ABSTRACT

This paper presents a thermal circuit model to predict the behaviour of a three phase cage rotor induction motor during steady state operation under rated load. The proposed model GroCE (Gross Climatic Effect) allows the calculation of temperature distribution and thermal heat source parameters of motor including temperature variations due to different climatic conditions. A twelve months experimental study was conducted in variable climates of Indore City (India), on a 1.1 kW three phase Totally Enclosed Fan Cooled (TEFC) Induction motor. On the basis of study GroCE thermal model is developed which is helpful to design more efficient electric motorized system.


I. INTRODUCTION

Three phase induction motors consume approximately 60% of industrial electricity. Just 1% increase in efficiency of all the motors in India will save approximately 500MW power [1]. Three phase induction motors are widely used in heavy and medium industrial load application and agriculture purposes supplied to the industrial load is consumed by induction motorized system. It is therefore important to improve the efficiency of this type of electric motorized system [2]. The efficiency of induction motor is mainly depends on the properties of enamel used for coating of the windings of motor and the thermal withstanding capacity of the insulation used in motors. Thus the efficiency and performance of motor has very strong relationship with its operating and surrounding temperature [3]. For the purpose of rise in sufficiency and improving thermal withstanding capacity, an effective thermal model is required to predict the overall temperature rise in Totally Enclosed Fan Cooled (TEFC) motors.

The prediction of temperature distribution inside and operating electric motor is one of the most important issues during its design. This prediction is the key factor for the machine designer to evaluate the thermal class of motor, establishing the bearing lubrication intervals as well as maintaining the supplied air flow of the cooling system for ensuring the sufficient normal motor operation at rated conditions. Recognising the importance of the thermal factor in the overall effectiveness of motor design, different techniques have been proposed for thermal monitoring in practical those related to rotor and stator temperature [4].

Several works have been done for the induction motor based on thermal circuit modelling as in [5], [6] and [7]. These works allow predicting the motor’s temperature variation and distribution can be used for determining the effect of different designs, duties and cooling mechanisms during its operation but still there is no model which describes overall effect of temperature variations due to climatic changes, weather impact of different location on the performance of induction motor. In this paper, a mathematical Gross Climatic Effect (GroCE) model is developed which is based on the overall effect of temperature variation on motor due to climatic and seasonal changes. $T_{gce}$ (Gross Climatic Effect Temperature) is formulated on the basis of the study conducted during the period of 12 months (1 January 2014 to 31 December 2014) at the location of Indore city (India).

GroCE model allowing one calculate the distribution of motor temperature accurately with the specific ambient temperature as a function of input parameters determined by the operating conditions. This paper is divided in two sections, in section II formulation of Gross Climatic Effect Temperature $T_{gce}$ is derived which is an important parameter to develop GroCE thermal model and in section III thermal analysis of three phase induction motor using GroCE model is shown.
II. FORMULATION OF GROSS CLIMATIC EFFECT TEMPERATURE T\textsubscript{gce} FOR INDUCTION MOTOR.

An electric machine is a complex engineering system that consists of different materials with different thermal properties and distributed heat sources. A good knowledge of internal thermal condition of motor is very important for proper utilization of the motor, for optimum de-rating of the motor and to save the motor from burn out [8][9]. The performance of induction motor mainly effected due to the inside and outside temperature. Various thermal modelling have been done on the inside temperature behaviour of motor [10] but still no model is developed which shows a strong relationship between variation in temperature of surroundings due to climatic change (seasonal effect) and motor’s thermal performances.

In earlier thermal model calculations surrounding temperature is taken by default as ambient temperature and after this there is no significance of the climatic condition of that particular location and its temperature effect on motor is taken into calculation. In this paper a study was conducted on a 1.1kW three phase industrial induction motor, which is operated approximately 8 hour in day. Study was done at Indore, India from the period 1 Jan 2014 to 31 Dec 2014 (1 year period) and motors surrounding temperature was noted which is shown in table 1. On the basis of study a simple relation is developed as

\[ T_{gce} = T_{amb} \pm T_{variable} \]

T\textsubscript{gce} is the gross climatic effect temperature which is the combined effect of the previously adopted ambient temperature T\textsubscript{amb} and variable temperature T\textsubscript{variable} due to climatic changes.

Table 1 Temperature variation of motor surrounding (2014).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>26.5</td>
<td>18.2</td>
<td>9.8</td>
</tr>
<tr>
<td>Feb</td>
<td>28.8</td>
<td>20.2</td>
<td>11.4</td>
</tr>
<tr>
<td>Mar</td>
<td>34.3</td>
<td>25.3</td>
<td>16.2</td>
</tr>
<tr>
<td>Apr</td>
<td>38.7</td>
<td>30</td>
<td>21.1</td>
</tr>
<tr>
<td>May</td>
<td>40.4</td>
<td>32.4</td>
<td>24.4</td>
</tr>
<tr>
<td>Jun</td>
<td>36.2</td>
<td>30.1</td>
<td>24.1</td>
</tr>
<tr>
<td>Jul</td>
<td>30.3</td>
<td>26.5</td>
<td>22.6</td>
</tr>
<tr>
<td>Aug</td>
<td>28.2</td>
<td>25.1</td>
<td>21.9</td>
</tr>
<tr>
<td>Sep</td>
<td>30.9</td>
<td>26</td>
<td>21.1</td>
</tr>
<tr>
<td>Oct</td>
<td>32.4</td>
<td>25.3</td>
<td>18.1</td>
</tr>
<tr>
<td>Nov</td>
<td>29.7</td>
<td>21.8</td>
<td>13.9</td>
</tr>
<tr>
<td>Dec</td>
<td>26.9</td>
<td>18.8</td>
<td>10.6</td>
</tr>
</tbody>
</table>

III. GROCE MODEL FOR THERMAL ANALYSIS OF THREE PHASE INDUCTION MOTOR

GroCE model is based on following energy balance equation:

\[ \rho \left( \frac{d\rho}{dt} + \rho \nabla \text{v} \right) = \sigma - \nabla q + eQ \]  

\[ \rho \frac{de}{dt} + \nabla q = \tilde{Q} \]

Where \( \tilde{Q} = \rho Q + \sigma T \) accounts for the energy supply and change in different types of losses. Example: friction and cooling losses, electromagnetic losses. Assuming that the internal energy can be expressed as \( e = e(v) \) then

\[ \frac{de}{dv} = C_v \frac{dv}{dt} \]

Where

\[ C_v = \frac{de}{dv} \]

is the specific heat at constant volume. Equation (1)-(3) is based on boundary and initial conditions depending on the part of the motor under consideration.

Dirichlet-Neumann’s specific flux or radiation boundary condition will be used as Fourier’s law \( q = -k \nabla T \) then the whole model is convenient to introduce a scalar quantity \( W_{out} \) representing heat losses at the surface.

Then the energy balance at the surface is defined by the equation:

\[ W_{out} = K \nabla T - h(T_{gce} - T) - C_{cons}(T_{gce}^4 - T^4) \]

(4)

Equation 4 includes coefficients \( k, h, C_{cons} \) depending on which specific type of heat transfer (conductive, radiative or convective) should be accounted for a particular part of induction motor. \( W_{in} \) denotes the heat generated within the system [13] then the whole model can be schematically reformulated as a basic conservation law in the form

\[ W_{out} = W_{in} - W_{change} \]

(5)
Where \( W_{\text{change}} = \rho C_v \frac{\partial T}{\partial t} \) would represent the change in energy stored within the system. In order to complete the GroCE model formulation we need to specify functions and coefficients entering the equation (1)-(5), because they depend on the geometry and mature of the region of motor and boundary segment under consideration.

1. Power losses in induction motors: heat sources modelling

Fundamentals of induction motor are described before the modelling of heat sources. In this paper, a basic structure of a three phase, 1.1kW, TEFC (Totally Enclosed Fan Cooled) induction motor is analyzed. AC voltages are induced in the rotor circuit by the rotating magnetic field of the stator. When three phase balanced and symmetric currents are applied to the stator windings a rotating magnetic flux is produced in the sìr gap. If the frequency of applied currents is f(50 Hz) then the speed of the rotating magnetic flux \( n \) can be calculated in rpm as [14]

\[
ns = \frac{120f}{p}
\]

where \( p \) is the number of poles per phase. The rotating flux in the air gap will induce a voltage in the rotor winding and a current flow in it since the rotor winding circuits are closed.

The current in the rotor winding will interact with the rotating magnetic field in the air gap and a Lorentz force will be produced and act on rotor conductors as \( F = qv \times B \), where \( q \) is a charge moving through an external magnetic field \( B \) with velocity \( v \). As a result of this force, a torque is produced and the rotor assembly starts rotating. It is well known that the speed of rotor should be less than the speed of the rotating magnetic flux produced by the stator. The difference in rotating speeds between the stator produced magnetic flux and the rotor is measured by the slip [15]

\[
s = \frac{n_s-n}{n_s}
\]

Where \( n \) is the rotor speed in rpm. When a motor is used to drive the load connected on its shaft it inevitably encounters losses which serve as heat sources distributed throughout the whole motor and changes with various operating conditions. Induction motor power losses are divided into five major categorized [16]

I. Stator core losses (iron losses \( P_I \))
II. Stator coil losses (copper losses \( P_{cu1} \))
III. Rotor coil losses (copper losses \( P_{cu2} \))
IV. Friction and winding losses (mechanical losses \( P_m \))
V. Stray load losses

At the supply frequency \( w \) (angular form \( w = 2\pi f \)), it is possible to approximate the power losses by experimentally fitted dependency.

\[
P_{\text{losses}} = F(w)
\]

Or

\[
P_{\text{losses}} = a_0 + a_1w + a_2w^2 + a_3w^3
\]

Equation 9 shows the approximation of power losses by a cubic polynomial. The estimates of friction losses usually account for a small part of the total losses but when the speed increases their contribution should be included in particular in the air gap, end rings, rotor shafts, and bearings. Most of the losses are electromagnetic losses (75%-90%) of the overall losses [17]. Therefore, to develop a thermal model, evolution of electromagnetic losses is necessary which contributes substantially to the temperature distribution in the motor.

Fig. 1 shows the induction motor equivalent circuit model constructed by using the following set of parameters: \((R_1, X_{1\sigma}), (R_m, X_m)\) and \((R_2, X_{2\sigma})\). Each pair represents resistance and leakage reactance respectively. The first pair deals with the stator parameters, second pair of parameters gives magnetising effects and air gap flux within the induction motor, while the third one with the rotor parameters.

\[
R_1 = R_2
\]

\[
P_{cu1} = M R_1 I_1^2 \quad \text{(Stator copper losses)}
\]

\[
P_m = M R_m I_m^2 \quad \text{(Stator core losses)}
\]

\[
P_{cu2} = M R_2 I_2^2 \quad \text{(Rotor copper losses)}
\]

Where \( M \) is the phase number of motor (in this case \( M=3 \)), equations (10)-(12) are used with the values for the phase currents by:

\[
I_1 = \frac{U_1 (Z_m + Z_2)}{Z_{1\sigma} Z_m + Z_{1\sigma} Z_2 + Z_{2\sigma} Z_2}
\]

\[
I_2 = \frac{U_1 Z_m}{Z_{1\sigma} Z_m + Z_{1\sigma} Z_2 + Z_{2\sigma} Z_2}
\]

\[
I_m = \frac{U_1 Z_2}{Z_{1\sigma} Z_m + Z_{1\sigma} Z_2 + Z_{2\sigma} Z_2}
\]

Where \( Z_{1\sigma}, Z_m \) and \( Z_2 \) are the phase independence of stator, magnetising and rotor circuit, respectively.

\[
Z_{1\sigma} = R_1 + jX_{1\sigma}, Z_2 = \frac{R_2}{s} + jX_{2\sigma}
\]

\[
Z_m = R_m + jX_m
\]

Where \( X_{1\sigma}, X_{2\sigma} \) and \( X_m \) are the leakage reactance. Next part of the modelling is to evaluate heat transfer
mechanism parameters. All three main heat transfer mechanisms, conduction, radiation and convection are involved in the heat exchange in TEFC type motors [18].

2. Heat transfer in induction motors via conduction and radiation

In the solid parts of motors, such as the rotor and stator, heat is typically transferred by conduction. Hence, for these parts we use the standard Fourier’s law to connect the heat flux and the temperature gradient:

\[ q = -k \nabla T \]  \hspace{1cm} (17)

Temperature gradient \( \nabla T \) is the function of GroCE temperature \( T_{gce} \) which is in logarithmic relationship with stator temperature of motor.

A part of heat in induction motors is transferred by radiation. The actual amount of energy transferred in the form of electromagnetic waves depends not only on the emissivity properties of the part of the motor under consideration but also on the temperature itself in a strongly non-linear way [19]. Due to a temperature difference between the motor surface and the surrounding temperature which is modelled as GroCE, the heat will be radiated out from the whole of the motor surface and the energy radiated can be evaluated according to Stefan-Boltzmann law of radiation:

\[ Q = \varepsilon \sigma A (T_s^4 - T_{gce}^4) \]  \hspace{1cm} (18)

Where \( A \) is the surface area of the motor under consideration, \( \varepsilon \) is the emissivity coefficient and \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \) is the Stefan–Boltzmann constant.

3. Heat transfer in induction motor via conduction

The motor analysed in this paper as a case study on TEFC with an external fan. This will cause force convection on the frame of motor which is shown in fig. 2.

In evaluating the convection coefficient \( h \) for the heat transfer from frame to the external environment, heat dissipated from the fins of frame (denoted by \( h_a \)) and heat dissipated from the surface between the fins (denoted by \( h_l \)) are also taken into account[20]. A method for calculating the forced convection coefficient depending on the Reynolds number:

\[ R_e = \frac{V_a F_l}{\kappa} \]  \hspace{1cm} (20)

Where, \( V_a \) is the air flow velocity at beginning of the fins, \( F_l \) is the axial length of the fins and \( \kappa \) is the kinematic viscosity of the air.

General procedure for the evaluation of \( h_a \) and \( h_l \), on the basis of Reynolds number procedure follows one of the following two directions.

a. Laminar airflow case

In this case overall heat transfer \( H' \) can be defined as,

\[ H' = \frac{0.7 (Re)^{0.5} \left[ 1 - 0.12 \left( \frac{F_h}{F_w} \right)^{1/3} \right]}{F_l} \kappa \]  \hspace{1cm} (21)

Where \( F_w \) is the distance between two fins and \( F_h \) is the height of the fins and \( K \) is the thermal conductivity of air.

And the value of connection coefficient related to the dissipation from the surface between the fins as,

\[ h_a = H' \left[ 1 - 0.02 \left( \frac{F_h}{F_w} \right) \right] \]  \hspace{1cm} (22)

b. Turbulent airflow case

In this case \( H' \) is calculated as,

\[ H' = \frac{0.035 \left( \frac{F_h}{F_w} \right)^{0.5}}{F_l} \kappa \]  \hspace{1cm} (23)

\( H_a \) is calculated by using equation (22) while for the calculation of \( h_l \) following formula is used,

\[ h_l = \frac{0.03 \left( \frac{F_h}{F_w} \right)^{0.5}}{F_l} \kappa \]  \hspace{1cm} (24)

Finally for this convection coefficient including the climatic effect, following formula is used:

\[ h_{free} = 6.5 + 0.05 (T - T_{gce}) \]  \hspace{1cm} (26)

IV. CONCLUSION

In this paper, a mathematical thermal model GroCE, for accurate estimation of thermal conditions of cage rotor induction motors including the temperature variations due to climatic effect is developed. Limitations of previously developed thermal models
which consider the motor’s surrounding temperature as constant are eliminated by GroCE model. This model can be applied for various frequency and loads as well as identified temperature that can be compared to the thermal limits and alarm thresholds to prevent motors from overheating and damage.

This model is helpful for designing aspects of induction motors in efficiency improvement and better thermal withstanding capacity.

REFERENCES


