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New approaches towards the investigation on defects and failure mechanisms of insulating composites used in high voltage applications

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ABSTRACT

Stator insulations are critical to the reliability of high voltage rotating machines. Currently, state-of-the-art inspection systems mainly focus on electrical properties such as partial discharges to assess the performance of these composite materials. In the present work, non-destructive testing techniques and thermomechanical characterization methods are employed to characterize typical failures and defects of winding insulations and the resistance against delamination. X-ray computed (micro)tomography and ultrasonic measurements are performed to visualize defects in stator bar insulations. Both sample preparation as well as measurement set-up have been optimized to inspect defects in whole stator bars by means of X-ray CT. Additionally, the delamination resistance of insulation materials manufactured by resin rich and vacuum pressure technology are determined by TMA and DMA. The results give evidence that the evaluated inspection techniques provide a useful tool for the electrical industry regarding quality control, development of new materials or process optimization of stator windings.

1. Introduction

Regarding the reliability and lifetime of high voltage rotating machines the electrical insulation represents a key factor [1]. Recent studies have demonstrated that the failure of electrical machines such as hydro generators for instance, is mostly attributable to insulation damage (>50%) whereas mechanical or thermal damages are not the dominating factors [2,3]. The electrical insulation comprises a composite material containing inorganic components that offer resistance against corona discharge (mica) and support the mechanical strength of the insulation (glass fabric). In addition, an organic binder (thermally curable epoxy-based resins) is required to laminate the glass and mica layers and to prevent air inclusions within the insulation [4].

Over the past decades, two technologies have been employed to manufacture winding insulations in rotating machines for industrial applications. In the vacuum pressure impregnation (VPI) process, a resin infusion technique, mica tapes reinforced with glass fabric are wrapped around a copper conductor (Roebel bar) repeatedly and form the main wall insulation. Field grading tapes are wound around the main wall insulation to enhance the corona resistance. The basic structure of the electrical insulation used in high voltage rotating machines is provided in Fig. 1. The impregnation of the winding is carried out by submerging the Roebel bar in liquid resin under vacuum which is followed by a pressure step ensuring that it fills the free volume between the various mica and glass layers. In the final step the resin is cured by a thermal reaction. The advantage of the VPI process involves the impregnation of a larger amount of stator bars obtained at low cost. An alternative to the VPI process is the resin rich (RR) technology, in which a resin, solid at ambient temperature, is provided on the mica tapes of the main wall insulation. These tapes (prepregs) are manually wound around the mechanically formed copper conductors. During the heating step, where pressure and temperature are applied in a tank with an asphalt bath, the resin within the tape cures and a solid composite material is accomplished. With both processes a comparable inherent insulation quality can be achieved if similar design and quality control are employed [5,6].

In literature different causes of insulation failures are described, ranging from a contamination of winding during manufacturing to various ageing processes [4,7]. During the operation the insulation is exposed to a combination of mechanical, electrical, ambient and thermal stresses that can lead to a deterioration of its dielectric and mechanical strength [8,9]. The characterization of electrical properties (e.g. voltage endurance, partial discharge activity, etc.) and

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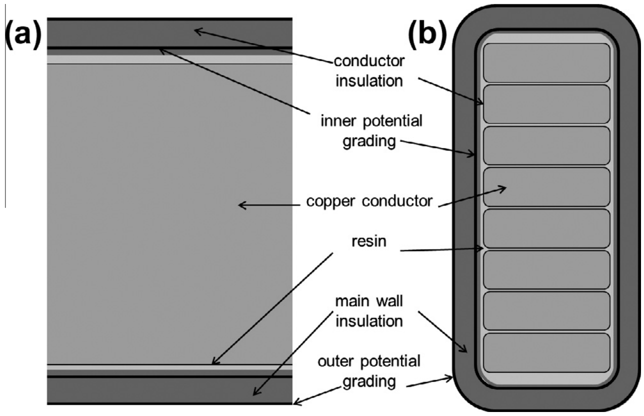

Fig. 1. Design of a stator bar used in high voltage rotating machines (a) axial cross-section (b) lateral cut.

the correlation of electrical performance with the life time of the insulation have been subjects of many publications [10–12]. With respect to the measurements of partial discharge (PD) activity, it has to be considered that they are only an indicator for the number of voids filled with air (or some other gas) within the insulation. Although these voids may increase in size by exposure to electrical stress, their origin is usually not caused by partial discharges.

Whereas in recent publications destructive and non-destructive testing (NDT) methods of numerous composite materials are described in detail, no investigations of glass–mica–epoxy resin composites used in high voltage applications were performed [13–23].

The present work focuses on the evaluation of different characterization techniques for the study of defects (e.g. voids) and delamination mechanisms in electrical insulation for high voltage applications. In this study NDT techniques such as X-ray computed tomography (CT) or ultrasonic testing (UT) are applied to characterize the type, geometry and orientation of defects making the investigation of both impregnation failures and delamination effects feasible. With at least 5–50 μm spatial solution high-resolution X-ray computed tomography is additionally used to determine micro-voids which can be weak spots for partial discharges and corona degradation under operation conditions. Furthermore, TGA is used to determine the amount of epoxy resin between selected mica-tape layers which offers another tool to assess the quality of the impregnation process.

Regarding the failure mechanism upon ageing, it is well known that mechanical, thermal and internal stresses within the composite material represent a key role whereas the influence of the electrical stress plays a minor part [1]. As a consequence destructive techniques including thermal mechanical analysis (TMA) and dynamic mechanical analysis (DMA) are applied to characterize the thermo-mechanical properties of the composite materials. The thermo-mechanical analysis allows the evaluation of internal stresses within the insulation caused by different directional coefficients of thermal expansion.

It has to be considered that the evaluated techniques make not only the detection of defects feasible but offer new insights into the failure mechanisms of electrical insulations. Furthermore, the correlation of mechanical properties and failure mechanisms is crucial when developing new materials for electrical insulations with increased lifetime.

2. Experimental part

2.1. Materials

In order to evaluate the selected inspection techniques, industrially manufactured stator bars as well as model insulating composites have been characterized. The stator bars differ in type (VPI and RR) and operation conditions (untreated and in-service aged). The thermal rating of the bars was F class comprising a temperature resistance up to 155 °C.

Additionally, model insulations have been prepared employing the VPI process to simulate typical failures in fabrication (insufficient impregnation and defects). In the first step a partly impregnated insulating composite was prepared with gradual resin content through the layered structures. For the sample preparation, 40 layers of mica tapes were wound around an aluminum tube (d = 5 cm, l = 10 cm). The end walls of the composite were sealed with silicone rubber to prevent an axial and to ensure a radial flow of the resin. The sample was impregnated with a bisphenol A based epoxy resin (Huntsman) using phtalic acid anhydride as curing agent and thermally cured at 155 °C for 10 h. Using this experimental set-up, a VPI composite was obtained with a gradual impregnation (non-impregnated innermost mica-glass layers and highly impregnated outermost layers). After the curing step, thin slices (lateral cuts) were cut with a diamond-saw and the mica-resin composites were cut from selected layers of the sample (see Fig. 2) with a scalpel.

To simulate air inclusions within the insulating composites, hollow glass microspheres (Akzonobel) with an average diameter of 40 μm were incorporated in a VPI model insulation. For the sample preparation, 10 layers of mica tape were wound around a rectangular pressing form. Between layer 5 and 6 the glass microspheres were placed on the mica tapes and the impregnation and curing were carried out as described in the previous paragraph. The composition and characteristics of the various composite samples are summarized in Table 1.

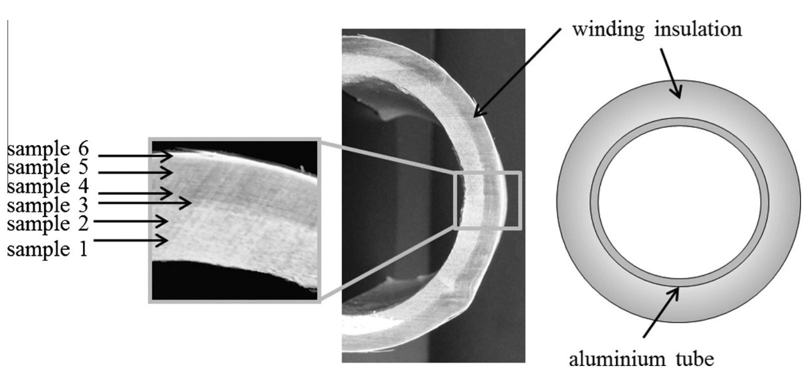

Fig. 2. VPI model insulation with insufficient resin impregnation employed for TGA measurements.