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Improvement of Stator Slot Structure based on Insulation Stresses Analysis in HV Generator

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***Abstract*—**High voltage generators are being subject to higher voltage rating and are being designed to operate in harsh conditions. Stator windings are the main component of generators in which Electrical, magnetical and thermal stresses remain major failures for insulation degradation accelerated aging. A large number of generators failed due to stator winding problems, mainly insulation deterioration. Insulation degradation assessment plays vital role in the asset life management. Mostly the stator failure is catastrophic causing significant damage to the plant. Other than generation loss, stator failure involves heavy repair or replacement cost. Electro thermal analysis is the main characteristic for improvement design of stator slot's insulation. Dielectric parameters such as insulation thickness, spacing, material types, geometry of winding and slot are major design consideration. A very powerful method available to analyze electro thermal performance is Finite Element Method (FEM) which is used in this paper. The analysis of various stator coil and slot configurations are used to design the better dielectric system to reduce electrical and thermal stresses in order to increase the power of generator in the same volume of core. This paper describes the process used to perform classical design and improvement analysis of stator slot's insulation.

***Keywords*—**Electrical field, field distribution, insulation, winding, finite element method, electro thermal

I. INTRODUCTION

NOWADAYS, in our developed world, many generators are utilized in such a condition more difficult than they designed for. This application of generators, in critical conditions may cause an irrecoverable damage to the system. Safe utilization of electrical machine, particularly high power generators intensely depend upon the health of stator coil insulation. Industrial researches show that problems initiated in the stator winding insulation are one of the leading root causes of electric machine failures [1, 2 and 3]. It is shown in [4, 5] that 30-40 % of ac machine failures are stator related and also shown in [6] that 60-70 % high voltage machine failures result from stator insulation problems. The winding and core of stator integrity plays vital role in the reliability of the alternator [7-11]. Thus, performing the optimal design consist of electro thermal analysis in core, winding and insulation of stator slots is necessary. To achieve an improved design electro thermal analysis with regard to real condition is performed which completes pervious researches.

The purpose of applying the method is investigating the effects of electrical and thermal stresses on insulation parts. The main idea involves finding the proper structure of stator slot's insulation with respect to possible stresses. FEM analysis is used to simulate the electric field, magnetic field and thermal distribution simultaneously. The main supremacies of the simulations in comparison with other researchers are:

- Coupling electromagnetic field with thermal analysis.
- Simulating ordinary rotation of rotor.
- Considering magnetic saturation of core.

According to this method, various configurations of stator (winding, core, slot, insulation) for operation conditions are proposed to investigate the possibility of improvement high voltage generator characteristics.

II. CLASSICAL DESIGN

M phase machine classical design has definite steps which are considered in this section. The induced KVA by armature can be obtained from:

$$Q = m\left(\sqrt{2}\pi f \varphi T_{ph} K_w\right)\left(I_{ph}\right) \times 10^{-3} \;\; KVA \tag{1}$$

Where:

φ: total flux
I_{ph}: phase current
K_w: winding factor
f: frequency
T_{ph}: winding turn in phase
The equation (1) can be rewritten as (regarding to $f = \frac{pn_s}{2}$, $I_z = I_{ph}$ and$z = 2mT_{ph}$) :

$$Q = \frac{\pi}{2\sqrt{2}}(P\varphi)(I_z Z) n_s k_w \times 10^{-3} \tag{2}$$

Total magnetic flux in air gape is called magnetic loading which is used to calculate especial magnetic loading (B_{av}) as bellow:

$$Total\ magnetic\ loading = \varphi_p \tag{3}$$

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$$B_{av} = P\varphi/\pi DL \quad (4)$$

Where:

D: is diameter
L: is length

Total current loading and especial current loading introduced by the following equations:

$$Total\ current\ loading = I_z Z \quad (5)$$

$$ac = \frac{I_z Z}{\pi D} \quad (6)$$

By replacement $P\varphi$ and $I_z Z$ from equations (4) and (6) in equation (2), it can be shown that:

$$Q = \frac{\pi}{2\sqrt{2}}(\pi DLB_{av})(\pi Dac)n_s k_w \times 10^{-3}$$
$$= (1.11\pi^2 B_{av} ack_w \times 10^{-3})D^2 Ln_s$$
$$= C_0 D^2 Ln_s \quad (7)$$

Where:

$$C_0 = 1.11\pi^2 B_{av} ack_w \times 10^{-3} \quad (8)$$

k_w is winding factor which is calculated by multiplying k_c and k_d. k_c is assumed one and k_d is obtained from equation (9).

$$k_d = \frac{\sin q\alpha/2}{q \sin \alpha/2} \quad (9)$$

III. CASE STUDY

According to section 2, a generator with different insulation is designed as the case study. The selected generator is synchronous, three phase and two poles. Rated frequency, voltage and power are respectively 50Hz, 20 KV and 1 MVA. Wiring is form-wound multi-turn type and has many insulation layers with different specifications. In this study the turn insulation and the strand insulation are the same, i.e. nylon type. Ground wall insulation type is PTEF and semi conductive coating is Si(c) with characters identified in table I.

TABLE I
ELECTRICAL AND THERMAL SPECIFICATIONS OF USED INSULATIONS

Quantities	Symbols & Dimensions	Nylon insulation	PTEF insulation	Si(c) insulation
heat capacity	*C* *[J/(kg*K)]*	1700	1420	700
young's modulus	*E* *[Pa]*	2e9	3e9	170e9
Thermal expansion coeff.	*A* *[1/K]*	280e-6	70e-6	2.6e-6
relative permittivity	*ε*	4	2	11.7
thermal conductivity	*K* *[W/(m*K)]*	0.26	0.19	130
density	*Rho* *[kg/m^3]*	1150	1190	2329

IV. ELECTROMAGNETIC MODELS [12]

Ampere's law is the main part to derive electromagnetic system equation.

$$\nabla \times H = J + \frac{\partial D}{\partial t} = \sigma E + \sigma v \times B + J^e + \frac{\partial D}{\partial t} \quad (10)$$

Where:

- E is the electric field intensity
- D is the electric displacement or electric flux density
- H is the magnetic field intensity
- B is the magnetic flux density
- J is the current density
- J^e is the externally generated current
- σ is the electrical conductivity
- v is the velocity

Time variant-harmonic fields effect can be introduced by equations (11) and (12):

$$B = \nabla \times A \quad (11)$$

$$E = -\nabla V - \frac{\partial A}{\partial t} \quad (12)$$

Ampere's law is rewritten by equations (11) and (12) Combining with constitutive relationships $B=\mu_0(H+M)$ and $D=\varepsilon_0 E+P$, as:

$$\left(j\omega\sigma - \omega^2\varepsilon_0\right)A + \nabla \times \left(\mu_0^{-1}\nabla \times A - M\right) - \sigma v \times \left(\nabla \times A\right) + \left(\sigma + j\omega\varepsilon_0\right)\nabla V = J^e + j\omega P \quad (13)$$

In which ω, ε_0, μ_0, M and P respectively refer to Angular frequency, Relative permittivity, Relative permeability, magnetization vector and electric polarization vector.

In the case of 2-dimensional-plane, there are no variations in z-direction, so the electric field is parallel to z-axis. , therefore $\nabla V is$ written as $-\Delta V/L$, where ΔV is the potential difference over the distance L. Now these equations are simplified to:

$$-\nabla.\left(\mu_0^{-1}\nabla A_z - \begin{bmatrix} -M_y \\ M_x \end{bmatrix} + \sigma v.\nabla A_z + \left(j\omega\sigma - \omega^2\varepsilon_0\right)\right)A_z = \sigma\frac{\Delta V}{L} + J_z^e + j\omega P_z \quad (14)$$

In the ax-symmetric case, another form of the electric potential gradient has been used ($\nabla V = \frac{-V_{loop}}{2\pi r}$) as the electric field is only present in the azimuthally direction. The above equation, in cylindrical coordinates, becomes:

$$-\left(\begin{bmatrix}\partial/\partial r & \partial/\partial z\end{bmatrix}\left(r\mu_0^{-1}\begin{bmatrix}\partial u/\partial r\\ \partial u/\partial z\end{bmatrix}+\mu_0^{-1}\begin{bmatrix}z\\0\end{bmatrix}u-\begin{bmatrix}M_z\\-M_r\end{bmatrix}\right)\right)$$
$$+r\sigma\left(v.\begin{bmatrix}\partial u/\partial r\\ \partial u/\partial z\end{bmatrix}\right)+r\left(\sigma j\omega-\omega^2\varepsilon_0\right)u+2\sigma V_r u \quad (15)$$
$$=\sigma\frac{V_{loop}}{2\pi r}+J_\varphi^e+j\omega P$$

The dependent variable u is the nonzero component of the magnetic potential divided by the radial coordinate r, so that:

$$u=A_\varphi/r \quad (16)$$

The application mode performs this transformation to avoid singularities on the symmetry axis.

V. THERMAL MODEL

The fundamental law governing all heat transfer is the first law of thermodynamics, commonly referred to as the principle of conservation of energy. However, internal energy (U) is a rather inconvenient quantity to measure and use in simulations. Therefore, the basic law is usually rewritten in terms of temperature (T). For a fluid, the resulting heat equation is:

$$\rho C_p\left(\frac{\partial T}{\partial t}+(u.\nabla)T\right)=-(\nabla.q)+\tau:S-\frac{T}{\rho}\frac{\partial\rho}{\partial T}|_p\left(\frac{\partial p}{\partial t}+(u.\nabla)_p\right)+Q \quad (17)$$

Where

- ρ is the density (kg/m3)
- Cp is the specific heat capacity at constant pressure (J/(kg·K))
- T is absolute temperature (K)
- u is the velocity vector (m/s)
- q is the heat flux by conduction (W/m2)
- p is pressure (Pa)
- τ is the viscous stress tensor (Pa)
- S is the strain rate tensor (1/s):

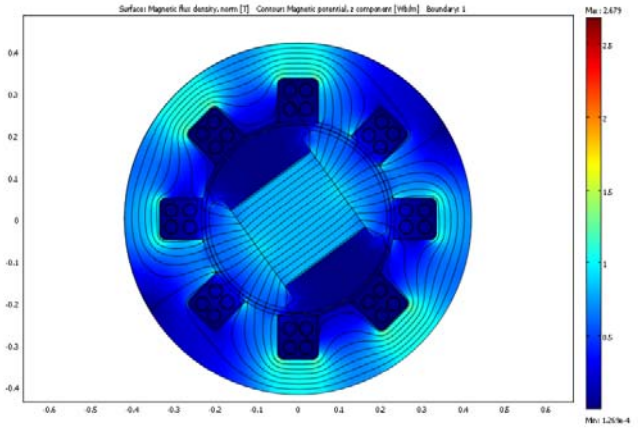
$$S=\frac{1}{2}(\nabla u+(\nabla u)^T) \quad (18)$$

- Q contains heat sources (W/m3)

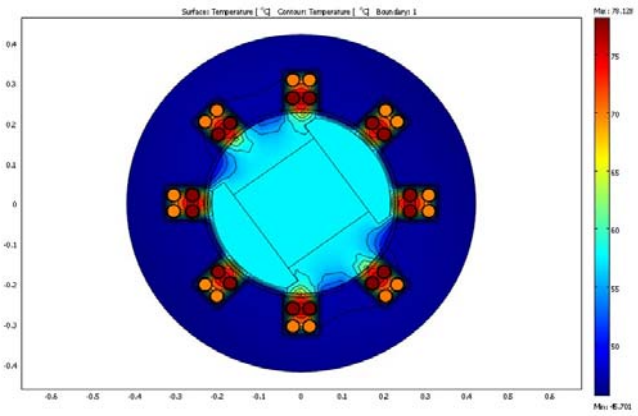
Electromagnetic and thermal equations are coupled by calculating thermal loss (Q) which includes core loss and winding loss.

VI. SIMULATION AND RESULTS

Following the development of the study, magnetic field and thermal distribution for cylindrical windings with two layers simulated (Fig.1).



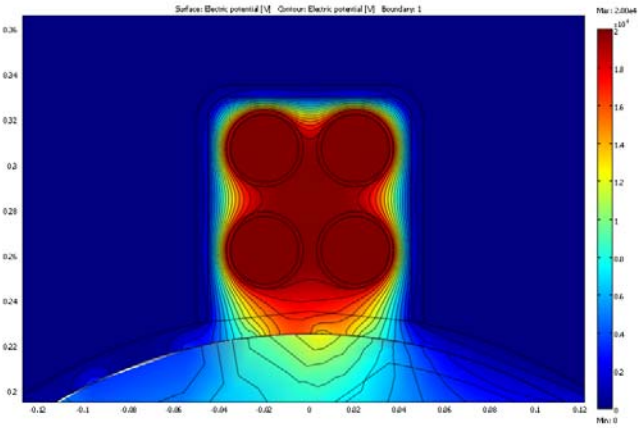
(a)



(b)

Fig. 1a: Magnetic field distribution and flux lines
b:thermal distribution

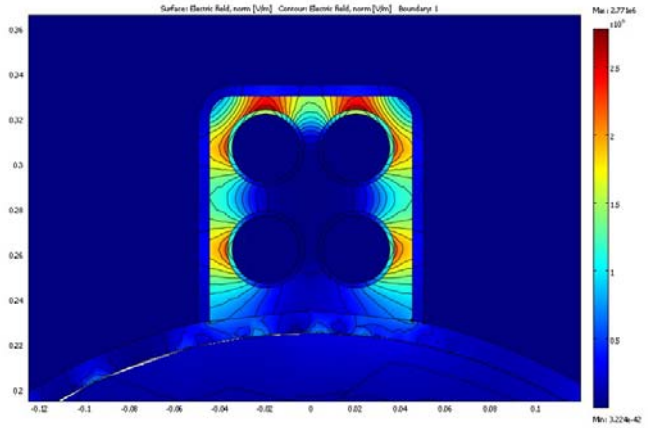
Coupling the equations makes the capability of simulating electrical field and potential distribution as shown in (Fig. 2):



(a)

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(b)
Fig. 2 a: Potential distribution in a sample slot
b: Electrical field in a sample slot

Over Voltage Conditions

According to Arrhenius model, over voltage condition reduces the life of insulation as:

$$L = cE^{-n} \quad 9 < n < 11 \tag{19}$$

Where:

n, c: are constants related to material type
E: is the electrical field or $-\nabla V$

Therefore, over voltage effects on the other parameters such as temperature and electrical field have to be presented. The results of simulation for 20 % and 300 % over voltages show that there is a nonlinear relation between temperature and electrical field (for 20 % over voltage temperature increases 1^{oC} and for 300 % over voltage temperature increases 3^{oC}). The results can be verified by equation (20):

$$P_{loss} = E^2 \omega \varepsilon tan\delta \tag{20}$$

Over voltage and temperature are two constraints of designing insulation system which limit enhancement generator power application. To conquest the problem, 3 slot and winding configurations are proposed.

Configuration Improvement

Varying configuration can include winding's geometry, slot depth, slot width, winding layers and material types of insulation. To investigate the effects of each varying on operation conditions some configurations are proposed. In first step, cubic windings in the same cross section are used as Fig.3. The results of simulations show that electric field distribution has changed but the maximum electric field value is constant.

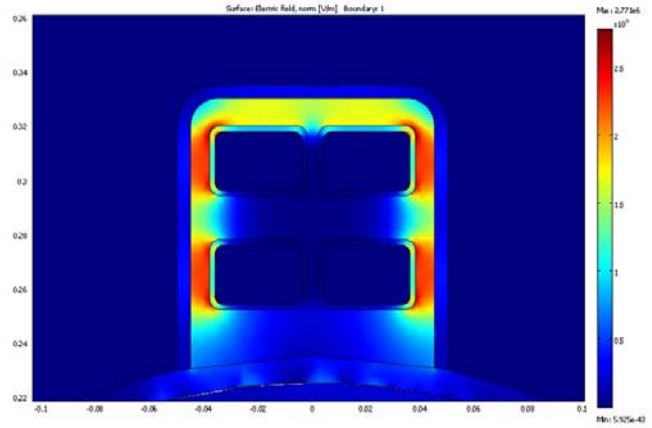


Fig. 3 Electrical field distribution for cubic winding

The electric field distribution between winding layers has reduced intensively which allows adding a more layer (Fig.4). This means that the operation power can be enhanced 50 %.

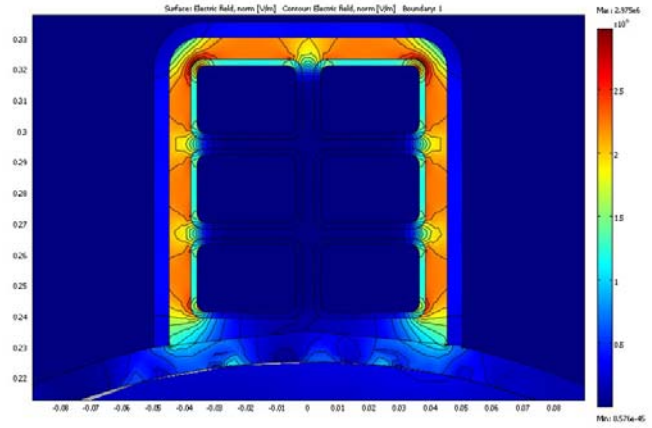


Fig. 4 Electrical field distribution for cubic windings with three layers

In this case the temperature increased to 87^{oC}. To consequent this problem, higher insulation class must be used. However high insulation class implicates more cost, the increasing operation power makes the changes beneficial. The width and depth of slots are two other options which impress design parameters. For this purpose, in the following section the width of slot is increased. This is required the reduction of core volume which causes core saturation (Fig.5).

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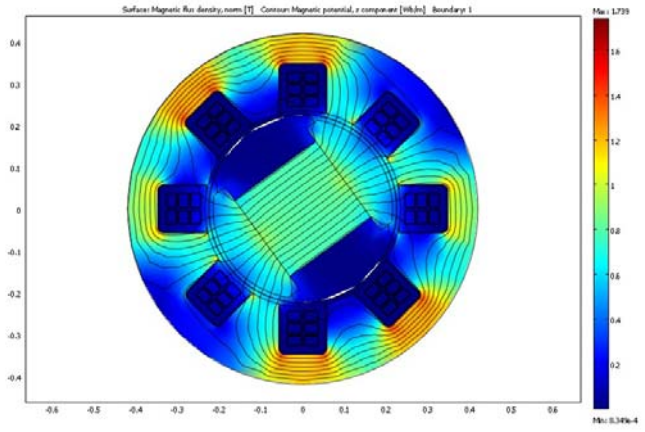


Fig. 5 Flux lines and magnetic distribution in generator with larger slot

Maximum temperature in larger slot configuration arrives to 112^{oC}. Comparing between varied configurations indicates that changing in the shape of winding geometry and insulation class are more effective.

VII. CONCLUSION

The majority of high voltage machine failures result from stator insulation problems. On the other hand electrical and thermal stresses are the important factors of exhaustion in generators. Therefore selection of proper wiring scheme can decrease these stresses. Different schemes with regard to different construction have different characters and specification. The finite element electromagnetic and thermal analyses are useful to improve the configuration of stator which conquests the previous problems in classical design. In this paper, some proposed configurations presented and compared. The main points extract from comparing the results can be categorized as:

- Selecting appropriate material with high permittivity reduces electrical field in critical zones whit respect to thermal limitations.
- Cubic windings makes appropriate using of slot volume, on the other hand, electric field in edges increases, therefore, the material of insulation layer has to have higher permittivity.
- Core saturation occurs in lower power operation due to increasing slot volume.

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