MODELLING OF OUTER CORONA PROTECTION SYSTEMS OF LARGE ROTATING MACHINES USING FINITE ELEMENT METHOD

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Abstract: The effective operation of large rotating electrical machines basically depends on the condition of the electrical insulation system. The main insulation system is the arrangement of subcomponents with individual electrical field relevant functions. With different stator constructions adapted outer corona protection (OCP) system designs are realised by using conductive tapes or/and brushed varnishes. The service relevant main attribute of the OCP is its resistance. It is well-known that deviations of the target resistance value could lead to different material degradation effects due to partial discharge occurrence which increase the breakdown probability of the insulation system. This essay introduces the finite element method (FEM) as a capable tool to complete an in-depth understanding of OCP systems of large rotating machines. Here the effects of deviations of OCP square resistance are evaluable with little expense by variation of the resistance as input parameter of the FEM model. Therefore these results can represent a basis for improvement of target resistance values and for optimisation of future OCP designs. Additionally the model could be extended by defined local structural features to simulate the inhomogeneous electrical field distribution in the area of abnormalities of the OCP like surface damaging or erosion scenarios.

1 INTRODUCTION

The lifetime of high voltage power apparatus systems mainly depends on the quality of the electrical insulation system. In particular large rotating electrical machines have to suffer multiple ageing and degradation mechanisms to ensure a dedicated operating life of up to 40 years and even longer. This assumes a substantiated construction and design knowledge. Modern main insulation systems of large rotating electrical machines consist of diverse interacting materials in complex spatial structures. The understanding of the electrical field defining elements is essential. Here one element is the outer corona protection system witch forms the interface between ground potential and high electrical field strength. This essay deals with the demands and functions of outer corona protection materials and systems. The finite element method is introduced as one tool to improve the understanding and development of such systems.

2 OUTER CORONA PROTECTION SYSTEMS

The core element of the overall electrical insulation system of a large rotating machine represents the stator bar as a subsystem. This comprises the sub elements inner corona protection (IPS), main insulation, outer corona protection (OCP) and end corona protection (ECP) [1]. The ICP as the HV electrode and the OCP as the ground electrode assure the geometry dependent optimised electrical field distribution in the intermediate main insulation volume [2].

The ECP as the field grading component at each end of the OCP layer prevents surface discharges mainly in case of heightened test voltages but also under service stress [3].

2.1 OCP Construction Variants

The wide range of rated power classes of electrical rotating machines up to more than 2000MVA at nominal voltages of up to U_n=27kV demands adapted insulation system constructions and manufacturing processes to cope with the different stator sizes. Hence different overall machine construction variants are associated with aligned OCP variations. This paper focuses on OCP variations as they are applied for example on large turbo generators manufactured by Siemens.

The largest types of generators are characterised by a stator completion after finishing the main insulation system. Here each single stator bar has to pass through an impregnation and curing cycle to build up the mica insulation volume. The accordant process at Siemens is the single bar vacuum pressure impregnation (SVPI) [4]. After this the mechanically smoothened surface is painted with OCP varnish as the electrical field grading layer in the slot area. Additionally the painted area is laminated with conductive tape or wallpaper to ensure mechanical surface protection. From the electrical point of view these two different outer corona protection layers effectively form a single layer OCP configuration (see **Figure 1**).

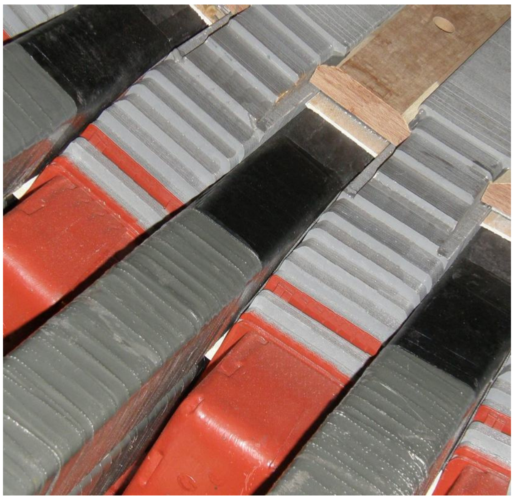

Figure 1: SVPI stator bars at slot end area with visible OCP layers

After inserting the completed (impregnated, cured and painted) stator bars into the core slots they have to be retained with side filler straps. These straps usually are wavelike ripple springs which are conductive and fix the bar tangentially against excessive moving due to electro-magnetic forces. The mechanical fixing pressure also provides electrical contact between grounded laminated core and OCP bar broadside surfaces. The radial fixing is realised by ripple spring straps placed under the slot wedges.

Turbo generators which are of medium size with stator core lengths up to about 6m and rated power up to more than 500MVA are assembled by Siemens commonly applying the global vacuum pressure impregnation process (GVPI) [5]. Here the stator bar insulation system is build up by wrapping the ICP layer, the mica main insulation and the OCP system and ECP areas. Hence the completed bars carry the dry insulation system when they are inserted into the core slots. After completing the whole dry insulation system frame-work by wedging the slots, connecting end win-dings and blocking the end winding baskets the entire stator is impregnated with epoxy resin. The final curing sequence accomplishes the intensive bonding between OCP tape surface of the bar and the stator core slots.

To endure the thermo-mechanical stresses the GVPI OCP system is realised as a double OCP layer structure. The inner layer is bonded to the mica main insulation volume. The outer layer is bonded to the slot walls of the laminated core. The interjacent mica splitting layer works as the rated breaking point in case of mechanical tension forces due to thermally induced differing expansions of stator bar and stator core. A longitudinal connecting OCP tape which alternatively connects the inner or outer OCP layer while braiding the mica splitting layer ensures contact of inner layer to ground potential.

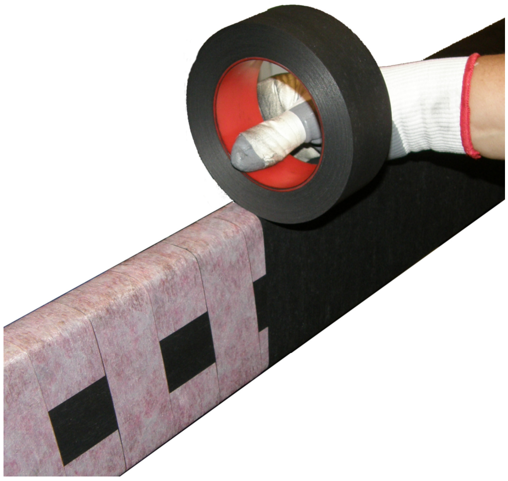

Figure 2: Dry wrapping sequence of OCP on insulated stator bar prior to GVPI process

2.2 Service Relevant Aspects

2.2.1. Basic Functionality

The main attribute of any conductive OCP material applied in electrical machines is the resistance. This trivial insight turns out to be extremely complex when resistance affecting parameters are examined and furthermore when the resistance related consequences for the complete insulation system are clarified.

Conductive varnishes, tapes and straps are used as OCP raw materials. They are generally pro-cessed in terms of thin conductive layers. Hence the commonly used parameter for characterisation and assessment is the surface resistance phrased as geometry independent square resistance $R_{\square}$ [6]. As shown in 2.1 the OCP raw materials have to be arranged as complex three-dimensional structures to obtain an operational OCP system at all. Together with the main insulation layer the elec-trical insulation system has to be regarded as an ohmic-capacitive arrangement. Furthermore this system is embedded in the grounded laminated stator core. This results in a complicated spatial distribution of conductive and capacitive areas with multiple ground connection points [2].

2.2.2. Notions of Resistance Optimum

The basically aspired limitation of square resistance values when applying OCP materials in an electric machine is obvious and well-known [6]. On the one hand the OCP system has to be conductive enough to furnish the ground potential to the main insulation surface in each region of the OCP. But on the other hand the OCP material must work resistively enough to confine the currents in the OCP system induced by the longitudinal induced voltage to prevent inaccep-table losses in the laminated core sheets and in the contact points between OCP and core.

These drivers act diametric contrarily so that the existence of a resistance optimum is comprehensible. But firstly this formulation is diffuse. Due to the multiple stator constructions and stator insulation system manufacturing processes a universally valid optimum of the square resistance can not be appointed in a general manner. It is rather essential to concrete the object whose resistance optimum shall be discussed. In fact either it is the globally resultant resistance of the complete OCP system in the stator slot or it is the localised effective surface resistance.

This differentiation has to be conducted necessarily if contingent degradation mechanisms are considered. Here the phenomenon “vibration sparking” is mainly affected by a too low overall OCP system resistance which limits the current induced by the longitudinal voltage only in an insufficient way [6]. If the locally effective square resistance is too high the phenomenon “slot discharges” can appear if the electrical field strength on an OCP surface gets critically high due to improper potential gradients driven by the high voltage between stator bar copper and stator core [2].

Figure 3 illuminates the existence of multiple OCP resistance values which are relevant for any resistance examination or discussion. Finally both examination variations applied on stator insulation systems - global and local - base on the square resistances of the primary raw OCP materials.

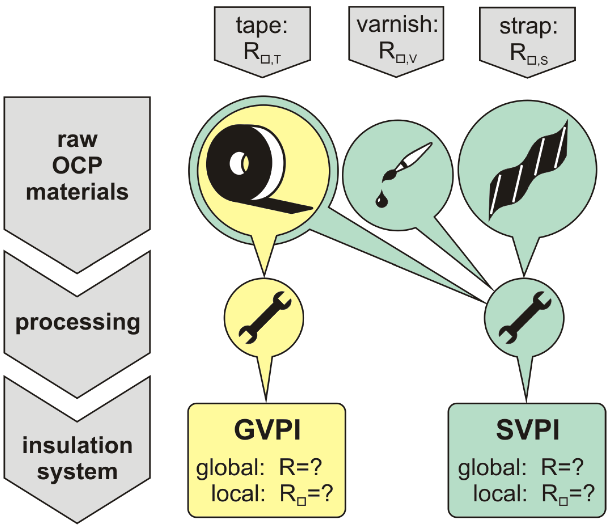

Figure 3: Relevant resistances arranged in terms of insulation system manufacturing processes

These different materials pass through the adapted OCP manufacturing processes like SVPI or GVPI. That means in detail that they are winded, impregnated, painted, heated, pressed and/or pulled. Hence while being processed the raw materials could be stressed chemically, thermally and/or mechanically.

Thus depending on the raw material its specific resistance can experience changes. Common examples for this phenomenon are the resin content dependent square resistance of specific OCP tapes applied in the GVPI process or the time dependent drying condition of OCP varnishes. Furthermore the manufacturing process implicates a major geometric complication of the resistive structure. Here the raw single OCP materials perform a transformation into a real OCP system with interacting components.

2.2.3. Conclusions for OCP System Understanding

It was clarified that a proximate correlation between the square resistances of applied raw OCP materials and the square resistance of the completed complex OCP system or the overall OCP system resistance is not settable if the interaction effects are not determinable exactly.

The all-embracing experiences collected by Siemens prove the successful operation of the applied OCP systems on site. But any improving development like application of new materials, optimisation of manufacturing processes, assessment and implementation of new OCP system constructions is enhanced by the in-depth understanding of the OCP system. Additionally a concretion of target resistance values could be realised beyond diffuse phrases like “too low” or “too high”.

In the course of actual investigation the finite element method (FEM) established as an adequate tool to overlook multiple real OCP systems as a whole in the electrical machine as well as to get insight in locally relevant resistance effects.

3 FEM MODELLING AND SIMULATION

In principle the overall high voltage insulation system could be simplified as an equivalent circuit. This would consist of capacities and resistors as concentrated elements. With it the determination of the spatial distribution of partial voltage drops could be possible. Subsequently from this the electrical potential distribution could be derived. Here the accuracy directly depends on the local resolution of the equivalent circuit elements. It was explained that an OCP system represents a complex three-dimensional structure. Recognising and analysing critical aspects like electrical limits of the OCP system or understanding of degradation effects requires at least the knowledge about the electrical field strength distribution. But this information can not be extracted from an equivalent circuit because field relevant macroscopical geometry features can hardly be emulated with concentrated elements [6].

In contrast to this inhibition the FEM allows the creation of any three-dimensional complex geometrical structures. Here the accuracy of information (i.e. distributions of electrical potential and electrical filed strength) depends on the resolution of the finite element mesh. In principle this resolution is arbitrary and limited by computing power and time.

3.1 Geometry Creation and Meshing

The FEM has proved its practicability in the field of simulations and calculations of the sub element end corona protection (ECP) in the rotating machine main insulation system [1]. In the present investigation one divergent challenge is the handling of enormous OCP system dimension spread where the total system length can reach more than 7 metres with resistive OCP elements with thicknesses in the range of just parts of a millimetre.

It was obvious that a modelling of the complete OCP system structures is not applicable due to the aspired high resolution of the thin layers. Therefore the first step in modelling was the analysis of the real structure to find out in which way a representative simplification is possible. As the focus was on the geometrical complex GVPI and SVPI insulation systems it turned out to be adequate to border the models' dimensions according to the spatial periodic insulation system structure. This principle is illustrated in **Figure 4** with the help of the GVPI OCP system.

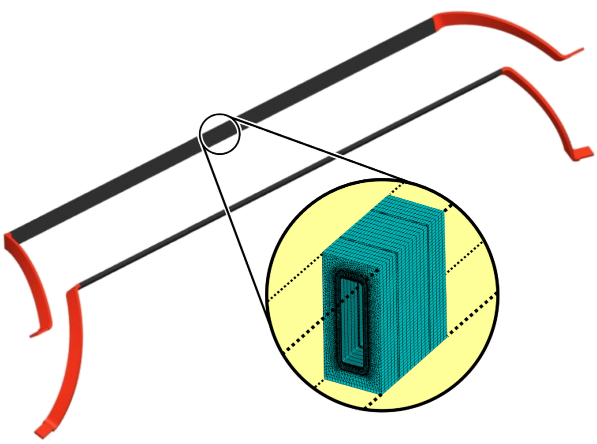

Figure 4: GVPI bars with representing separated FEM model section

This dimensional reduction of the calculated model is feasible if the overall OCP system conclusions are extractable out of this representative model. It is plausible that the overall resistance is the result of the series connection of the calculated resistance between the two section ends. If information about the currents in the resistive layers is needed it has to be distinguished between the driving voltage components.

The longitudinal induced voltage is characterized by the nominal generator voltage and the number of windings per phase. It leads to a current flow through the overall OCP resistance which connects the ends of the laminated stator core. Hence the FEM analysis of a short stator bar section is plausible if the driving voltage is reduced to a driving voltage drop according to the dimensional sectioning. This longitudinal induced current flows in the resistive layers which nearly have ground potential. Whereas the current component which is caused by the high voltage between copper and stator core flows in a kind of radial direction and crosses the multiple resistive OCP layers vertically.

Figure 5 shows the geometric model of an investigated GVPI bar section with concretion of the relevant insulation system components.

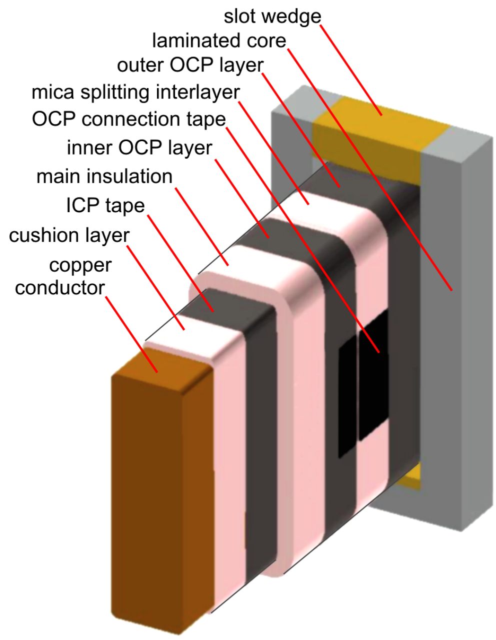

Figure 5: Model of GVPI bar section with visually separated elements

Here the major difficulty was to realise the longitudinal connecting OCP tape which alternatively connects the inner or outer OCP layer while braiding the mica splitting layer in this double OCP arrangement.

Both variants of insulation system – GVPI and SVPI – where modelled as one bar slots. This means that even of course there are two stator bars put in each core slot it is sufficient to calculate just a one bar configuration. This is plausible because if a harmonic electrical analysis focussed on electrical potential and field distribution is conducted a mutual influence of top and bottom bar is insignificant in this arrangement. In the models this fact was accommodated for example by constituting the slot bottom material parameters resistive or insulating properties.

Figure 6 illustrates the SVPI model variant. Similar to the GVPI model the challenging component was the side ripple spring. Here the wavelike shape had to be modelled in a way that the spring thickness as well as the wavelength and the wave shape amplitude can be adjusted for prospective parameter investigations.

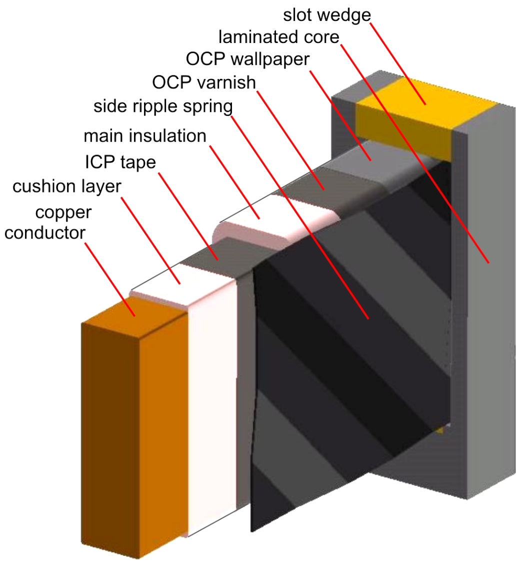

Figure 6: Model of SVPI bar section model with visually separated elements

Figure 7 and **Figure 8** deliver an insight in the meshing characteristics when using tetrahedron elements. This type of element ensured a meshing of the complete models.

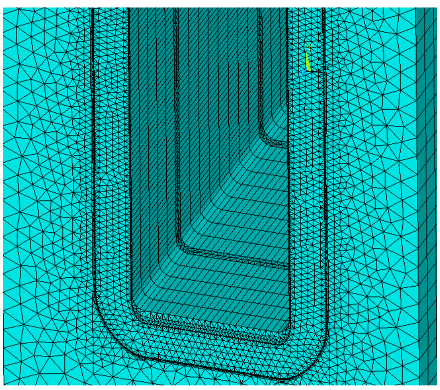

Figure 7: Meshed FEM model of a GVPI bar section

Both introduced insulation system arrangements do not have any symmetry planes which could be used for simple optimisation of the meshing process. Actually the meshing turned out to be challenging at all because the information carrying very thin layers had to be connected with relatively large volumes where only few relevant information was expected. Here the result is an in principle too fine meshing of the homogeneous volumes. That resulted in a large number of elements which prolonged the calculating and solving times.

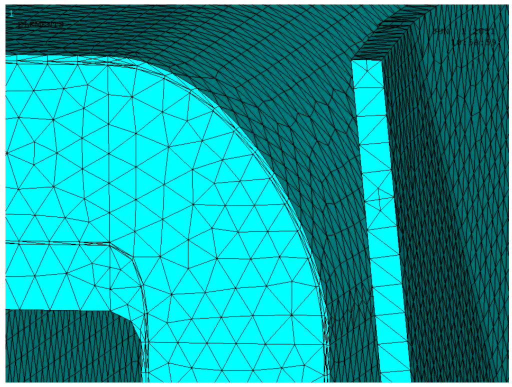

Figure 8: Meshed FEM model of a SVPI bar section with side ripple spring

3.2 Results

In this first step of FEM modelling and simulation basic calculation results are presented to evidence the feasibility of application of FEM on complex OCP systems as part of high voltage insulation systems of large rotating electrical machines. In the following diagrams there are illustrated potential distributions in the resistive material volumes of the OCP system. Here a relative scaling represented by the colour code was chosen to simplify these first conclusions. The spread between the lowest and the highest potential value in each mapping is translated into the colour variation. Hence the same colours do not mean comparable potential values. The possibility of visualising separated areas of interest after the solving process ensures the locally detailed assessment of electrical effects in areas which are inaccessible in real OCP systems. One example for this is shown in **Figure 9**. Here the principle potential distribution of the visually separated inner OCP layer of the double OCP system used in GVPI machines is presented.

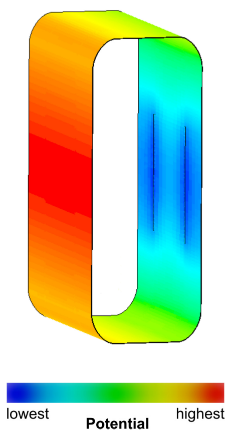

Figure 9: Distribution of electrical potential on inner OCP layer of GVPI bar section

The qualitative assertion is that the inner OCP layer experiences a potential increase over its circumference. The absolute potential difference is not evaluable by means of this specific mapping.

Here further concrete parameter variations will deliver detailed assessments. The first results achieved with the SVPI model show **Figure 10** and **Figure 11**. Here the OCP layer together with the conductive side ripple spring is separated. Each figure contains two mappings to increase information by viewing from different directions on the inner side of the OCP layer and on the broadside of the side ripple spring.

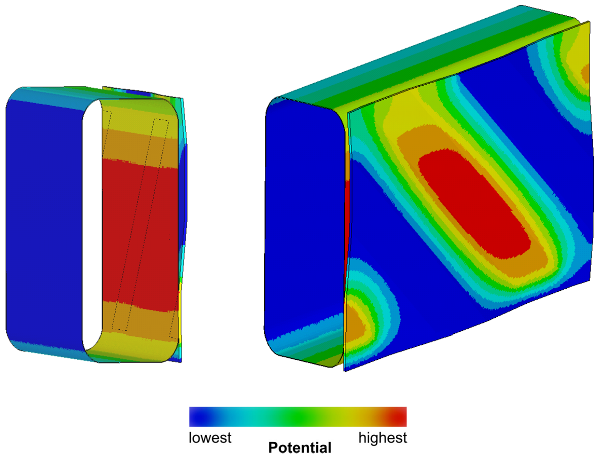

Figure 10: Electrical potential distribution on low resistance OCP layer and ripple spring of SVPI bar section

The differences between the electrical potential distributions in **Figure 10** and **Figure 11** are caused by the variation of the OCP layer square resistance. The low resistive OCP layer is characterised by a potential distribution which seems not to be affected by the contact behaviour of the conductive side ripple spring.

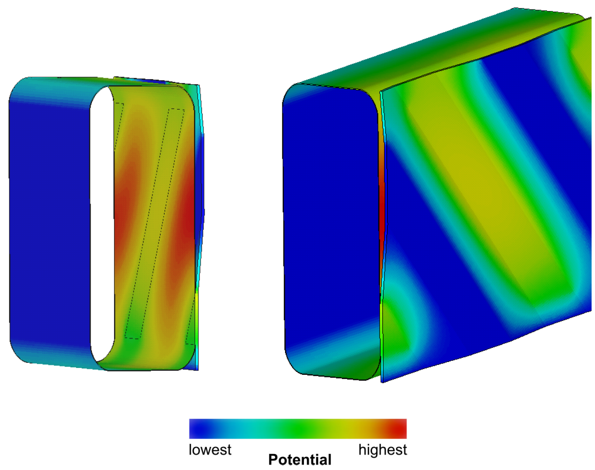

Figure 11: Electrical potential distribution on high resistance OCP layer and ripple spring of SVPI bar section

Whereas the increase of the OCP layer square resistance (applied in **Figure 11**) leads to significant potential distributions on the ripple spring contacting bar side.

The comparing variation of the OCP square resistance emphasises the principle feasibility of the SVPI FEM models because the resistance affected changing of the electrical potential distribution is qualitatively plausible. This example gives an idea about the opportunity to accelerate OCP development activity or to deeply analyse degradation effects by facile varying resistance values as input parameters of the FEM models.

4 CONCLUSIONS

The outer corona protection system (OCP) has decisive functions as part of the stator bar insulation system of large rotating machines.

The OCP resistance optimum depends on the construction of the machine and the OCP system.

The finite element method (FEM) has proved to be the adequate tool for modelling and simulation of even extreme complex spatial structures.

The optimisation of meshing characteristics will result in a decreased number of finite elements and shortened calculation time.

Prospective investigations will base on comprehensive variations of geometry and resistance parameters.

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