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Research paper

Development and thermal modeling of an induction machine

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Abstract

In induction machines, the major concern is the temperature rise since it determines the maximum loading, in an attempt to avoid insulation deterioration and eventual loss of motor life. The effect of excessive heat in the motor stator and rotor windings and the stator magnetic circuit can degrade the developed performance of the machine and also affect the motor loading and life span if not dispensed properly. This research work examines the thermal model for estimating the stator and rotor temperatures in cage induction motor. A state-variable model of the induction is used. The twin-axis stator reference frame is used to model the motor's electrical behavior, because physical measurements are made in this reference frame. The thermal model is derived by considering the power dissipation, heat transfer and rate of temperature rise in the stator and rotor. The non-linear equations for electrical behavior of the motor and the thermal state equations for the stator and the rotor are solved using the MATLAB/Simulink blocks. This is to give room for the determination of the temperature of the stator and rotor windings inside the induction machine so as to evaluate the thermal stability of the induction motor and to check whether the insulation of the copper windings is sufficient at different operating conditions. It was found out from the thermal model analysis that the temperature of the stator and rotor windings increases due to stator and rotor copper losses which depend on the stator current. As the stator current is increased by increasing the torque, the temperature of each element is consequentially made to increase.

Keywords: *Induction Motor; Thermal Analysis; Modeling; MATLAB Simulation; Temperature.*

1. Introduction

The advent and successful take off of the transformer gave rise to serious research in the area of alternating current generation, transmission and distribution. The power system industry, witnessed a speedy growth with the presence of the AC machine; Synchronous and Induction Machines. Induction motors are the most common motors used in industrial motion control systems, as well as in main powered home appliances. Simple and rugged design, low-cost, low maintenance and direct connection to an AC power sources are the main advantages of induction motors [1]. Various types of induction motors are available in the market. Different motors are suitable for different applications. Although induction motors are easier to design than DC motors, the speed and the torque control in various types of induction motors require a greater understanding of the design and the characteristics of these motors. Three-phase induction motors are widely used in industrial and commercial applications. They are classified either as squirrel cage or wound-rotor motors [2]. These motors are self-starting and use no capacitor, starting winding, centrifugal switch or other starting devices. They produce medium to high degrees of starting torque. The power capabilities and efficiency in these motors range from medium to high compared to their single-phase counterparts. Popular applications include grinders, lathes, drill presses, pumps, compressors, conveyors, also printing equipment, farm equipment, electronic cooling and other mechanical duty applications. Due to the growing need of induction motors in the industrial sector, there is a growing emphasis on an acceptable and adequate analysis and modelling methodology of this type of Electrical Machine for all modes of operation. Problems concerning stability of power systems, computer-aided simulation techniques are commonly used. In recent years, [3] shows that, significant improvements have been obtained in the area of power system simulation; in particular, attention has been given to the statement of the mathematical problem suitable for computer implementation, as well as to the modeling and identification, of the single components of a system (generators and motors). Nevertheless, no common agreement has been reached on the fact that known procedure can achieve a degree of accuracy adequate for new requirements.
The Induction Machine is constructively, composed of a stationary member called the stator where the armature winding is located and a rotating member called the rotor where the field winding is located. One basic and distinguishing feature of the induction machine is that it is a singly excited machine. Although such machines are equipped with both field and armature winding, in normal use an energy source is connected to one winding alone, the field winding. Currents are made to flow in the armature winding by induction, which creates an ampere-conductor distribution that interacts with the field distribution to produce a net unidirectional torque. The frequency of the induced current in the conductor is affected by the speed of the rotor on which it is located; however, the relationship between the rotor speed and the frequency of the armature current is such as to yield a resulting ampere-conductor distribution that is stationary relative to the field distribution of the stator. As a result, the singly excited induction machine is capable of producing torque at any speed below synchronous speed. For this reason, induction machines are placed in the class of asynchronous machines.

The energy conversion in an electrical machine is inevitably accompanied by losses of power which emerge in calorific form. When stator winding insulation materials are heated beyond their temperature limits by excessive heat from motor losses, the winding insulation materials may experience accelerated and irreversible deterioration, resulting in reduced motor life or even total motor failure [4].To prevent such excessive thermal stress and ensure continuous and reliable motor operation, the National Electrical Manufacturers Association (NEMA) has established permissible temperature limits for stator windings of induction machines based on their insulation classes [5]. However, it is commonly assumed that the motor's life is reduced by 50% for every 10°C increase above its stator winding temperature limit. Therefore, an accurate estimate of the stator winding temperature is crucial in ensuring proper motor operation below its thermal limit [4]. Majority of the industrial electrical machines run continuously where the steady-state temperature is reached. Such applications are for example power plant generators, different kinds of conveyors, air conditioning motors, propulsion motors, etc. This has led to the fact that very often the heat transfer in electric machines is studied in the steady-state, and the heat capacitances of the machine are neglected in the model. Such a model is adequate enough for properly estimating the steady-state temperature rise of the machine; however, it cannot model the heat transfer mechanisms during the loading variations [6-8]. High over loadings means high losses, and consequently high temperature gradients. Such model is not suitable for prediction of temperature. This study focuses on the thermal analysis of a three phase induction motor with particular emphasis on the stator temperature and rotor temperature in squirrel cage induction motor. During the operation of the induction motor, the heat generated losses (i.e. iron losses, stator copper losses and rotor losses) affect the efficiency and performance of the induction motor, to the extent of increasing the temperature to a limit larger than the allowable operating temperature, which causes some important problems [9- 14]. The major determining factor for how much an electric machine can be loaded continuously is usually the temperature. When a machine exceeds its thermal limit there are various outcomes: the oxidation process in insulation materials is accelerated, which eventually leads to loss of dielectric property. Bearing lubricants may deteriorate or the viscosity may become too high, resulting in reduced oil film thickness. Other problems are mechanical stress and changes in geometry caused by thermal expansion of the machine elements. The essence of this research work is to develop a thermal model for an induction machine that will enable the prediction and estimation of stator and rotor temperature of the induction motor. This is very important first to the manufacturer or designer of an induction motor because with these predictions one can decide on the insulation class limits the induction motor belongs. Also modern trends in the construction of induction motors is moving in the direction of making them with reduced weights, costs and with increased efficiency. In order to achieve this, the thermal analysis becomes very crucial in deciding on what types of insulators and other materials that would be used to make these motors. In industries, the knowledge of the thermal limits of machines increases the life span of their induction motors and reduces downtime; thereby increasing production and profit.

2. Literature survey

A wealth of literature exists in the thermal analysis and modelling of induction machines, most of the earlier researchers and designers have traditionally adopted thermal network model on lumped parameter thermal model for electric machines both under steady and transient thermal conditions. In [10] a thermal network method (TNM) to analyze thermal field of the induction motor which has air ducts in stator and rotor core as forced cooling channels was presented. In [11], [14] the lumped – parameter thermal model for induction machines was used. His model considered just stator and environment representative temperatures also parameter estimation was carried out. In [14-16] the lumped-parameter thermal model was used to predict both the steady-state and transient solution to the temperatures within a 7.5-KW induction machine. A finite difference is one of the popular numerical methods widely used. Even though this method predicts hot spot temperatures, the method is not as flexible as finite element method in handling complex boundary conditions and geometry. In [17], two dimensional times stepping finite difference scheme was adopted to solve the thermal transient problem. Pure analytical strategy is limited and it has too many major assumptions. While [12] used a one dimensional lumped model for predicting cooling curves in electric motors, the heat transfer coefficients was determined on the surface as well as within the machine. However, the internal heat transfer coefficients used seems to be unrealistic. In [13], winding temperatures were predicted analytically. However, they assumed that the model is made of rings placed one over another with constant lengths. In [18] the two dimensional model containing only one slot pitch of the stator was solved analytically. He assumed that there is no heat interaction between rotor and stator. In [19], ANSYS package was used for three dimensional analysis of electromagnetic and thermal behavior of induction motor rotors. In [20], the finite element method was used to solve the three-dimensional steady-state and/or transient heat flow equation which described the thermal model of the induction motor while [21] studied the failures of large cage rotors of induction motors using three dimensional finite elements via electrical- thermal analysis of bar and end rings. In [22], two dimensional steady state thermal analyses of electric machines using FEM carried out.

Furthermore, Temperature estimation in the induction motor has been dealt with by many authors [23–28], with most of these works describing either a very complex lumped-parameter network or the finite-element method. A complex model would be inappropriate in this work, where estimation is being performed in real time. As such, a simple lumped-parameter thermal model has been developed empirically. This model can be adapted for use with any induction machine without requiring information about the machine size and dimensions or materials' properties. In extension, thermal parameters, such as thermal capacities and power transfer coefficients, can be determined by a few simple tests.

3. Model development

In many cases the model is the familiar steady-state equivalent circuit, but for high performance drives a full transient model of the motor is required. Effective modelling, and therefore the effectiveness of drive control and estimation, is limited by the complexity of the physical processes occurring within the motor. Frequency dependence of the rotor electrical circuit, non-linearity of the magnetic circuit, and temperature dependence of the stator and rotor electrical circuits, all impact on the accuracy with which the motor can be modelled. The modelling of induction motor taking all the real behaviors without assumptions, simplifying is very difficult or impossible. For that, one will propose a model with simplifying assumptions. This research addresses the thermal model of an induction motor incorporating the estimation of stator temperature and rotor temperature. The frequency dependence of the rotor electrical circuit and non-linearity of the magnetic circuit are not included. A state-variable model of the induction motor is required. The twin-axis stator reference frame [29, 30] is used to model the motor's electrical behavior, because physical measurements are usually made in this reference frame. The twin-axis model in the stator reference frame is

$$V_{ds} = R_1 i_{ds} + L_1 P i_{ds} + L_m P i_{dr} \quad (1)$$

$$V_{qs} = R_1 i_{qs} + L_1 P i_{qs} + L_m P i_{qr} \quad (2)$$

$$0 = R_2 i_{dr} + L_2 P i_{dr} + L_2 \omega_r i_{qr} + L_m \omega_r i_{qs} + L_m P i_{ds} \quad (3)$$

$$0 = R_2 i_{qr} + L_2 P i_{qr} - L_2 \omega_r i_{dr} - L_m \omega_r i_{ds} + L_m P i_{qs} \quad (4)$$

The twin- axis model in the stator reference frame above can be rearranged into state-space format as shown below;

$$P\sigma i_{ds} = -R_1 L_2 i_{ds} + L_m^2 \omega_r i_{qs} + R_2 L_m i_{dr} + L_2 L_m \omega_r i_{qr} + L_2 V_{ds} \quad (5)$$

$$P\sigma i_{qs} = -L_m^2 \omega_r i_{ds} - R_1 L_2 i_{qs} - L_2 L_m \omega_r i_{dr} + R_2 L_m \omega_r i_{qr} + L_2 V_{qs} \quad (6)$$

$$P\sigma i_{dr} = R_1 L_m i_{ds} - L_1 L_m \omega_r i_{qs} - R_2 L_1 i_{dr} - L_1 L_2 \omega_r i_{qr} + L_m V_{ds} \quad (7)$$

$$P\sigma i_{qr} = -L_1 L_m \omega_r i_{ds} - R_1 L_2 i_{qs} - L_1 L_2 \omega_r i_{dr} + R_2 L_1 i_{qr} + L_m V_{qs} \quad (8)$$

Where $\sigma = L_1 L_2 - L_m^2$.

For the purposes of temperature estimation this four-state electrical model must be augmented by appropriate models of the mechanical and thermal processes in the motor. The mechanical behavior can be modelled by;

$$T = B\omega_r + JP\omega_r + T_l \quad (9)$$

In which the electromagnetic torque of the motor T can be represented in terms of stator and rotor current components. Thus;

$$T = P_n L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (10)$$

Therefore, the state-space equation for the rotor speed is given as;

$$P\omega_r = \frac{P_n L_m}{J}(i_{qs} i_{dr} - i_{ds} i_{qr}) - \frac{B}{J}\omega_r - \frac{T_l}{J} \quad (11)$$

4. The thermal model equations

The thermal model is derived by considering the power dissipation, heat transfer and rate of temperature rise in the stator and rotor. The stator power losses include contributions from copper losses and frequency-dependent iron losses.

$$PL_1 = (i_{ds}^2 + i_{qs}^2) R_1 + K_{ir} \omega_r^2 \quad (12)$$

The rotor power losses are dominated by the copper loss contribution if the motor is operated at a low value of slip, so

$$PL_2 = (i_{dr}^2 + i_{qr}^2) R_2 \quad (13)$$

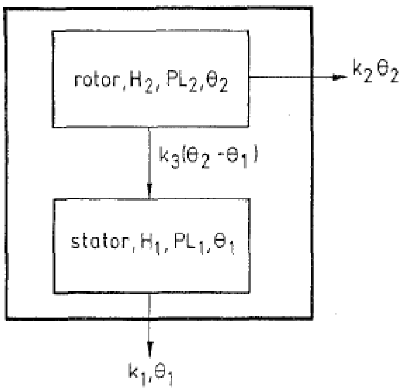

Fig. 1: Structure of Thermal Model of Induction Motor.

A simple representation of the assumed heat flow is given in figure 1. Heat flow from the rotor is either directly to the cooling air with heat transfer coefficient K_2 , or across the air gap to the stator with heat transfer coefficient K_3 .

$$PL_2 = K_2 \theta_2 + H_2 P\theta_2 + K_3(\theta_2 - \theta_1) \quad (14)$$

Heat flow from the stator is directly to the cooling air, with heat transfer coefficient K_1 .

$$PL_1 = K_1\theta_1 + H_1 P\theta_1 - K_3(\theta_2 - \theta_1) \tag{15}$$

For an induction motor with a shaft-mounted cooling fan, the heat transfer coefficients are dependent on the rotor speed. This dependence has been modelled approximately by a set of linear relationships;

$$K_1 = K_{10}(1 + K_{1\omega}\omega_r) \tag{16}$$

$$K_2 = K_{20}(1 + K_{2\omega}\omega_r) \tag{17}$$

$$K_3 = K_{30}(1 + K_{3\omega}\omega_r) \tag{18}$$

The well-known linear relationship between resistance and temperature must be taken into account for the stator and rotor resistances

$$R_1 = R_{10}(1 + \alpha_1\theta_1) \tag{19}$$

$$R_2 = R_{20}(1 + \alpha_2\theta_2) \tag{20}$$

Substituting into equations 14 and 15 from equations 12, 13, 16-20 and rearranging yields the thermal state equations for the stator and for the rotor.

$$P\theta_1 = \frac{R_{10}(1+\alpha_1\theta_1)}{H_1}(i_{ds}^2 + i_{qs}^2) + \frac{K_{ir}}{H_1}\omega_r^2 \ldots$$

$$\ldots - \frac{K_{10}(1+K_{1\omega}\omega_r)}{H_1}\theta_1 + \frac{K_{30}(1+K_{3\omega}\omega_r)}{H_1}(\theta_1 - \theta_2) \tag{21}$$

$$P\theta_2 = \frac{R_{20}(1+\alpha_2\theta_2)}{H_2}(i_{dr}^2 + i_{qr}^2) - \frac{K_{20}(1+K_{2\omega}\omega_r)}{H_2}\theta_2 \ldots \; \ldots - \frac{K_{30}(1+K_{3\omega}\omega_r)}{H_2}(\theta_1 - \theta_2) \tag{22}$$

4.1. Summary of the model equations

The whole of the preceding equations give the model of the following states:

$$P\sigma i_{ds} = -R_1L_2i_{ds} + L_m^2\omega_r i_{qs} + R_2L_m i_{dr} + L_2L_m\omega_r i_{qr} + L_2V_{ds} \tag{23}$$

$$P\sigma i_{qs} = -L_m^2\omega_r i_{ds} - R_1L_2i_{qs} - L_2L_m\omega_r i_{dr} + R_2L_m\omega_r i_{qr} + L_2V_{qs} \tag{24}$$

$$P\sigma i_{dr} = R_1L_m i_{ds} - L_1L_m\omega_r i_{qs} - R_2L_1i_{dr} - L_1L_2\omega_r i_{qr} + L_mV_{ds} \tag{25}$$

$$P\sigma i_{qr} = -L_1L_m\omega_r i_{ds} - R_1L_2i_{qs} - L_1L_2\omega_r i_{dr} + R_2L_1i_{qr} + L_mV_{qs} \tag{26}$$

$$P\omega_r = \frac{P_nL_m}{J}(i_{qs}i_{dr} - i_{ds}i_{qr}) - \frac{B}{J}\omega_r - \frac{T_l}{J} \tag{27}$$

$$PL_1 = (i_{ds}^2 + i_{qs}^2)R_1 + K_{ir}\omega_r^2 \tag{28}$$

$$PL_2 = (i_{dr}^2 + i_{qr}^2)R_2 \tag{29}$$

$$P\theta_1 = \frac{R_{10}(1+\alpha_1\theta_1)}{H_1}(i_{ds}^2 + i_{qs}^2) + \frac{K_{ir}}{H_1}\omega_r^2 - \ldots$$

$$\ldots\frac{K_{10}(1+K_{1\omega}\omega_r)}{H_1}\theta_1 + \frac{K_{30}(1+K_{3\omega}\omega_r)}{H_1}(\theta_1 - \theta_2) \tag{30}$$

$$P\theta_2 = \frac{R_{20}(1+\alpha_2\theta_2)}{H_2}(i_{dr}^2 + i_{qr}^2) -{}_2)\ldots$$

$$\ldots\frac{K_{20}(1+K_{2\omega}\omega_r)}{H_2}\theta_2 - \frac{K_{30}(1+K_{3\omega}\omega_r)}{H_2}(\theta_1 - \theta_2) \tag{31}$$

4.2. Matlab simulation of the model

The three-phase induction motor is modeled using Matlab /Simulink embedded blocks. This model is implemented using the sets of equations above. The main goal of this section is to present a fast MATLAB simulation of the developed thermal model for an induction machine that will enable the estimation of stator and rotor temperature of the induction motor. For clarity purposes, electrical part simulations, power loss simulations and thermal simulations of induction motor are separated.

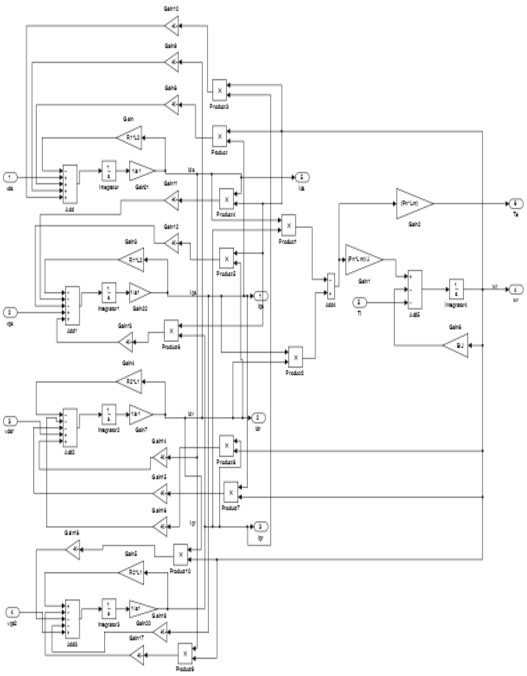

Fig. 2: Simulation Model of the Electrical Part.

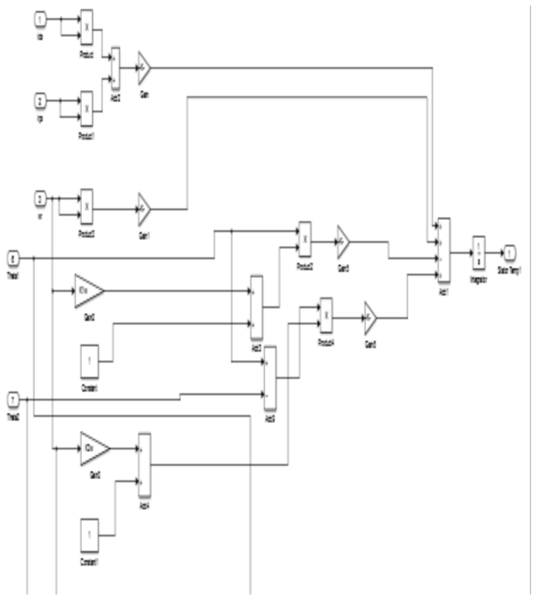

Fig. 3: Thermal Simulation Model of Stator Temperature.

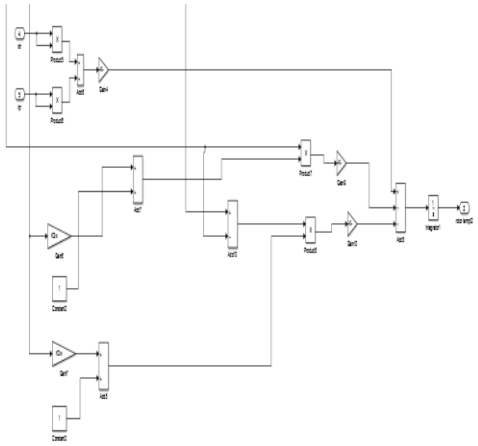

Fig. 4: Thermal Simulation Model of Rotor Temperature.

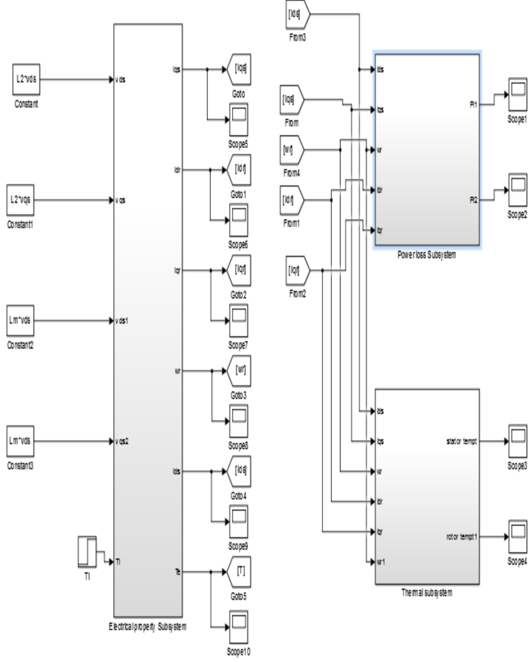

Fig. 5: The Proposed Model of the Induction Motor.

5. Results and discussion

The following figures are obtained from the model equations developed.

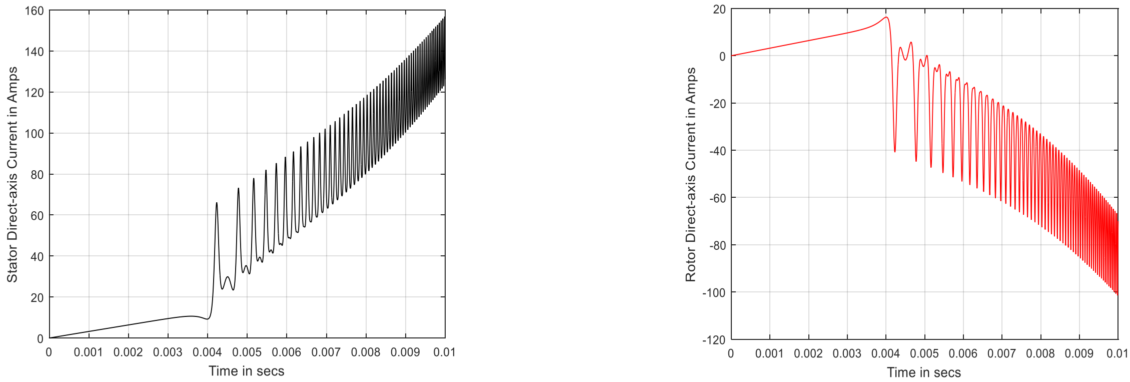

Fig. 6: Graphs Of i_{ds} and i_{dr} Against Time.

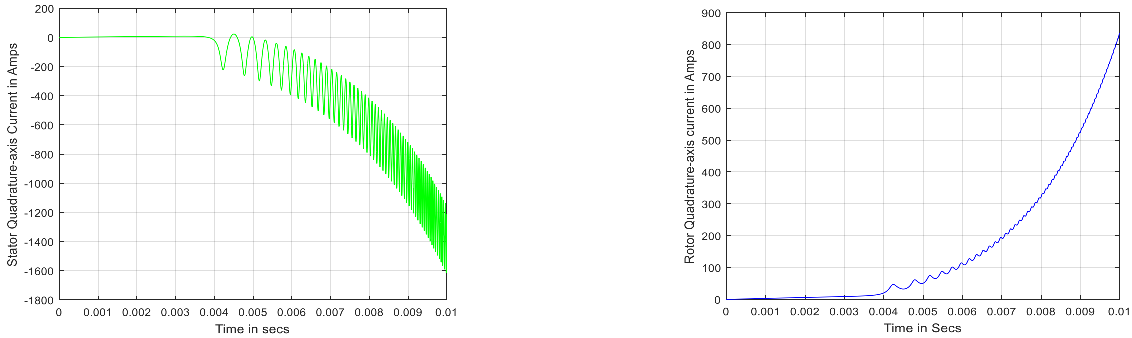

Fig. 7: Graphs Of i_{qs} and i_{qr} Against Time.

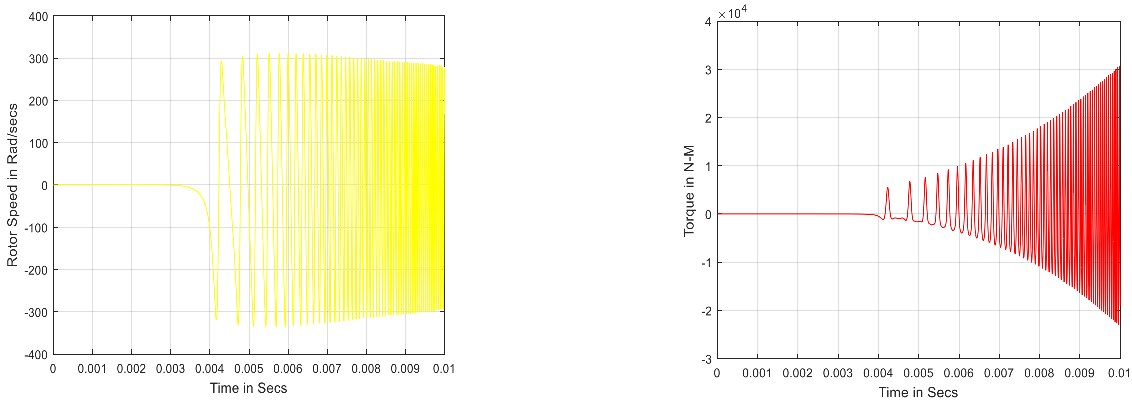

Fig. 8: Graphs of Rotor Speed and Motor Torque against Time.

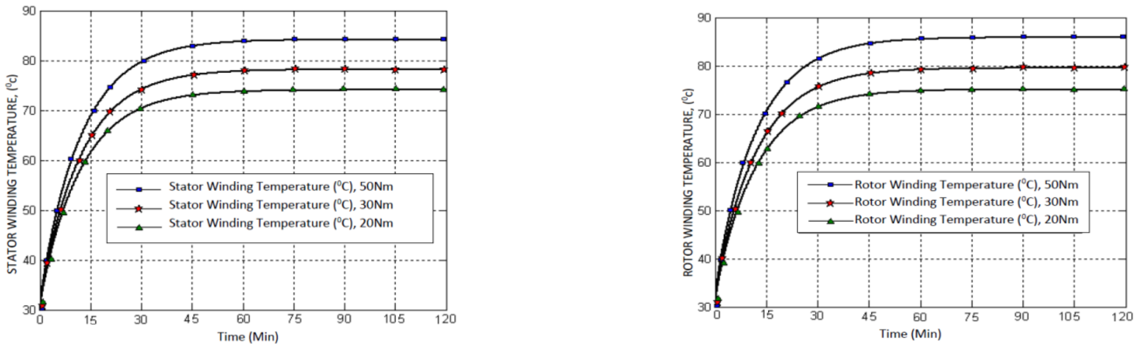

Fig. 9: Graphs of Stator and Rotor Winding Temperature at Different Values of the Applied Torque.

From the observed performance attributes, it is clear that in figures 6 and 7, there is a swift in the stator and rotor current values from about 0.004s as they drift towards instability. This is so at both the direct and quadrature axes. In figures 8, the attendant rotor speed and torque versus time response depicted the same trend from about the same time. However from figure 9, increasing the applied torque at constant frequency leads to the increase of stator copper and rotor losses which increase the heat of the induction motor. This will draw a higher stator current to compensate for the reduction in the magnetic flux. The induction motor draws larger stator current than the rated stator current, which means that the stator copper losses and the rotor copper losses will increase, pushing the induction motor elements temperature especially the winding to increase more and more until the limit exceeds sometimes the allowable temperature level. This high temperature will damage the insulation of windings and burnout the induction motor if prompt action is not taken.

6. Conclusion

For the fact that the induction machine is one of the most important and valuable equipment in the industry because of its robustness and low-cost, there is need for appropriate temperature monitoring and loading to ensure efficient operation and long-life span. An aging induction motor is subject to faults which reduces its mechanical and dielectric withstand strength. The insulations now start suffering a dielectric failure, thereby reducing the motor ability to withstand short-circuit faults. This insulation deterioration is primarily dependent on the stator and rotor windings temperature and the stator magnetic circuit temperature, which is the major factor limiting the induction machine lifespan. This study concentrated on the thermal analysis of the induction motor, where a thermal model is derived by considering the power dissipation, heat transfer and rate of temperature rise in the stator and the rotor. This model is used to determine the temperature of the stator and the rotor. The thermal model is used to give a clear picture of the temperature inside the induction motor, to give precaution about any problems about to occur during the operating conditions, like the induction motor insulation. This is because if the internal temperature of the induction motor exceeded the motor insulation thermal class, the motor's life would be reduced. A 10℃ increase in motor operating temperature actually decreases the motor's useful service life by half. The thermal model of induction motor is found to be capable of calculating the temperatures in the induction motor elements with good accuracy at different operating conditions.

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Appendix

A). Definition of symbols

i_{ds}, i_{qs} : *D-q* stator currents

i_{dr}, i_{qr} : *D-q* rotor currents

K_{ir} : Iron loss constant

K_{10}, K_{20}, K_{30} : Thermal power transfer coefficients at zero speed

K_{1w}, K_{2w}, K_{3w} : Variation of thermal power transfer with speed

P : Time differential operator (d/dt)

P_n : Pole number

V_{ds}, V_{qs} *D-q: stator voltages*

B : Viscous friction constant

H_1 : Stator thermal capacity

H_2 : Rotor thermal capacity

J : Total inertia

L_1 : Stator self-inductance

L_2 : Rotor self-inductance

L_m : Stator rotor mutual inductance

P_{L1} : Stator power loss

P_{L2} : Rotor power loss

R_{10} : Stator resistance at

H_2 : Rotor thermal capacity

J : Total inertia

T : Motor torque

T_l : Load torque

α : Temperature coefficient of resistance

σ : Coupling coefficient

θ_1 : Stator temperature above ambient

θ_2 : Rotor temperature above ambient

w_r : Rotor speed

B). Motor parameters (squirrel cage)

Voltage =415V,
Frequency = 50Hz
Rated current = 6.5A;
Rated power = 3kW;
Rated speed = 1420rev/min;
Electrical parameters calculated values from the standard DC test, locked rotor test, and no-load test

R_1 = 2.4252Ω, R_2 = 2.0552Ω

L_1 = 0.237H, L_2 = 0.237H

L_m = 0.23H, R_m = 95.552Ω