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Optimization of semiconductive coating and groundwall insulation layers in stator slot of HV generator

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ABSTRACT

The stress relief (semiconductive) coatings are critical components for insulation system in stator windings which operates at 6 kV or above. These coatings are presented to prevent any partial discharges (PD) on the surface of the stator bars or coils. They prevent any PD in any air gap that might be presented between the coil/bar surface and the stator core, or in the end-winding close to the end of the stator core. Electrical conductivity of these semiconductive coatings is a major design factor for insulation system of high voltage (HV) generators. On the other hand, electrical conductivity of ground-wall insulation is another major design factor that need to be taken into considerations since having little electrical conductivity of insulation layers can result in less and more uniform electrical field tensions across them. A very powerful method available to analyze electromagnetic performance is finite element method (FEM), which is employed in this paper. These processes of optimization have been done based on the proposed optimization algorithm. In this algorithm, the technical constraints is also considered. This paper describes the process used to perform improvement analysis of stator slot's insulation with respect to objective function and constraints.

1. Introduction

The electrical insulation system of high voltage (HV) rotating machines is one of the most important parts with respect to the manufacturing costs as well as the maintenance and life time aspects [1]. Stator winding insulation is one of the most critical components for reliable operation of ac electric machines of all types and sizes. Since the stator insulation is continuously exposed to an electrical stress, gradual degradation of the insulation is inevitable [2]. Industrial researches show that troubles initiated in the stator winding insulation are one of the primary root causes of electric machine failures [3] because one-third of the forced outages of large generators in generating stations and industrial plants are caused by the failure of insulation system in stator windings [4].

The stator insulation system of generators consists of groundwall insulation, phase–phase insulation, turn and the strand insulation, and semiconductive coatings. The ground-wall insulation is the main part of the insulation system that separates the HV copper conductors from the grounded stator core, and the turn or strand insulation prevents shorts between the turns or the strands in a coil. Modern machines use mica flake or mica paper tapes bonded with epoxy or polyester resin as ground-wall insulation [3,4].

The reason PD may occur between the coil and the core is similar to the reason that PD can occur in air pockets within the ground-wall. Since coils and bars are fabricated outside of the stator core, they must be thinner in the narrow dimension than the width of the core's steel slots; otherwise, the coils/bars cannot be inserted into the slot. Thus, an air gap between the coil/bar surface and the core is inevitable. Fig. 1(a) shows the gap that appears in the slot adjacent to the coil surface, since the coil is undersized. An equivalent circuit, only slightly different from the ground-wall case, is shown in Fig. 1(b). As for the ground-wall voids, a significant percentage of the copper voltage will appear across the air gap. The electric stress in the air gap larger than 3 kV/mm will cause PD at least in an the air-cooled machine. This PD will eventually erode a hole through the groundwall, causing failure. Discharges on the coil/bar surface are sometimes referred to as slot discharge, since it can occur in the slot. Under practical conditions, most stators rated 6 kV or more will experience this PD on the coil/bar surface. In addition to deteriorating the insulation, surface PD in air-cooled machines creates ozone. The ozone combines with nitrogen which creates acids that poses a health hazard. The resulted acids can weaken rubber materials and corrode metal in areas such as heat exchangers.

To prevent PD on the coil or bar surfaces, manufacturers have been coating the coil/bar in the slot area with a partly conductive

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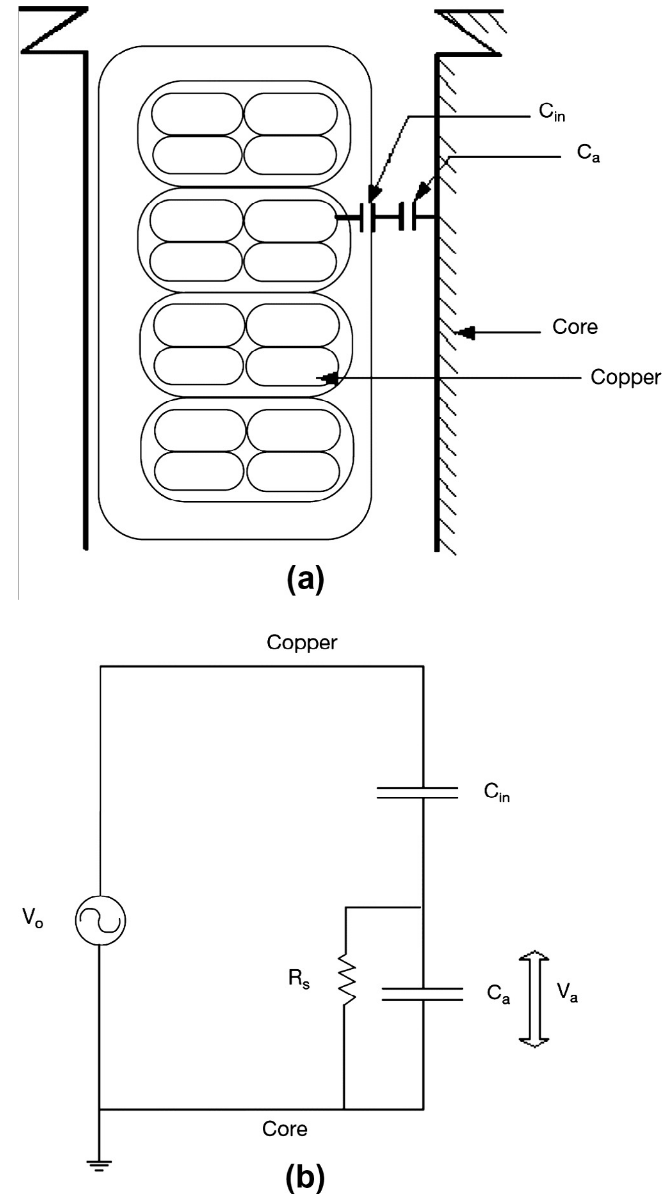

Fig. 1. (a) Cross section of a coil in a slot where PD can occur at the surface of the coil and (b) the equivalent electrical circuit.

coating for a long time. The coating is usually a carbonblack-loaded paint or tape. This coating, often called a semiconductive coating (although this has nothing to do with semiconductors in the transistor sense), is likely to be in contact with the grounded stator core at many places along the length of the slot. With a sufficiently low resistance (Rs in Fig. 1(b)), this coating is essentially at ground potential because of the contact with the core. Thus, the voltage across any air gap is zero. Therefore, PD cannot occur in the gap since the electric stress will never exceed 3 kV/mm. It can be concluded that semiconductive coatings with surface resistance from 0.1 to 10 kΩ per square prevent surface discharges in the slot. The coating cannot be highly conductive, since this will short out the stator core laminations. Semiconductive coatings on coils in the slot are not normally needed for stators rated at 6 kV or less. Clearly, this is due to the fact that the critical threshold of 3 kV/mm (electric breakdown strength of air) in unlikely to occur at this low operating voltage, even if a substantial gap exists between the coil and the core. Therefore, the optimization of conductivity for semiconductive coatings in stator slot of synchronous generator is very a important issue that will be thoroughly studied in this article.

In 2009 Diako Azizi analyzed the impact of the destructive factors on the stator slot insulation using finite element analysis [5]. James described some laboratory tests and finite element simulations that examined the effect of applied surge test voltage and number of applied pulses on voltage endurance life in 2005 [6]. Jun Zhang performed two-dimensional finite element analysis (FEA) to compute the electric field in stator slot of a synchronous machine in 2012 [7]. His research that is the last research about the electrical insulation of electrical machines that has been published yet, does not include the regular method such as optimization procedure to decreasing the electrical field tensions, but only proposed some methods to analysis the electrical field distribution along the stator slot insulation system at some of the possible cases.

Thus, performing the optimal design including the electromagnetic study in core, winding and insulation of stator slots to improve the operation of generator is necessary. In this paper, electromagnetic analysis which considers real condition is performed and using the proposed optimization algorithm, the semiconductive coating characteristics will be modified to completes pervious researches. The main idea is to find the optimum electrical conductivity of semiconductive coating layer in order to minimize the PD activities. FEM analysis is used to simulate the performance of generator. The main supremacies of the simulations in comparison with other researchers are as follows:

- Simulating of ordinary rotation of rotor.
- Considering of magnetic saturation of core.
- Considering of technical constraints.
- Considering of core losses.
- Considering of insulation losses.
- Considering of copper losses.
- Considering of eddy currents.
- Considering of ambient conditions.
- Using the SNOPT (general-purpose system for large-scale nonlinearly constrained optimization) optimization method that can couple to FEM.

According to this method, electrical conductivity of stator slot semiconductive coating and groundwall insulation layer are optimized simultaneously to investigate the possibility to improve characteristics of HV generators.

2. Case study

To study a sample, it is required to determine or design the sample first. Therefore, in order to do field analysis and to study the generator insulation status, a generator with a given profile has been selected. The selected generator is synchronous, three phase, 4 poles that have 24 slots in stator. The rated frequency and voltage are 50 Hz, 28 kV, respectively. In this study, the wiring type is form-wound multiturn, and it has many insulation layers with different specifications (Fig. 2). Here, the turn insulation and the strand insulation are the same.

3. Optimization method

3.1. SNOPT method

In this paper, the optimization algorithm builds on the proven SNOPT package developed by Prof. Philip Gill (University of California, San Diego) along with Profs. Walter Murray and Michael Saun-