NEW GRADING MATERIAL ENABLES OPTIMIZED DESIGN OF END CORONA PROTECTION FOR LARGE ROTATING MACHINES

S. Kempen[1*], S. Lang[2] and F. Pohlmann[1]
[1]Siemens AG Energy Sector, Mülheim an der Ruhr, Germany
[2]Siemens AG Corporate Technology, Erlangen, Germany
*Email: <stefan.kempen@siemens.com>

Abstract: To achieve better control of the electrical parameters and to allow more precise ECP designs a new filler material has been developed. This new material is based on microscopic mica flakes with a typical platelet shape. To obtain the desired electrical characteristic the mica flakes are coated with a thin metal oxide layer. Depending on the metal oxide used, different nonlinearity exponents are possible. The intrinsic electrical resistance of the particles can be precisely adjusted by doping the thin oxide layer. The combination of the increased number of particles in the composite material and the platelet shape result in an overall resistance which is independent from the number of established conductive pathways and the contact resistance between particles. Hence the resulting composite material will show a much lower scattering range. It allows adjustment of a predefined electrical characteristic.

1 INTRODUCTION

Winding coils for large rotating machines require an appropriate end corona protection system (ECP) to control the electric field strength of the triple point at the end of the outer corona protection (OCP) layer. Current ECP systems are built by applying one or multiple semi-conductive layers in an overlapping connection to the OCP end. For many years these semi-conductive layers have been made either by using grading paints or by wrapping with grading tapes [1, 2]. Grading paints and tapes typically contain silicon carbide particles to obtain the required electrical characteristic defined by both the surface square resistance at a given electric field strength and the nonlinearity exponent. In order to obtain an optimized ECP configuration the electrical designer aims to have precise control of both parameters. In the case of the existing filler material, silicon carbide (SiC), the square resistance can be controlled by the average size of the particles.

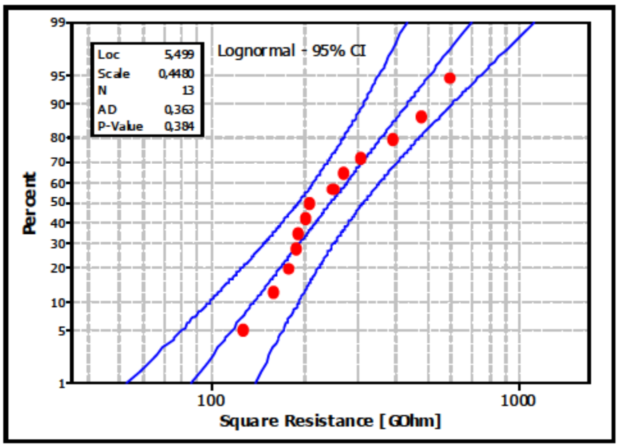

Figure 1: Scattering of square resistance for commercially available grading tape obtained during incoming test inspections over a longer period of time

This size determines the average number of conductive pathways established through the ECP composite material. Furthermore, the particle shape determines the contact resistance between the particles. As the particle sizes and shapes scatter across a large range, the resulting surface resistance can also scatter across a large range. Fig. 1 shows the typical large scattering of surface resistance of commercially available grading tape that is based on SiC. Furthermore the nonlinearity exponent is basically an intrinsic property of the filler material which cannot be controlled. Hence the current ECP layouts have to include a large safety margin to ensure good overall ECP performance and have limited optimization options.

2 NEW FILLER MATERIAL FOR GRADING PAINTS AND TAPES

To achieve better control of the electrical parameters and to allow more precise ECP designs a new filler material has been developed.

2.1 Structure of Filler Particles

Filler particles were designed with the goal that the desired electrical characteristic is independent from the particles outer contour and particle size. This goal can be achieved if the filler particles have a uniform geometric structure with high aspect ratio and same dimensions for any desired electrical characteristic. High aspect ratio will allow good overlapping contact between individual particles which results in low electrical contact resistances in the overlapping areas. Furthermore this configuration will avoid local current concentration which will make the material more robust against electrical overstressing and typical aging mechanism.

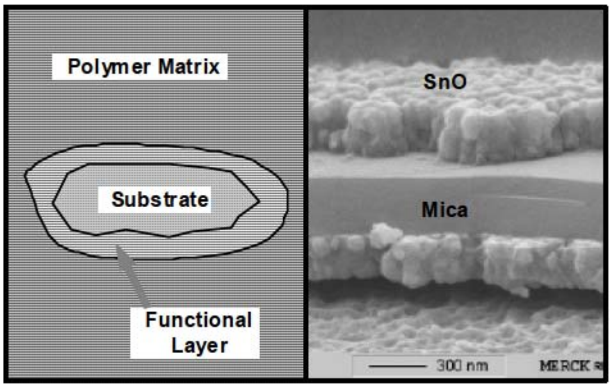

Figure 2: Structure of filler particles

In the present case mica particles with a platelet shape are utilized as a substrate material for the particles. For rotating electrical machines mica is a well known material for high voltage insulation applications. The mica particles provide a very high aspect ratio and therefore they fulfil the above given requirement. Because of its mineral nature mica is an electrically perfect insulating material that is resistant against corona and has a good specific thermal conductivity [3]. To provide an electrical function to this insulating substrate the mica particles are coated with a semiconductive functional layer. As this functional layer will define the electrical properties of the composite particles can have the same size for any desired electrical characteristic. The typical structure of the particles is also shown in Fig. 2.

2.2 Structure of Composite Material

For ecp tape or varnish applications the filler particles have to be integrated into a resin matrix. Fig. 3 shows a microscopic picture of the new ecp filler particles integrated in a resin matrix in comparison to conventional ecp tape based on silicon carbide (SiC). The picture of the new ecp filler material demonstrates the good overlapping and parallel alignment of the platelet shape particles while the standard system contains fragments of silicon carbide of irregular shape and sizes and more or less undefined contact between the individual particles. A further requirement for good overlapping of the particles and high filling degree in the composite matrix is parallel alignment. To achieve this alignment special chemical additives are added to the resin system.

In today's silicon carbide (SiC) based ecp systems the resulting electrical characteristic also depends on the filling degree resp. filler material content in the composites resin matrix. This occurs in particular if the filling degree is within area of percolation. In this area small deviations of nominal filler content will lead to large variation of the electrical characteristic. To become independent of this effect the filler degree for the new particles is adjusted to a value which is significant above the percolation threshold.

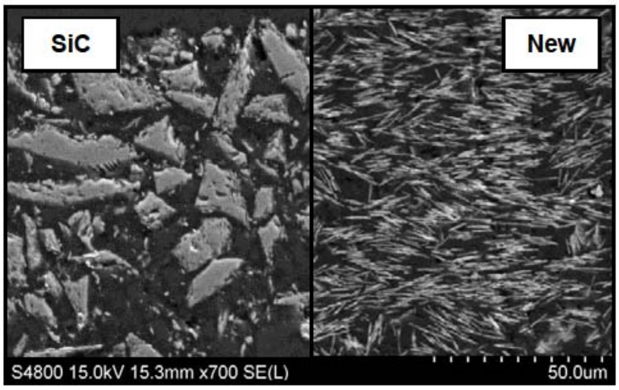

Figure 3: Structure of new composite material in comparison to silicon carbide based ECP – material

The fact that the new filler particles will have same sizes for any resulting electrical characteristic can be used to result economic application benefits. If for example materials would be needed with different steps of electrical resistance at a specified reference field strength E_{REF} it would be possible to manufacture a very high and a very low Ohmic filler material. Hence any desired intermediate resistance could be adjusted by mixing the high and low Ohmic fraction according a specified ratio. This method is already deployed for today's SiC-based systems but it's limited due to large differences of particle sizes of SiC filler material. While for the current ecp systems different resin matrices would be required the same matrix could be used for the new filler material for any desired mixture ratio.

The high aspect ratio and parallel alignment of the new filler particles in the composite (Fig. 3) lead to the assumption that the resulting electrical characteristic of the composite is anisotropic. Experimental investigations resulted that the electrical resistance of a reference coating was in tangential direction about 10 - 15 times of the resistance in normal direction. This fact has to be taken into account if an new ecp layout is calculated for example by use of finite element method [4].

2.3 Control of Electrical Characteristics

Semiconductive coated mica particles such as Minatec™ have been already used in the past as a filler material for antistatic floor applications or other antistatic varnish applications [5-7]. For these applications the focus was basically set on the optical performance of the filler material while it was not necessary to precisely specify the electrical characteristic of the filler. For these applications it was sufficient to result a surface resistance R_{Sq} that was below a specified value which is typically somewhere in the range of 10^4 – 10^9 Ohms. A characteristic interdependence on the applied electrical field strength was not specified.

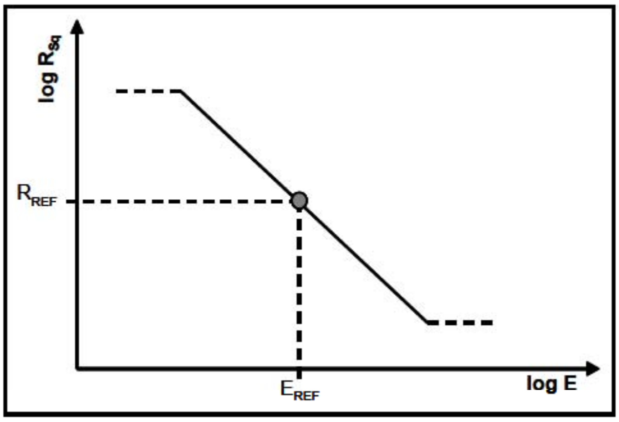

Figure 4: Parameters of nonlinear electrical characteristics

However, for ECP applications it is necessary to precisely specify the electrical characteristic of the composite. The required electrical characteristic for can be described by the following three parameter exponential model that takes the field limiting effect into account:

$$\left(\frac{R_{Sq}}{R_{REF}}\right) = \left(\frac{E}{E_{REF}}\right)^{1-\alpha} \tag{1}$$

In this equation R_{Sq} is the surface square resistance of the material at the electrical surface field strength E. The parameter R_{REF} is reference surface square resistance that is measured at the reference field strength E_{REF}. The third parameter $1\text{-}\alpha$ is called nonlinearity exponent for the resistance. It describes the gradient of the characteristic line of (1) which occurs as a straight line in a double logarithmic scale. A qualitative plot of equation (1) is displayed in Fig. 4. The dotted lines at the beginning and at the end of the characteristic line indicate that the typical semiconductive materials show almost linear behaviour below and above specific electrical field strengths. For ecp applications the nonlinear behaviour is required to limit the electrical field by lowering the resistance rapidly according the nonlinearity exponent α in equation (1). For existing ecp applications based on SiC the nonlinearity exponent α has values in the range of 3 – 4 and can not be changed.

In contrast to that the new ecp filler material will allow to adjust the nonlinearity exponent α by choice of functional layer material. For example a nonlinearity exponent which is comparable to that of SiC can be achieved if the mica flakes are coated with thin layer of tin oxide. As pure tin oxide is an insulating material the oxide becomes a semiconductor if it is doped by use of appropriate dopants, such as antimony. While the nonlinearity exponent basically depends on the choice of functional layer material the concentration of the dopant controls basically the resistance R_{REF} at the reference field strength E_{REF}. Hence the characteristic line is shifted in parallel to the axis of ordinate (Fig. 5). While it is possible to control the parameter α independently from R_{REF} (E_{REF}) any desired characteristic can be adjusted by choice of coating material and dopant concentration. This opens a new space for the electrical designer where the desired nonlinear characteristic may be a result of innovative top down design method based on FEM- calculation.

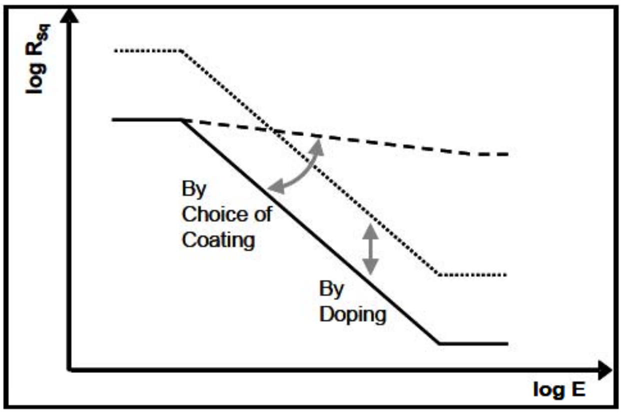

Figure 5: Control of nonlinear electrical characteristics

3 GRADING PAINTS AND TAPES

3.1 Design of New Polymer Matrices

The main function of the matrix is the fixing of the functionalized filler without affect its electrical conductivity. Another ECP-tape requirement is that the tape is supposed to be flexible during its application (B-stage) whereupon by a further thermal treatment the tape will be cured (C-stage). The third claim consists in a thermal stability up to 160 °C. In order to accomplish these demands the right choice of resin monomers is very important. Because of their excellent mechanical strength and toughness, outstanding chemical resistance as well as dielectric and insulation properties epoxy resins were the right choice (a). They cure in general by an additional chemical reaction, and therefore the resulting thermosets are not intrinsically foamed. In order to make sure that the epoxy will only cure at elevated temperatures the resin and the hardener have to be sluggish in reaction at room temperature (RT). This could be achieved by either the resin or the hardener is solid at RT and simultaneously cycloaliphatic or better aromatic in its structure. In epoxies, polymerized with amines, the allylic amine C–N bond is less stable than the allylic ether C–O bond, and therefore in general, the amine cured epoxy resins are less stable than anhydride-cured epoxies. Therefore the hardener was chosen to be an amine in a substoichiometric amount that catalyses the homopolymerization of the epoxy resin when its amine groups are already reacted. The resulting thermoset consists mainly of C-O groups and only little C-N groups in its chemical backbone and thereby a high thermal stability combined with a superior glass transition temperature.

3.2 Manufacturing of Grading Tapes

The major challenge in homogeneous tape coating is ensuring that the filler is not settling out during grading tape manufacturing. Because of mica substrate the density of stannic oxide can be reduced from 7 g/cm³ to about 3.5 g/cm³ and the geometrical shape can be transformed from globular to flaky. Both material properties reduced significantly the settlement of the functionalized filler and hence improve it in comparison with a SiC filled matrix. Besides tailoring thixotropy and viscosity of the filled resin the velocity of tape manufacturing was adjusted and subsequently in bench tests tapes were manufactured that show almost no deviation in square resistance.

4 ELECTRICAL CHARACTERIZATION

4.1 Test Setup

In order to determine the electrical characteristic the new tape binder resin was loaded with about 50 weight percent of new filler material. This varnish was then applied onto a glass plate with a coating knife and cured in an oven according to a predefined temperature profile. Silver paint was

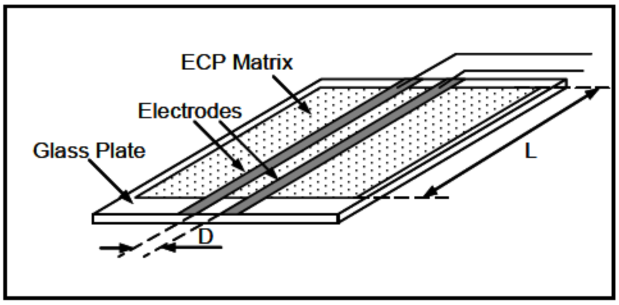

Figure 6: Test setup to measure nonlinear electrical characteristic of composite material

used to apply electrodes on top of the cured ecp material. To minimize the influence of the electrode ends the electrode length L was chosen to be ten times of the electrode distance D (Fig. 6). The electrode distance was adjusted to D = 10 mm. Respectively the electrode length was L = 100 mm. After curing the painted silver electrodes were contacted by strips of adhesive copper tape. With regard to the large measuring range resulting from the high from the nonlinear material characteristic it was necessary to deploy different measuring devices. For lower electrical field strengths (< 0.1 kV / mm) but high resistance values a Megohmmeter[1] with 1500 V DC maximum test voltage and high accuracy even for very low measuring currents was connected to the test samples. For electrical field strength above 0.15 kV / mm another insulation resistance measuring device[2] with maximum output voltage of 5 kV was used. Since the resistance of the nonlinear material is already significant reduced at this test field strengths the measurement accuracy was excellent also with this test device. As the measuring current is limited for this test device it was not possible to measure the resistances of the low resistive material throughout the entire range of electrical field strength. Using another DC voltage supply with higher current capability would extend the measuring range for some amount. However this would result in excessive heating of the material due to relevant Ohmic losses produced at this operating point. On the other hand the measuring range o also limited in field strength for the high resistive material because surface corona occurs at electrical surface field strength exceeding about 0.64 kV / mm [8]. All measurements were performed at controlled ambient temperature of 35°C.

4.2 Results

Several test samples were made according as described above and measured. The purpose of these initial trails was

- to evaluate the limits of feasible resistance range,
- to demonstrate the effect of different coating materials,
- and to demonstrate the effect of different dopant concentrations.

Hence different filler materials were produced in a

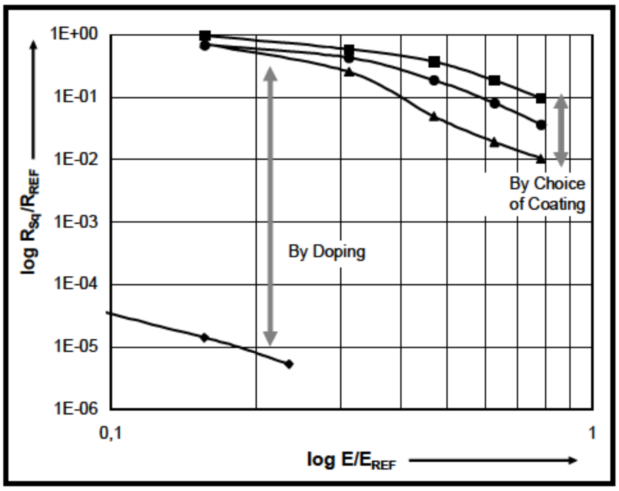

Figure 7: Measured resistance values show adjustable nonlinear characteristics of new filler material.

lab scale process that had different coatings on the one hand and different concentration of dopant on the other hand. Some typical curves are displayed

[1] Sefelec M1500P

[2] GOSSEN METRAWATT METRISO 5000 D-PI

in Fig. 7. The diagram shows characteristic lines for the surface square resistance measured at 35 °C ambient temperature which differ up to five magnitudes at the same electrical reference field strength. This huge difference of five magnitudes was achieved by different dopant concentration. While the most upper curve represents a sample with almost no doping the lower curve was taken from a sample with quite high dopant concentration. The lower curve ends at 0.23 E/E_{REF} because of it's very low Ohmic character. On the one hand the connected DC voltage supply reached it's current capability at this point. On the other hand field strengths resp. currents above this value would result significant self heating of the ecp material. This would be in contradiction to the approach to measure isothermal characteristics. The three curve in the upper area represent filler material samples with low dopant concentration but with different coating materials wich result in different gradients of the curves. Resulting nonlinear exponents α are in the between 1.3 and 3.7. Furthermore it can be seen that the gradient begins to differ significantly when the electrical field strength exceeds a level of about 0.2 E/E_{REF}. For low electric field strengths the material shows almost linear behaviour as already indicated in Fig. 4 and Fig. 5.

5 SUMMARY AND CONCLUSION

A new ecp filler material based on platelet mica flakes was developed. The major advantage of the new filler material results from the fact that the nonlinear properties described by the electrical reference field strength and the nonlinearity exponent can be controlled independently according to the requirements of an optimized ecp design. The resistance at a specified electrical reference field strength can be shifted over several magnitudes manly by doping of the coating material while the nonlinear exponent can be controlled mainly by choice of coating material. Hence it was shown that this new process for designing and manufacturing of filler particles it will be possible to result almost any nonlinear characteristic that might be of interest for innovative ECP layouts. Additional application benefits result from the regular and uniform particle size for very low and also very high resistance values. The uniform particle size will allow for example to produce a very low and a very high Ohmic batch of filler material. Any desired resistance value between the resistance values of this both batches can be achieved simply by mixing of both according to a predefined ratio. Furthermore a new resin matrix with increased thermal capabilities was developed which aligns the platelet particles in parallel to result good contact between the platelet filler particles. It is expected that ECP tape or paint based on the new particles will result much lower scattering as the overall surface resistance becomes independent from the contact resistance between the particles.

6 ACKNOWLEDGMENTS

Authors may wish to acknowledge Dres. Rüger and Kuntz, Merck KGaA for excellent contribution to this successful work.

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