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Thermal analysis of a three-phase induction motor based on motor-CAD, flux2D, and matlab

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ABSTRACT

This paper adopted a thermal network method (TNM) based on Motor-CAD software, and Matlab/SIMULINK, with finite element method (FEM) based on Flux2D software to perform a thermal analysis of a totally enclosed fan-cooled (TEFC), squirrel cage, three-phase induction motor. The thermal analysis is achieved based on a precise knowledge of the test motor geometry, materials, and heat sources (losses). The estimation of heat distribution inside the test motor by this three software is done successfully with a good agreement between its results. The proposed triple-software methodology for this work can be adopted from the motor designer instead of using an experimental test based on a real motor.

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1. INTRODUCTION

An electric motor is an electrical machine that converts electrical energy into mechanical energy. While converting energy from one form to another, it produces losses. These losses are responsible for generating heat inside the motor. Temperature is an important factor that affects the performance of electric machines. Due to their thermal design, electric machines can suffer problems such as insulation breakdown, reduction in torque provided, shortened lifetimes and so on. Other problems are changes in geometry caused by thermal expansion of the machine components and mechanical stresses. Therefore, because of these problems, the temperatures inside the machines must be kept within safe limits. To predict the machine temperatures, thermal models are used to determine the temperature for different parts of motor. So, thermal analysis is a very important stage in the design of electric machines. To study the thermal behavior of the machines, and show how heat is distributed inside it. As the industrial market demands for less power consumption, low cost, small size, low weight, and high efficiency, the thermal analysis will assist the motor designers to get these required specifications. Also, the thermal analysis improves machine performance, increase its operational lifetime, and reduce the maintenance periods. In order to avoid the problem of heat in the machines, the temperature of the windings are monitored by thermal analysis, since the windings are considered the weakest part of the machine, as an increase in the temperature of the windings by the rate of 10 oC than the permissible limit will weaken the life of the insulation by half [1]. Motor insulation systems contain sticky material, this material will be affected by temperature and lead to friction and causes heat in the windings.

The performance of the machine is improved either by selecting a high-temperature to withstand insulation material or by choosing the best cooling system for the machine. Thermal analysis depends on the calculation of losses and aims to find the temperature distribution inside the motor, to select the best motor cooling system, to keep the windings, core, and frame temperatures within safe limits. The most methods used in the thermal analysis of the electric machines are thermal network method (TNM) and finite element method (FEM) [2]. Many research works have been done to study the thermal analysis of a three-phase induction motor. Gnffith and Mc Coy (1986), used ANSYS package for 3D FEM analysis of electromagnetic and thermal behavior of induction motor [3]. Boys et al (1994), described a thermal model that provides an estimate of temperatures of the stator and rotor in an induction machine by a driven inverter in both transient and stable conditions, and under constant and variable flow control [4]. Mezani et al (1999), implemented a steady-state finite element method of the heat inside an induction motor. The thermal calculation is carried out in a 2D radial view that represents an angular space of one pitch of rotor tooth [5]. Huai Ying et al (2003), developed and experimentally validate a model for accounting losses and thermal phenomena of an induction motor, implemented by FEMLAB [6].

Mario J. Duran et al (2004), presented a lumped-circuit thermal model for induction machines that can be adopted in real-time applications. Its modeled just stator, rotor, and environment representative temperatures. Thermal parameters are experimentally obtained and a sensorless vector control application with induction motor [7]. Khalifa et al (2009), presented and discussed the theoretical and experimental results of the associated effects of temperature rise on the performance of induction motor. These effects are studied theoretically in a model for the induction motor is developed by Matlab program [8]. Mahdi Atig et al (2018) presented the results of an experimental investigation to see the impact of the open phase fault on the thermal behavior in the 2.2 kW three phase squirrel cage induction motor and to display the stator current with healthy and faulty conditions under different loads [9]. The aim of this work is to study the heat distribution inside a three-phase, squirrel cage, induction motor based on Motor-CAD, Flux2D, and Matlab programs including both thermal network method(TNM), and finite element method (FEM).

2. METHODS OF THERMAL ANALYSIS

2.1. Lumped Circuit Method

The principle of the thermal network method (TNM) is based on divided motor into basic thermal elements representing a combination of conduction, convection, and radiation heat transfer operations. The structure of a TEFC induction motor model similar to electrical network, and consists from [10]:

a. Thermal resistances rather than electrical resistances.
b. Power sources rather than current sources.
c. Thermal capacitances rather than electrical capacitors.
d. Nodal temperatures rather than voltage.
e. Power flow through resistances rather than current.
f. Geometries of components of particular motor, thermal resistances and thermal capacitances of all components can be calculated.
g. 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.

In the steady state thermal analysis, the thermal circuit of a three-phase induction motor consists of thermal resistances and thermal sources connected between the motor component nodes. While, in the transient analysis, thermal capacities are used to observing changes in the internal energy of the body over time. TNM is very fast, simple mathematical form, easy to implement, and more suitable with the degree of temperature gradients in small machines.

2.2. Thermal Analysis by Finite Element Method

The finite element method (FEM) is a numerical method used to solve engineering problems such as electromagnetic, mass transport, heat transfer, and fluid flow. The method produces the approximate values of the unknown at the number of separate nodes above the range [11]. For solving the problem, it divides the big problem to smaller parts called finite elements. The equations that compose these finite elements are then assembled into a larger system of equations that constitute the whole problem. Although Motor-CAD uses TNM in motor thermal analysis, it has a finite element solution for the stator winding only. The thermal study of the test motor by FEM is achieved by using Flux2D software to determine the temperature distribution in the case of a steady state at any point of the induction motor. This method is particularly appropriate with large temperature gradients [12], but the defect takes time to process with respect to TNM.

3. MATHEMATICAL FOUNDATION

The heat transfer basics in the thermal network analysis of a three-phase induction motor are described as follows [13]:

3.1. Heat Transfer by Conduction

The heat is transferred by conduction in solid material such as stator and rotor, and can be described by (1).

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda x\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda y\frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda z\frac{\partial T}{\partial z}) + Q \tag{1}$$

Where ρ is the density, λ is the thermal conductivity, T is the temperature, and Q is the dissipated power density. Fourier's law is used to connect the heat flux and the temperature gradient, The heat flux q is given by (2).

$$q = -\lambda\frac{\partial T}{\partial x} \tag{2}$$

3.2. Heat Transfer by Convection

The heat is transfered from one place to another by the movement of fluids. In this work, the test motor is totally enclosed fan cooled (TEFC), where the air is pushed by forced convection on the frame of the motor. The equation for convection can be expressed as:

$$q = \alpha\, As\, (Tw - T\infty) \tag{3}$$

Where α is heat transfer coefficient, As is surface area, Tw, and T∞ are the temperature of the surface and the ambient cooling medium respectively.

In thermal analysis of a three-phase induction motor conduction and convection are only take into account, while radiation is ignored.

3.3. Heat Sources (Power Losses)

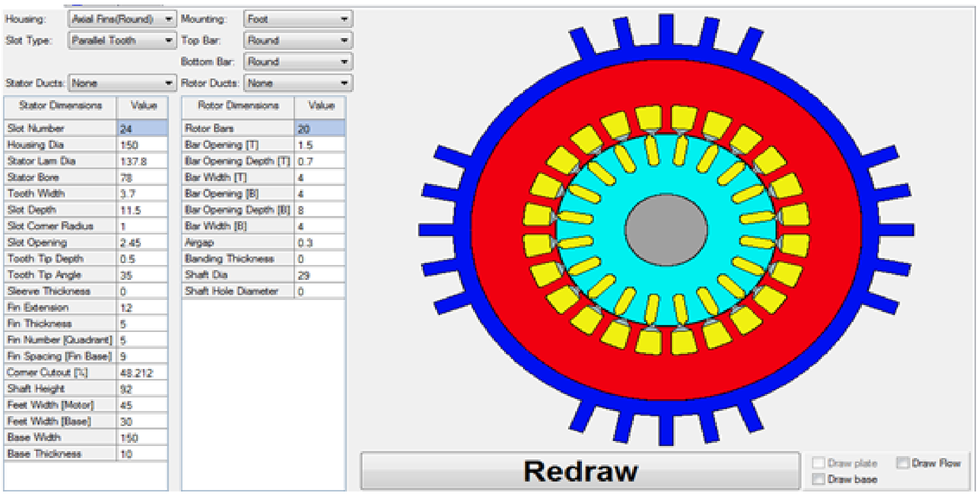
The motor power losses are divided into six types :

a. Stator iron losses P_{Fe1}.
b. Rotor iron losses P_{Fe2}.
c. Stator copper losses Pcu_1.
d. Rotor copper losses Pcu_2.
e. Mechanical losses (Friction and windage losses).
f. Stray load losses.

These losses must be calculated to entered as heat sources before solving the test motor model.

4. MODELLING BY MOTOR-CAD

A 2.2 kW, 2 pole, TEFC, insulation class F, squirrel cage, three-phase induction motor is modeled by Motor-CAD. All dimensions of the machine were entered in the radial cross section, as shown in Figure 1.



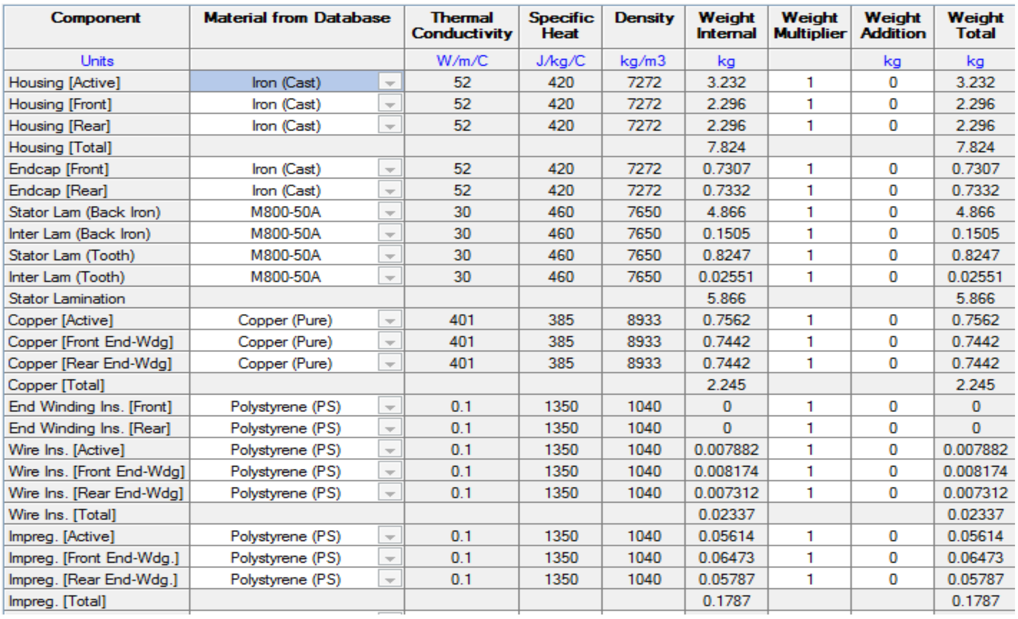
Housing: Axial Fins(Round)
Slot Type: Parallel Tooth
Stator Ducts: None
Mounting: Foot
Top Bar: Round
Bottom Bar: Round
Rotor Ducts: None

Stator Dimensions	Value
Slot Number	24
Housing Dia	150
Stator Lam Dia	137.8
Stator Bore	78
Tooth Width	3.7
Slot Depth	11.5
Slot Corner Radius	1
Slot Opening	2.45
Tooth Tip Depth	0.5
Tooth Tip Angle	35
Sleeve Thickness	0
Fin Extension	12
Fin Thickness	5
Fin Number [Quadrant]	5
Fin Spacing [Fin Base]	9
Corner Cutout [%]	48.212
Shaft Height	92
Feet Width [Motor]	45
Feet Width [Base]	30
Base Width	150
Base Thickness	10

Rotor Dimensions	Value
Rotor Bars	20
Bar Opening [T]	1.5
Bar Opening Depth [T]	0.7
Bar Width [T]	4
Bar Opening [B]	4
Bar Opening Depth [B]	8
Bar Width [B]	4
Airgap	0.3
Banding Thickness	0
Shaft Dia	29
Shaft Hole Diameter	0

Figure 1. Radial cross section of the test motor by Motor –CAD

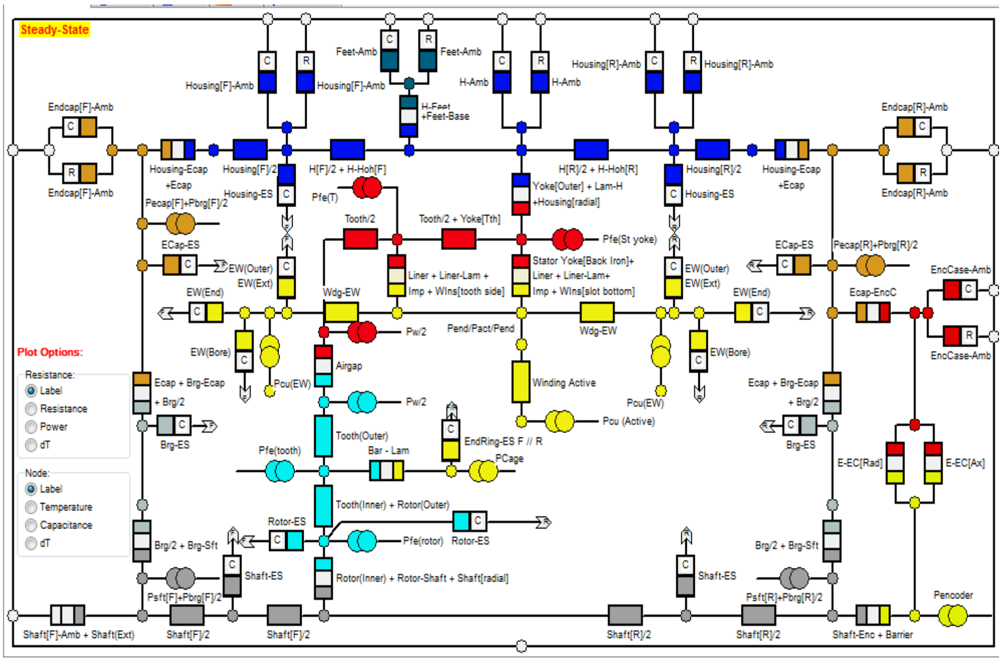
The winding pattern for the (slot/pole) combination of this machine is set up automatically by Motor-CAD software. In the test motor, we have a single layer winding with 184 turns per phase, thermal resistance values are calculated automatically from motor dimensions and material data. The materials used in modeling the test motor are shown in Figure 2.



Component	Material from Database	Thermal Conductivity	Specific Heat	Density	Weight Internal	Weight Multiplier	Weight Addition	Weight Total
Units		W/m/C	J/kg/C	kg/m3	kg		kg	kg
Housing [Active]	Iron (Cast)	52	420	7272	3.232	1	0	3.232
Housing [Front]	Iron (Cast)	52	420	7272	2.296	1	0	2.296
Housing [Rear]	Iron (Cast)	52	420	7272	2.296	1	0	2.296
Housing [Total]					7.824			7.824
Endcap [Front]	Iron (Cast)	52	420	7272	0.7307	1	0	0.7307
Endcap [Rear]	Iron (Cast)	52	420	7272	0.7332	1	0	0.7332
Stator Lam (Back Iron)	M800-50A	30	460	7650	4.866	1	0	4.866
Inter Lam (Back Iron)	M800-50A	30	460	7650	0.1505	1	0	0.1505
Stator Lam (Tooth)	M800-50A	30	460	7650	0.8247	1	0	0.8247
Inter Lam (Tooth)	M800-50A	30	460	7650	0.02551	1	0	0.02551
Stator Lamination					5.866			5.866
Copper [Active]	Copper (Pure)	401	385	8933	0.7562	1	0	0.7562
Copper [Front End-Wdg]	Copper (Pure)	401	385	8933	0.7442	1	0	0.7442
Copper [Rear End-Wdg]	Copper (Pure)	401	385	8933	0.7442	1	0	0.7442
Copper [Total]					2.245			2.245
End Winding Ins. [Front]	Polystyrene (PS)	0.1	1350	1040	0	1	0	0
End Winding Ins. [Rear]	Polystyrene (PS)	0.1	1350	1040	0	1	0	0
Wire Ins. [Active]	Polystyrene (PS)	0.1	1350	1040	0.007882	1	0	0.007882
Wire Ins. [Front End-Wdg]	Polystyrene (PS)	0.1	1350	1040	0.008174	1	0	0.008174
Wire Ins. [Rear End-Wdg]	Polystyrene (PS)	0.1	1350	1040	0.007312	1	0	0.007312
Wire Ins. [Total]					0.02337			0.02337
Impreg. [Active]	Polystyrene (PS)	0.1	1350	1040	0.05614	1	0	0.05614
Impreg. [Front End-Wdg.]	Polystyrene (PS)	0.1	1350	1040	0.06473	1	0	0.06473
Impreg. [Rear End-Wdg.]	Polystyrene (PS)	0.1	1350	1040	0.05787	1	0	0.05787
Impreg. [Total]					0.1787			0.1787

Figure 2. Materials of the test motor selected by Motor-CAD

The losses have been calculated at full load condition, and entered in Motor-CAD. The thermal model is set up with housing type, materials, and cooling options etc. The model can be solved by click on the “solve thermal model”, to calculate the temperatures at different motor regions as shown in the motor equivalent thermal model of Figure 3.



Plot Options:

Resistance:
● Label
○ Resistance
○ Power
○ dT

Node:
● Label
○ Temperature
○ Capacitance
○ dT

Figure 3. Equivalent thermal network of the test motor by Motor-CAD

5. MODELING BY MATLAB/SIMULINK

A three-phase induction motor was simulated by Matlab/Simulink version 2013, based on a lumped thermal model. Heat generated due to power losses in the stator iron back, stator winding and the rotor is represented by three heat flow sources: stator iron losses, stator winding power losses, and rotor copper losses. The motor losses were inserted directly to the thermal model. The motor thermal circuit is built of thermal conductive and convective heat transfer blocks, which reproduce heat paths in the motor parts: motor frame, stator winding, stator iron, rotor iron, rotor bars, front, and rear bearing plates. The temperature measurements at different points within the motor were obtained using 6 sensors made in 6 positions: frame, stator winding, stator yoke, rotor yoke, rotor bar, and shaft. The motor exchanges heat with the atmosphere through the frame-atmosphere. The thermal equations used in the model are the same as those used in Motor-CAD software. Figure 4 show the test motor circuit modeling by Matlab/Simulink.

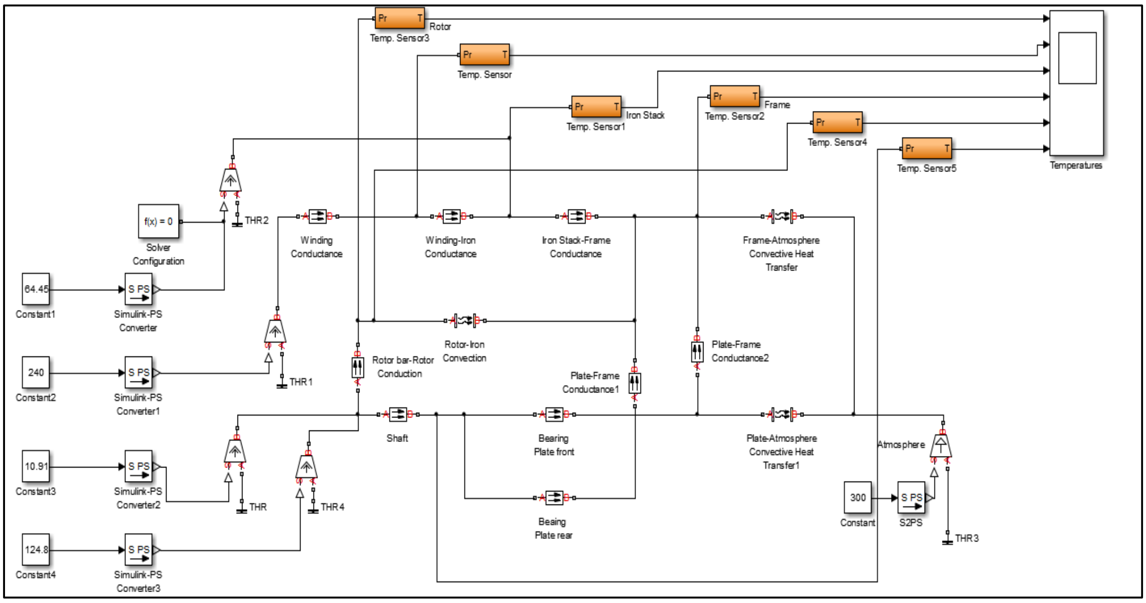


Figure 4. Test motor thermal circuit by Matlab/Simulink

6. MODELING BY FLUX2D

The finite element method model for the test motor is done by using Flux2D software as shown in Figure 5.We used software sketcher to draw the motor geometry. The machine consists of five different materials: shaft steel type CK45, electrical steel type M800-50A, cast iron for frame, pure aluminum for rotor bars ,and copper for stator winding.

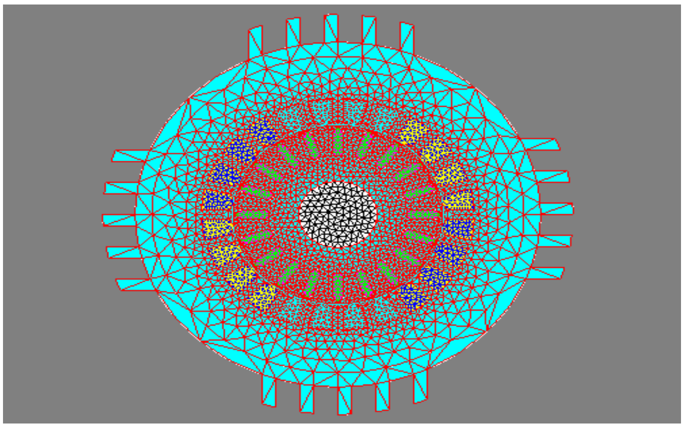


Figure 5. FEM model for the test motor by Flux2D

7. RESULT AND DISCUSSION

Figures 6 and 7 show the temperature distribution obtained from Motor-CAD in the axial and radial view of the test motor at full load, steady state condition.

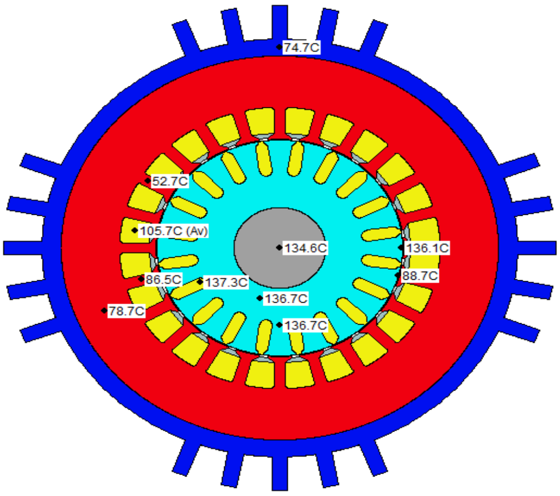


Figure 6. Radial view of the test motor temperature distribution by Motor-CAD

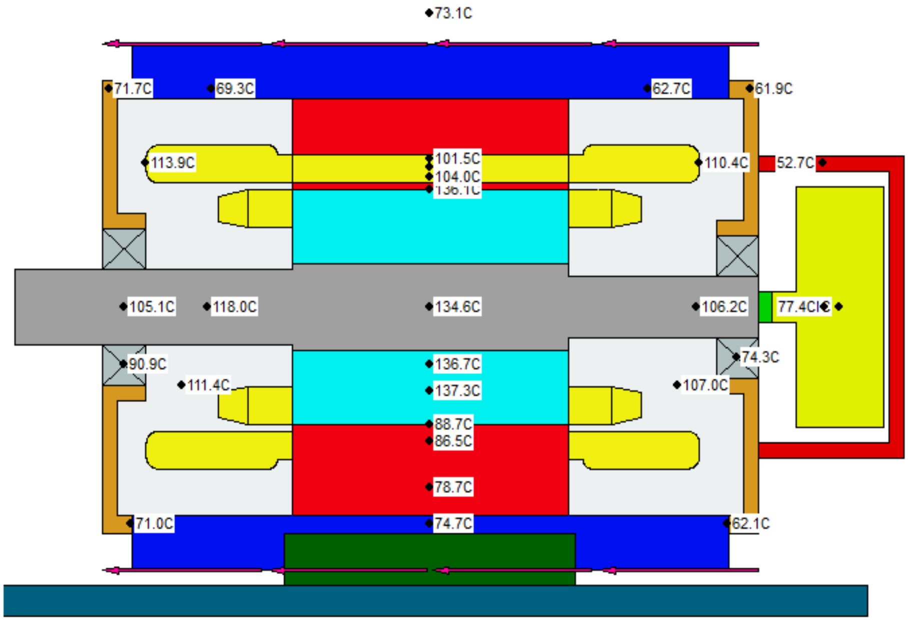


Figure 7. Axial view of the test motor temperature distribution by Motor-CAD

The temperature of each component of the test motor has been determined, at an ambient temperature of 40 oC. The losses of the test motor induction are used as the heat sources (stator and rotor copper losses, stator and rotor core losses), and inserted into the thermal model. The accuracy of the thermal model results at full load steady state obtained from Motor-CAD has been evaluated by comparing with the finite element method results obtained from Flux2D (Error1), and with the results obtained from Matlab/SIMULINK (Error2), as shown in Table 1. Figure 8 show the comparsion of the test motor temperatures at no load and full load conditions ,taken from the simulation of the test motor by the three software.

Table 1. Comparison of Steady State Temperatures of Different Motor Parts at Full Load

Motor part	Motor-CAD (°C)	Flux2D (°C)	Error1	Matlab/Simulink (°C)	Error2
Frame	75.85	84.4	- 10.27%	75	+1.12%
Stator yoke	79.76	87.7	-9.95%	77	+3.46%
Stator winding	104.15	104.6	-0.43%	97	+6.86%
Rotor bars	137.28	131.96	+1.72%	136	0.93%
Rotor yoke	136.6	129.98	+4.84%	137	-0.29%
Shaft	134.6	124.04	+7.84%	124	+7.87%

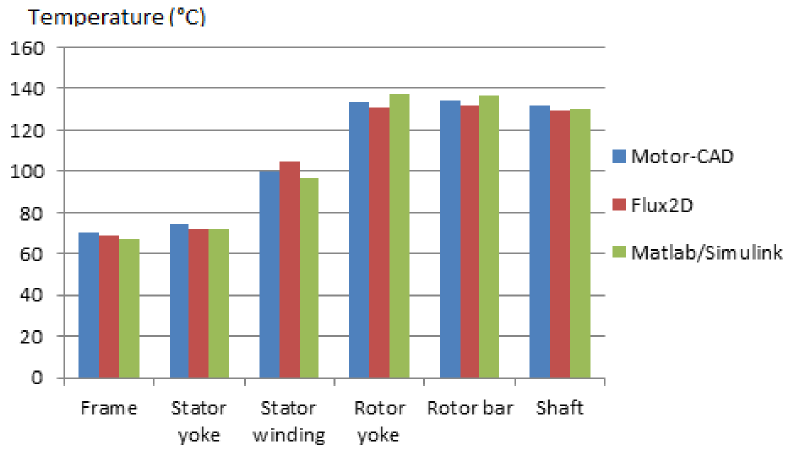


Figure 8. Temperature distribution of each motor part at full load

Figure 9 show the effect of changing motor loading (from no load to full load) on increasing of the test motor temperatures. Radial temperature distribution plotted from center of the shaft to the frame fins is illustrated in two curves: one for no load condition, and the other for full load condition.

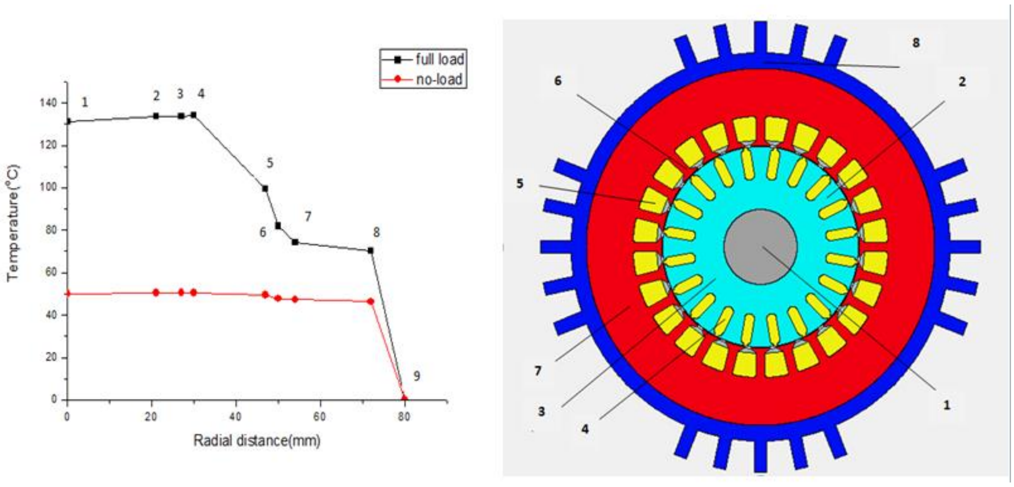


Figure 9. Temperature distribution of each motor part at no load and full load

8. CONCLUSION

In this paper, a thermal analysis of a TEFC, squirrel cage, three-phase induction motor has been performed successfully by approach use thermal network method (based on Motor-CAD and Matlab) together with finite element method (based on Flux2D) under full load steady-state condition. Motor-CAD results illustrate in a good manner all heat exchanges between different parts of the motor, so can be considered as the main software in this work. The results obtained from Motor-CAD show a good agreement with other results obtained from the other two software (Flux2D and MATLAB), which can be considered as a two comparative software. The straightforward methodology for this work can assist the motor designer to obtain well thermal motor results without needing to conduct tests based on a costly produced prototype motor.

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