Thermal Analysis of a Three-Phase Induction Motor with Frame Design Considerations

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Abstract. The present work investigates the temperature distribution inside different parts of a three-phase induction motor when motor frame dimensions (fins thickness, fins height, fins spacing) were changed, and when frame material is changed from cast iron to cast aluminum. A 2.2 kW, 2 poles, insulation class F, totally enclosed fan cooled (TEFC), squirrel cage, three-phase induction motor is modeled according to its design documents and it is analyzed by a thermal network method (TNM) based on Motor-CAD software. The results show the motor temperatures are in direct proportional with fins thickness, fins spacing, and in inverse proportional with fins height. In addition, the motor temperature will decrease when using the cast aluminum frame. The results were verified by finite element method (FEM) results obtained based on Flux2D software with a good agreement. This work will help the induction motor designer in prediction the thermal state of induction motor when modifying the frame, without needing manufacturing and testing expensive prototype motor.

1. Introduction

With the widespread use of different electric motors, maintaining these machines to extend their life is important and necessary. The housing of the motor is designed to protect the motor from damage such as hot, humid, corrosive, dry and other conditions. It helps to regulate the ambient temperature of the machine, making it cooler and reducing the chances of damage. It is demanded from electric machines to be with a small size, efficient operation, long life, and requiring minimum maintenance. To make smaller machines without decreasing the output power, or to have a more output power without increasing the size of the machine, it is important to get better cooling of the machine without the addition of external coolers. TEFC motors has a fan attached to the non-drive end (NDE) that drives the air along the frame fins, which usually runs along the axial direction of the device. This will give adequate cooling in the NDE, but cooling is reduced along the machine, so it is recommended to be more efficient and distribute the cooling. Motors with fins on the outer body have a fan at one end of the shaft, with a fan cover. When the motor is running, the fan forces air over the fins and cools the motor [1]. Although, there are much research works study the thermal analysis of a three-phase induction motor (without changing the frame design) based on : TNM as in [2], FEM as in [3], and both TNM and FEM as in [4], but the present work (as saw from reviewing the relevant researches) is unique in studying the effects of changing the dimensions of frame fins, and changing of frame material on the heat distribution inside a three-phase induction motor, by using TNM (Motor-CAD software) and FEM (Flux2D software).
2. Methods of heat transfer

Heat is transferred from one place to another in three ways: conduction, convection, and radiation. Conduction is the heat transfer between substances that are in related contact with each other. The heat transfer is happening in solids, liquids or gases. The rate of heat conduction depends upon the type of material, the shape, thickness and temperature differences. The thermal conductivity of material shows how good the heat transfer is in that material. The higher thermal conductivity of material makes it has better conduction compared with the lower thermal conductivity of a material. The conduction is happening when a substance is heated, particles will gain more energy and vibrate more, hence molecules collide with nearby particles and transfer some of their energy to them. This action continues and carries the energy from the hot end to the colder end of the material. The convection occurs when warmer areas of a liquid or gas rise to cooler areas in the liquid or gas. Cooler liquid or gas then takes the place of the warmer areas which have risen higher. The radiation is a method of heat transfer that does not rely upon any contact between the heat source and the heated object as in the case with conduction and convection. Heat can be transmitted through empty space by thermal radiation. This is a type of electromagnetic radiation. No mass is exchanged, and the radiation process does not require a medium [5].

3. Cooling fins

The rapid increase in power density of advanced machines and minimization of motion control devices have led to the emergence of improved cooling techniques to obtain high rates of heat dissipation. The most common method of passive cooling techniques is the use of natural convection flows that are stimulated and developed along hot surfaces due to gradients in fluids (air or liquid). In order to improve the motor cooling, it is recommended to increase the motor surface area exposed to the cooling air by putting the cooling fins directly on the motor frame. This surface area magnification will increase the heat transfer rate from the motor to ambient without changing other motor components [6].

4. Mathematical foundation

Heat transfer of motor with or without fins depends on Fourier law of heat conduction, and Newton’s law of cooling as follows [7]:

\[
\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (\lambda x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (\lambda y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (\lambda z \frac{\partial T}{\partial z}) + Q
\]

(1)

Where \( \rho \) is density of material, \( \lambda \) is the thermal conductivity of material, \( T \) is the surface temperature, \( q \) is heat flux, and \( Q \) is heat transfer, which can be calculated as follows:

\[
Q = h A \Delta T
\]

(2)

Where \( h \) is heat transfer coefficient, \( A \) is surface area, \( \Delta T \) is the temperature differential between the heat source and the ambient.

In TEFC machines with open fin channels, local fluid velocity can be more difficult to predict. The correlation used in Motor-CAD for open fin channel constructions that is of Heiles [8] and relies on testing on actual electric motors. In the correlation, it is assumed that the flow is always turbulent due to the fact that, the radial fans are used in these machines lead to turbulence. heat transfer coefficient convection (hc) is calculated as follows:

\[
h_c = \frac{\rho C_p v D}{4L(1-e^{-m})}
\]

(3)
\[ m = \frac{0.1448(L^{0.946})}{D^{1.16}(\frac{k}{\rho C_p}^{0.214})} \]  \hspace{1cm} (4)

Where:

- \( D \) is hydraulic diameter = 4 x channel area / channel perimeter (including open side).
- \( L \) is axial length of cooling fin.

Within the technical literature of heat transfer, there are many empirical relations that are used to predict the convection cooling of surfaces in electrical machines [9], [10]. For example, there are natural and forced convection relations from simple shapes such as open and closed fin channels in different shapes and sizes. Such relation is usually based on the dimensionless numbers: Reynolds (Re), Grashof (Gr), Prandtl (Pr), and Nusselt (Nu) numbers. For convection the typical form of the correlation is:

\[ Nu = a (Re)^b (Pr)^c \]  \hspace{1cm} (5)

Where a, b and c are constants given in the correlation. Also:

\[ Re = \frac{\rho v L}{\mu} \]  \hspace{1cm} (6)
\[ Gr = \beta g \Delta T \rho^2 L^3 / \mu^2 \]  \hspace{1cm} (7)
\[ Pr = c_p \mu / k \]  \hspace{1cm} (8)
\[ Nu = h L \]  \hspace{1cm} (9)

Where:

- \( v \) is the kinematic viscosity.
- \( k \) is the thermal conductivity of air.
- \( \beta \) is the thermal expansion coefficient.
- \( g \) is the acceleration of gravity.
- \( h \) is the convective heat transfer coefficient.
- \( c_p \) is the heat capacity.

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

**5. Motor 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 [11]. All dimensions of the machine were entered in the radial cross-section window of Motor-CAD as in figure 1. The temperature of each component of the test motor has been determined at an ambient temperature of 40 °C. The motor losses of the test motor are used as heat sources and inserted to the motor model.

![Figure 1. Test motor radial cross section by Motor-CAD](image-url)
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 is shown in figure 2.

![Figure 2. Materials of the test motor input to Motor-CAD](image)

The model can be solved by clicking the “solve thermal model”, to calculate the temperatures at different motor regions, as shown in the motor equivalent thermal model of figure 3.

![Figure 3. Equivalent thermal network of the test motor by Motor-CAD](image)

5.1. Modelling the frame fins with variable dimensions
The fins design of the motor frame has an important role in motor heat transfer. In the test motor, fins are provided on the frame, the amount of heat dissipated to air depends on the amount of air flowing through the fins. The default dimensions defined as 5 mm for fin thickness, 12 mm for fin depth, and 9 mm for fin spacing. We study the effect of changing the fin dimensions mentioned in figure 4(a) on the motor temperature, and changing frame type to round (without fins) as shown in figure 4(b).
5.2. Modelling with changing frame material
In addition, the present work studied the effect of changing material of motor frame (from cast iron to cast aluminum) on the heat distribution in the test motor at full load. This research activity shows the importance of using Motor-CAD for motor designers in studying the effect of changing motor materials (due to economic or emergency considerations) on its thermal behaviour.

6. Modelling 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.

7. Results and discussion
Simulations are performed by using Motor-CAD to obtain the temperature in six positions: frame, stator windings, stator yoke, rotor yoke, rotor bars, and shaft. Four cases studies of changing fin dimensions are taken into account, figure 6 shows the effect of changing fin thickness on motor
temperature, figure 7 for changing fin depth, figure 8 for changing fin spacing, and figure 9 shows the effect of decreasing the number of frame fins on increasing the stator winding temperature.

Figure 6. Motor temperatures vs fin thickness

Figure 7. Motor temperatures vs fin depth
From results obtained we see that, the increase in fin thickness will lead to a slight increase in heat in all parts of the motor (since we take a low fin thickness variation), the increase in fin depth leads to the reduction in heat dissipated from the motor, the increase in fin spacing leads to a slight increase in heat of each part of the motor, and remove fins from frame leads to high increasing in motor temperatures with respect to frame with fins as shown in figure 10.
To verify the motor parts temperature obtained from Motor-CAD at full load, full fins cast iron frame, we compare it with that obtained from finite element method software (Flux2D), as shown in table 1.

Table 1. Comparison of Motor-CAD results with Flux2D results

| Motor component | Results of TNM (Motor-CAD) | Results of FEM (Flux2D) | Error % |
|-----------------|----------------------------|-------------------------|---------|
| Frame           | 75.85                      | 84.4                    | -10.1%  |
| Stator yoke     | 79.76                      | 87.7                    | - 9.05% |
| Stator winding  | 104.15                     | 104.6                   | - 0.43% |
| Rotor bars      | 134.28                     | 131.96                  | + 4.07% |
| Rotor iron      | 136.6                      | 129.98                  | +5.2%   |
| Shaft           | 134.6                      | 124.04                  | +8.5%   |

Table 2. shows the effect of using the cast aluminum frame in decreasing the temperature distribution inside different parts of the motor, due to the high thermal conductivity of aluminum with respect to cast iron. The TNM results of Motor-CAD were compared with FEM results of Flux2D as in table 2 and figure 11.
Table 2. Motor temperatures comparison between cast aluminium frame and cast iron frame

| Motor Part   | Material     | Result of TNM using Motor-CAD (°C) | Result of FEM using Flux2D (°C) | Error % | Material     | Result of TNM using Motor-CAD (°C) | Result of FEM using Flux2D (°C) | Error % |
|--------------|--------------|-----------------------------------|---------------------------------|---------|--------------|-----------------------------------|---------------------------------|---------|
| Frame        | Aluminum     | 73.37                             | 81.9                            | -10.4%  | Cast iron    | 75.85                             | 84.4                            | -10.1%  |
| Stator yoke  | Silicon Steel| 76.68                             | 84.2                            | -8.93%  | Silicon Steel| 79.76                             | 87.7                            | -9.05%  |
| Stator winding| Copper       | 101.8                             | 99.9                            | -1.9%   | Copper       | 104.15                            | 104.6                           | -0.43%  |
| Rotor bars   | Aluminum     | 134.9                             | 127.30                          | -5.97%  | Aluminum     | 137.28                            | 131.96                          | 4.07%   |
| Rotor yoke   | Silicon Steel| 134.32                            | 125.41                          | -7.10%  | Silicon Steel| 136.6                             | 129.98                          | 5.2%    |
| Shaft        | Alloy Steel  | 132.38                            | 123.52                          | -7.17%  | Alloy Steel  | 134.6                             | 124.04                          | 8.5%    |

8. Conclusions

This work study the effect of changing frame material and fins dimensions of a three-phase induction motor on heat distribution at different parts of the motor. Thermal network method software (Motor-CAD), and finite element method software (Flux2D) were adopted in this study. The study was done in three stages: the first stage with changing the fin dimensions, the second stage with changing the number of frame fins, and the third stage with changing the motor frame material from cast iron to cast aluminum. The results obtained with the round frame (without fins) show that the motor temperatures were significantly increased with respect to fins one. The results show that the motor temperatures are
in direct proportional with fins thickness, fins spacing, and in inverse proportional with fins height. When we use an aluminum frame instead of cast iron, the motor temperature will decrease significantly. The results obtained from Motor-CAD were compared with that obtained from the finite element method of Flux2D, with a good agreement. This work will give the induction motor designer a straightforward thermal study approach to assist its motor design when changing frame design, without needing to manufacture a costly prototype motor, and without conducting complicated thermal tests.

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