advancement (IJMRTA)

Volume 1 Issue 1, Year Nov-Dec 2023 *Available at www.ijmrta.in*

The Influence of Conductivity on the Electrical and Thermal Characteristics of an Inverter-Fed Rotating Machine's Stress Grading System

Shinde Shital Raju

Department of Computer Technology

K.K. Wagh Polytechnic, Nashik, Maharashtra, India

Shitalshinder674@gmail.com

Dhondge Divyani Sandip

Department of Computer Technology

K.K. Wagh Polytechnic, Nashik Maharashtra, India

dhonndgedivya001@gmail.com

Kiran Shithole

Department of Computer Science and Engineering,

Priyadrashani College of Engineering, Nagpur, Maharashtra, India

kiranshitole45@gmail.com

****

Abstract:

Simulations and measurements of the electric field and temperature distributions in the overhang area of a form wound medium voltage motor coil are used to study the thermal and electrical features of a stress grading system. Stress grading tape (SGT) with high conductivity decreases maximum electric field in this area but increases temperature and heat generation, according to simulations. A highly conductive Armour tape (CAT), on the other hand, lowers the maximum electric field in this area, lowers stress grading system temperature and heat output, and slightly raises the electric field in the SGT zone. Considering the impact of the vacuum pressure impregnation (VPI) process, temperature, and tape constructions, precise electrical and thermal conductivity measurements of materials are acquired for the purpose of the simulation studies. Conductivity measurements are performed between 30 and 100 oC for both single and double half-lap layers of CAT and SGT. The simulation model was tested by measuring and simulating the temperature profile along the stress grading system at room temperature and near normal operating temperatures under pulsed voltage.

Keywords – Thermal Electrical Properties, SGT, CAT, Armor Tape, Vacuum Pressure Impregnation VPI

I. Introduction

Form-wound medium-voltage (MV) motor coil insulation methods rely heavily on stress grading and conductive tapes. Both the air gap between the coil and the armour and the end winding area of the coil are protected against partial discharge (PD) by these. When the electric field strength in a medium voltage motor is higher than the corona onset, PD occurs. This may lead to insulation degradation and, ultimately, motor failure. To get around these issues, a stress grading method is utilised, which primarily consists of two components: stress grading tape (SGT) and conductive armour tape (CAT). While the SGT inhibits PD at the end of the CAT, the CAT—typically composed of carbon black embedded in a resin-rich fibreglass tape—prevents slot discharges [1]. A resin-rich fibreglass tape often contains silicon carbide or zinc oxide varistor powder, making up SGT. The conductivity of both powders is quite sensitive to changes in temperature and electric field strength [2, 3].

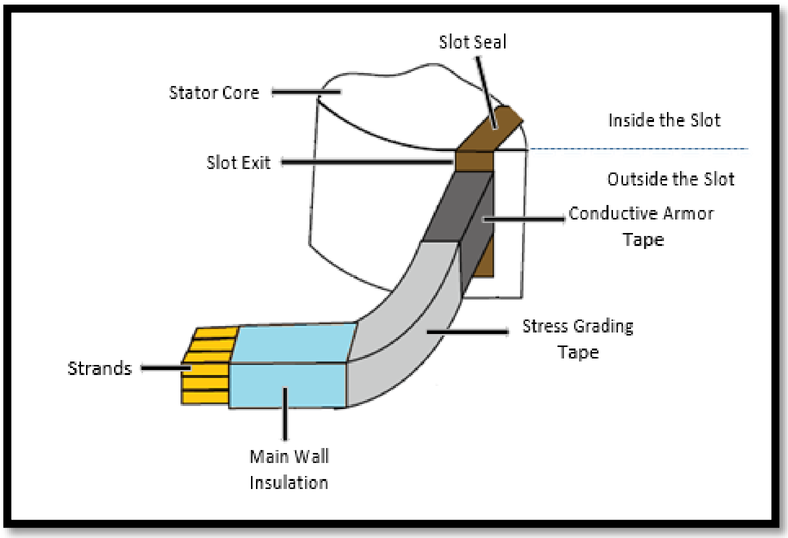


Fig. 1. illustrates the insulation system in the overhang region ofa motor.

Motor stators with a voltage rating of 2400 V or above are required to adhere to the specifications outlined in IEC standard 60034-18-42 [4]. While in operation, this insulation system is vulnerable to PD, which shortens its lifespan. Inverter pulses are characterised by high frequencies, rapid increase times, and voltage amplitudes; the standard also specifies the requirements for stress grading systems and insulation to withstand these pulses. The electrical and thermal conductivities of the CAT and SGT, respectively, determine the electric field, joule heat production, and temperature profile of a stress grading system. The electric conductivity of the CAT affects the electric field profile, peak voltage, and heat production on the SGT [5, 6 and 7]. Electrical conductivity of SGT is field-dependent and is enhanced in the presence of strong electric fields. As a result, the conductivity gradually decreases along the SGT, reaching its maximum at the very end of the CAT, where the electric field is very strong [8]. When compared to power frequency voltage systems, pulse width modulation (PWM) voltage systems perform worse when it comes to conventional stress grading. This is due to the fact that PWM systems include components with high frequencies, leading to increased electrical and thermal strains. Three parameters—rapid rising time, high repetition rate, and voltage overshoots of PWM pulses—influence the electric field and temperature profiles of the stress grading system [9]. Because the distribution of the electric field along the coil in the overhang area is modified by pulse characteristics, hot spots in these locations are caused by a greater electric field in the CAT or the SGT. A recently developed surface potential measuring device for monitoring voltage distribution under PWM voltage [10] may be used to assess the simulation findings. This device makes use of a Pockels sensor. Insulation systems typically have a thermal life expectancy of 20,000 to 25,000 hours when operated at its class temperature rating, under perfect conditions [11]. In accordance with the Arrhenius equation for chemical reaction time vs temperature [11], the half-life of insulation systems is cut in half when operating temperatures are raised by 10 °C. This can reduce the stress grading system's thermal lifetime since it might easily create hot spots. This study presents the results of an investigation into the effect of electrical conductivity of stress grading materials on the end winding area temperature profile. All important simulation parameters were determined under real-world conditions, after VPI and at operating temperature. With the use of a coupled electro-thermal finite element method (FEM) model, we determined the temperature distribution over the overhang region of a form-wrapped medium voltage coil. The idea is supported by temperature profiles that were measured along portions of the overhang region.

II. Experimental Survey

The coils were subjected to electrical conductivity testing after vacuum pressure impregnation (VPI) in accordance with ASTM D257-14 [12]. Along the coils, two small incisions were made, spaced 10 mm apart, through the tapes, and down to the insulation in the main wall. The incisions were used to make electrodes for testing electrical conductivity by applying silver paint. To reduce joule heating, a pulse voltage was used to evaluate the SGT electrical conductivity, which requires a large electric field. For CAT, see [5], and for SGT, see [8], for specifics on the methods of preparation and measurement, respectively.

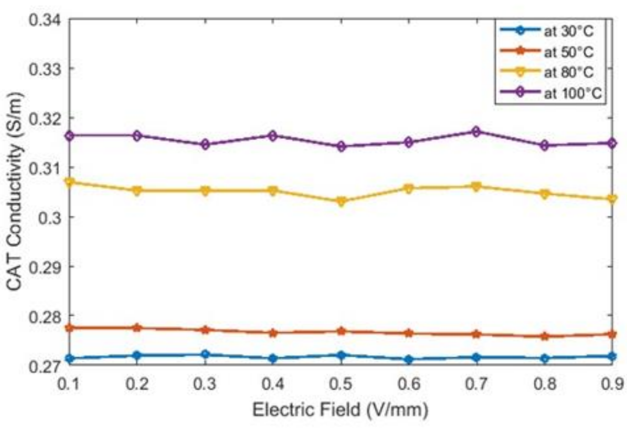


Figure 2. Conductivity of single-layer CAT as a function of electric field and temperature outside the slot.

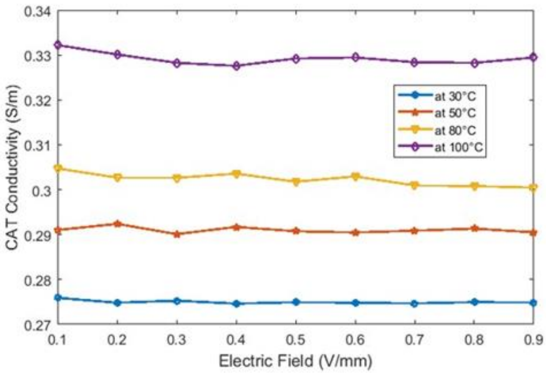


Figure 3. Conductivity of double-layer CAT as a function of electric field and temperature outside the slot

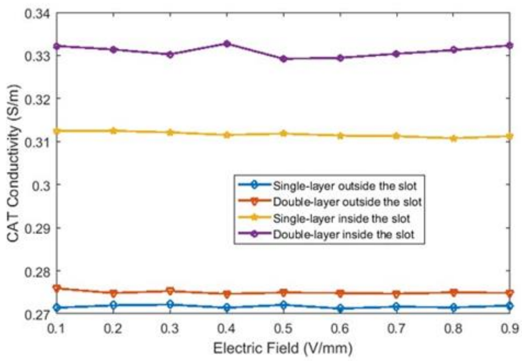


Figure 4. Conductivity of CAT as a function of electric field and VPI process (inside and outside the slot) at 30°C

The displays the observed electrical conductivity for a single-layer CAT and Figure 3 shows the same data for a double-layer CAT, both taken outside the slot and from 30 to 100 0C. Although, as predicted, the conductivity is a constant function of electric field, it is enhanced with increasing layer thickness and temperature. Figure 4 shows how VPI affects the electrical conductivity. The electrical conductivity of the layer is reduced in the VPI process because resin is able to penetrate between layers, therefore lowering the number of connections between them. Figure 5 shows the electrical conductivity of single-layer SGT, whereas Figure 6 shows the same data for double-layer SGT. In contrast to SGT, CAT electrical conductivity is increased by increasing temperature. Adding more layers somewhat raises the conductivities of both materials. Equations (1) and (2) provide the formulae for determining the electrical conductivity of single-layer and double-layer SGTs with respect to electric field and temperature, respectively. These formulae are obtained from the experimental results.

$$\sigma = (-4 * 10^{-8} * T + 5 * 10^{-6}) * exp^{(2*10^{-5}*T+0.0061)*E} \quad (S/m) \qquad (1)$$

$$\sigma = (-9 * 10^{-8} * T + 1 * 10^{-5}) * exp^{(1*10^{-5}*T+0.0057)*E} \quad (S/m) \qquad (2)$$

where T is temperature in ^{o}C, and E is the electric field in V/mm.

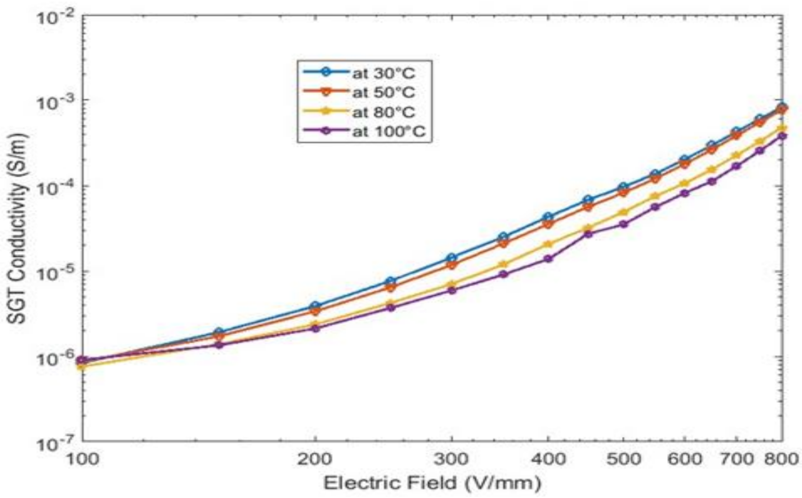


Figure 5. Conductivity of single-layer SGT as a function of electric field

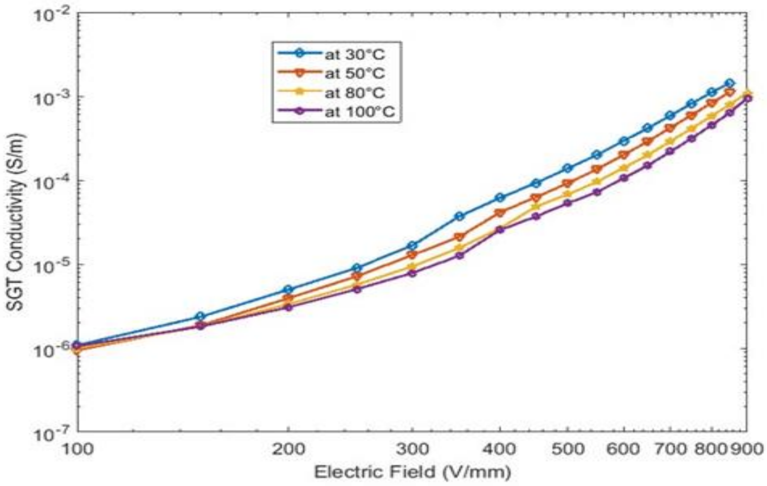


Fig.

The two the CAT and the SGT were tested for thermal conductivity according to the standards set forth by ISO 22007-2:2015 [13]. A transient plane source (TPS) equipment with a heated disc is used in the procedure. We measured two samples of every substance. In Table 1 you can see all of the thermal conductivities that were employed for the simulations.

Table 1. Thermal conductivity of materials.

Material	Thermal Conductivity (W/m.K)
Main Wall Insulation	0.52
Conductive Armor Tape	0.46
Stress Grading Tape	0.39

III. Simulation Model

In Figure 7, the stress grading system's shape is shown using the 2D axisymmetric module in COMSOL® 5.2a. A 13.8 kV bar sample's measured electrical and thermal conductivities, in addition to its real dimensions, were used for the simulation investigations. Figure 8 shows the results of the simulation and measurements conducted on the system using a unipolar pulsed voltage with a rise time of 0.3 µs and a peak voltage of 11.3 kV. In order to determine the temperature profiles along the sample, a coupled electro-thermal FEM simulation was used. The amount of heat generated by a single pulse of pulsed voltage is negligible. For example, a transient coupled electro-thermal FEM simulation lasting 1 hour is not feasible because of the very

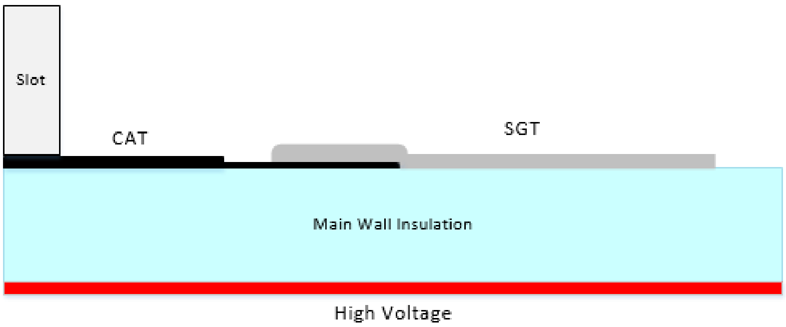
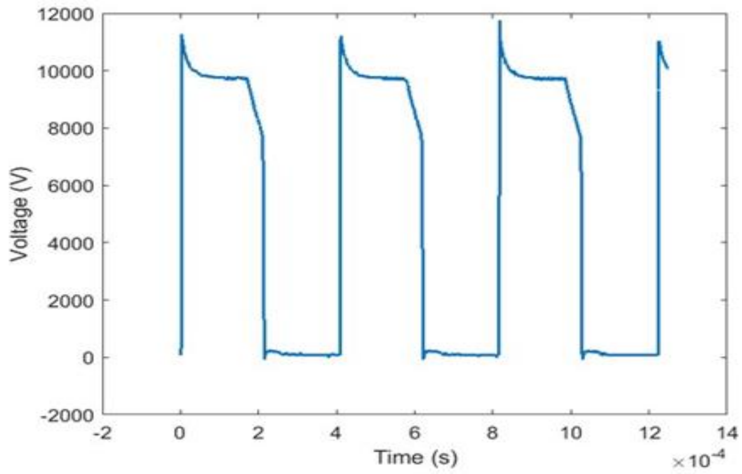


Figure 7. Structure of the stress grading system studies using

The results demonstrate that boosting the electrical conductivity of CAT has several advantages; nevertheless, due to its use within the slots, this conductivity increase might lead to eddy losses and short circuits in the core laminated sheets. In order for PDs to take place in the SGT area, increasing the electrical conductivity may raise the electric field there over the threshold.



There are three different CAT electrical conductivity conditions, and the figure shows the average heat output throughout one cycle of the pulsed voltage. Increasing the electrical conductivity of the CAT definitely decreases heat generation in the CAT. When the CAT electrical conductivity is at its lowest, the heat output peak is twice as high. Due to the higher electric field in this location, this peak is somewhat greater under situations of high CAT electrical conductivity at the SGT, as illustrated in Figure.

IV. Results and Discussion

For this study, we chose to examine the impacts of three distinct CAT electrical conductivity values on the stress grading system's thermal and electrical performances: 0.1 S/m, 0.32 S/m, and 1 S/m. Diagrams 13 and 14 depict the electric field distribution and voltage distribution over the surface of the end winding area, respectively, at the conclusion of the rising time of the applied voltage. For the three chosen CAT electrical conductivity parameters, Figure 15 shows the temperature profiles along the stress grading system.

The stress grading system's temperature clearly rises as the CAT electrical conductivity drops. Furthermore, it has been shown that as the electrical conductivity of the CAT decreases, the peak of the temperature profile shifts from the SGT area to the CAT region, which in turn causes the CAT at the slot exit to deteriorate. The results demonstrate that boosting the electrical conductivity of CAT has several advantages; nevertheless, due to its use within the slots, this conductivity increase might lead to eddy losses and short circuits in the core laminated sheets. In order for PDs to take place in the SGT area, increasing the electrical conductivity may raise the electric field there over the threshold. On average, the three CAT electrical conductivity settings produced the same amount of heat during a single pulsed voltage cycle (see Figure 16). Increasing the electrical conductivity of the CAT definitely decreases heat generation in the CAT. When the CAT electrical conductivity is at its lowest, the heat output peak is twice as high. Figure 14 shows that in situations of high CAT electrical conductivity at the SGT, the higher electric field causes this peak to be somewhat greater. In order to study the impact of SGT electrical conductivity, three different kinds of conductivity were chosen: the measured conductivity value, the lowest at one order below it, and the greatest at one order above it. At the conclusion of the rising period, Figures 17 and 18 illustrate the distributions of voltage and electric field on the surface of the stress grading system. Increasing the electrical conductivity of the SGT at the CAT's end decreases the electric field, according to the results. Additionally, it was discovered that the electric field in the CAT area was somewhat affected by the SGT electrical conductivity. See Figure 19 for the stress grading system surface temperature profile for the three chosen SGT conductivities. Increasing the electrical conductivity of the SGT lowers the electric field in the SGT area, but also raises the temperature of the stress grading system. According to equation (3), the quantity of joule heating is proportional to the product of the electrical conductivity and the square of the electric field.

$$Q \propto \sigma E^2 \quad (3)$$

As Figure 18 shows, an increase in the SGT electrical conductivity by one order of magnitude leads to a reduction in the

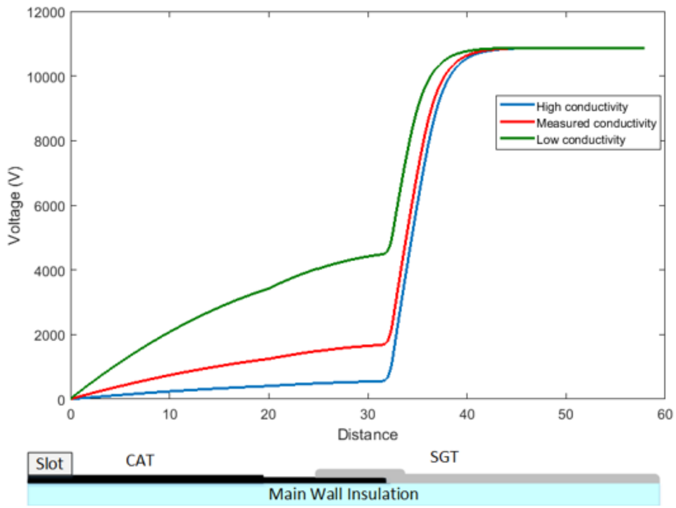


Figure 13. Voltage distribution along the surface of the stress grading system for three CAT electrical conductivity conditions at the end of rise time of the pulsed voltage.

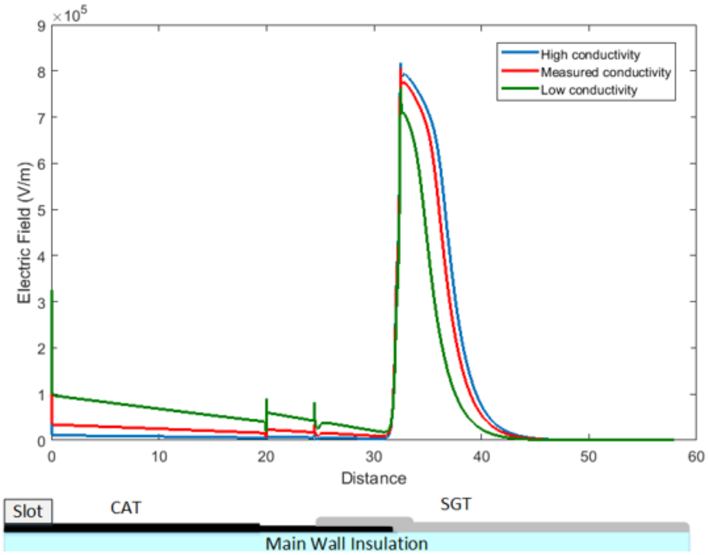


Figure 14. Electric field distribution along the surface of the stress grading system for three CAT electrical conductivity conditions at the end of rise time of the pulsed voltage.

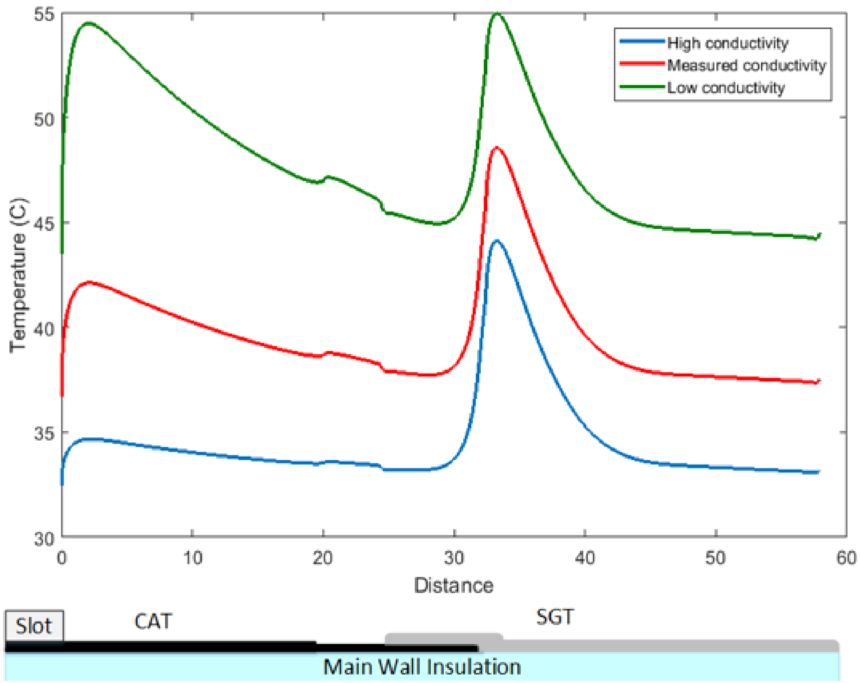


Figure 15. Temperature profile along the surface of the stress grading system for three CAT electrical conductivity conditions

This electric field ranges from 0.8 to 0.6 kV/mm. This results in a halving of the squared electric field drop and a tenfold increase in conductivity. If the conductivity of the SGT is increased, the electric field area may be further expanded. For each of the three SGT electrical conductivity values, Figure 18 displays the distribution of the electrical field over the surface of the stress grading system, making this extension very apparent. Extending the region of the SGT with a strong electric field allows it to achieve its maximum electrical conductivity.

Figure 20 shows the typical amount of heat generated during a single pulsed voltage cycle. As mentioned earlier, increasing the electrical conductivity of SGTs decreases the electric field but increases heat generation inside the SGT. The heat output in the CAT area is marginally affected by SGT electrical conductivity.

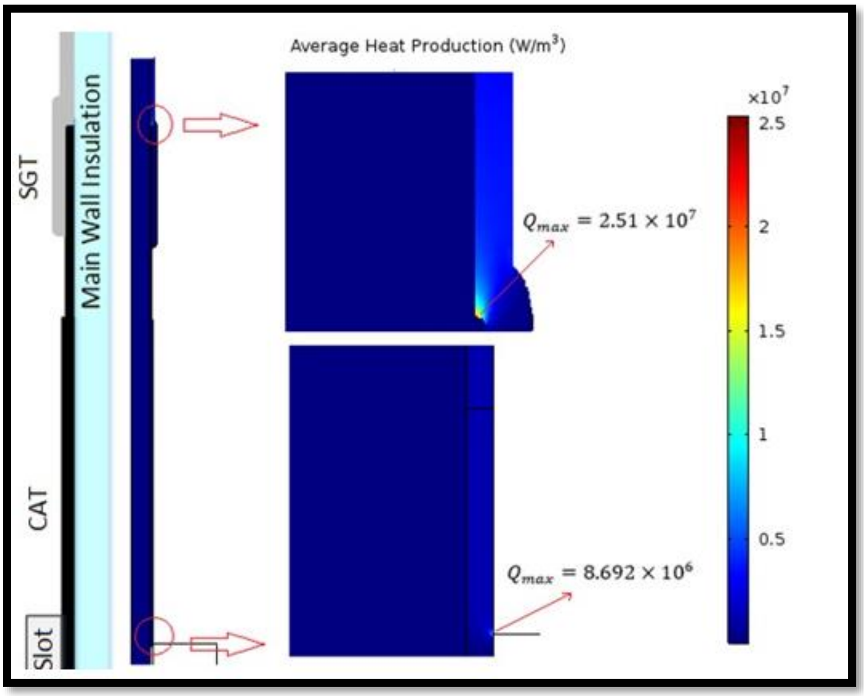


Figure 16. The average heat production during one cycle of the pulsed voltage for (a) high CAT electrical conductivity,

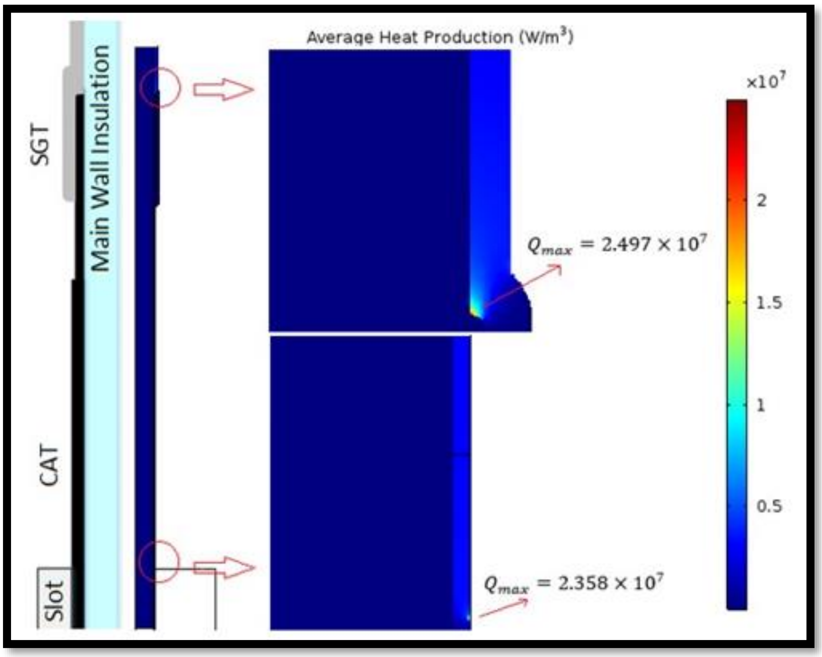


Figure 16. The average heat production during one cycle of the pulsed voltage, (b) measured CAT electrical conductivity

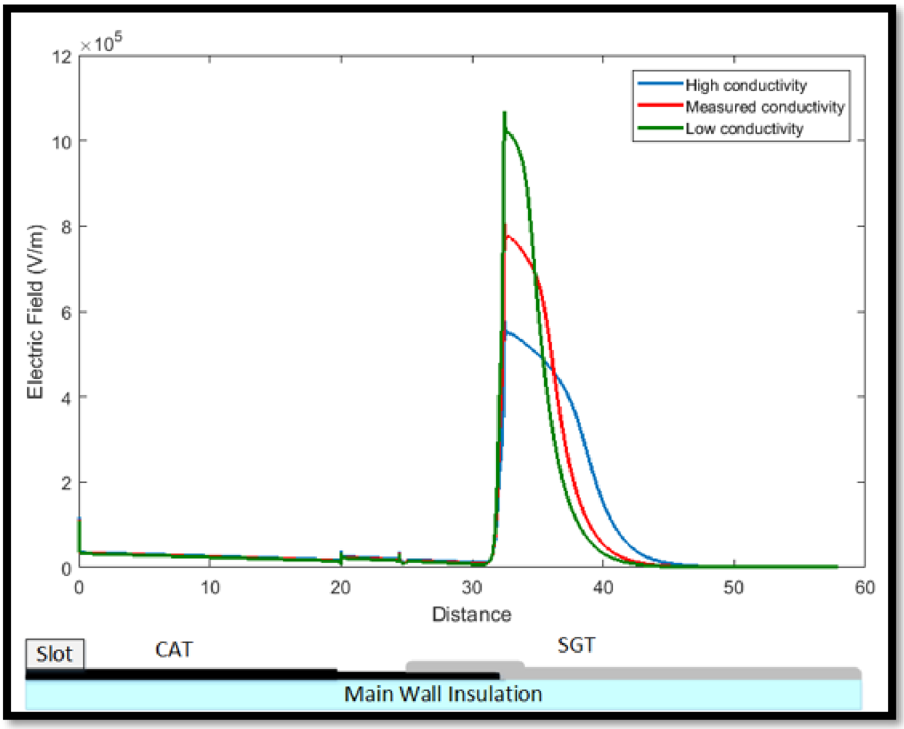


Figure 18. Electric field distribution along the surface of the stress grading system for three SGT electrical conductivity conditions at the end of rise time of the pulsed voltage

When it comes to the conductivity of the tapes after VPI, the manufacturer's quoted value—often supplied at ambient temperature—does not reflect reality. Due to the fact that the VPI procedure might change electrical conductivity, it is crucial to conduct simulation experiments utilising conductivity values determined after VPI. Another consideration is that electrical conductivity at typical operating temperatures—which are much higher than room temperature—must be used for precise measurement when dealing with motors. When measuring SGT electrical conductivity, it is necessary to utilise both the operating temperature and a strong electric field, since the electric field at the SGT area may surpass 1 kV/mm. Measurements over 0.6 kV/mm under DC circumstances cause the temperature to increase too much in the SGT, hence pulse conditions are required for the measurement. The material characteristics under operating circumstances may explain why the predicted and observed temperature profiles illustrated in Figure 11 match so well. Continuous operating below 155 oC is typical for a class F motor insulation system, which can withstand an 80 oC temperature increase in a 40 oC environment. When operating continuously under a pulsed voltage, the stress grading system shows a temperature increase of around 8 oC in the SGT zone along the high-temperature profile. Consequently, lowering the insulation system's design temperature either lowers system efficiency or necessitates a higher insulation class. Raising the electrical conductivity of the CAT area lowers the electric field during the rising period and coolings the CAT zone. In the SGT area, the electric field is somewhat amplified when the CAT electrical conductivity is raised. Because eddy currents inside the slot reduce the electrical conductivity of the CAT, one possible approach is to boost the conductivity only outside the slot [2]. Because the coils are produced outside the core and then put into the slots, making it difficult to precisely identify where the slot exits are, this technique adds another layer of complexity to the production process. Switching gears, raising the electrical conductivity of the CAT might potentially raise the electric field in the SGT over the threshold, causing PDs to happen in this area. Keep in mind that increasing the electrical conductivity of CAT is only possible within certain limits set by the eddy current and electric field in the SGT area.

V. Conclusion

Here are some conclusions that may be derived from the measurements and simulations: The electrical conductivity may be changed by adjusting the temperature and the construction of the tape; in CAT, increasing the number of layers and the temperature both improve the conductivity. Raising the temperature and number of layers in SGT both increase conductivity. The motor's efficiency could be negatively affected if the stress grading system is heated up using a pulsed voltage, since this lowers the insulation system's design temperature. There will be less of an electric field in the CAT area as its electrical conductivity increases. The electric field in the SGT area is somewhat amplified, while the temperature and heat generation are reduced. Raising the electrical conductivity of the SGT leads to a uniform distribution of electric fields by reducing their strength in the SGT area. Conversely, it raises the stress grading system's temperature and heat production, and it has the potential to broaden the SGT's heat production zone. The electric field distribution in the CAT is unaffected by the SGT electrical conductivity when subjected to a pulsed voltage.

References

[1]. Ayat A. Nada Department of Computers and Systems Received February 20, 2018, accepted March 27, 2018, date of publication April 2, 2018, date of current version April 23, 2018. **[2]** Basu, S. 1997. The Investment Performance of Common Stocks in Relation to their Price to Earnings Ratio: A Test of the Efficient Markets Hypothesis. Journal of Finance, 33(3): 663-682.

[2]. SS. Makgopa, "Determining shopping malls customers' satisfaction and loyalty," Journal of Business and Retail Management Research (JBRMR), Vol.13, No. 1, pp. 121-130,2019.

[3]. Emad Sharifi, Edward. A. Cherney, Shesha H. Jayaram, "Anisotropic Dielectric Properties of Stress Grading Materials used in Medium Voltage Form-Wound Motor Coils to Study Thermal Effects of Repetitive Fast Pulses," *IEEE Electr. Insul. Conf. (IEC)., 2009,* pp. 333-337.

[4]. F.P. Espino-Cortes, E.A. Cherney, and S. Jayaram, "Effectiveness of Stress Grading Coatings on Form Wound Stator Coil Groundwall Insulation Under Fast Rise Time Pulse Voltages," IEEE Trans. Energy Conversion, vol. 20, no. 4, pp. 844-851, 2005.

[5]. F.T. Emery, "The Application of Conductive and Stress Grading Tapes to Vacuum Pressure Impregnated, High Voltage Stator Coils," IEEE Electr. Insul. Mag., vol. 12, no. 4, pp. 15-22, 1996.

[6]. Qualification and Acceptance Tests for Type II Electrical Insulation Systems used in Rotating Electrical Machines Fed from Voltage Converters, IEC/TC 60034-18-42, Ed. 1.0, 2008.

[7]. Alireza Naeini, Edward. A. Cherney, Shesha H. Jayaram, Saeed Ul Haq, "Effect of Vacuum Pressure Impregnation Process on Electrical Conductivity of Conductive Armor Tape having various Tape Builds and Constructions," in *Electr. Insul. Conf. Proc. (EIC),* 2017, pp. 451-454.

[8]. Steven A. Boggs, Akiko Kumada, and Tetsuo Yoshimitsu, "Analytical Approximations for the Rotating Machine End-Turn Field Distribution," IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 6, 2015.

[9]. T. Nakamura, Y. Morita, A. Kumada, H. Ikeda, K. Hidaka, Y. Tsuboi, T. Kisakibaru, T. Sakurai, K. Karasawa, "Optimal Resistance of Stress Grading System in Converter-fed Rotating Machines," *Electr. Insul. Conf. (EIC),* 2016, pp. 15-18.

[10]. Alireza Naeini, Edward. A. Cherney, Shesha H. Jayaram, "Effect of Stress Grading Tape Conductivity on the Electric Field Distribution in Stress Grading System of an Inverter-Fed Rotating Machine," *Electr. Insul. Conf. (EIC),* 2018.

[11]. Emad Sharifi, Shesha H. Jayaram and Edward A. Cherney, "Analysis of Thermal Stresses in Medium-voltage Motor Coils under Repetitive Fast Pulse and High-frequency Voltages," IEEE Trans. Dielectr. Electr. Insul., vol. 17, no. 5, pp. 1378 –

1384, 2010.

[12]. A. Kumada, T. Nakamura, K. Hidaka, Y. Tsuboi, T Yoshimitsu, "Potential distribution on the stress grading system of high-voltage rotating machines – I. measuring system," IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 6, pp.3163-3169, 2016.

[13]. G. C. Stone, E. A. Boulter, I. Culbert, and H. Dhirani, *Electrical Insulation for Rotating Machines*, IEEE Press, 2004.

[14]. Standard Test Methods for DC Resistance or Conductance of Insulating Materials, ASTM International D257 – 14, 2014.

[15]. Determination of thermal conductivity and thermal diffusivity-Part 2: Transient plane heat source (hot disc) method, ISO 22007-2:2015, 2015-08.

[16]. Yunis A. Cengel and Michael A. Boles, *Thermodynamics an engineering approach*, sixth edition, McGraw Hill