Review of physical and mathematical modelling aspects of thermal management of induction motors

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Abstract. This review paper summarizes the importance of thermal management system and mathematical models used in the prediction of temperature distribution of an induction motor. The lumped parameter thermal network modelling approach is explained in detail with a suitable example. The recent computational methods and their pros and cons on estimating the temperature distribution are discussed. The experimental method on estimating equivalent value for thermal resistance and capacitance is highlighted from the literature. The understanding on physical mechanism of heat transfer is emphasized to recognize thermal flow path for better utilization of cooling techniques. The recent trend in coupling electromagnetic and thermal phenomena is also considered. This study will be helpful on future design of induction motor to meet difficult constraints.

1. Introduction

Thermal management of electric motor is important to avoid the overheating of the motor components and hence it increases the life of the motor. The coil burnout is the extreme case of failure due to sudden load variation, wherein the dielectric strength of the insulation material reduces significantly due to overheating, and also the insulating material temperature rises to ignition temperature. In the motor, the increase in temperature also affects the electrical resistance of the material and magnetic flux density. Hence, there is a reduction in efficiency of the motor. Since the motor failure is the major problem, thermal management system was incorporated even at the early stages of motor development. However, there is a variation in thermal management system based on different types of motor. Broadly it is classified as natural cooling, forced air cooling, liquid cooling, and oil spray cooling depending upon the applications. Since the new design demands for compactness, variation in load conditions in electric vehicles, cost and life, there is a necessity to review the physical principles and mathematical models of already existing motors and explore recent trends in cooling techniques to propose new technologies for future motor cooling.

The heat is generated in the winding and core of the machine is due to iron and copper losses. The heat is dissipated to the atmosphere through conductive, convective and radiative modes of heat transfer. During the development stages of motor, calculations with mathematical models and experimental testing are performed to ensure that the temperature of various elements should not exceed the threshold limits. The thermal flow chart obtained through the analysis of heat flow from the source to atmosphere provides important information to understand the overall dissipation of heat in the thermal management system [1].

Generally, the motor is represented with various components as shown in Figure 1. Since most of the components are placed in a cylindrical geometry, the direction of heat transfer is generally recognized into axial and radial direction depending on the temperature gradient. The understanding
on the thermal flow path of the given motor is quite important for better prediction on temperature and also to provide suggestions to overcome problems.

Figure 1. Cross-sectional view of induction motor showing various components in the upper-half portion and representation of heat flow in the lower-half portion.

Most of the earlier heat transfer problem is analysed with the help of equivalent electrical circuit analysis [2]. Lumped parameter is a special case, where the internal conductive resistance of the component is very less as compared with external convective resistance to maintain thermal equilibrium at every instant of time. This simplifies the thermal analysis of a motor by representing it as a thermal network model comprising elements of thermal resistance and capacitance.

The lumped parameter thermal network model (LPTNM) was introduced in detail for electrical machines by Mellor et al [3] for steady state and transient analysis. Many designers used the thermal network model, with variation in number of components and heat flow path [1] [4] [5] [6]. This lumped parameter approach gives reasonable accuracy on the prediction of the temperature.

The successful in numerical solution to conduction equation through finite element method (FEM) and also in computational fluid dynamics (CFD), it is currently possible to perform thermal analysis with more details [7]. These approaches are useful to identify presence of any hot spots in the motor and also helpful in identifying suggestions for improvement. The computational time and cost involved is significantly high as compared with LPTNM.

The recent demands for hybrid electric vehicles and other applications, there is significant demand in power density and dynamic changes in load conditions. This requires a review on existing techniques and explore possible cooling techniques. The usefulness of low-fidelity LPTNM and high-fidelity CFD models are considered in this review.

2. Physical aspects of thermal management system

The amount of heat generation, path of heat dissipation and cooling techniques are of fundamental interest for the improvement on the thermal performance of an induction motor. A brief introduction to lumped parameter analysis is presented here for better understanding of the problem. The basic components and the heat flow path with adjacent component are quite important for the thermal analysis. A representative diagram for stator and rotor alone is shown in Figure 2 (a). The equivalent thermal network is presented in Figure 2 (b) with thermal resistance and capacitance. The heat source for the motor is the electrical losses of the motor. Figure 2 (c) represents approximate percentage of major losses in the motor to relate it for heat source in thermal circuit. An equivalent electrical circuit diagram of single-phase motor is shown in Figure 2 (d) to estimate the losses. The usefulness of the Figure 1 and Figure 2 is discussed in other sections to relate it for physical understanding and mathematical modelling.
2.1 Heat generation in the motor

The current passing in the windings and magnetic flux in the core generate heat in the motor. The single-phase equivalent circuit of induction motor with resistance (R), impedance (Z), reactance (X), current (I) and induced electromotive force (E) of a single-phase motor is represented in Figure 2(d). By introducing subscript 1 for stator, 2 for rotor and m for magnetizing components, the power loss equivalent to heat power generation in stator, rotor and core is represented respectively with the following relations [4]:

\[ P_{cu,\text{stator}} = 3I_1^2R_1 \] \hspace{1cm} (1)
\[ P_{cu,\text{rotor}} = 3I_2^2R_2 \] \hspace{1cm} (2)
\[ P_{S,\text{core}} = 3 \left( \frac{E_2^2}{R_m} \right) \] \hspace{1cm} (3)

Apart from major losses, there is a stray loss in the motor due to load variation and windage loss due to air resistance for the rotor. It is to be noted that the electrical resistance of metals increases linearly with operating temperature, and hence the power loss also increases with the operating temperature.

2.2 Heat transfer

The heat generated in the motor due to various losses is dissipated to ambient by combination of three different modes, namely conductive, convective, and radiative mode of heat transfer. The respective heat transfer relations for the three modes are given below:

\[ Q_{\text{cond}} = KA \frac{dT}{dx} \] \hspace{1cm} (4)
\[ Q_{\text{conv}} = hA(T_s - T_\infty) \] \hspace{1cm} (5)
\[ Q_{\text{rad}} = \varepsilon \sigma S_B A(T_1^4 - T_2^4) \] \hspace{1cm} (6)
Heat conduction \( Q_{\text{cond}} \) takes place in a solid medium by the vibration of intact molecules, where heat alone transferred due to temperature gradient without transport of molecules from one region to another. The Fourier’s law of heat conduction is used in calculating conductive heat transfer, by the equation (4). The physical property of thermal conductivity (K) of the material, the geometric parameter of the area of cross section (A) through which heat is transferred and the operating parameter of temperature gradient \( \frac{dT}{dx} \) dictate the amount of heat transfer.

In the case of convective heat transfer \( Q_{\text{conv}} \), either natural or forced convection, the heat is removed from the surface by the fluid carrying the heat. The heat transfer coefficient (h) depends on buoyancy force for the case of natural convection. The Reynolds number and Prandtl number are important for forced convection. The velocity of flow; viscosity, thermal conductivity, and specific heat capacity of the fluid; along with geometric properties dictates the amount of heat transfer.

 Radiative heat transfer \( Q_{\text{rad}} \) take place by radiation of heat from one surface to other without any medium. It depends on temperature power four and emissivity \( \varepsilon \). The proportionality constant in radiative heat transfer \( \sigma_{SB} \) Stefan-Boltzmann’s constant \( (5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4) \) [2]. The radiative heat transfer is comparatively less within the internal components of the motor. It contributes from the outer frame to ambiance.

To enhance heat transfer, few techniques are used. These techniques are discussed below.

### 2.3 Cooling Techniques

The major cooling techniques are as follow:

1) Fins
2) Fans
3) Liquid cooling and oil spray
4) Heat pipes

Fins are extended surface to increase the area of contact between the heat conduction and convection. If the surfaces are rougher against smooth, then there will be enhanced heat transfer due to increase in local turbulence. Heat sinks are used in electronic circuit cooling. Identification of local hot spots and incorporation of heat sinks may be helpful.

Generally, a fan is mounted on the rotor shaft to provide more cooling air. It enhances the velocity of the air and hence the convective heat transfer becomes effective. Separate variable speed fan is useful when there is frequent change in motor load and heat removal.

Liquid cooling technique is used in large induction motors either by a jacket or duct structure. Water and oils are used as coolant.

Heat pipes uses phase change materials to extract the heat.

### 3. Mathematical modelling aspects of thermal management system

Lumped Parameter Thermal Network Model (LPTNM), numerical solution to conduction equation through Finite Element Methods (FEM) and combined conductive, convective and radiative heat transfer through Computational Fluid Dynamics (CFD) are commonly used in the prediction of temperature distribution at various parts of the motor. The fidelity level increases with increasing computing power, introducing more physics in the models, better resolution on computational domain with fine grids in the high gradient regions and appropriate boundary conditions.

#### 3.1 Solution to system of ordinary differential equations in LPTNM:

It is one of the oldest methods [3] on building thermal network based on thermal resistance \( R_{th} = \frac{dT}{Q} \), thermal capacitance (mass x specific heat) and heat sources. The conductive thermal resistance depends on the material and geometric properties. Generally, cylindrical components are used in most of the parts, and it is straightforward to estimate conductive resistances [3]. The convective resistance dependents on Reynolds number, Prandtl number and geometric properties.
These resistances are built on thermal flow path by specifying each component as a node [3] [4]. For each node, the temperature variation with time is written as ordinary differential equation as:

$$\rho C_p V \frac{dT}{dt} = Q_{in} - Q_{out} + Q_{generated}$$

(7)

Here, \( \rho \) is density and \( V \) is volume to account for mass of the component. The \( Q_{in} \) and \( Q_{out} \) represents the heat transfer with the adjacent node in the thermal network model. The \( Q_{generated} \) is estimated based on electrical power loss of the motor. Numerical solution to the equation (7) provides time history of temperature at node points.

LPTNM is quite extensively used at the preliminary stages of design. The accuracy of prediction depends on the model considering the flow path and incorporating as many components as possible. In literature, two components model with the resistance and capacities from special experiments [8], four element model [9], ten element model [3] [4] and hundred and seven node models [5] are available.

For example, a 1.5 kW motor of Badran et al [4] is selected for analysis. A simple two element stator and rotor model is considered first to demonstrate the working principle. This analysis is extended with four nodes and six thermal resistances model. The four nodes are stator iron and frame, stator winding, rotor iron and rotor bar and end-winding.

The predicted rotor and stator temperatures are 304.5 K, 305.2 K respectively for two component model and for four model the temperatures are 306.4 K, 307 K, 307.2 K and 307.4 K respectively for four nodes of stator frame, stator winding, stator iron and rotor bar. These models take very less time of few minutes in MATLAB.

The simple thermal network can be added with additional details by considering various nodes and thermal resistances in the thermal flow path. The accuracy of the prediction depends on the increasing the number of nodes and the model parameters used in the network.

3.2 Numerical solution to heat conduction equation through FEM

In this approach the heat conduction equation is numerically solved in the solid domain. Though one can use basic finite difference method, finite element method is commonly used. It is easy to construct unstructured grid in the complex computational domain, and hence FEM is preferable. The boundary conditions are important to account for convection. The solution accuracy is improved by incorporating fine grids and higher order methods [10].

$$\frac{1}{r} \frac{\partial}{\partial r} \left( k_r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( k_{\theta} \frac{\partial T}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) + q_v = \rho C_p \frac{\partial T}{\partial t}$$

(8)

Where: \( k \) is thermal conductivity, \( \rho \) is density and \( C_p \) is specific heat capacity.

3.3 Combined fluid flow and heat transfer simulation through CFD

In this approach the fluid domain solved for continuity, momentum, and energy equations. In the solid domain, the heat conduction equation is solved. At the interface, the temperature data is exchanged. In this way, it couples both conduction and convection (mode of)heat transfer.

The fan is generally modelled with fan performance curve. The radiative heat transfer is also included in the CFD simulations. Further, it is possible to incorporate heat pipes in the simulation.

The 3-D grid generation is the first phase of the CFD. Generally, many commercial software are available to solve the set of governing equations. Grid study is required to assess the accuracy of the solution. Mostly, the steady calculations are recommended for CFD simulation.

The computational cost involved is much higher with complete CFD simulations. On the other hand, it provides detailed temperature distribution at various parts in more accurate way. It is possible to visualise the details on temperature and velocity distribution in the fluid domain. This visualisation of fluid path and temperature helps to identify any flow path modification and also helps to avoid local hot spots.
4. Experiments on thermal management of motors

The experiments related to thermal management system mainly uses temperature measuring instruments like thermocouples, liquid expansion thermometers and electrical resistance thermometers. The major purpose of measuring the temperature distribution and the consequence thermal analysis is to estimate the heat loss from various elements [1] and identify the thermal flow path and suggest for improvement in the thermal design. The experimental temperature data with all the geometric and material properties of motor serves as validation test case.

4.1 Experiment to determine losses of the motor

Heat generated in the motor is equivalent to the losses associated with the major elements of the motor. Hence, it is important to know the losses produced in the motor to predict the temperature of the motor. Specifications of the motors will not give the values of losses. The specifications may include the values of equivalent circuit parameters. Losses of the motor can be calculate using equivalent circuit parameters. If not mentioned, tests have to be conducted on IM to determine the losses in the motor [4].

No-load and blocked rotor tests are conducted to determine the losses in the motor. No-load test determines the core / iron losses in the motor. Blocked rotor test is conducted to find the value of copper losses in the windings of the motor. These tests also determine the values of the equivalent circuit parameters of IM, i.e. stator resistance (R1), rotor resistance (R2), stator reactance (X2), rotor reactance (X2) and magnetizing reactance (Xm).

4.2 Experiments to determine the parameters for thermal model

Equivalent thermal conductivity and coupling coefficient of motor can be found out, by feeding DC source with different voltages, by variable AC source and frequency with rotor blocked and variable load. The circuit of these test are as shown in Figure 3 (a), (b) and (c). It uses variable frequency drive (VFD) and variable voltage source (VVS). The measured equivalent circuit parameter values help to estimate the losses of IM at various operation conditions [8].

![Figure 3. Tests to find circuit parameters of IM (a) DC test on IM (b) VFD connected to IM (c) VFD along with VVS connected to IM.](image)

5. Future trends and technologies

5.1 Improvements in materials

The rotor material selection to be of lower electrical resistivity to account for lower rotor loss as well as better magnetic property. A study showed that the change from cast aluminium rotor to copper squirrel cage rotor increases the efficiency from 81.7 % to 86.3 % [11]. The material for stator core is recommended from non-grain-oriented silicon to grain-oriented silicon steel [12] and amorphous magnetic metal for better magnetic properties [13]. The insulating material plays a crucial role in thermal management system. Thermal conductivity of the insulating material is significantly increased through significant research effort in the last decade. The current high-grade insulating material is capable to withstand maximum hot spot temperature of about 250 °C. Copper is mostly used as
winding material. The material research to be in the direction of identifying better alloy with lesser temperature dependence on electrical resistance will be helpful.

5.2 Improvements in thermal flow path

The status of motor cooling is towards micromanagement of heat transfer by investigating thermal flow path. For high power density machines, liquid cooling channel is proposed to place in the stator tooth apart from the main cooling channel in the frame region [14]. The polymer material used in the core of the machine is added with metal nano powder to improve the thermal conductivity of the overall block [14]. The air pockets in the insulation materials can be removed by vacuum pressure impregnation process for stator encapsulation. This helps on better heat transfer.

In the case of fan cooled motors, the amount of air passing through the motor is split into inner and outer air circuit. This can be achieved by modifying the air flow passage in the motor. There may be two fans to control in inner and outer cooling. By this arrangement, there are two types of cooling is achieved namely enclosed fan cooled (EFC) motor and an open fan cooled (OFC) motor. In the case of EFC, the inner air circuit is closed, and heat removal of inner circuit air is through the external frames, where the external frames are cooled with outer air cooling [15]. This EFC has an advantage for large motor to use better thermal conductivity gas such as hydrogen for inner closed loop circuit, to enhance heat transfer. The lower molecular weight of hydrogen helps in reduction in windage losses. The OFC arrangement of convention cooling where all the air enters on one side and leaves at the other side, but the air split to inner and outer makes the effectiveness in the cooling [16].

5.3 Combined thermal and electromagnetic analysis

Significant amounts of research work were carried out in the past on the electromagnetic circuit and performance improvements in the motor. The cooling of motor was given attention in the recent past to design high power density motor with extension of life. These two streams are evolved separately in the past. The current and future trend is to combinedly analyse magnetic circuit design and thermal analysis even at the conceptual design level. Inclusion of both the effects at the preliminary design level will helps to predict the performance and temperature distribution with better accuracy.

There is other motor design with axial magnetic flux instead of radial magnetic flux [17]. It helps in compact construction, improved efficiency, and better ventilation and cooling.

5.4 Active thermal control and protection

The coolant flow rate is one of the important parameters in convective heat transfer techniques implemented in motor cooling. Control of coolant flow rate with the help of microcontroller utilising sensors for load variation and active components of variable speed fans and pumps is expected to provide improvements in cooling performance. Incorporation of spray cooling in the control system helps to overcome excessive local heating [14].

The protection of motor from overheating and failure is managed with the help of fuses and overload relays. Microprocessor-based thermal overload relays are also available to prevent catastrophic failures. Active thermal protection technique with non-intrusive temperature estimation techniques is also proposed with moderate torque pulsation techniques [18].

As a summary, the motor application in the automotive, aerospace and other domain is emerging to meet stringent requirements to meet frequent variation in load, weight reduction, compactness, better efficiency and more life. It leads to utilization of better materials, improved design for magnetic circuit and thermal flow path optimization, control and newer technologies.
6. Conclusions

The physical insight on enhancing heat transfer and mathematical aspects of thermal analysis of induction motor are reviewed. Commonly available heat extraction techniques and recent developments are considered in this study.

The LPTNM is simple and attractive for temperature prediction. This model is still going to play important role at the preliminary stages of design. This model can be improved by considering many numbers of nodes on various components and accurately incorporating thermal flow paths. Development of complex network and improving the accuracy of the prediction is going to be challenging.

Calculation of conductive heat transfer with appropriate boundary condition is computationally cost effective as compared with CFD. Most of the thermal process and phase changes in heat pipes can be appropriately modelled in CFD.

Though the magnetic circuit calculation and thermal analysis are separately done in the past, the current trend is to include changes in temperature effect on electric resistance and magnetic properties in the design of magnetic circuit calculations. The overall calculation is of coupled way to provide the losses from magnetic circuit to account for heat generation in thermal calculation and predicted temperatures to account for changes in material properties on magnetic circuit calculation.

Depending on the application and motor rating, different cooling techniques are available to implement. The recent developments on materials, thermal flow path design, control techniques and protection system to prevent catastrophic failures are considered for efficient design.

Acknowledgement:

The authors thank publication committee of Ramaiah University of Applied Sciences for allowing to publish this work.

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