Thermal network model of electrical motor by lumped heat method

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***Abstract* - Electrical machines is widely used in industry for manufacturing the components or running the plant utilities. Electrical machines has to be work continuously throughout the operation or production. It is required to maintain the temperature generated in the electrical machines. For maintaining the temperatures in electrical machines, It has to be measured correctly. There is no any direct methods to measure temperatures of electrical machine components. It can be possible by a lumped heat method. A lumped parameter thermal network model can be described by steady state and transient solutions for temperature measurement of the electrical machines. This paper describe the both methods of getting temperatures in TEFC machine. With this method, online measurement of temperature is possible in the case of transient conditions. It is sufficient to measure temperatures of machines, including rotor temperatures. This method can be applied to any electrical machines.**

***Index Terms* - Thermal network model, Lumped heat method, Thermal model.**

I. INTRODUCTION

Totally Enclosed Fan Cooled (TEFC) induction motors are the simplest category of squirrel cage induction motors (SCIM). Components of motor may be treated as lumped, if there is no significant temperature variation in its volume.

This component may be represented as a single node in the thermal network model (TNM). Nodes get separated by therm Totally Enclosed Fan Cooled (TEFC) induction motors are the simplest category of squirrel cage induction motors (SCIM). Components of motor may be treated as lumped, if there is no significant temperature variation in its volume.

This component may be represented as a single node in the thermal network model (TNM). Nodes get separated by thermal resistances. Heat transfer takes place between components (nodes). Inside the machine, a set of conduction thermal resistances represent the main heat transfer paths, such as from copper winding to the stator tooth and back iron (in this case, the heat transfer is through the winding insulation consisting of a combination of enamel, impregnation, and slot liner materials), from the tooth and stator back iron nodes to the stator bore and housing interface, etc.

Knowing thermal properties and geometries of components of motor, thermal impedances, thermal resistances and thermal capacitances of all components can be calculated. These thermal properties and heat losses are applied into the thermal network, to calculate temperature rises of the motor components for all the operating conditions of motor.

The thermal network can be easily adapted to a range of machine sizes, boundary conditions and configurations. But the temperature corresponding to a component from TNM is only average temperature. FEA is employed for evaluation of distribution of temperatures at regions of interest to confirm safety margins of temperatures. For those regions of motor where standard convection correlations are not available, computational fluid dynamics models (CFD) will be built and convective heat transfer correlations will be evaluated.

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II. LITERATURE SURVEY

Published technical papers of electrical motors highlight difficulties in analyzing the thermal design of motors. Some of them discuss the analysis of TEFC and Totally Enclosed Water cooled (TEWC) for which the rotor construction is of squirrel cage type.

Most of the literature dealing with thermal design of motors uses thermal networks. The TNM or flow networks are analogous to electrical networks. The most famous research paper of P.H. Mellor, D Roberts and D.R. Turner **[1]** described in detail lumped method**.** In that paper, TNM is represented with consideration of assumption.

III. LUMPED HEAT PARAMETER

The lumped-parameter thermal model is sufficiently detailed to include all the major components and heat transfer mechanisms within the machine without being over complex. Previous work on these models by many authors has demonstrated how heat transfer between bulk components can be successfully determined in the steady state. In particular Perez and Kassakian **[2]** modelled each component in terms of a thermal node which approximated to the mean temperature within the component. Any heat generation due to the losses in the component was introduced as a point source at the node. The work can be the full transient case by including thermal storage as an additional heat transfer at the node, related to the mean temperature and the components total thermal capacity.

The general layout of motor is given in the Fig.1

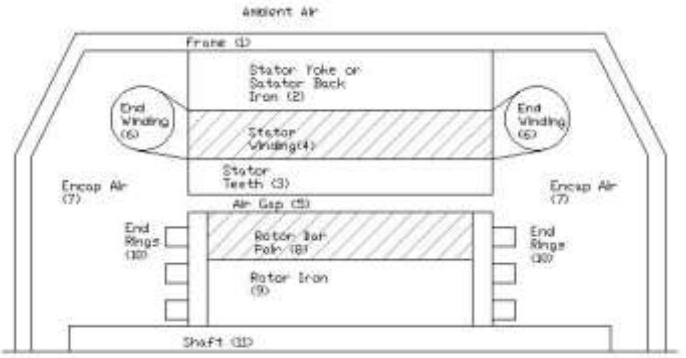

Fig. 1 - Construction of Thermal Network Model of SCIM motor

There is radial symmetry is considered. Any heat generated from the radiation is neglected. There is heat transfer between node 1 & node 2 is due to convection. Node 2 & Node 3 is having heat transfer medium of conduction. The external fan is not considered in the analysis.

IV. CYLINDRICAL COMPONENT UNDERSTANDING

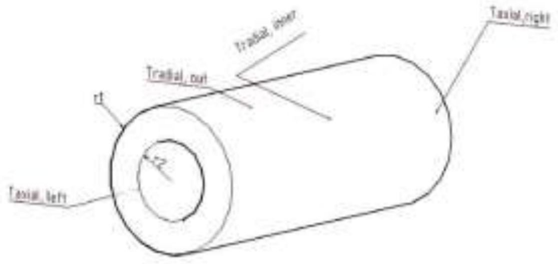

Fig. 2 - General cylindrical components with four unknown temperatures: two at the axial edges and two on the outer and inner surfaces

In Fig. 2, a simple solid cylinder is given for understanding of axial and radial resistances. The solid components of the induction motor are based on the general cylindrical component shown in Fig. **3.** To obtain simple, but physically significant, expressions for the network of thermal resistances that describe the heat conduction across the general component, the following assumptions are made (i) the heat flow in the radial and axial directions are independent. (ii) A single mean temperature defines the heat flow both in the radial and axial directions. (iii) There is no circumferential heat flow. (iv) The thermal capacity and heat generation are uniformly distributed.

This node configuration is suitable also when heat is uniformly added or subtracted along the element, e.g. due to convection. In each network, two of the terminals represent the appropriate surface temperatures of the component, and the third represents the mean temperature Tm of the component. The internal heat generation is introduced in the mean temperature node. The central node of each network gives the mean temperature of the component if there is no internal heat generation. If there is heat generation the mean temperature will be obtained as a result of superposition of internal heat generation.

The equations for the each thermal resistance are given below:

$$R_{1r} = \frac{1}{4*\pi*kr*l}\left[1-\frac{2r_2^{\,2}\ln\left(\frac{r_1}{r_2}\right)}{\left(r_1^{\,2}-r_2^{\,2}\right)}\right] \qquad (1)$$

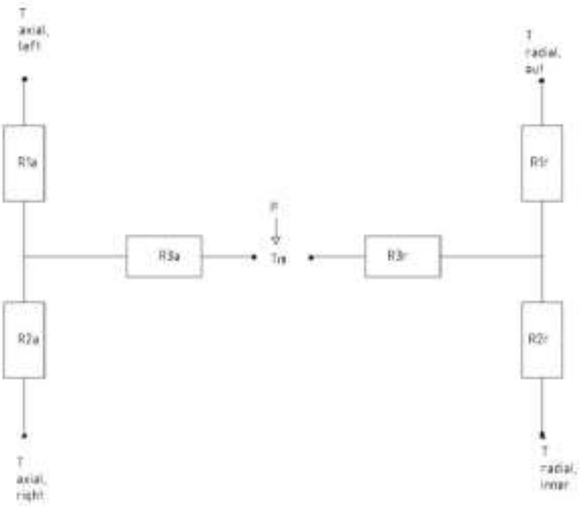

Fig. 3 - Independent axial and radial thermal networks, Tm is the average temperature, and the losses are denoted by P the dimensions of the cylinder and the radial and axial conductivities kr, ka are required for the calculation of thermal resistances.

$$R_{2r} = \frac{1}{4*\pi*kr*l}\left[\frac{2r_1^2\ln\left(\frac{r_1}{r_2}\right)}{\left(r_1^2 - r_2^2\right)} - 1\right] \tag{2}$$

$$R_{3r} = \frac{-1}{8*\pi*\left(r_1^2 - r_2^2\right)*kr*l}\left[\left(r_1^2 + r_2^2\right) - \frac{4r_1^2r_2^2\ln\left(\frac{r_1}{r_2}\right)}{\left(r_1^2 - r_2^2\right)}\right] \tag{3}$$

$$R_{1a} = \frac{l}{2*\pi*ka*\left(r_1^2 - r_2^2\right)} \tag{4}$$

$$R_{2a} = \frac{l}{2*\pi*ka*\left(r_1^2 - r_2^2\right)} \tag{5}$$

$$R_{3a} = \frac{-l}{6*\pi*ka*\left(r_1^2 - r_2^2\right)} \tag{6}$$

If it is assumed that the face temperatures $T_{axial,right}$ and $T_{axial,left}$ are equal, since the temperatures in the cylinder are symmetrical about a central radial plane. Reduced thermal network is presented in Fig. 4, where the half of the cylinder is modelled with only a half of heat generation.

This network consists of two internal nodes and four thermal resistances R_a, R_b, R_c and R_m.

$$R_a = R_{1a} + R_{3a} = \frac{l}{6*\pi*ka*\left(r_1^2 - r_2^2\right)} \tag{7}$$

$$R_b = 2R_{1r} = \frac{1}{2*\pi*kr*l}\left[1 - \frac{2r_2^2\ln\left(\frac{r_1}{r_2}\right)}{\left(r_1^2 - r_2^2\right)}\right] \tag{8}$$

$$R_c = 2R_{2r} = \frac{1}{2*\pi*kr*l}\left[\frac{2r_1^{\,2}\ln\left(\frac{r_1}{r_2}\right)}{\left(r_1^{\,2}-r_2^{\,2}\right)}-1\right] \tag{9}$$

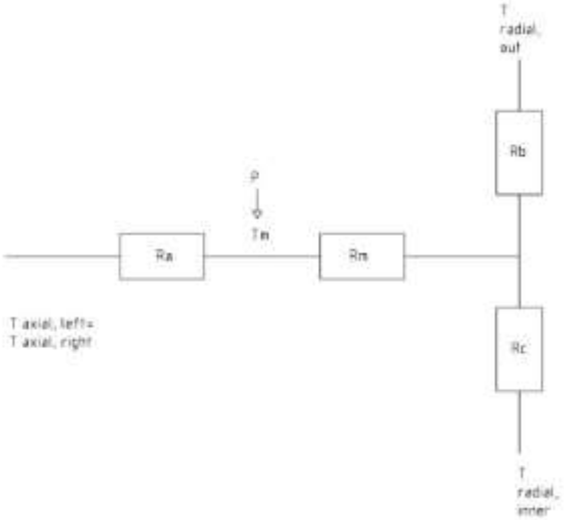

Fig. 4- Combined thermal network for symmetric component

$$R_m = 2R_{3r} = \frac{-1}{4*\pi*\left(r_1^{\,2}-r_2^{\,2}\right)*kr*l}\left[\left(r_1^{\,2}+r_2^{\,2}\right)-\frac{4r_1^{\,2}r_2^{\,2}\ln\left(\frac{r_1}{r_2}\right)}{\left(r_1^{\,2}-r_2^{\,2}\right)}\right] \tag{10}$$

This combined network allows different thermal conductivities in the radial and axial directions. Thus, the thermal effect of the stator and rotor laminations can be considered. For more detailed description of the different machine parts the axial and radial thermal resistance networks are obtained by applying instead of T-equivalent blocks. This approach is used for modeling complex structural shapes. It allows getting desired accuracy.

V. THERMAL NETWORK MODEL

The thermal behavior of SCIM motor for transient and steady-state conditions can be studied by using equivalent thermal circuit. Several elements: heat sources representing the losses in different parts of motor and thermal conductivities. These elements of motor are interconnected and connected to the environment by means of thermal conductivities.

In developing the thermal network model, the machine geometry is divided in to basic elements and each element being identified by a node in the thermal network with its corresponding thermal capacitance and heat source. The choice of subdividing a machine in to elementary components remains a compromise between the simplicity of the model and the accuracy required of the results.

The common equivalent thermal circuit of motor by transient behavior may be represented by a system of equations (which are like the nodal equations of electrical circuits)

$$P_n = C_n\frac{dT_n}{dt}+\frac{1}{R_{1n}}\left(T_1-T_n\right)+\frac{1}{R_{(n-1),n}}\left(T_{n-1}-T_n\right) \tag{11}$$

Where, P_n= The losses in the i-th element, T = Temperature rise in the i-th node, R_{ij}= Thermal resistance between nodes i and j, C_i = Thermal capacitance of ith node

For the steady state regime, all derivatives should be zero: $\frac{dT}{dt}$ =0.

Therefore, for the steady state regime equation is simplified to a system of equations with left side being zero. Its solution will be

$$P_n = \frac{1}{R_{1n}}\left(T_1-T_n\right)+\frac{1}{R_{(n-1),n}}\left(T_{n-1}-T_n\right) \tag{12}$$

VI. CALCULATION FOR STEADY STATE REGIME

For steady state temperature difference calculation of the nodes, inverse metrices of conductivity (g) and losses are multiplied. The equation is given below **[3].**

$$\Delta T= [g]-1*P \tag{13}$$

Metrices of conduction and losses are given for the calculation.

$$g = \begin{bmatrix} g_{11} & -g_{12} & 0 & 0 & 0 & 0 & -g_{17} & 0 & 0 & 0 & -g_{111} \\ -g_{12} & g_{22} & -g_{23} & -g_{24} & 0 & 0 & -g_{27} & 0 & 0 & 0 & 0 \\ 0 & -g_{23} & g_{33} & -g_{34} & -g_{35} & 0 & -g_{37} & 0 & 0 & 0 & 0 \\ 0 & -g_{24} & -g_{34} & g_{44} & -g_{45} & -g_{46} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -g_{35} & -g_{45} & g_{55} & 0 & 0 & -g_{58} & 0 & -g_{510} & 0 \\ 0 & 0 & 0 & -g_{46} & 0 & g_{66} & -g_{67} & 0 & 0 & 0 & 0 \\ -g_{17} & -g_{27} & -g_{37} & 0 & 0 & -g_{67} & g_{77} & -g_{78} & -g_{79} & -g_{710} & 0 \\ 0 & 0 & 0 & 0 & -g_{58} & 0 & -g_{78} & g_{88} & -g_{89} & -g_{810} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -g_{79} & -g_{89} & g_{99} & -g_{910} & -g_{911} \\ 0 & 0 & 0 & 0 & -g_{510} & 0 & -g_{710} & -g_{810} & -g_{910} & g_{1010} & 0 \\ -g_{111} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -g_{911} & 0 & g_{1111} \end{bmatrix} \tag{14}$$

$$P = \begin{bmatrix} 0 \\ \dfrac{p_{fer}}{2} \\ \dfrac{(p_{fes}+0.3*p_{ad})}{2} \\ \dfrac{(p_{cus}*0.48+0.4*p_{ad})}{2} \\ 0 \\ \dfrac{p_{cus}*0.52}{2} \\ 0 \\ \dfrac{0.9*p_{cur}}{2} \\ \dfrac{0.3*p_{ad}}{2} \\ \dfrac{p_{cur}*0.1}{2} \\ 0 \end{bmatrix} \tag{15}$$

The calculation is done using Matlab® software **[4]**. Atmosphere temperature is assumed 40^0 C.

Therefore, Actual temperature of component is given by equation given below:

Component Temperature = Difference of temperature for component (ΔT) + 40

This obtained temperature calculations can be verified by the ANSYS® analysis by applying boundary conditions.

VII. CONCLUSION

A thermal network model using lumped method is developed for the thermal analysis of TEFC motors. This model is known to be an effective analytical method of estimating both steady-state and transient temperatures in the motor.

The thermal resistances are derived entirely from the information and thermal properties of materials and standard convective heat transfer coefficients available in literature.

The benefit of an analytical model when compared to numerical methods is the lesser computation time. The model can be easily applied for most TEFC motors. But the accuracy of the analytical model is limited due to several simplifications. There may be variation in the comparison of results. Efforts are being to improve this handicap.

VIII. FUTURE SCOPE

There are a few issues for future development.

More number of nodes to be considered in the model namely

1. At bearings
2. Nodes corresponding to all the parallel resistances corresponding to rotor and stator slots.

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