Designing of End-winding Corona Protection of Generators by Help of Simulation

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Abstract: The job of designing end-winding corona protection (ECP) system is one of the very important and complex phases for insulation configuration of high voltage rotating machines. This complexity stems on one hand from the highly nonlinear characteristics of the ECP material and on the other hand from the coupled multiphysic phenomena of the involved performance evaluation. Simulation based ECP design is considered as a time-saving approach and finite element method was adopted in order to understand and solve this problematic. In this work a simulation tool with COMSOL Multiphysics was developed to calculate the electrical-thermal behavior of the ECP system. By using this tool, compare to the traditional experimental approach, the designing process could be simplified and the results are presented in an intuitive way. To fulfill different geometrical conditions, 2D and 3D modeling techniques were applied.

Keywords: end-winding corona protection, FEM, electrical-thermal simulation.

1. Introduction

The insulation system of stator winding of a high voltage rotating machine (rated voltage ≥ 6 kV) mainly consists of three basic components: the main insulation; the semi-conductive layer as outer corona protection (OCP) and the ECP (also called stress grading). The whole winding could be geometrically divided into two categories: the slot part, which is inserted into the iron core, and the end-winding part which is outside of the core. This work focuses on the end-winding part. Figure 1 depicts the concept of end-winding insulation of a stator bar. The main insulation, which is normally mica based, is used to separate the current-carrying conductors from the ground and from each other. OCP, a layer of conductive material, is used to define a ground potential on the surface of the slot part main insulation in order to prevent localized air breakdown, known as partial discharge (PD), in the slot. The OCP layer normally expands a few centimeters out of the core. ECP is a layer of nonlinear resistance used to prevent PD between the end of OCP and the insulation surface adjacent to it. As shown in the x (distance)-V (voltage) diagram in Figure 1: If the ECP layer does not exist, the electric field concentrates at the end of OCP, which leads to PD; with ECP layer to exist, this field concentration could be. The field-relief function of ECP bases on the nonlinear electrical characteristics of the material: the conductivity stays very low in the low field area and increases exponentially when the electric field strength grows. The trade-off of this field relief function is the local overheating of the ECP layer, because of the extra current flow due to the higher conductivity. Modern generators are rated to higher output voltage to increase their output power that leads to higher electrical and thermal stress to the ECP. To control the quality, the insulation system has to be tested under voltage up to 3 times as high as rated voltage. This test voltage causes large current in ECP, which leads to severe thermal problems.

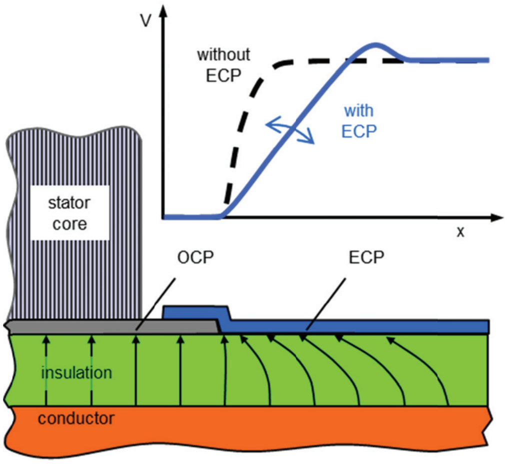

Figure 1. Insulation arrangement of end-winding in stator winding.

A properly designed ECP system should be able to control the electric field under the limit of

PD as well as keep the temperature low enough to ensure that no material damage occurs. To study the behavior of ECP under high AC voltage, 2D and 3D coupled electrical-thermal simulations of the in Figure 1 descripted system were carried out.

2. Physical Background

The direct goal of modeling is to calculate the electric field, the current density and the temperature of the object. Since the research is aimed to deal with 50 Hz AC values, the problems could be solved in a quasi-stationary manner. The basic equation that describes the electric field is the equation of continuity:

$$divJ = -\frac{\partial \rho}{\partial t}\,. \qquad (1)$$

As in conductor:

$$J = \sigma \cdot E; \qquad (2)$$

in dielectrics:

$$J = j\omega \cdot D = j\omega \cdot \varepsilon_0 \cdot \varepsilon_r \cdot E; \qquad (3)$$

and:

$$E = -\,gradV; \qquad (4)$$

Equation (1) turns to be:

$$div(\sigma \cdot gradV + j\omega \cdot \varepsilon_0 \cdot \varepsilon_r \cdot gradV\,) = -\frac{\partial \rho}{\partial t} = 0,(5)$$

where:

ρ is the electric charge density (C/m^3)
σ is the electric conductivity (S/m)
J is the current density (A/m^2)
E is the electric field (V/m)
D is the electric displacement field (C/m^2)
$\varepsilon_0 \cdot \varepsilon_r$ is the permittivity (F/m)
V is the electric potential (V).

V is the only dependent variable in equation 5 and it could be solved by using the boundary conditions. Except the conductivity σ of EGS material has to be measured, the rest of the values are available. By solving the equation 5, E, J and power dissipation are gathered.

The physic that describes the heat transfer of the object is the heat transfer in solid, which is pre-defined in the heat transfer module in COMSOL. The basic equation for this is:

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = div(k \cdot gradT) + Q \qquad (6)$$

where:

ρ is the density (kg/m^3)
C_P is the specific heat capacity (J/(kg · K))
T is the absolute temperature (K)
k is the thermal conductivity (W/(m · K))
Q is the heat source (W/m^3).

The coupled PDEs 5 and 6 could be numerically solved using FEM in COMSOL Multiphysics with given geometry and boundary conditions.

3. Description of the Model

3.1 2D Model using Axial Symmetry

Even if the real generator bar has a rectangular cross-section, it is still worth to use a 2D axial symmetric simplification for the first approach. It could also be used for benchmarking different EGS materials, whereas the geometrical conditions are irrelevant. Figure 2 depicts the axial cross section of the 2D model as the upper edge serves as the axis of symmetry. The model consists of three materials: copper (orange), mica insulation (grey) and ECP material (purple). The in COMSOL pre-defined property of copper was adopted. The characteristics of the other two materials were obtained from material analysis done by the author. The transition part of OCP and ECP is zoomed in to show the fact that the OCP was replaced with the ground boundary condition. An AC voltage source was set to copper as the other boundary condition.

The mesh was created separately for different domains to achieve accuracy and efficiency. As every domain has a rectangular shape, quad elements were chosen. For ECP, which is actually a ca. 0.5 mm thick thin film and should be meshed very fine, edge method with a maximum element size of 0.05 mm was used. The rest domains were meshed with free quads.

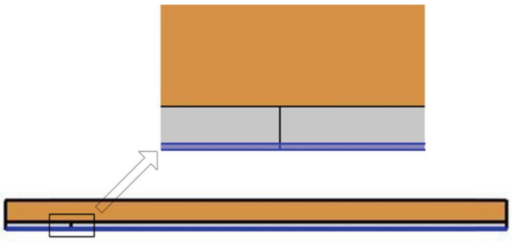

Figure 2. Geometry of 2D axial symmetric model

3.2 3D Model

As observed during experiments, the real geometry of the generator bar does have some influences on the thermal behavior of EGS. To study this and to optimize the geometry of endwinding, 3D models were built. The drawing of the model was created in Solidworks and imported into COMSOL. Figure 3 depicts a simplified 3D model of the in Figure 1 discussed system, dimensioned with data from a real generator bar. As the material domains and boundary conditions similar to the 2D counterpart, the meshing method of this model is different. Because of the large difference between the thickness of ECP and of the rest, special meshing technique has to be considered. Swept mesh was used to mesh this thin layer. Free mesh was used for the domains of insulation and copper.

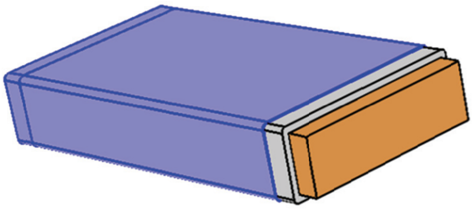

Figure 3. Geometry of 3D Model

4. Material Characteristic

The EGS material with nonlinear field dependent conductivity is the key component of field grading. This material is applied onto the surface of the insulation in form of a varnish or a tape. Silicon Carbide (SiC) based products are widely used for EGS since decades. Pure SiC does not show field dependent resistance. Once SiC particles are embedded into an insulated polymer matrix (e.g. epoxy resin), this property appears. It was reported in [1] that this nonlinear conductivity stems from the interface built from SiC particles and the polymer between them. Measurements were done to get data about the relationship between conductivity and field. In the literature different analytical models have been suggested to describe this nonlinear relationship. The results of measurements had been fitted with the exponential model

$$\sigma = A \cdot \exp(B \cdot E) \qquad (7)$$

at best. Where σ is the electric conductivity and E is the electric field. A and B are intrinsic constants of materials which could be controlled to some extent by doping or by controlling the grain size of SiC particles. Similar analytical formulations were reported in [2] and [3]. If equation 7 is implanted directly into the model, numerical instability could be introduced. A piecewise linearization of equation 7:

$$\sigma(E) = \begin{cases} E_0, & E \leqq E_0 \\ A \cdot \exp(B \cdot E), & E > E_0 \end{cases} \qquad (8)$$

solved this problem. Proper value of E_0 was determined individually for each material according to measurements.

As the conductivity is also influenced by elevated temperature, σ could be corrected by using

$$\sigma(T) = \sigma(T_0) \cdot \exp\left(\beta \cdot \left(\frac{1}{T} - \frac{1}{T_0}\right)\right), \qquad (9)$$

where T is the temperature, T_0 is the reference temperature and β is a constant. By combining the equations 8 and 9 the field dependent conductivity $\sigma(E, T)$ could be used for the EGS material in FEM simulation.

5. Results of application examples

If the aim of the simulation is for example just to study the performance of a material, a stationary study with a 2D axial symmetric modeling should be enough. Electric field and temperature distribution of an example model was assessed. Electric field stays under the 5 kV/cm threshold of PD incept, Figure 4. One can conclude that this material is intact with respect of stress grading function. Figure 5 shows the temperature distribution of this model under high potential test voltage. The highest temperature appears near the junction of EGS and ground, which is consistent with the observation in experiments. The 251 °C hotspot will highly probably lead to damage of the material, which means this design is not appropriate for the applied test voltage.

Observation during the test has shown the temperature at the edge of the generator bar is higher than in the flat area. This also point is supported by the 3D simulation, Figure 6. The hotspot locates at the edge in 3D model whereas distributes homogenously in 2D. Despite the fact that models in Figure 6 and Figure 7 have all parameters the same except there shapes, 3D model has clearly higher temperature.

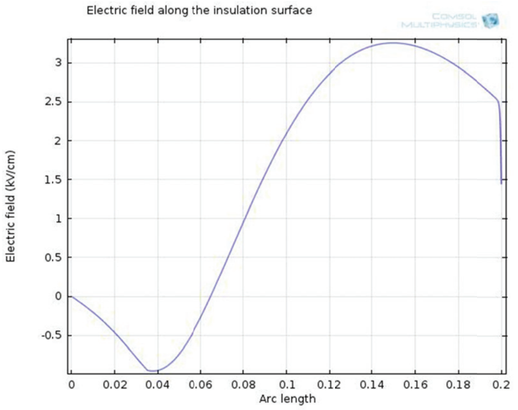

Figure 4. Electric field along the insulation surface. (Under rated voltage U_N)

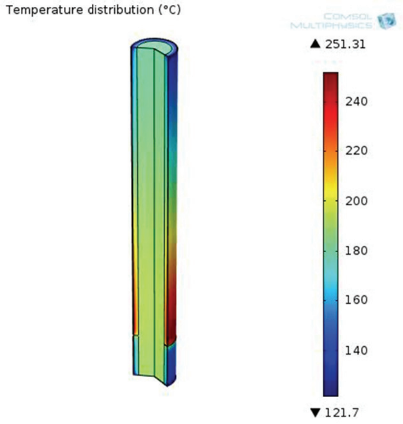

Figure 5. Temperature distribution of 2D model. (Under test voltage $3U_N$)

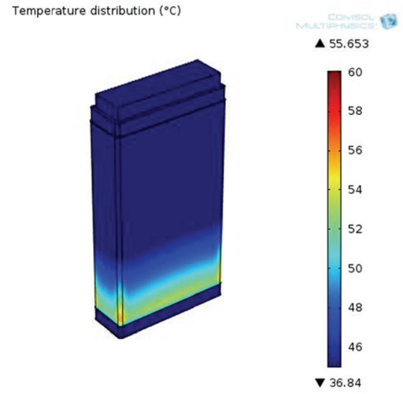

Figure 6. Temperature distribution of 3D model. (Under rated voltage U_N)

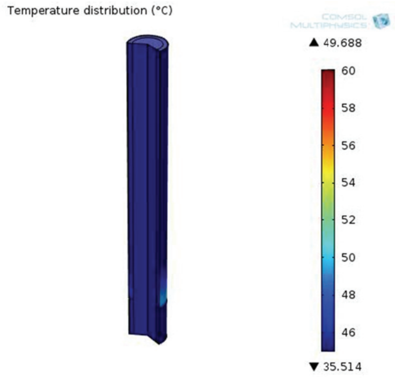

Figure 7. Temperature distribution of 2D model. (Under test voltage U_N)

6. Conclusions

In this work 2D and 3D coupled electrical thermal simulations of endwinding corona protection system have been done. The accuracy of the simulation results was verified by experiments. These simulations are utilized as calculation tool for the further design work. Compare to the experiments based design, high efficiency and flexibly were achieved. These tools were successfully implemented in a recent design for insulation system of a machine with high rated voltage.

7. References

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