Selection the Optimum Cooling Scheme for Generators based on the Electro-Thermal Analysis

Diako Azizi, Ahmad Gholami and Vahid Abbasi

***Abstract*—**Optimal selection of electrical insulations in electrical machinery insures reliability during operation. From the insulation studies of view for electrical machines, stator is the most important part. This fact reveals the requirement for inspection of the electrical machine insulation along with the electro-thermal stresses. In the first step of the study, a part of the whole structure of machine in which covers the general characteristics of the machine is chosen, then based on the electromagnetic analysis (finite element method), the machine operation is simulated. In the simulation results, the temperature distribution of the total structure is presented simultaneously by using electro-thermal analysis. The results of electro-thermal analysis can be used for designing an optimal cooling system. In order to design, review and comparing the cooling systems, four wiring structures in the slots of Stator are presented. The structures are compared to each other in terms of electrical, thermal distribution and remaining life of insulation by using Finite Element analysis. According to the steps of the study, an optimization algorithm has been presented for selection of appropriate structure.

***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. Since the main part of electrical and thermal stresses imposes to them, i.e. stator coil insulation, so insulation fracture, basically occurs in the stator of the generators [1], [2]. Therefore designers developed many channels for cooling; (Receptacle water and hydrogen) tend to reduce the effects of thermal stresses.

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Wire construction (i.e. circular or rectangular) can cause an increase or decrease in temperature of the generators insulations, because of different electro-magnetic field distributions and different thermal resistance. For finding a proper view point and offer optimized algorithm, four different structures are compared. Note that all analyses were performed with finite element method.

II. CASE STUDY

Because of the importance of generators in power systems, their insulations failure rates have to be reduced. In order to reduction in failure rates, electro-thermal investigations and redesigning insulations are practical. To obtain the point, a generator with different insulation and cooling structures has been chosen as the case study. The selected generator is synchronous, three phase, two poles with 24 slots in stator. Rated frequency, voltage and power are respectively 50Hz, 13.8 KV and 1 MVA. Wiring is form-wound multi-turn type and has many insulation layers with different specifications. The turn insulation and the strand insulation are the same, i.e. nylon type. Ground wall insulation type is PMMA and semi conductive coating is Si(c) with characters identified in table 1. For simplification, only one layer of the slot as a sample has been analyzed. Fig.1 shows the cross section of slots containing form-wound multi-turn coils.

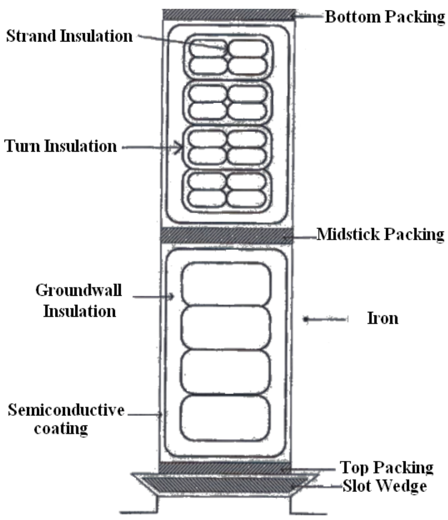

Fig. 1 Cross section of slots containing form-wound multi-turn coils

TABLE I
ELECTRICAL AND THERMAL SPECIFICATIONS OF USED INSULATIONS

Quantities	Symbols & Dimensions	Nylon insulation	PMMA 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	3	11.7
thermal conductivity	*K* *[W/(m*K)]*	0.26	0.19	130
density	*Rho* *[kg/m^3]*	1150	1190	2329

III. ELECTROMAGNETIC MODELS [3]

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

$$\nabla \times H = J + \frac{\partial D}{\partial t} = \sigma E + \sigma v \times B + J^e + \frac{\partial D}{\partial t} \quad (1)$$

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 field effect can be introduced by equations (2) and (3):

$$B = \nabla \times A \quad (2)$$

$$E = -\nabla V - \frac{\partial A}{\partial t} \quad (3)$$

Ampere's law is rewritten by equations (2) and (3) Combining with constitutive relationships $B=\mu_0(H+M)$ and $D=\varepsilon_0 E+P$ **,** as:

$$\left(j\omega\sigma - \omega^2\varepsilon_0\right)A + \nabla \times \left(\mu_0^{-1}\nabla \times A - M\right) - \sigma v \times \left(\nabla \times A\right) + \left(\sigma + j\omega\varepsilon_0\right)\nabla V = J^e + j\omega P \quad (4)$$

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:

$$-\nabla.\left(\mu_0^{-1}\nabla A_z - \begin{bmatrix} -M_y \\ M_x \end{bmatrix}\right) + \sigma v.\nabla A_z + \left(j\omega\sigma - \omega^2\varepsilon_0\right)A_z = \sigma\frac{\Delta V}{L} + J_z^e + j\omega P_z \quad (5)$$

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:

$$-\left(\begin{bmatrix} \partial/\partial r & \partial/\partial z \end{bmatrix}\left(r\mu_0^{-1}\begin{bmatrix} \partial u/\partial r \\ \partial u/\partial z \end{bmatrix} + \mu_0^{-1}\begin{bmatrix} z \\ 0 \end{bmatrix}u - \begin{bmatrix} M_z \\ -M_r \end{bmatrix}\right)\right) + r\sigma\left(v.\begin{bmatrix} \partial u/\partial r \\ \partial u/\partial z \end{bmatrix}\right) + r\left(\sigma j\omega - \omega^2\varepsilon_0\right)u + 2\sigma V_r u = \sigma\frac{V_{loop}}{2\pi r} + J_\varphi^e + j\omega P \quad (6)$$

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

$$u = A_\varphi / r \quad (7)$$

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

IV. 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:

$$\rho C_p\left(\frac{\partial T}{\partial t} + (u.\nabla)T\right) = -(\nabla.q) + \tau{:}S - \frac{T}{\rho}\frac{\partial\rho}{\partial T}\Big|_p\left(\frac{\partial p}{\partial t} + (u.\nabla)_p\right) + Q \quad (8)$$

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):

$$S = \frac{1}{2}\left(\nabla u + (\nabla u)^T\right) \quad (9)$$

- Q contains heat sources (W/m3)

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

V. INSULATION LIFE

Arrhenius model usually has been used for estimating the life time of the insulation parts when thermal stress is applied alone, but with regard to faster deterioration in the sections of the insulation which are under the both electrical and thermal tensions, Arrhenius model must be comprehensive [4], [5]. Therefore, Hatch and Endicott presented the Eyring model for taking to account the thermal and voltage stresses simultaneously. But using special methods for determining the coefficients of the equation to estimate the life of Eyring insulation is actually a challenge [6], [7]. Thus Ramu proposed [8] a model for the estimation of the insulation life time which uses the power law, and its parameters are temperature dependent.

When the insulation is only under thermal stress, the life time is obtained using the following relationship:

$$L = A\exp\left[\frac{E}{kT}\right] \tag{10}$$

Where E is the activation energy and k is the Boltzmann's constant.

A detailed analysis of the data has been performed which is obtained in the presence of thermal stress alone or when both electric and heat are applied. The results show that activation energy applying both tensions simultaneously is less than the case in which one stress is applied. Taking to account this point, the model for Arrhenius can be corrected by decreasing the activation energy using the $exp\left[-\frac{\sigma\xi}{KT}\right]$ factor. New model is expressed as follows:

$$L = A\exp\left[\frac{E-\sigma\xi}{kT}\right] \tag{11}$$

The ξ is electrically field (stress) applied.

VI. ELECTRO THERMAL ANALYSIS

In this section one layer of slot wiring which is already selected has been analyzed; in which water channels are positioned alternating between copper Strings (i.e. wiring is cooled directly). Fig.2 shows the field distribution and Fig.3 shows the temperature distribution in the Samples.

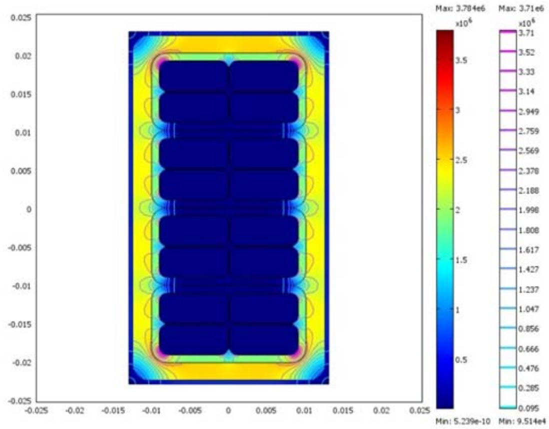

Fig. 2.a Electrical field distribution of rectangular winding- natural cooling (V/m)

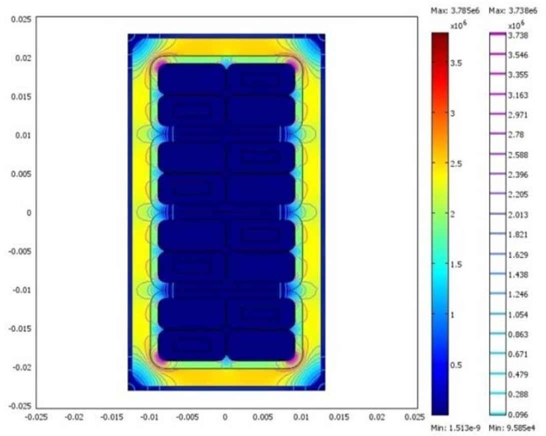

Fig. 2.b Electrical field distribution of rectangular winding (V/m) - direct cooling with water

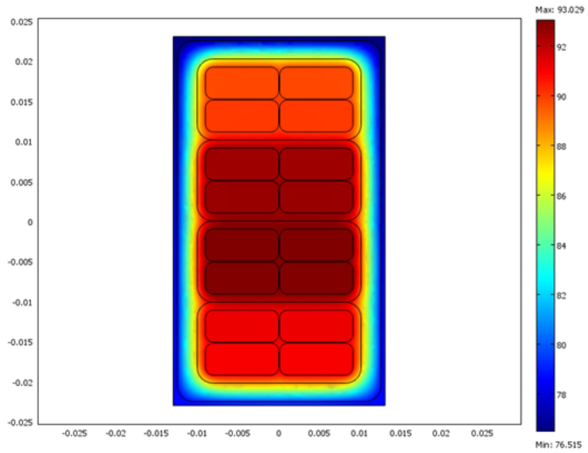

Fig. 3.a Thermal distribution of rectangular winding (ºC) -natural cooling (structure 1)

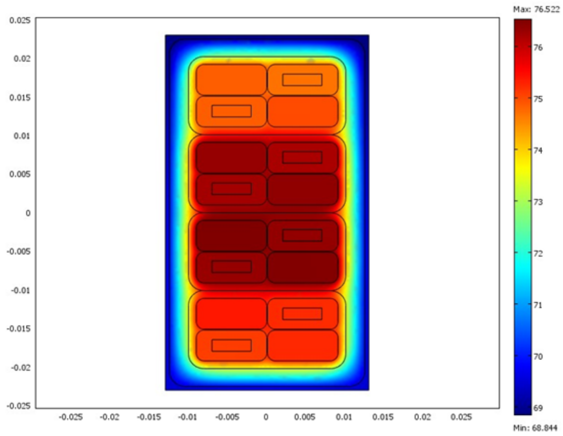

Fig. 3.b Thermal distribution of rectangular winding (ºC) -direct cooling with water (structure 2)

As it is shown in figures 2 and 3, there is no difference between field distributions in structures 1 & 2. But, in thermal distribution the difference is quite obvious due to different cooling systems. In the next step, it is assumed that the string is circular i.e. Instead of any 2 rectangular copper strings; one circular copper string has been used (structure 3). In refined structure, the water cooling channels are used alternately between circular copper strings (structure 4). Fig.4 and 5 show the field and the thermal distribution for both structures 3 and 4.

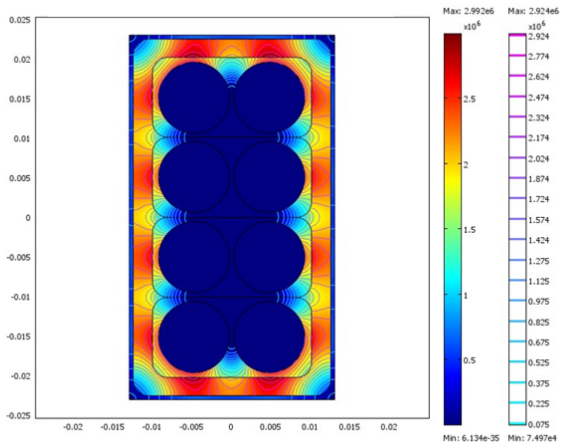

Fig. 4 Electrical field distribution of circular winding (V/m)

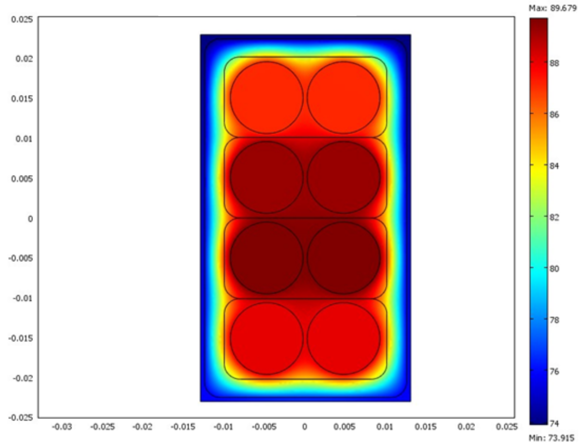

Fig. 5.a Thermal distribution of circular wiring (ºC)-natural cooling (structure 3)

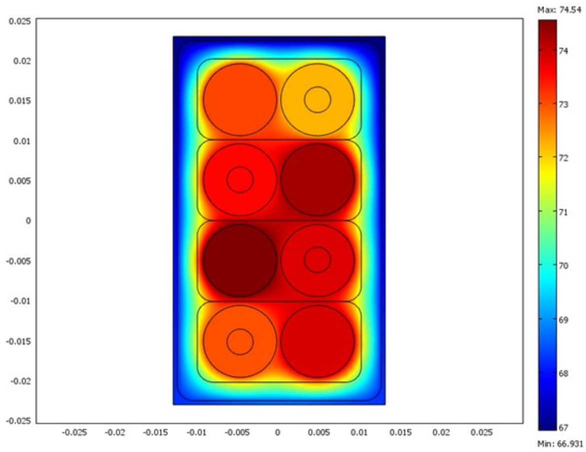

Fig. 5.b Thermal distribution of circular wiring (ºC) - direct cooling with water (structure 4)

VII. Comparing Structures and Selection of Optimum Structure

It is obvious from the results in structures 3 and 4, only form of strings was changed and the other characteristics were constant. Reduction in electrical field surrounding of string causes reduction in effective value of electrical field in insulation (layers seen) and so on, insulation losses decrease. The reason of field reduction in circular wiring is the absence of pick point which is fully evaluated in [4]. By the way, circular form of strings in the model causes better heat exchange in strings with surrounding insulation layers. Thermal distribution comparison performed along the slot for all 4 structures in Fig 6.

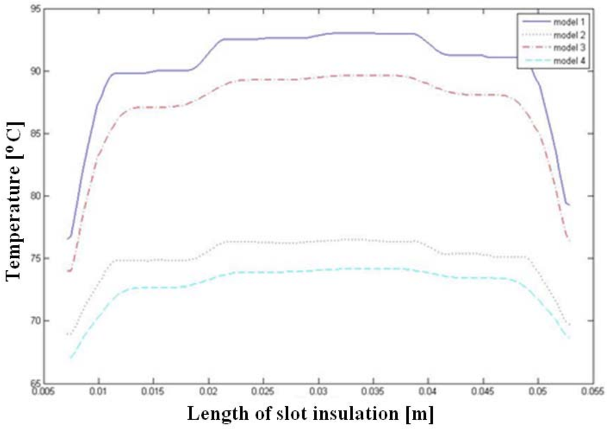

Fig. 6 Thermal distribution comparison in 4 structures studied

Therefore, in the performed comparison, structure 4 has the best thermal distribution and structure 1 has the worst, since in structure 4, electrical field intensity is less and has a direct water cooling system.

Because of reduction in both electrical field and temperature for circular form in comparison to rectangular form of string, the insulation age in string form is longer while they have no difference in cost. So, it can be concluded that circular construction is better than rectangular construction. The circular structure is divided to two structures which are simple structure (structure 3) and cooling with water (structure 4). In these two structures, as it is shown in the results, there is no difference between field distributions, but maximum temperature in water cooling structure decrease at rate of 15 ºC. This point increases loss of life in structure 3 comparing to structure 4 (Fig.7).

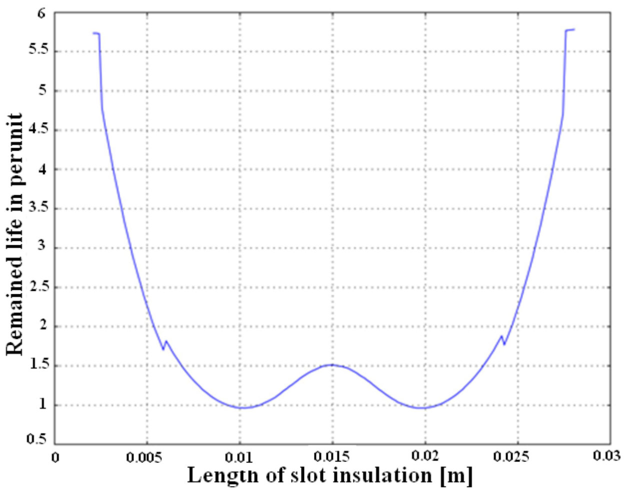

Fig. 7.a Remained life of insulation part of circular wiring- without cooler

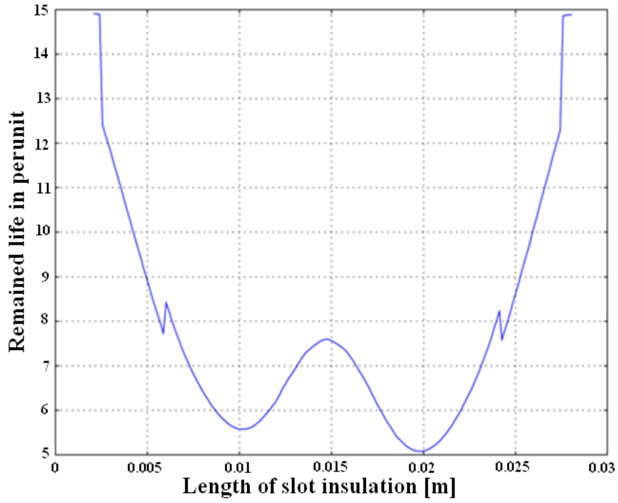

Fig. 7.b Remained life of insulation part of circular wiring - with cooler

Cost is an important criterion for practical applications that is considered for different models of the case study in this section. . In direct cooling, alternatively 25% of string area is used as water channels. So, the area of copper (which is used for current pass) is decreased 1/8. Noting that current density is constant, and the value of current passes decreases 1/8, and therefore generator nominal power decreases 1/8 as well.

Thus, in structure 4 comparing to structure 3, there is a 12.5% increase in cost. Therefore, the selection between structures 3 or 4 depends on economic studies, i.e. Constant cost and utilization cost. It is because in structure 3 constant costs are less and utilization costs are more while it is diverse in structure 4. For dealing with these two problems designers should know about economical optimization and it is not mentioned as a problem in this paper. Table 2 compares the results.

TABLE II
EFFECTS OF THE COOLING ON THE DISTRIBUTION OF ELECTRIC AND THERMAL FIELD, AND THE REMAINED LIFE OF INSULATION

Winding type	Electrical field	Thermal field	Remaining life of insulation [pu]	Cost [pu]
rectangular without cooling	Normal	Normal	1	1
Rectangular with cooling	Normal	18% decreasing	5	1.25
Circular without cooling	20% decreasing	3.6% decreasing	1.25	1
Circular with cooling	20% decreasing	20% decreasing	6	1.25

VIII. Conclusion

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. Changing wiring construction, for decreasing stress and increasing insulation age increases the cost. For optimum scheme selection, we need to balance between constant costs (i.e. institution) and operating cost, (utilization costs). In the paper, different structures are proposed and electro-thermal analysis as an important criterion for loss of life in any of them is simulated. Reduction of thermal stress is the consequence of optimal selection. To achieve an optimal structure various kinds of structures can be analyzed by designers based on the paper method and adding the other criteria. However, the proposed method takes time; the importance of generators applications in power systems makes it valuable.

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