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Thermal Modelling for Permanent Magnet Synchronous Machine (PMSM)

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ABSTRACT

It is important to predict the temperature in some of the essential parts in machine design to prevent the machine from any damage. Most researchers usually not given much attention on thermal analysis during machine design as much as the electromagnet design. Therefore, in this study, two types of thermal modelling were proposed to predict the temperature of a permanent magnet synchronous machine (PMSM). Infolytica ThermNet software has been used since the software is related to Infolytica Magnet and the losses obtained from the electromagnetic field analysis are used as the heat source in the thermal analysis. Comparison has been done between the predicted temperature from lumped parameter model and finite element analysis. The results also will be validated by using experimental setup. Since Infolytica Magnet has been used to analyse the electromagnetic output therefore finite element analysis model is the better choice.

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1. INTRODUCTION

Major challenges are faced in determining accurate values for thermal parameters such as the thermal conductivity of the composite mixture of conductors and potting materials within the slot, or thermal resistance between the stator lamination and the frame. It is extremely important to model the heat transfer behaviour in electrical machines properly, at least to some degree, as this defines the cooling capability and consequently the nominal power of the machine. Generally, the heat-transfer might be different if the machine is cooled with water instead of air. Accurate modelling of heat transfer is practically impossible without finite element analysis due to the complex three-dimensional geometries involves. Despite the fact that faster microprocessors are available, 3D FE analysis is still too time-consuming when used for dynamic thermal analysis, and often different kinds of analytical methods are applied to model the heat transfer in the machine instead.

There are three main types of thermal machine models: analytical modelling, lumped-circuit models and finite-element analysis. Analytical modelling is useful for obtaining physical insights into simple thermal problems, such as the temperature distribution within a slot. Meanwhile, a lumped-circuit model has intermediate complexity between analytical modelling and finite-element analysis [1]. It provides a rapid solution which can be utilized within optimization loops while still retaining good physical insights into the model structure. However, the most accurate method is finite element analysis, which can take into account the detailed motor geometry. At the same time, computational fluid dynamics (CFD) also becomes another choice for researchers [2], [3]. The researcher must choose which type of thermal modelling to use. Some choose just one type and some combine or compare more than one type of thermal modelling. Table 1 states the reasons why each thermal modelling type should be applied.

Table 1. Types of thermal model

Lumped parameter	FEM Modeling	3D CFD Calculation
a. Gives a rough estimate of the hotspot very quickly. b. Takes much less time. c. Accuracy higher than 2D FEA. d. Easy to use. e. With greater computational capabilities it will be much more detailed. f. Efficient, robust mathematical routines are used in the network solver.	a. The solution process is straightforward and does not require a lot of computational time. b. Better with a more complex component shape. c. Clearly illustrates more accurate and finer details in the conducting regions due to unsymmetrical flux density and related power loss distribution inside the machine.	a. The selection of optimal cooling flow for the selected thermal regime becomes straightforward. b. 3D transient thermal model, determining the temperature rise of the stator windings accurately. c. Reliable way of obtaining heat transfer coefficients or static temperature distribution. d. Very accurate.

However, each type of the thermal model has weaknesses. FEA modelling needs more time to build the geometry in order to use this method for thermal analysis. Thus, it is very time-consuming. Meanwhile, besides being an expensive and very slow process for CFD thermal modelling, it is also very time-consuming because there is a need to properly define physical material properties and boundary conditions and it is only applicable for steady state conditions [4]. It is important to model and analyse thermal behaviour in order to achieve the desired output. The most temperature-sensitive parameters for PMSM are stator winding resistance and the demagnetisation characteristics of the permanent magnet.

2. RESEARCH METHOD

2.1. Lumped Parameter Model

The lumped parameter model has been the most common approach for the thermal analysis of electric machines during the past few decades. It is the simplest way to analyse the thermal field based on the eddy current loss which is derived using Motor-CAD software package. During this analysis, an accurate thermal resistance network using a T-equivalent lumped-parameter network is defined. The components with similar temperatures are lumped together to represent a single node. Then, thermal resistances are placed in the circuit to separate the nodes, so that the model also shows the heat transfer pathways in the machine [5]. In addition, the power sources are placed at nodes where losses occur. The equation below is used to calculate the phase resistance at working temperature in order to find the stator copper losses:

$$R_{at} = R_{20}\,[1 + (T - 20)\,p_t] \tag{1}$$

where R_{20} is the resistance measured at 20°C, T is the working temperature and p_t is the temperature coefficient.

2.1.1. Conduction Resistances

It is essential to define the type of heat transfer for each part of the machine in order to calculate the thermal resistance. Transfer can be by conduction, convection or radiation. Generally, most parts of the machine, such as magnets and lamination, transfer heat by conduction. Thus, for conduction resistance, the equation is:

$$R_{cond} = \frac{l}{S.k} \quad [C/W] \tag{2}$$

where l is the length of the body in the direction of heat flow, S is the cross-sectional area and k is the thermal conductivity.

To find the value of the resistance in the thermal network, the thermal conduction coefficients are used as in Table 2.

Table 2. Material Properties [6]

Regions	Conductivity, λ (W/m/°C)	Density, ρ [kg/m^3]	Specific Heat Capacity, c$_\rho$ [J/kgC]
Copper coils	375	8900	390
Aluminum alloy	168	2790	833
Steel sheet stator and rotor	28	7600	465
Permanent magnet (NdFeB)	8	7500	450
Permanent magnet (SmCo)	10.5	8500	418
Shaft	40	7800	485
Air (at 40°C –ambient temp)	0.28	1.127	1007
epoxy	0.22	1200	1500
Nomex 410	0.14	1400	1300

2.1.2. Slot Resistances

Three main types of losses in the machine are copper, iron and PM losses. Thus, it is important to obtain more detail on the resistance at the slot area. The heat source starts from the slot, then transfers to the stator core back via the tooth. From the tooth, the heat is transferred to the atmosphere either by convection or radiation.

The slot resistance can be calculated as follows [7]:

$$R_{slot} = \frac{w^2}{8K_{winding} \times V_{slot}} \quad [C/W] \tag{3}$$

where V_{slot} is the slot volume,

$$w = \ slot\ width - (2\ \times liner_{thickness}) \tag{4}$$

The value of $K_{winding}$ depends on the conductivity of epoxy and copper insulation.

$$K_{winding} = \frac{K_{air}}{a+b\ (\%fillfactor)^c} \tag{5}$$

where the constants for the potted slot are as follow: $a = 0.1753$, $b = -0.0282$ and $c = 0.3973$. According to Dickinson [8], these constants were obtained by curve-fitting on the result of an FE model of the slot thermal conductivity factor over a range of values of fill factor value using the thermal conductivity for epoxy and copper insulation stated above.

It is also important to consider the temperature drop across the liner, because electric insulators are generally poor thermal conductors. Liner resistance can be calculated as:

$$R_{liner} = \frac{2\ l_{liner}}{k \times A_{liner}} \quad [C/W] \tag{6}$$

where l is the thickness of the slot liner, k is its thermal conductivity and A_{liner} is slot depth x axial length. The stator lamination resistance can be divided into two parts for the lower and upper parts. Therefore, only half of the tooth width and depth are considered in the calculation because the heat generated flows through the stator tooth by conduction and from the stator core back to the stator's outer surface by convection. Thus, the equations to calculate the thermal resistance are:

$$R_{stator\ tooth} = \frac{2\ D_{half\_slot}}{k \times A_{\frac{1}{2}tooh}} \quad [C/W] \tag{7}$$

where D_{half_slot} is half the depth of the slot, $A_{\frac{1}{2}tooh}$ is the product of half of the tooth width and the axial length, and $A_{coreback}$ is the product of slot depth and axial length.

On the other hand, for the upper part of the stator lamination convection heat transfer occurs and the convection resistance for the lamination can be calculated using the equation below:

$$R_{lam} = \frac{1}{h \times A_{lam}} \quad [C/W] \tag{9}$$

where h is the convection coefficient between the water cooling and the motor surface in the end-cap regions which is assumed to be 3280 W/m^2/°C which is obtained from MotorCAD model and A_{lam} is the product of the axial length of the lamination and the slot pitch arc.

2.1.3. Temperature Rise

For each node, the equation below is used to calculate the temperature rise of the components in the steady state compared with the initial surface temperature:

$$\Delta T = P \times R \tag{10}$$

where R is the thermal resistance of the motor components and P is the power source which corresponds to the current of the electric circuit.

The temperature of the winding should be fixed at a certain level according to the temperature limit of the magnet without a cooling system. If the temperature is higher, the machine needs a cooling system. The temperature rise in the slot can be calculated directly once the values of all related thermal resistances and losses have been obtained. By assuming the temperature of the water jacket, the equation below can express the temperature rise in the slot:

$$\begin{aligned}\Delta T_{slot} = T_{water\ jacket} + P_{slot} \times (R_{slot} + R_{liner} + R_{stator\ tooth} + R_{stator\ coreback} + R_{lam}) \\ + P_{iron} \times R_{lam}\end{aligned} \tag{11}$$

2.1.4. Capacitances for the Transient Analysis

Meanwhile for the transient analysis changes in the internal energy in the motor over time are taken into account. Thus, heat capacitances need to be calculated as in the equation below:

$$C = \rho \times V \times C_p \quad [W/C] \tag{12}$$

where ρ is density, V is volume and C_p is the heat capacity of the material. Consequently, the power source during transient analysis can be defined as:

$$P = C\frac{dT}{dt} + \frac{T}{R} \tag{13}$$

Therefore, to obtain the temperature rise, the power losses need to be defined first because the losses are removed either by convective heat transfer between the frame surface and the environment or with the coolant flowing through it.

2.2. Lumped Parameter with MotorCAD

For more detailed results in a thermal analysis, a lumped parameter circuit needs great software for simulation purpose. In this work, MotorCAD has been used to obtain accurate values in the thermal analysis. The machine topology should be the same as with the FEA design by using Infolytica Magnet. Some input data inside MotorCAD software needs to be completed first and then after choose the cooling option, the result for the temperature for each part in the machine can be calculated. This process is more accurate for a steady state analysis. Figure 1 shows the axial section of the machine that has been designed.

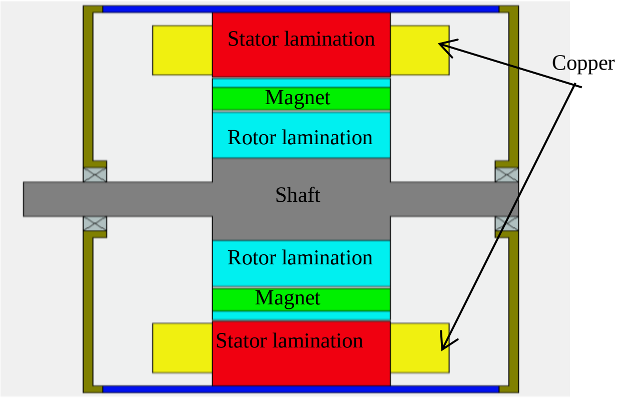


Figure 1. Axial Section of the PM Machine

2.3. Finite Element Analysis Thermal Model

In order to obtain accurate values of temperature increases in the important components the PMSM, another method of thermal analysis has also been applied. In this section, a 2D transient thermal analysis coupled to a 2D transient with motion magnetic analysis is conducted in order to calculate the transient temperature. This is not only restricted to the calculation of the magnetic field distribution, but is extended to quantitatively assess the temperature rise in the machine. The interchange of energy between the electromagnetic and thermal fields is taken into consideration. Additionally, a forced water cooling system is utilized to achieve better cooling.

The design procedure used for the proposed thermal modeling is illustrated as a flowchart in Figure 2. This shows that, when the required accuracy in electromagnetic design is reached, the proposed thermal model is implemented to calculate the temperatures of the various parts of the machine. The machine needs to be designed first using Infolytica Magnet and then analysed. The losses obtained from the electromagnetic field analysis are used as the heat source in the thermal analysis.

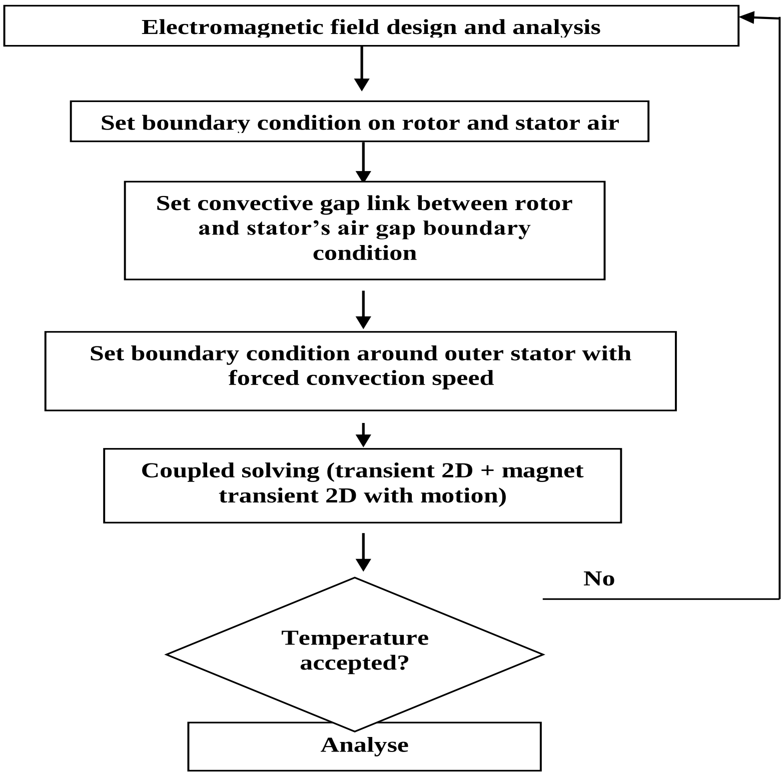


Figure 2. Flow chart for thermal analysis

During this part, a few design specifications have to be determined according to the output characteristics. The selection of appropriate configurations, materials, parameters and initial guess work should be accomplished. The output must follow the specifications with smooth running capability and to satisfy the torque-speed requirements, and the verification of overall performance is then achieved using by finite element analysis (FEA).

In high frequency machines, rotor eddy current losses are more significant. It is important to estimate these losses accurately and to keep them as low as possible. Two methodologies can be used to estimate the losses. The first is a 2D FEA harmonic method and the second is a comprehensive analytical method.

2.4. Electromagnetic Field Analysis

It is important to choose the appropriate electrical and magnetic loadings and thus to select the optimum distribution of losses, as well as to choose the most appropriate magnet material and grade. Moreover, it is needed when performing mechanical analysis, it is necessary to ensure that the material characteristics are modelled at the right temperature. For thermal analysis, the steps below are applied.

For the PM machine with distributed winding configuration, the following assumptions are made in order to simplify the numerical calculation [9]:

a. Constant ambient temperature.
b. The heat losses are considered to be uniformly distributed in the corresponding regions.
c. The influence of temperature rise on the thermal properties of materials and heat coefficients of boundary surfaces are neglected.
d. The insulation material is evenly distributed and the winding impregnation is good.
e. The machine is continuous along the axial direction and the axial temperature gradient is zero.
f. The material is isotropic and the influence of temperature on thermal conductivity is ignored [10].

Because of the symmetry of this machine, the analysis is described by 1/8 of 2-D model as shown in Figure 3 below. A 2D transient thermal analysis coupled to a 2D transient with motion magnetic analysis is used to calculate the transient temperature, which not only calculates magnetic field distribution, but also obtains the temperature rise in the machine with the interactive energy process between the electromagnetic and thermal fields taken into consideration.

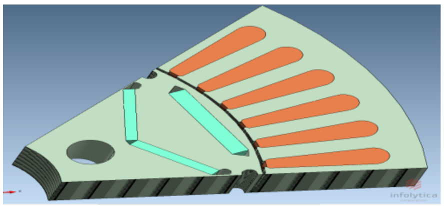


Figure 3. 1/8 of IPM Machine

The air gap is divided into two symmetrical parts during the mesh. To perform as stator airgap and rotor airgap. The size of mesh for each part should be set differently and reasonably to satisfy the corresponding discrete requirements. Even the time step of the transient electromagnetic field simulation should also be set accurately according to the discrete level of the mesh [11].

2.4.1. Convection Heat Transfer Coefficient at Motor Outer Surface

Convection heat transfer is related to the outer air velocity. If the air velocity is 0 ~ 25 m/s, the heat transfer coefficient can be expressed as follows [12]:

$$\alpha = \alpha_0 + 4v \tag{14}$$

where α_0 is the convection heat transfer in calm air and v is air velocity.

2.4.2. Convection Heat Transfer Coefficient in the Air Gap

When the motor is running, the rotation of the rotor will produce a flow of air through the air gap. Thus, the heat is transferred between the stator and rotor through the convection of air in the gap. As a result, the thermal field and fluid field are coupled together, which increases the difficulty of solving the motor temperature field. For this purpose, a convective link is used to simulate the convective transfer of heat. Figure 4 shows the periodic boundary conditions that have been assigned to this machine. The transfer of heat through the air gap needs convective transfer, which causes the significant cooling of the rotor. For this purpose, an empirical model has been used which is in the form of a temperature dependant convection coefficient between two surfaces. It depends on the rotor speed, Reynolds number and other properties of the fluid flow. In this study, air has been chosen as the coolant material between the rotor and stator.

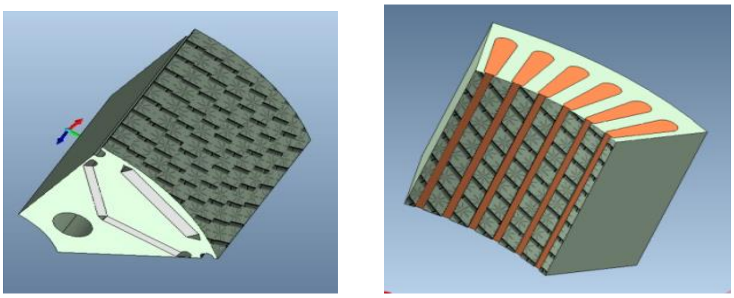


Figure 4. Periodic boundary condition for convective heat transfer

2.4.3. Environmental Condition of the Motor Outer Surface

This condition, which is defined by the conductive heat transfer coefficient (hc), the radiation heat transfer coefficient (hr) and the external environmental temperature (Te), specifies the way heat flows through the boundary. It can be expressed as in the equation below:

$$q = hc * (T - Te) + hr * (T^4 - Te^4) \tag{15}$$

where T is the temperature at a point on the boundary and q is the heat flux through it. The radiative heat transfer coefficient is related to emissivity by the Stefan-Boltzmann constant:

$$hr = emissivity\ x\ 5.6697e - 8 \tag{16}$$

3. RESULTS AND ANALYSIS

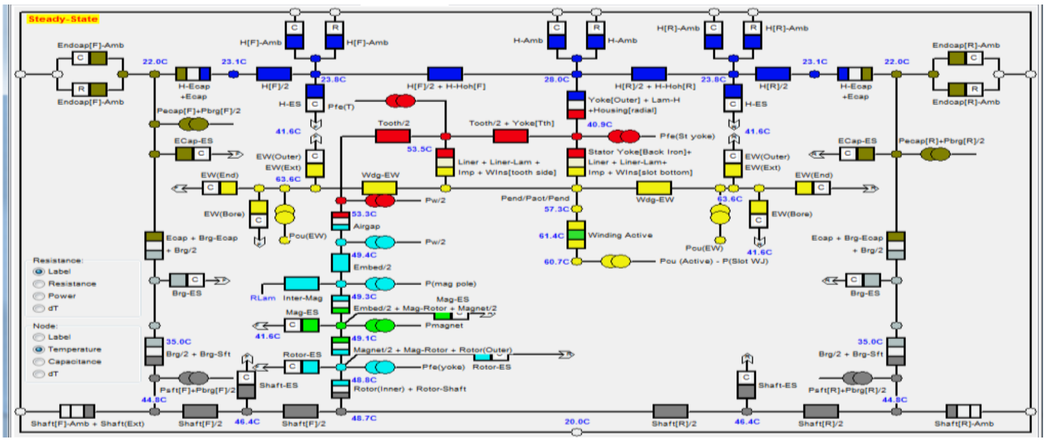
Both thermal analysis methods have been applied to the same machine, and both gave the same results. Thus, either of the lumped parameter circuit or FEA models can be used for the thermal analysis of the PM machines. The water jacket contains the coolant for the machine and the flow rate of the coolant is 10 litres/min. The main specifications and parameters of the machine for the electromagnetic field analysis are as given in Table 3 below:

Table 3. Specifications and parameters of the machine

Maximum power	80 kW
Maximum torque	280 Nm
MMF	2500 A_{rms}
Rated speed	2500 rpm
Stator outer diameter	269 mm
Stator inner diameter	176.3 mm
Rotor outer diameter	173.2 mm
Rotor inner diameter	59.28 mm
Air gap	0.9 mm
Machine length	83.5 mm

3.1. Thermal Analysis of the IPMSM using Lumped Parameter circuit

After the thermal resistance and the power losses have been calculated and defined as the input, MotorCAD is used to calculate and display the thermal analysis results as shown in Figure 5 and Figure 6 which present the temperature for each part of the machine.



Resistance:
● Label
○ Resistance
○ Power
○ dT

Node:
○ Label
● Temperature
○ Capacitance
○ dT

Figure 5. Schematic circuit for PM machine

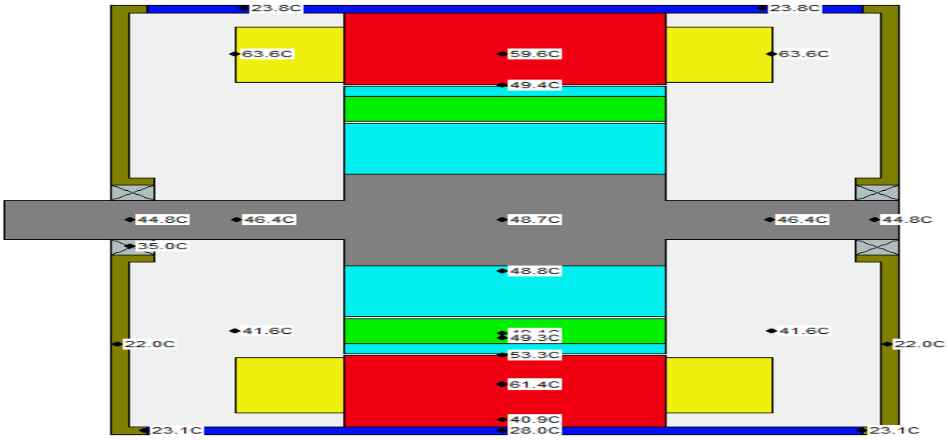


Figure 6. Axial Section of the PM Machine

3.2. Thermal Analysis of the PMSM by using FEA

Figure 7 presents the results of the thermal analysis by applying coupled solving magnet transient and thermal transient and using finite element analysis. The electromagnetic field analysis is simulated first in order to the derive values of losses which are they then act as the heat source for the thermal analysis. Coolant has been applied around the outer side of the stator and the force speed convection for the water as a coolant is 10 litres per minute.

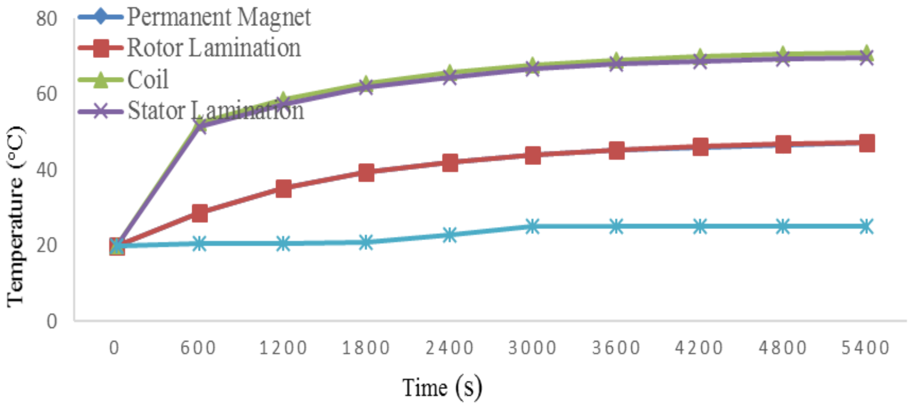


Figure 7. Temperature variation in the PM machines

3.3. Experimental Setup

Thermal testing of the prototype machines has also been conducted as shown in fig. 8. A chiller has been used to supply the water coolant into the water jacket. A digital flow meter is used to measure and adjust the flow rate of the water coolant from 1litres/min to 15 litres/min. The meter was installed between chiller and the water inlet on the prototype machine.

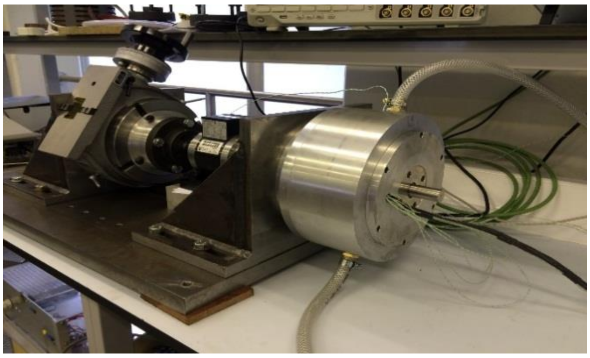


Figure 8. Test rig for thermal testing

3.4. Comparison between Lumped- Circuit Parameter and FEA for Thermal analysis

Table 4 presents the predicted temperature comparison between lumped-circuit parameter and finite element analysis. Both machines are using water jacket as cooling method and water as the coolant with flow rate 10 litres/min. Both methods of thermal analysis show the good agreement of the temperature in the essential part of the machine. To measure the temperature of parts of the machine, a type K thermocouples have been used. The temperature range is between -75°C to +250°C. The thermocouples are connected to a data logger which can display and save the temperature data of each essential part. During the testing of the machine, the temperature needs to be monitored to make sure that the machine is not running over the temperature limit, especially at the stator winding. Thermocouples have been located at the end winding, end slot, middle of slot, stator laminations and housing. The predicted temperatures from lumped parameter model and finite element analysis model as shown in Table 4.

The experimental result also can be seen in the table. Temperature at rotor and permanent magnets are not available because need other method in order to get the data.

Table 4. Temperature for the PM machine

	Lumped circuit parameter	Finite Element Analysis	Experimental
Stator core	53.3 °C	64.6 °C	60°C
Coils	79.5 °C	69.1 °C	75°C
Rotor	48.8 °C	45.3 °C	NA
Permanent magnets	49.1 °C	45.6 °C	NA
Housing	28.0 °C	25 °C	26°C

4. CONCLUSION

Two different types of thermal analysis have been applied in order to define the heat transfer for each essential part of the PM machine. Each method has advantages and disadvantages. In order to choose the better method for thermal analysis, the preference will be to do all analysis in multiphysics environment linking electromagnetic finite element and thermal element in one operation. For lumped parameter thermal model, all resistances are need to be calculated first and by applying the value to MotorCAD software, the output will be the temperature rise of the calculated part. The lumped parameter analysis can be used to get accurate values of temperature increases. The reason for this is that the temperature rise can be calculated for each part depending on the thermal resistance that has been previously defined. The thermal field also can be analysed using thermal lumped parameters based on the eddy current loss derived using MotorCAD software. However, if FEA combining a 2D transient magnet and thermal analysis is applied, the difficult part only during the beginning of the machine design. The machine needs to be designed first and a simulation has been conducted of the electromagnetic analysis. The values of losses obtained from the electromagnetic analysis act as the values of heat transfer for the thermal field analysis. Thus, the result of electromagnetic can be used directly to perform the thermal field analysis. Comparison has been done with thermal network and found it to be accurate enough. Therefore, the design approach will be using finite element analysis which is less time consuming once the machine has been designed by following the specifications and desired output.

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