Thermal Analysis and Temperature Distribution of Two-Layer and Spoke-Type Ferrite Interior Permanent Magnet Machine

Hayder Abdulraham
Electronic and electrical department
University of Thi-Qar
Nasiriyah, Iraq
Email: hayder.alrubyee@gmail.com

Patrick Chi-Kwong Luk
School of Water, Energy and Environment (SWEE)
Cranfield University
Bedfordshire, U. K
Email: p.c.k.luk@cranfield.ac.uk

John Economou
Centre for Defence Engineering
Cranfield University
Shrivenham, Swindon SN6 8LA, U.K
Email: j.teconomou@cranfield.ac.uk

Abstract- The main requirements for a rotating electric machine are the torque/power density and the energy efficiency. Producing an efficient electric machine required not only studying and analysing the electromagnetic properties but also deeper thermal analysis. It has been found that attention to the thermal design can be improve the total machine performance. In this paper a thermal model of the two-layer and spoke-type ferrite interior permanent magnet (IPM) machines is developed. FEA models are built to run the thermal studies and temperature distribution of the machine under different operating conditions. A prototype machine is built and tested for the experimental validations of the FEA. A prototype machine is tested under various working conditions. The testing results validate analytical model and the FEA methods.

1. Introduction
The performances of a rotating electric machine were governed in the past by its electromagnetic design with less attention to thermal analysis. Motor designers have only superficially dealt with the thermal design aspects, maybe by specifying a limiting value of current density. Nowadays, an impressive effort is done to improve the efficiency even with a small fraction without compromising the torque density. With increasing availability of high-performance computing and the acute interest in efficiency improvement it is now necessary to analyze the thermal circuit to the same extent as the electromagnetic design. Both designs are in fact interrelated [1,2]. Not only are the losses depending on the temperatures and vice-versa, but more complex issues arise at the design stage However, the number of published technical papers relating to the thermal analysis of electric motors is still many orders of magnitude fewer than those associated with electromagnetic analysis. The published papers to date highlight a number of thermal design issues that are more difficult to analysis than others. Electric-motor thermal analysis can be divided into three basic types: analytical lumped-circuit, numerical methods and FEA calculations. The analytical approach has the advantage of being very fast to calculate; however, the developer of the network model must invest effort in defining a circuit that accurately models [2–5] the main heat-transfer paths. The analysis consists of the calculation of conduction, convection, and radiation resistances for different parts of the motor construction. The formulations for such resistances are really quite simple. The conduction resistance is equal to the path length divided by the product of the path area and the materials’ thermal conductivity. The convection and radiation resistances are equal to one divided by the product of the surface area and the heat-transfer coefficient. An accurate FEA solution requires the knowledge of the thermal parameters and a superficial knowledge of the geometrical and material properties used in a machine construction is often not sufficient to give an accurate prediction of the thermal performances. The main role of FEA is in the accurate calculation of
conduction heat transfer in complex geometric shapes, such as heat transfer through strands of copper in a slot. For this problem, FEA analysis can be used to calculate the equivalent thermal conductivity that can then be used in the network analysis [6]. A comprehensive understanding and modelling of the loss production mechanism are required to accurately predict the main heating source in the machine.

In this paper a thermal FEA model is proposed for the novel two-layer spoke-type ferrite IPM machines based on the equivalent thermal circuit., to predict the temperature distribution in IPM motors. Then, a model is presented It considers that: (1) the flux waveform in the yoke and tooth are trapezoidal with regard to time; (2) the eddy current loss is proportional to the square of time change rate of the magnitude of flux density. and finally, a prototype machine is tested to validate the developed analytical model of the two-layer spoke-type ferrite machine The specification of the machine is given below together with the experimental results. The experimental results show an acceptable prediction of the total temperature distribution using FEA model.

2. **Machine Specification**

The structure of one layer spoke type machine shown in the Error! Reference source not found. general sizing parameters are listed in table I [9]

![Fig. 1. Models of two-layer configurations](image)

| Table I | General Sizing Parameters |
|---------|---------------------------|
| Parameters | Value | Unit |
| Stator Outer Diameter (Dso) | 160 | mm |
| Rotor Outer Diameter (Dro) | 94.5 | mm |
| Air gap Length (g) | 0.25 | mm |
| Stack Length (l) | 90 | mm |
| Base Rotating Speed | 1500 | rpm |
| Number of Poles (p) | 6 |  |
| Number of Slots (q) | 36 |  |
| Lamination Material | 50CS470 |  |
| PM Material | Y30 |  |

3. **FEA Thermal Model**

The cross-section of the machine is given in Fig1 Error! Reference source not found. the winding is 3-phase with 6 coils per phase giving a single layer winding with a coil pitch of 6 slots. The rated current was 6.2A and the speed fixed at 1200rpm. The frame size was 160mm with an axial core length of 90mm To carry out an accurate thermal analysis, it is necessary at first to find the amount and location of heat generation. It would be essential to calculate the losses in copper and that caused by the magnetic field
using the finite element method, and from there to carry out a thermal analysis using the resulting loss distribution. Table II shows the loss in each part of the motor at rated load and speed. Copper loss in the coils and iron loss in the core are the dominant heat sources, so this analysis mainly evaluates the effects of this heat. The loss in the coil is relatively large, about 2/3~3/4 of the total loss, so it is expected to be the main source of heat.

| Heat generation parts | Iron loss in the rotor core | Iron loss in the stator core | Iron loss in the coils |
|-----------------------|-----------------------------|----------------------------|-----------------------|
| Losses (W)            | 9.49                        | 38.28                      | 117.8                 |

According to the structure of the designed ferrite IPM machine, a thermal circuit model is built and shown in Fig 2. The square blocks in the circuit represent the motor’s core parts that generate and transmit heat, and they are meshed in FEA simulation. The circle blocks represent the surroundings and ambiences, and they absorb the heat from inner motor.

The resistance signs are illustrated as thermal resistance among the square and circles blocks, such as thermal resistance between coil and stator core, stator core and cover, cover and air, and so on. The capacitor sign attached to cover is heat capacitor, and the cover’s heat capacity is related to its volume, density and specific heat. All the heat will eventually transfer into the ambient air.

4. FEA Results

4.1. Temperature Distribution at Steady State
The simulation of thermal circuit model is carried out with rated motor load. The motor operates continuously until a thermal balanced state is reached. The final balanced state is also called steady state, and the temperature distribution of it is shown in Fig.3.
According to the temperature distribution, the motor is generally divided into three thermal regions: the copper coils, the rotor and the stator. The highest temperature region is the copper coils, as copper loss is the dominant source of heat. The highest temperature is about 104°C. Most of the heat from the coils is transferred to the cover through the stator core, and the rest goes through the air inside of motor to the cover and finally dissipates to the ambience. The moderate temperature region is the rotor. Since ferrite PM is non-conductive, no loss is generated in magnets. The heat accumulated in the rotor is mainly from its iron loss. As the majority of the rotor’s surface area is encompassed by air, which has high heat transfer resistance, it is hard for the rotor to dispel the generated heat. The accrued heat increases the temperature of the rotor and the magnets imbedded. The rotor has higher temperature than the stator core. Most of the heat generated in the rotor flows through the air around it and then to the stator and cover, and the rest is transferred to cover through the bearings and shaft.

To further understand the process of temperature changing, the temperature of some typical points in the motor are measured and compared. The measuring points are shown in Fig 4.

The temperature of the four points increase fast in the first two hours and gradually become stable in the last two hours. The highest temperature appears in the coil. As the main source of heat comes from copper loss, the winding temperature is growing faster at the beginning and more than 10°C higher than other measuring points at the end. In the first 100 minutes, the temperature of stator core is higher than rotor core and magnet, but it is exceeded later. The losses in the stator are much higher than rotor, and
the stator temperature rises much faster than rotor at first. However, the rotor has worse heat dissipation conditions as it is surrounded by air and the heat generated in rotor is difficult to transfer to the outside; while the stator core is directly (interference) fitted to motor housing that transfer the heat from stator efficiently. The accumulated heat in rotor makes it hotter than stator in relatively long running time. The results are consistent with the temperature distribution of steady state in Fig 5.

4.2. Continuous Operating Time at Over-Load Conditions
In some applications, motors are required to work in overload conditions for a short while. The overload ability is an essential characteristic to evaluate a motor and useful for motor selection. Larger output power requires larger input current. Although increasing the current produces a higher torque, it also boosts the heat generation in terms of copper losses and core losses. Owing to the large input current, the copper losses generated in the windings increase exponentially. Along with coil temperature surging up, the resistivity of the copper rises, which further deteriorates the copper losses. The iron losses in stator and rotor cores are also increased due to the large armature reaction of the designed IPM machine. Accordingly, the temperature of stator and rotor will increase dramatically with current, and the properties of the ferrite PMs will be worsening by high temperature. Therefore, it is vital to find the longest consecutive operating time under over load condition before causing any irreversible damage. The rated current is 6.2 A (RMS value), designated as 1C, and the corresponding average torque is 13.32 Nm, designated as 1pu. When the input current is increased from 1C to 3C, the output torque grows from 1pu to 3.1pu, which are summarized in Table III.

### Table III Current and average torque

| Input Current | 1C | 2C | 3C |
|---------------|----|----|----|
| Average Torque (pu) | 1 | 2.1 | 3.1 |

The enameled copper wire used in the designed motor is in thermal Class H (180°C), and the temperature limit is indicated in green dash-dot line in Fig 6. The shape of the temperature variation lines with various currents is similar but slop of them is different. The larger the input current, the steeper the temperature changing line is. In rated load condition (input current is 1C) the temperature of the coil is always under the temperature limit; in double load condition (input current is 2C) it takes about 13 minutes to reach the temperature limit; and in triple load condition (input current is 3C) the coil’s temperature exceeds the temperature limit in about 3 minutes, which is much shorter than double load condition. The magnet material used in the designed motor is ferrite Y30, the maximum working temperature of which is 180°C that is indicated in green dash-dot line Fig7.

Fig. 6. Temperature variation of the coil with various currents
Similar to the temperature variation of the coil, the temperature trend of the magnet with various input currents have similar shapes but different slops. In the rated load condition (input current is 1C) the magnet’s temperature stays under 70°C; in double load condition (input current is 2C) it does not reach the temperature in the 78 minutes running time; and in triple load condition (input current is 3C) the magnet’s temperature exceeds the temperature limit in no more than 34 minutes.

5. Experimental Validation

The stator, rotor, shaft and PMs of the two-layer ferrite IPM prototype machine are demonstrated in Fig 8, and the dimensional specification is listed in table I. The setup of the testing rig for loaded experiments is depicted in Fig 9. The IPM prototype machine is powered by TI HVDMC Kit. The torque sensor is connected directly to the motor shaft to measure the output torque. The programmable dynamometer is connected to the other side of the torque sensor to provide required loading.

![Fig. 7. Temperature variation of the magnet with various currents](image1)

![Fig. 8. Models Of Two-Layer 2kW proposed machine](image2)

![Fig. 9. Setup of the testing rig. Of IPM](image3)
The prototype machine is tested with different load conditions (0.5, 1, 2, and 3) times rated power. Fig 10 and Fig 11 show how the thermal sensors are installed in different positions of the tested motor to generate data for this work.

![Thermal props installation](image1)

![Motor with the thermal props installation](image2)

The Motor is thermally monitored by K-type wired thermal meter and sensors. Sixteen sensors are used on the end winding (one for each phase), other sensors are insert inside a stator slot. The last sensors group is in a hole positioned in the stator core. This measurement set up allows measurement of the winding and iron core temperatures during the tests. The housing temperature can be measured by Infrared thermal meter.

As shown in Fig 12, 16 thermal probes are divided in two groups, and each group has 8 probes and numbered from 1 to 8. Measure point 2, 3, 4, and 5 are fixed on the surface of copper windings, where point 2 is around the corner between winding and stator teeth. Measure point 1, 6, and 7 are fixed on the top surface of stator core, where point 6 is at the corner between winding and stator core. And measure point 8 is mounted on the inner surface of housing frame.

![Cross-section of stator end and thermal measuring points](image3)

When all the thermal probes have been properly adhered inside of the motor housing, the prototype motor is reassembled and installed on the testing rig. As shown in Fig 9 the setup of the thermal testing consists of two groups of thermal probes, a wired thermal meter and a infrared thermal meter. The wires of the first and second group of thermal probes are bundled in red and blue heat-shrink tube respectively.

6. Experimental Results.

Several results were run over time however here we will concentrate on four sets of results. Since the relative measuring positions of the two groups of thermal probes are same, the temperature results will be the average of the two groups. Before the starting of the motor, the temperatures of all the parts of the machine are same, which is the ambient temperature 27.2 °C. To compare with simulation results conveniently, the beginning temperature is adjusted to 20 °C while the temperature increases are kept unchanged.
The thermal test of the designed ferrite IPM motor takes 240 minutes and the measuring results are displayed in below figures.

![Fig 13 Measured temperature of the ferrite IPM motor](image1)

![Fig 14 Temperature distribution of the motor](image2)

As shown in Fig 13, the temperatures of the motor grow fast in the first hour and gradually slow down in the second hour. After two hours of running, the motor is getting into thermal balanced state, and there is no much variation of its temperature in the last two hours. Although the temperature growing rates are different for these various measuring positions, there is no cross lines in the temperature changing curves. That means all the measuring points keep the same thermal gradients all the time, and the temperature distribution of the motor at steady state is depicted in Fig 14. The temperature sequence of the measurement is: Probe 4 > Probe 3 > Probe 5 > Probe 2 > Probe 1 > Probe 6 > Probe 7 > Probe 8 > Cover. Because the copper loss is the primary heat source, the temperature of the winding increases rapidly and is always higher than any other part of the motor. Since all the generated heat is transferred from the inside to the outside and the area near the housing is cooler, the temperature of point 5 is slightly lower than that of point 3. The point 2, at the corner of copper coil and stator tooth, is heated by the winding but is easier than point 3, 4 and 5 to dissipate its heat as it is adhered to stator core.

7. Comparison with experimental

The thermal testing results of the designed ferrite IPM motor are compared with its simulation results that are obtained in previously. The comparison of copper coil temperature and stator core temperature are depicted in, Fig 14 and Fig 15 respectively.

| Table IV Comparison of steady state temperature |
|-----------------------------------------------|
| Analysis (°C) | Stator | Copper Coil |
| 98.5 | 115 |
| Simulation (°C) | 88 | 106 |
| Experimental(°C) | 90 | 108.5 |
The analytical results show about 7% higher temperature than the FEA one and 10% higher than experimental test. There are two main possible explanations for this difference: firstly, it is difficult to calculate the accurate coefficient of heat transfer for the thermal equivalent circuit, secondly, the radiation effect has been ignored in analytical model. However, the results of the proposed analytical model still show a good agreement and Therefore, it can be an effective method to predict the temperature of the two-layer spoke-type ferrite machine in the design process.

In the first half hour, the temperature results of experiment have good agreement with that of simulation, as shown in Fig 15 but after that the experimental temperature is about 2°C higher than the simulated temperature. This might be because the actual thermal testing is conducted in a closed room and the ambient temperature is increasing during the experiment, which is caused by the heat that is generated.

Fig. 15. Temperature comparison of copper coil

Fig. 16. Temperature comparison of stator core
from the running motor. But the ambient temperature in the simulation is set to be constant, no increase during the operating process. Since there is no direct measurement that is carried out at the same position where is sampled in the thermal simulation. According to the sampling position in Fig 4, the stator core temperature at the corresponding position is estimated from the temperatures of its nearby measuring point 6 and 7 and compared with simulated results in Fig 16. The actual testing stator core temperature grows a litter faster than the simulated temperature, and all get into balanced state after around 150 minutes. The testing temperature is larger, and the largest difference is about 4°C happening around the 60th minute. And in the steady state the temperature is about 1.5°C. The difference of the stator core temperature may be caused from the inconsistency of lamination material.

8. Conclusion
This paper proposed a thermal equivalent circuit of a Two-Layer Spoke-Type Ferrite Interior Permanent Magnet Machine to estimate the temperature. A FEA model has been developed (using a combination of an electromagnetic analysis is and a thermal model) to Comair the analytical results. The results show that the proposed thermal equivalent circuit method can be a effective method to estimate the temperature distribution in the motor in the design process. From the FEA simulation and experiment test, it’s seen that the high temperature region is the winding, as copper loss is the dominant source of heat. The moderate temperature region is the rotor, in which the heat is accumulated from its iron loss. Because the heat generated in the stator core are easier to be dissipated into ambient air, the temperature of which is relatively low. Moreover, the consecutive operating time of the ferrite IPM machine is determined by the thermal limitation of enamelled copper wire. The FEA results show that the motor can continually work for 29 minutes in double load condition, but it can only last for 5 minutes under triple load. Finally, a prototype machine is tested to validate the developed analytical model and FEA model of the two-layer spoke-type ferrite machine

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