Considerations on Evaluation Methods for Reliable Stress Grading Systems of Converter-fed High Voltage Rotating Electrical Machines

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Abstract—SiC-based nonlinear resistive grading materials have been used for end turn stress grading of form-wound rotating electrical machines, such as high voltage motors and turbine generators, over a long period. Although these materials work well under power frequency, the electric field and local heating become problematic under PWM repetitive pulses for the stress grading systems of converter-fed rotating machines. In order to select the appropriate stress grading materials and to optimize the insulation design of end turn structure for PWM waveforms, accurate knowledge of the nonlinear conduction characteristics of stress grading materials as a function of temperature and electric field is required. In this paper, the authors analyze sophisticated sample configurations for accurate measurement of nonlinear conductivity characteristics of the materials based on transient nonlinear FEM computations.

Keywords—converter-fed rotating electrical machine; end turn; stress grading; non-linear conductive material;

I. INTRODUCTION

IEC document, IEC60034-18-42TS is being discussed as an international qualification standard for converter-fed high voltage rotating electrical machines. In this document, qualification test methods for “main insulation”, “turn to turn insulation” and “end turn stress grading” of form-wound rotating electrical machines will be documented. Among these, “main insulation” and “turn to turn insulation” should be able to satisfy the qualification standard through extensions of the present insulating technology. On the other hand, if the “end turn stress grading” cannot satisfy the qualification test, improved stress grading material should be developed with appropriate nonlinear conductivity.

Typical cross section of end turn stress grading structure is shown in Fig. 1. SiC (silicon carbide) based nonlinear conductive tape or paint has been used for end turn stress grading of large rotating electrical machines, such as high voltage motors and turbine generators, over a long period. These materials work well under power frequency sinusoidal waveforms. However, recent studies show that the electric field and local heating can become severe under high frequency repetitive pulses or PWM (pulse width modulation) waveforms, depending on the rise time of waveforms and physical properties of the stress grading materials. For example, the potential distribution, surface temperature as well as power loss density along the stress grading system have been examined experimentally or numerically [1-4].

In order to optimize the insulating design of end turn structure for PWM repetitive pulses, accurate knowledge of the nonlinear conductivity of the stress grading materials as a function of temperature and electric field is essential. Although various methods have been proposed for conductivity measurement of the stress grading materials [5, 6], sample configurations for both higher field and temperature have not been established. In this paper, the authors examine issues related to conductivity measurement based on the experiments and propose an appropriate sample configuration for the accurate measurement of conductivity of the stress grading materials based on nonlinear FEM (finite element method) computations.

II. EXPERIMENTAL SETUP AND RESULTS

A. Sample Configurations for Conductivity Measurement

In this experiment, we used two types of samples. Figure 2a indicates type A sample configuration, in which two aluminum tapes separated by a 4 mm gap are applied to the surface of an FRP tube as electrodes. Figure 2b indicates type B sample configuration in which the electrodes are applied to a machined surface so that the outer radius of the 60 µm thick Al foil electrode is the same as that of the unmachined FRP tube. Inner and outer diameters of the FRP tube are 17.5 and 20.5 mm, respectively. A hollow tube is employed to reduce the interelectrode capacitance.

SiC-based stress grading tape (ISOVOLTA EGSB2709) was wound so as to cover the both electrodes, after which the sample was subjected to VPI (vacuum pressure impregnation) processing. Thickness of the stress grading material over and
between the electrodes is typically in the range of 0.5 mm for both type A and type B samples.

Figure 2. Sample configurations of stress grading material.

B. Experimental Procedure

Figure 3 shows a typical measurement system. We apply DC voltage for low field conductivity measurements and a series of single voltage pulses of varying amplitude in the high electric field region to measure the stress grading conductivity while avoiding influence of joule heating of the sample [3]. The test sample was set in an oven. The current shunt was 1 kΩ or 100 kΩ, depending on the applied voltage and resulting current.

Figure 3. Typical measurement system. The current shunt was 1 kΩ or 100 kΩ depending on the applied voltage and resulting current.

C. Results and Issues for Accurate Measurement

An example of a voltage pulse waveform and resulting current through a type B sample is shown in Fig. 4. Current decreases rapidly with applied voltage as a result of the field-dependent conductivity of the sample. The sample conductivity for range of electric field can be calculated based on the sample geometry and the ratio of current to applied voltage during a single pulse, without significant joule heating.

In type A sample, partial discharge often occurs at relatively low electric field, (≈0.6 kV/mm), and flashover occurred below 1.0 kV/mm. Typical applied voltage and current waveforms in type A sample are shown in Fig. 5. In this sample, conductive current flowing inside the stress grading material could not be measured correctly. This may be the result of discharge and breakdown along the interface between the stress grading and the FRP tube or could be caused by high current density at the raised corner of the electrode. Considering this result, we adopted the electrode configuration of type B sample.

Figure 6 shows σ-E (conductivity vs. electric field) characteristics of type B sample up to 1.0 kV/mm and 100°C. Conductivities measured with DC and voltage pulses align well. In the high electric field region, the conductivity increases with electric field and decreases with increasing temperature. On the other hand, in the low electric field region (0.1-0.2 kV/mm), the conductivity increases with increasing temperature. We confirmed that the conductivity of stress grading materials could be successfully measured using DC at low fields and pulse voltage at high fields to avoid excessive joule heating.

In this sample with the gap distance of 4 mm, measurable maximum field is approximately 1.0 kV/mm, limited by the maximum voltage of the pulse generator employed. In the next section, we employ FEM computations to examine issues related to reducing the gap between electrodes to achieve greater field in the stress grading material.

Figure 6. E-σ characteristic of stress grading tape.
III. OPTIMIZED SAMPLE CONFIGURATION

As we mentioned in section II, a gap distance less than 4 mm is preferable to facilitate field measurements above 1.0 kV/mm. However, nonuniform conductive current distribution within the stress grading material and temperature rise are of concern as the gap distance is reduced. In this section, we evaluated the above matters based on nonlinear FEM computations and propose an appropriate sample configuration for accurate measurement of nonlinear conductivity.

A. Nonlinear FEM Computation Method

The type B of stress grading sample was modeled in axisymmetric 2D as shown in Fig. 7. Thickness of the stress grading material and electrodes is 600 µm and 60 µm, respectively. The gap distances modeled were 2, 3, 4 and 10 mm. The E-σ characteristics of the stress grading material were based on the experimental result at room temperature in Fig. 6. In this FEM computation, we applied both transient calculation in the high electric field region over 0.5 kV/mm and resistive field calculation in the low electric field region below 0.5 kV/mm, as in our experiments.

![Fig. 7. Computation model of stress grading sample (axisymmetric 2D).](image)

A typical input waveform for \( d = 4 \) mm is shown in Fig. 8. In this FEM computation, we changed the peak voltage of input pulse waveform depending on the gap distance, so as to keep the maximum average field at 1.0 kV/mm for each gap distance. Current density distribution inside the stress grading material was computed, and the sample conductivity was calculated using the total conductive current and corresponding voltage amplitude at 0.02, 0.14 and 0.35 ms from the wave crest. Considering the dielectric time constant of this sample, potential distribution is substantially resistive within 10 µs after the pulse rise.

![Fig. 8. Input waveform for transient FEM computation (\( d = 4 \) mm).](image)

B. Temperature Rise of Stress Grading Sample

The average temperature rise, \( \Delta T \), just after pulse voltage application was estimated using equations 1 and 2 based on the assumption that the stress grading sample was heated uniformly by the electrical energy stored in the high voltage capacitor of the pulse generator.

\[
\frac{1}{2}CU_0^2 = c \cdot V_0 \cdot \Delta T \quad (1)
\]

\[
\frac{V}{V_0} = 2\pi r \cdot t \cdot d \quad (2)
\]

with \( C \) the high voltage capacitance (0.011 µF), \( U_0 \) the peak voltage (2000~10000 V), \( c \) the volumetric heat capacity (2.5×10^6 J/m^3 K), \( V_0 \) the sample volume, \( r \) the sample thickness, \( t \) the gap distance between electrodes.

Average temperature rise of the sample for each gap distance is shown in Fig. 9. The temperature rise increases with the gap distance but remains less than 1 K. As a result, the temperature rise is negligible up to \( d = 10 \) mm.

![Fig. 9. Calculation of average temperature rise of stress grading sample for a 1 kV/mm peak voltage pulse. The temperature rise increases linearly with gap distance but the energy stored in the discharge capacitor increases quadratically with voltage.](image)

C. Current Density Distribution and Calculation of Nonlinear Conductivity

Current density distributions at low (0.1 kV/mm) and high field (0.96 kV/mm) are shown in Fig. 10. In this figure, current densities are calculated in the middle of the gap from FRP surface into stress grading material. Conductive current does not flow uniformly within the stress grading at shorter gap distances, especially at higher fields. Also the absolute value of current density tends to reduce at shorter gaps, even for the same average electric field, presumably as a result of high current density and resulting potential drop at electrode edges, the effect of which increases with decreasing gap distance and increasing field.

![Fig. 10. Current density distribution as a function of radial position within the stress grading material at the midpoint of the gap between electrodes.](image)
E-σ characteristics were obtained numerically based on the total conductive current through the stress grading material and are shown for various gap distances in Fig. 11. Ratios of calculated conductivity to the material property on which the computations are based are shown in Fig. 12. Measured conductivity of stress grading materials may be reduced with shorter gap distances as a result of the nonuniform field and current density distributions. For example, for the present material, the measured conductivity is reduced by 60% at \( d = 2 \) mm and 0.96 kV/mm average field.

The simulation results indicate that the longer gap distance is preferable for accurate measurement of field-dependent conductivity, contrary to our desire for higher average fields at lower applied voltages. The alternative to larger gap distances is improved electrode configurations.

Thus the type C measurement configuration may provide adequate accuracy given the typical dispersion of stress grading conductivity.

**Fig. 13. Proposed sample configurations.**

**Fig. 14. Comparison of calculated conductivities with input ones for proposed samples.**

**IV. CONCLUSIONS**

In this paper, we confirmed that the conductivity of stress grading materials in high electric field region up to 1.0 kV/mm can be measured successfully using pulse voltage to avoid excessive joule heating. Based on transient nonlinear FEM computations, we propose an improved configuration for high field measurement of stress grading material which provides adequate accuracy at reduced gap distance to limit the required measurement voltage. The proposed measurement configuration should be adequate to select the optimum stress grading materials for converter-fed rotating machines.

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