THERMAL ANALYSIS OF AN ELECTRIC MOTOR

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DECLARATION

I declare that this thesis entitled “THERMAL ANALYSIS OF AN ELECTRIC MOTOR is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : NOR SYAKILLA BINTI MOHD FAUZI

Date : ....

APPROVAL

I hereby declare that I have checked this report entitled “title of the project” and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATIONS

To my beloved mother and father

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In preparing this report, I was in contact with many people, researchers, academics and practitioners. They have contributed towards my understanding and throughout. In particular, I wish to express my sincere appreciation to my main project supervisor, Assoc.Prof.Ir.Dr.Md.Nazri bin Othman, for encouragement, guidance critics and friendship. I am also very thankful to my panels, Dr.Raja Nor Firdaus Kashfi bin Raja Othman and Assco.Prof.Ts.Dr Mohd Luqman bin Mohd Jalil for their guidance, advices and motivation. Without their continued support and interest, this project would not have been same as presented here.

My sincere appreciation also extend to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to my parents and all my family members.

ABSTRACT

A thermal management of an electric motor is one of the important factor to ensure optimum performance and efficiency of the motor. The thermal behaviour of the motor depends on the motor geometry and the heat sources. The performance of electric motor is influenced by its temperature due to the heat dissipated from the motor. During the operation of the electric motor, more heat will dissipated from the motor which cause the temperature of the motor rised. An excessive heat that generated from the motor will affect the motor performance and may cause a failure. Understanding the importance of the thermal management had motivated the aim of this study is in creating thermal model of motor and letting the capability of the motor performance. The Permanent Magnet Synchronous Motor (PMSM) is selected to its highest performance and necessary to avoid demagnetized due to excessive heat. The model of the motor simulated using Finite Element which is 2D Flux Altair software. The expected result for this study is to predict the thermal capability of the motor performance before it reaches the failure level and known as Mean Time Before Failure (MTBF). The simulated result showed that the heat generated in the motor is directly proportional with the increased torque of the motor..

ABSTRAK

Pengurusan termal motor elektrik adalah salah satu faktor penting untuk memastikan prestasi dan kecekapan motor yang optimum. Sifat haba motor bergantung kepada geometri motor dan sumber haba. Tindak balas motor elektrik dipengaruhi oleh suhu dan kadar haba yang dihasilkan dari motor. Semasa motor elektrik beroperasi, lebih banyak haba telah terhasil dari motor yang menyebabkan suhu motor meningkat. Haba yang berlebihan yang dihasilkan dari motor akan memberi kesan kepada prestasi motor dan boleh menyebabkan kegagalan. Dalam memahami kepentingan pengurusan haba, matlamat kajian ini adalah untuk mencipta model termal motor dan mampu menganalisa keupayaan prestasi motor. "Permanent Magnet Synchronous Motor (PMSM)" dipilih kerana mempunyai prestasi tertinggi dan perlu untuk mengelakkan dari nyah magnet disebabkan oleh haba berlebihan. Model motor telah dijalankan menggunakan perisian"Finite Element", iaitu "2D Flux Altair. Hasil yang dijangkakan untuk kajian ini adalah untuk meramalkan keupayaan prestasi motor sebelum mencapai tahap kegagalan dan dikenali sebagai "Mean Time Before Failure (MTBF)". Hasil simulasi menunjukkan haba yang dijana di dalam motor adalah berkadar terus dengan peningkatan tork motor.

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LIST OF SYMBOLS AND ABBREVIATIONS

PMSM	-	Permanent Magnet Synchronous Motor
T	-	Temperature
G	-	Thermal conductances
λ	-	Thermal conductivity
A	-	Cross sectional area
R	-	Thermal resistance
α	-	Heat transfer coefficient
f	-	Frequency

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

In this chapter, the research background, problem statement, objective and scope of the project will be explained briefly for the understanding towards the project purpose.

1.2 Research Background

In globalization era, the technologies development used a lot of electric application such as electric vehicles (EV) in order to minimize the pollution. An electric motor that has high power density high of efficiency and wide constant power operating region as well a low cost of manufacturing is required foe EV to use in order to continue to be competitive with conventional vehicles. Permanent Magnet Synchronous Motor (PMSM) are appropriate for electric vehicle because PMSM contain the necessary advantages such as has high torque, has no windings at its rotor and has no contact sliding which simple in rotor construction with good dynamic performance that help to optimizing of cost, mass and electric vehicles performances. The size of Permanent Magnet Synchronous Motor (PMSM), the torque of the motor will increase although the range of speed is large [1]. Permanent Magnet Synchronous Motor also one of the type of motor that reaches the higher efficiency levels [2] [3].

In electric vehicle, the thermal management of the motor is very important because the efficiency of the motor effected by its temperature. Motor is the most important part in energy conversion system. The failure of the motor may cause the failure of the whole system [4]. The motor must operate and deliver the power at a specific temperature without any risks of stator windings failure and demagnetization of the magnet [5]. During its operation, the temperature should not reach the levels that could destroy the sensitive parts such as winding insulation and the permanent magnet. In avoiding the winding from overheating during operation, heat generated should be monitored and stop the operation reaching up maximum temperature [6]. Because of this, thermal modelling and analysis is important to analyse the performance of the motor for the motor’s thermal model to make sure the motor can operate for longer life span [7].

1.3 Problem Statement

The limitation of thermal cause the restraint of the motor. If the motor exceed the thermal limit, this will decrease the life time of the motor. Heat sources and motor geometry is important in order to reduce the thermal stress because thermal behaviour is important for the lifetime of motor, the limit of temperature insulation and the motor efficiency. Heat stress may cause the damage of the motor.

Electric motors have the problem with regards to the temperature that dissipited during the motor operation. Electric motors also have problem about the maximum temperature that the windings and permanent magnet of the motor can stand. During the operation of the electric motor, the temperature of the motor will rise and more heat will dissipated from the electric motor. The excessive heat that produce from the electric motor will effect the performance of the electric motor and may cause the failure of the motor [8].

1.4 Objective

The objectives of this project are:

i) To understand the thermal behaviour in electric motor.

ii) To model and simulate the thermal generated in electric motor.

iii) To analyse and predict the motor thermal capability before reaching Mean Time Before Failure (MTBF).

1.5 Scope of Project

The main scopes of project are:

a) The thermal behaviour is investigated by heat sources and the motor geometry.

b) The type of electric motor used for this project is Permanent Magnet Synchronous Motor (PMSM).

c) The analytical lumped circuit used as the design technique for the thermal analysis.

d) The capability of the thermal motor is analysed using the finite element simulated model.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter is about the studied that related to the subject of the project. The background theory that related to the project is also included in this chapter to make sure the project is properly understand.

2.2 Thermal Behaviour in Electric Motor

In electric motor thermal analysis is very important because the temperature of the motor will effect the efficiency of the motor. The thermal behaviour of the motor depends on the heat sources and the motor geometry [4].

2.2.1 Heat Sources in motor

The heat sources in a motor are generated due to copper losses and iron losses in the electric motor. The copper losses is from ohmic resistances and eddy current. Ohmic resistance losses depend on the current of the coils, while eddy current copper losses depend on the speed of motor. Iron losses from eddy currents and hysteresis depend on the motor speed. The mechanical losses which from motor bearing friction also depend on the speed of motor [4] [9].

Copper losses

The copper losses is come from ohmic resistance and eddy current. Ohmic resistances losses depend on the current in the coils while eddy current copper losses depend on motor speed. In synchronous permanent magnet motor, the copper losses are function by phase current and phase resistance. The copper losses are given by the following expression [9]:

$$\boldsymbol{P_j = 3R_{ph}I_{eff}^2 = 3R_{ph}\left(\frac{i_{max}}{\sqrt{2}}\right)^2} \quad (1)$$

R_{ph} is the phase resistance given by the following expression:

$$\boldsymbol{P_j = 3R_{ph}I_{eff}^2 = 3R_{ph}\left(\frac{i_{max}}{\sqrt{2}}\right)^2} \quad (2)$$

Iron losses

The iron losses are described as losses in the stator yoke and teeth [9] [10]. The iron losses in the teeth are given by:

$$\boldsymbol{P_{f\_d} = q\left(\frac{f}{50}\right)^{1.5}\left[M_{ds}B_d^2\right]} \quad (3)$$

Where q is quality coefficient of the meta sheets, f is frequency supply of the motor, B_d is the value of peak flux density in the teeth and M_{ds} is the teeth mass. The iron losses in the stator yoke are given by following:

$$\boldsymbol{P_{f\_c} = q\left(\frac{f}{50}\right)^{1.5}\left[M_{cs}B_{cs}^2\right]} \quad (4)$$

Where B_{cs} is the value of peak flux density in the stator yoke and M_{cs} is the stator yoke mass.

2.2.2 Heat Transfer Mechanism

During the heat transfer process, the heat energy from the coil of the motor will transfer into the motor's body. Then, the heat generated from the motor will transfer out from the motor's body due to the losses of heat [11]. According to second law of thermodynamics, in the real processes the net entropy is always increase. Entropy is the measure of disorder in a system, it also describe as the energy quality in a system. Low quality means a high level of disorder, and the highest possible entropy would be having the energy evenly distributed in space. The second law of thermodynamic also can be explained that an isolated system always strives for thermal equilibrium which heat flow from hot place to cooler places. There are three process of heat transfer can occur which are conduction, convection and radiation. Conduction is the energy transmission between molecules in medium. It is the only mechanism takes place in solid but it is not exclusive and it also take place in solid as well [9] [12].

This process is linear and described by:

$$\boldsymbol{P = G(T_i - T_j)} \qquad (5)$$

Where P is the power flow, G is the thermal conductance while T_i and T_j are the temperature in two adjacent nodes.

The convection phenomena can be found in fluids and gases. In non-solid medium the molecules move freely. Transportation of the molecules improved the heat transfer ability of the medium. The molecule will contact to each other and cause the intermixing molecule of different energy level and increasing the rate. The mechanism is linear for the pure conduction and can be described by (5).

Another process of heat transfer is radiation, it is describes as the mechanism of energy carrying by body photons emitting. The amount of body emit radiation depends on the emissivity of object, the surface area and the most strongly depends to temperature. The net energy transfer can described by (6)

$$P = G(T_i^4 - T_j^4) \tag{6}$$

Figure 2-1 below shows the cross-section of the Permanent Magnet Synchronous Motor (PMSM). From this, the value of thermal resistance and capacitances can be calculated based on the dimension of motor geometry. In this motor, there will be heat transfer form one element of the motor to another element of the motor [5].

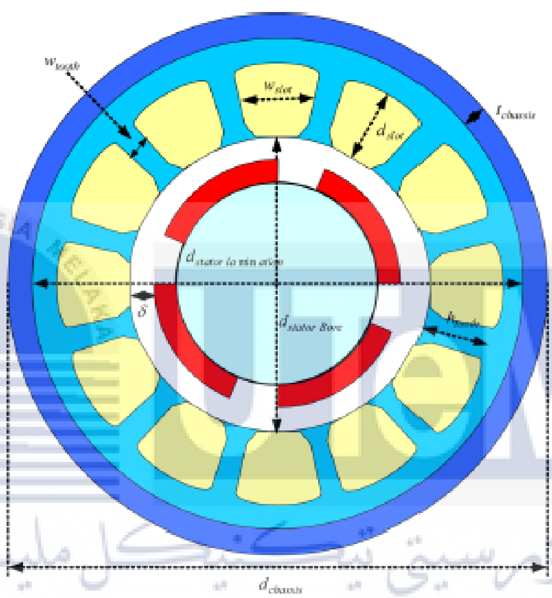

Figure 2-1 The Cross-section of Permanent Magnet Synchronous Motor (PMSM)

Figure 2-2 below shows the diagram of heat transfer in PMSM, the arrow in red colour is represent as the conduction hear transfer. The arrow with purple colour is show the radiation heat transfer while the arrow with green colour is represent as convection heat transfer. All three type of heat transfer occur in the electric motor [5].

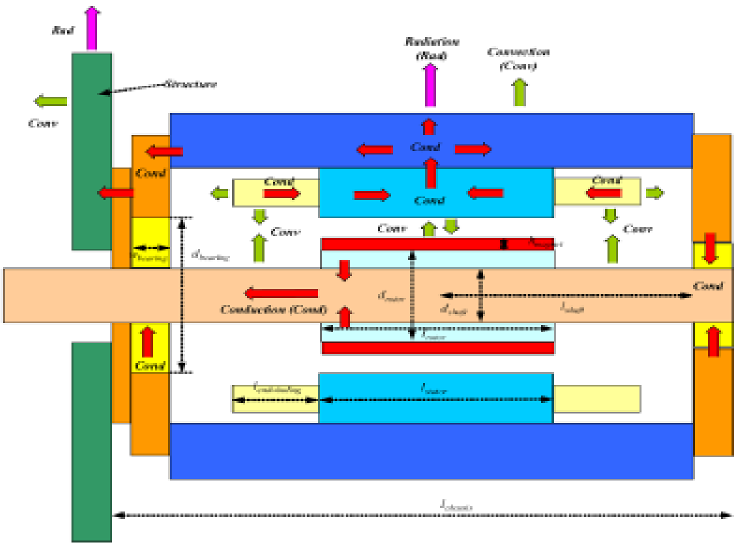

Figure 2-2 The Diagram of Heat Flow in PMSM

2.2.3 Thermal Resistance of Solid

The thermal resistance of an object is calculated in respect to the heat flow direction unlike the properties of mass or conductivity. The thermal conductance across the homogenous object can be describe as following [9]

$$G = \frac{\lambda A}{L} \tag{7}$$

where λ is the thermal conductivity, A is the cross sectional area and L is the distance between the nodes. Thus according to the thermal resistance is:

$$R = \frac{1}{G} = \frac{L}{\lambda A} \tag{8}$$

2.2.4 Thermal Resistance of Gases and Fluids

The thermal model representation for air is mainly due to the convection heat transfer process. The heat transfer process is convection need to consider. The modelling of air is a complex matter because the motion of fluid is depend on many factors such as rotational speeds, structure of surface, geometry dimension, forced flow and other factors. The thermal resistance between the solid surface and ambient temperature can be described as [9]:

$$\boldsymbol{R} = \frac{\boldsymbol{1}}{\boldsymbol{\alpha A}} \tag{9}$$

where A is the surface of area subjected to convection and α is the heat transfer coefficient $[W/m^2C]$. α can be calculated by:

$$\boldsymbol{\alpha} = \frac{\boldsymbol{\lambda_{Air} Nu}}{\boldsymbol{2L}} \tag{10}$$

Nu is the ratio of convection for conductive heat transfer normal to the boundary [Nu = 2 correspond to a laminar flow which means the molecules are only moving perpendicular to the normal of the plane. When that in case, the equation (9) will become the same as for any solid if equation (10) is inserted into (9).

2.2.5 Motor Geometry

Thermal behaviour of the motor also depends on the motor geometry. Figure 2-3 below shows the geometry of the PMSM design. This design of motor is a permanent magnet, concentrated winding, opened slot, axial flux and sinusoidal wave-form [4].

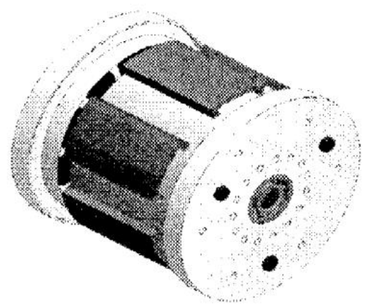

Figure 2-3 Geometry of PMSM

Figure 2-4 below shows the stator and rotor geometry of PMSM. The thermal behaviour in electric motor also depends on the motor geometry [4].

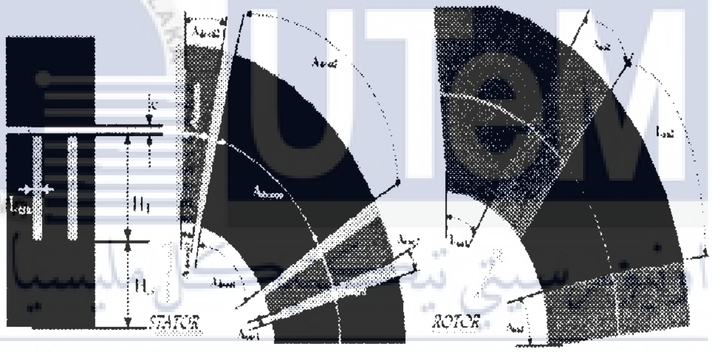

Figure 2-4 *The stator and rotor geometry*

The height of magnet is given by:

$$\boldsymbol{H_a} = \frac{\boldsymbol{\mu_r B_e e}}{\boldsymbol{B_r} - \frac{\boldsymbol{B_e}}{\boldsymbol{K_{fu}}}} \tag{11}$$

Whereμ_r is magnet relative permeability, B_e is air-gap magnetic induction, e is air-gap thickness, B_r is magnet permanent magnetic induction and K_{fu} is flow escapes coefficient.

The height of teeth given by:

$$H_d = \frac{3N_{sph}I_d}{N_t \delta K_f L_{enc}} \tag{12}$$

Where N_t is the number of principal teeth, I_d is the motor rated current, K_f is the slot load factor, N_{sph} is the number of spire by phase, L_{enc} is the width of the notches and δ is the density of the acceptable current in copper.

The rotor yoke thickness is given by:

$$H_d = \frac{B_e}{B_{cr}} Min \frac{(S_d, S_a)}{(D_{ext} - D_{int})} \frac{1}{K_{fu}} \tag{13}$$

Where D_{ext} is the outer diameter of motor, D_{int} is the inner diameter of motor, S_d is the teeth section, S_a is the magnet section and B_{cr} is the magnetic induction of rotor yoke.

The stator yoke thickness is given by:

$$H_d = \frac{B_e}{B_{cs}} Min \frac{(S_d, S_a)}{(D_{ext} - D_{int})} \tag{14}$$

Where B_{cs} is the stator yoke magnetic induction while B_e is the air-gap magnetic induction.

The electromagnetic torque given by the equation following:

$$C_{em} = \frac{3EI}{2\Omega} \tag{15}$$

Where I is phase angle while E is electromotive force.

The electric motor constant, K_e calculated so that the electric vehicle can function at speed stabilized with a weak undulation of the couple. The electric motor constant can be described as below:

$$K_e = \frac{3}{2} N_{sph} \frac{(D_{ext}{}^2 - D_{int}{}^2)}{4} B_e \qquad (16)$$

The electromotive force E deduced from the analytical model, the relation is given by the following:

$$E = 2N_{sph}\Omega \frac{(D_{ext}{}^2 - D_{int}{}^2)}{4} B_e \qquad (17)$$

So that electromotive force, E also can be written as:

$$E = \frac{2}{3}\Omega K_e \qquad (18)$$

For the electromagnetic torque, C_{em} can be deduced from the equation (16), (17) and (18) so that the expression of the couple can be obtained as following:

$$C_{em} = K_e . I \qquad (19)$$

2.3 Thermal Model

Electric network can be used in order to study the thermal behaviour of a system. When the thermal resistance network is set up, the place of nodes and the calculation of equivalent resistances are considered. Table 2-1 below shows the relation between the electric and thermal parameters [9].

Table 2-1: Relation between the electric and thermal parameters

Electric Parameters	Thermal Parameters
Electric Voltage, u [V]	Temperature, θ [K]
Current, I [A]	Heat loss, Q [W]
Electric resistance, R [Ω]	Thermal resistance, R_{th} [K/W]
Electric capacitance, C [F]	Thermal capacitance, C_{th} [J/ K]
Electric conductivity, σ [S/m]	Thermal conductivity, λ [W/m K]

2.3.1 Thermal Resistance Network Modelling

The steady state of thermal system behaviour can be find out, this can be represented by network which consist of the thermal resistance, heat flow and sources of temperature. The conductance matrix of a system described as below [9]

$$\boldsymbol{G} = \begin{bmatrix} \sum_{i=1}^{n} \frac{1}{R_{1,i}} & \frac{1}{R_{1,2}} & \cdots & \frac{-1}{R_{1,n}} \\ \frac{-1}{R_{2,n}} & \sum_{i=1}^{n} \frac{1}{R_{2,i}} & \cdots & \frac{-1}{R_{2,n}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{-1}{R_{n,1}} & \frac{-1}{R_{n,2}} & \cdots & \sum_{i=1}^{n} \frac{1}{R_{n,i}} \end{bmatrix} \tag{20}$$

The loss vector can be defined to represent the power loss injected in each node,

$$\boldsymbol{P} = \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix} \tag{21}$$

and then the corresponded temperature vector as below :

$$\boldsymbol{\Theta} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{bmatrix} \tag{22}$$

The temperaure vector, $\boldsymbol{\Theta}$ represent the increase in temperature in comparison with the ambient temperature. So, Θ can be calculate by inverting the conductance matrix and multiplied it with the power vector, thus the expression can be described as following:

$$\boldsymbol{\Theta} = \boldsymbol{G}^{-1}\boldsymbol{P} \tag{23}$$

2.3.2 Nodalization

Nodalization is dividing an object into sub elements which each element or point of connection is represent by not more than one or possibly contain a few nodes. The lumped parameter modelling notation means the simplified representation of the body properties in manageable entities such as temperature average, volume and thermal mass.

The object may principally be divided into nodes in an arbitrary way, there are many things that need to be considered which are accurate temperature prediction, expected temperature distribution and calculation of the geometry results. The node placed somewhere as a connection needed between other nodes or to increase the accuracy in the modelled path. More nodes mean more detailed information on different part of single section or more number of parts of object obtained.

Figure 2-5 below shows the thermal motor model connections. The black dots represents as a nodal which show the part of electric motor. The rectangular blocks show the heat transfer or heat flow from one part of the motor to another part of motor [9].

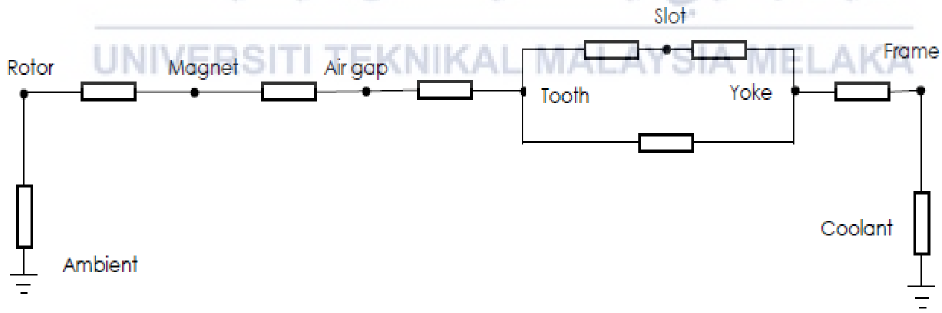

Figure 2-5: The Thermal Motor Model Connection

2.4 2D Flux Altair Software

The 2D Flux Altair software is used in this project to design the permanent magnet. Besides, this software also used to simulate and analyse the transient/time dependent magnetic and steady state thermal analysis. This software is efficient and user-friendly that generate high-performance product for electromagnetic and thermal simulation. It's features include embedded multi-parametric analysis capabilities, its open interface deals with different simulation domains and is well suited for multi physics couplings. This software's open interface addresses various simulation domains and suit for multi-physics couplings as well.

This software capable in delivering reliable analytical results, Flux can easily include in the workflow of design. Flux has ability to measure and reproduce the accurate complex phenomena results. This Flux also flexible because easy to adapt to specific needs and problem. One of the Flux fundamentals is to use a parameter to define a geometric dimension or a physical characteristic. It is also very easy to link multiple parameters together through equations, and users can intuitively explore any parameter's influence. The Altair Suite connection allows users to work in a creative global environment. Flux can be combined with the best available 3D analysis software to consider multi physics and obtain the most realistic phenomena representation, or to design control strategy tools at system level.[13]

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter is about the project methodology which shows the process of the project progression. Methodology is very important of the study discovery because methodology is one of the mechanism to guide the project requirement to obtain the results.

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3.1 Flowchart Project

Figure 3-1 below shows the project flowchart. This flow chart will guide the progress of the project. This project will start with choose the type of electric motor, for this project Permanent Magnet Synchronous Motor (PMSM) is selected. After that, understanding the thermal behaviour in electric motor which is depends on heat sources and motor geometry. After understanding the thermal behaviour, the process to design the thermal motor model of PMSM started. Then, simulate the motor to transient/time dependent magnetic to identify the losses of the motor and simulate for steady state thermal analysis to define the temperature. This model simulated by using 2D Flux Altair software. The result obtained will be analysed to determine the motor performance.

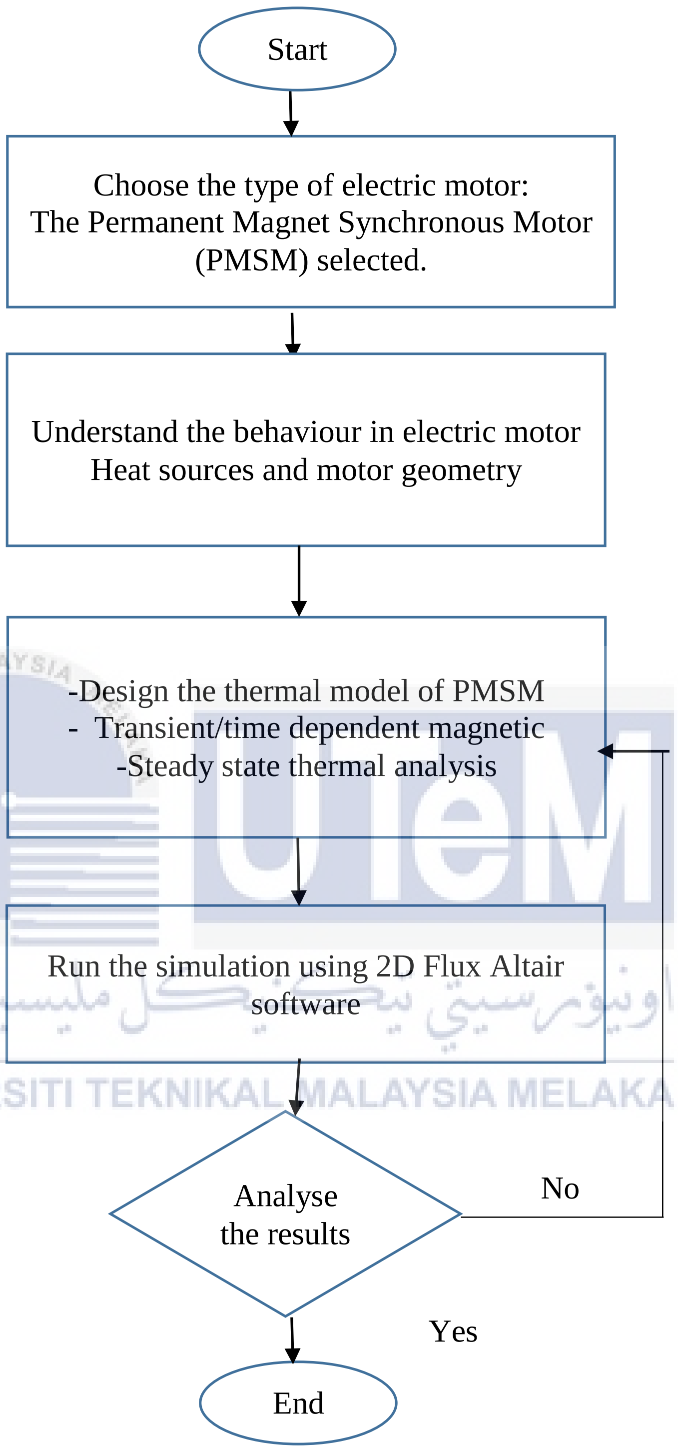

Figure 3-1: The Project Flowchart

3.2 Summary Flowchart of Project Simulation

The Figure 3-2 below shows the summarization of the overall project flowchart. This project used 2D Flux Altair software to run the simulation. This project contain three cases which are Case1 is about design the permanent magnet motor, Case 2 about transient/time dependent magnetic simulation and Case 3 about the steady state thermal analysis.

For Case 1, the permanent magnet motor will be designed by creating the motor geometry in the software. For Case 2, the simulation will analyse result about magnetic flux density, current density, joule losses and iron losses of the motor. For the Case 3, the joule losses and iron losses computed from previous case represent the sources in the steady state thermal analysis of the motor. From that, the temperature of the motor will analyse.

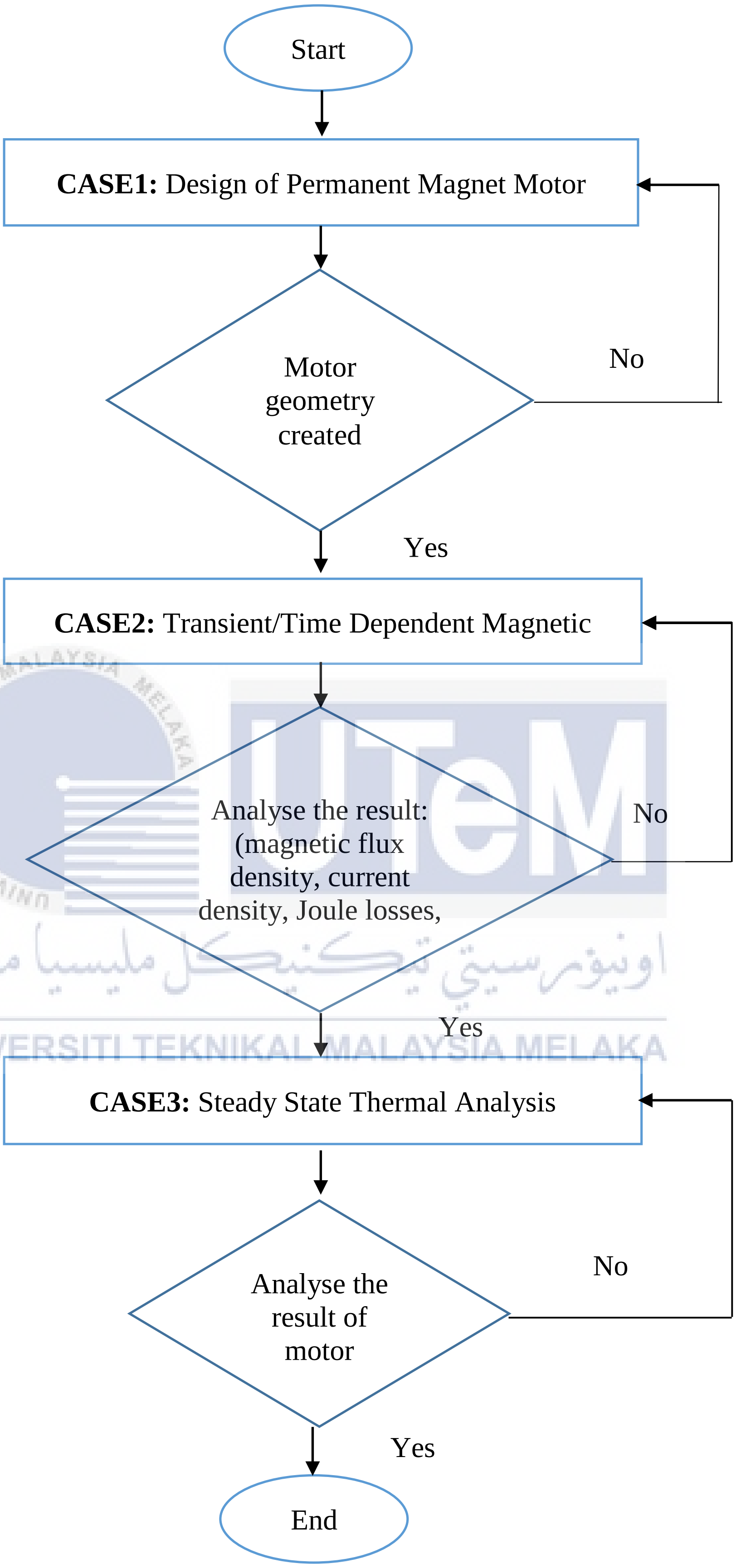

Figure 3-2: *The Summary Flowchart of Project Simulation*

3.3 CASE1: Design Permanent Magnet Motor

The Figure 3-3 below shows the flowchart for Case 1 to design the permanent magnet motor. 2D Flux Altair software is used to design the motor. BRUSLESS_PERMANENT_MAGNET_MOTOR_V11.1PFO is load for the overlay certified from the extension in the simulation. Then, all the parameter of the motor geometry is set in the simulation. If all the parameter set is correct the result of motor geometry of permanent magnet motor created but if the parameter set is incorrect the error will show up and the parameter must be reset.

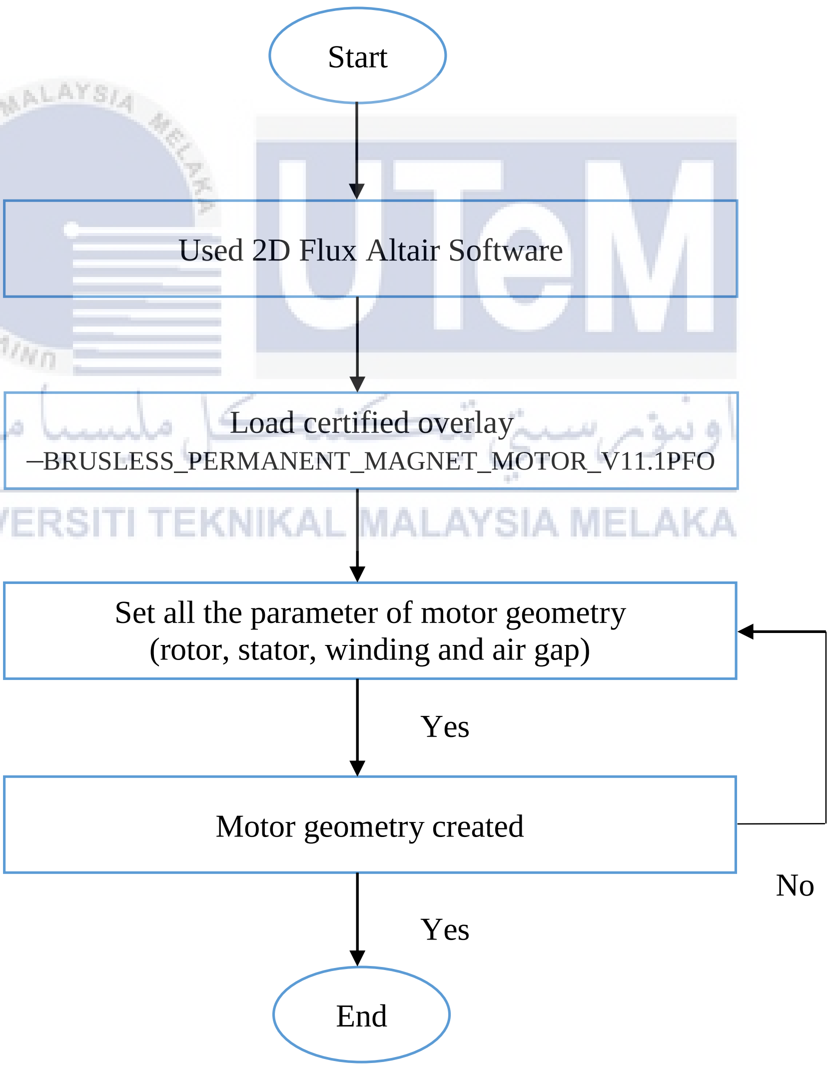

Figure 3-3: *Flowchart for Case 1*

3.4 CASE 2: Transient/Time Dependent Magnetic

The Figure 3-4 below shows the flowchart for Case 2 to simulate the transient/time dependent magnet. This simulation is continued from the case 1 which the permanent magnet motor that design in Case 1 is used. In this case the geometry must be completed by create the copper conductor, conductor insulation and liner by using 2D Sketcher. Transient Magnetic 2D Application is defined for this simulation and the geometry is meshed.

All the output/input parameter, material used and electric circuit is created but some of the material is imported from the simulation. The electric circuit also need to import before it assigns to the face region. Every parts of the motor need to be assigned to the face region and the mechanical set also created. After all the parameter created, the solving scenario for this simulation need to create to solve this simulation and obtained the result.

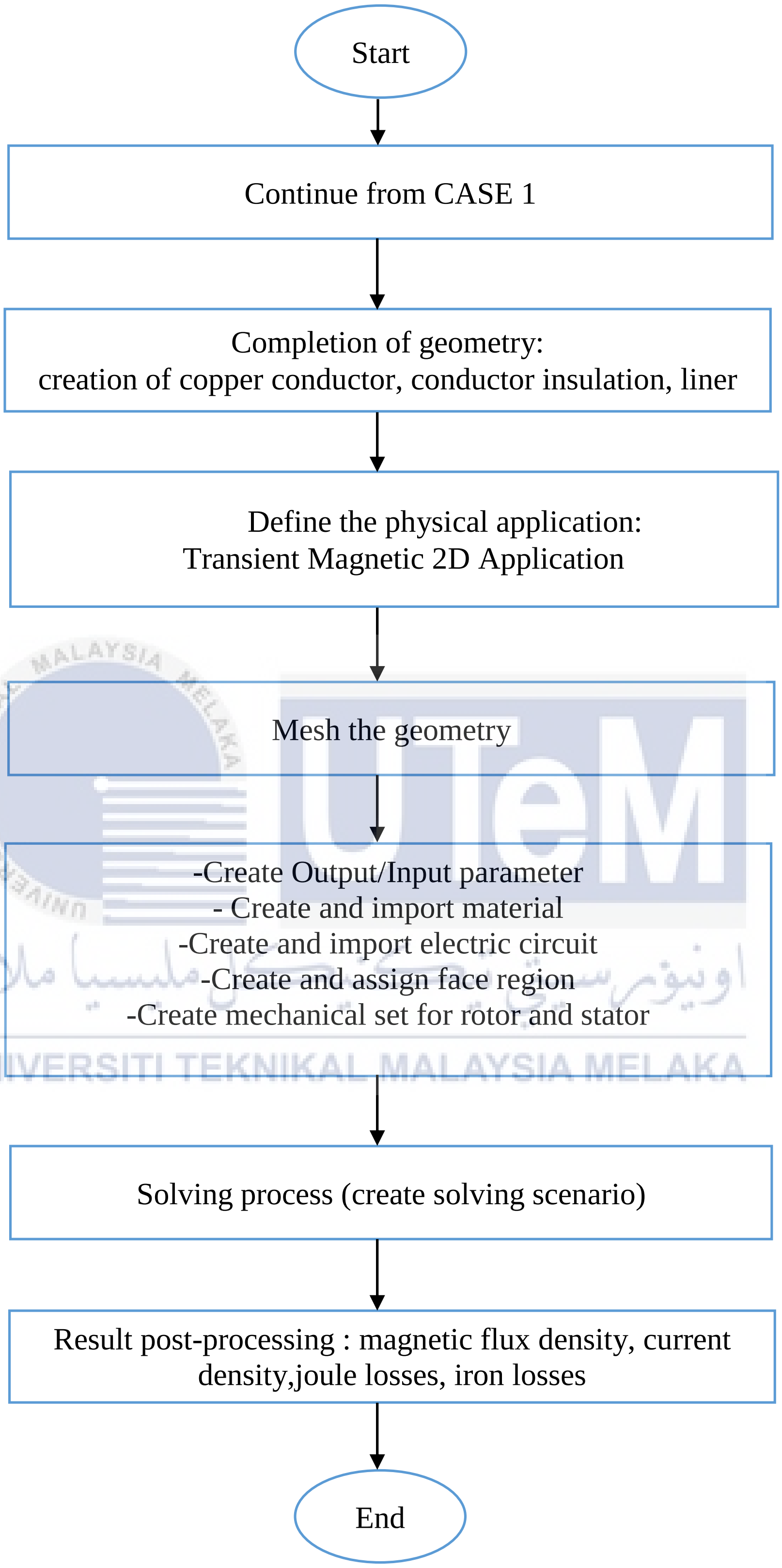

Figure 3-4: *Flowchart for Case 2*

Table 3-1 below shows the characteristics of the input/output(I/O) parameter that will be used and assigned in the simulation. The speed is refering to the motor speed which 200rpm while the frequency is setr to the frequency supply of the motor. Omega is angular speed of the motor, max_current is the peak value of current supply and gamma is shift angle used for defining the supply current.

Table 3-1: *Characteristics of the Input/Output(I/O)Parameter*

Name	Type of I/O parameter	Reference value
SPEED	Parameter defined by a formula	200rpm
FREQUENCY	Parameter defined by a formula	SPEED/60*POLES/2
OMEGA	Parameter defined by a formula	2*Pi()*FREQUENCY
MAX_CURRENT	Parameter defined by a formula	$I_{rms} = 13.78A$ $I_{max} = 19.48A$
GAMMA	Parameter defined by a formula	45

3.5 CASE3: Steady State Thermal Analysis

The Figure 3-5 below shows the flowchart for Case 3 which is a steady state thermal analysis. This simulation continues from the Case 2 but the application is changed to the Steady State Thermal 2D Application. Similarly to Case 2, this case required creating the input/output parameter which consist of convection coefficient, material for thermal conductivity and assign face and line region. Then, the solving scenario created to solve the simulation and obtain the temperature result of the motor.

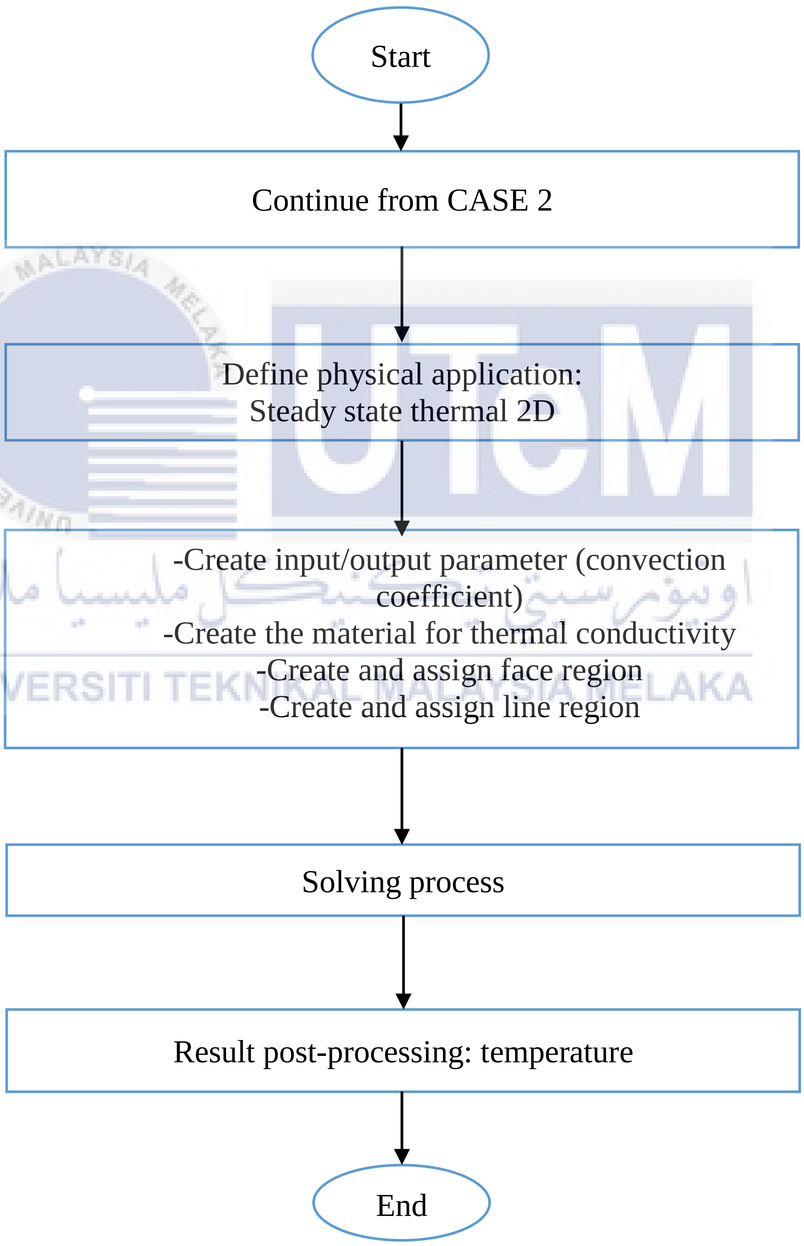

Figure 3-5: *Flowchart for Case 3*

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Overview

This chapter is discuss about the preliminary results based on the thermal motor model simulation that has been run in 2D Flux Altair Software. The discussion will come out with the output value of magnetic flux density, current density, losses and temperature of the motor

4.2 CASE 1: Design Permanent Magnet Motor

Figure 4-1 and Figure 4-2 below show the full and quarter view of permanent magnet motor that design from the 2D Flux Altair software. The motor designed based on the parameter in Appendix B. This motor will be used to solve for Case 2 and Case 3.

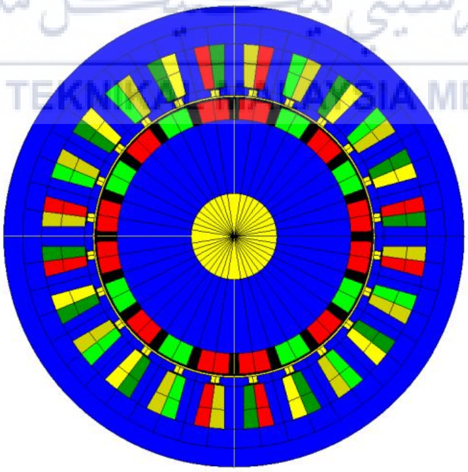

Figure 4-1: *Full permanent magnet motor overview*

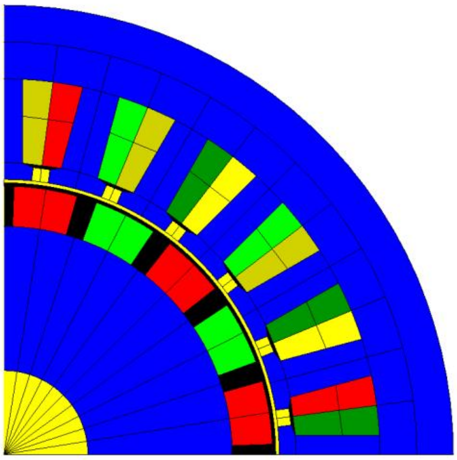

Figure 4-2: *Quarter of permanent magnet motor overview*

4.3 CASE 2: Transient/Time Dependent Magnetic

In this case, the transient/time dependent magnet for the motor is simulated, the result of magnetic flux density distribution, current density distribution, joule losses and iron losses of the motor are obtained in this case. This results is important and some of the results are applied to simulate the steady state thermal analysis in Case 3.

4.3.1 Magnetic Flux Density

For speed: 0rpm

Figure 4-3 below shows the magnetic flux density distribution of permanent magnet region at 0rpm speed. The value for magnetic flux density for permanent magnet region can be determined based on the colour shaded region. The highest value of magnetic flux is 1.253Tesla and the lowest value is 663.055x10^{-3} Tesla.

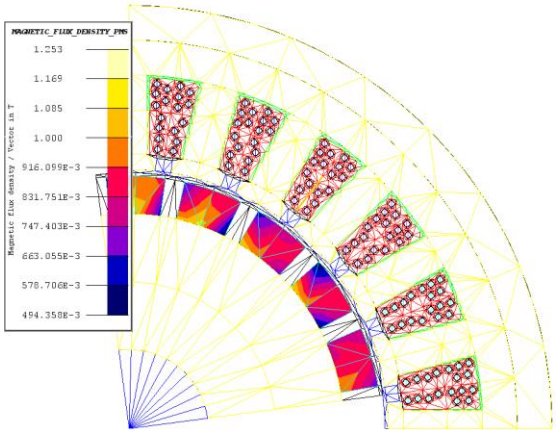

Figure 4-3: Distribution of Magnetic flux density of permanent magnet region for 0rpm speed

The Figure 4-4 below shows the distribution of magnetic flux density of the rotor and stator region for 0rpm speed. From the figure the value distribution of magnetic flux density around the stator and rotor region can be determined through the different colour shaded. The higher value magnetic flux density is 1.340Tesla while the lowest value is $302.979x10^{-3}$ Tesla.

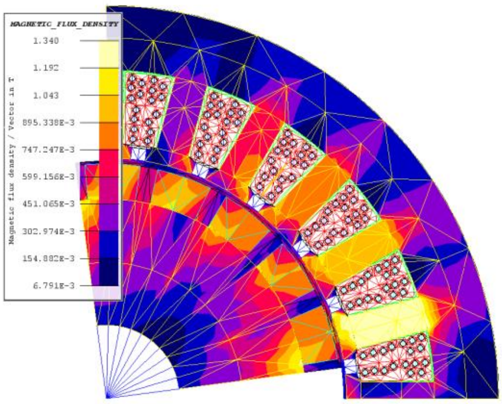

Figure 4-4: Distribution of Magnetic flux density of rotor and stator for 0rpm speed

For speed: 200rpm

Figure 4-5 below shows the magnetic flux density distribution of permanent magnet region for 200rpm speed. The value for magnetic flux density for permanent magnet region can be determined based on the colour shaded region. The highest value of magnetic flux is 1.3296Tesla and the lowest value is 493.736x10^{-3} Tesla.

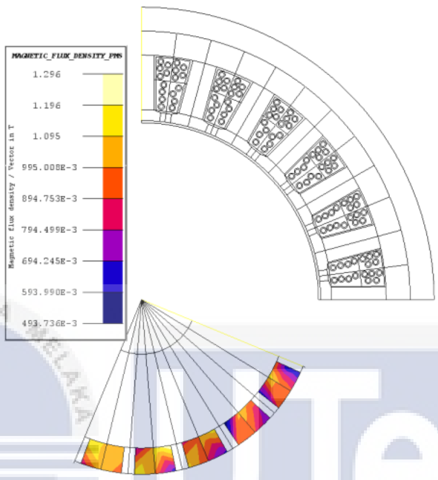

Figure 4-5: Distribution of Magnetic flux density of permanent magnet region for 200rpm speed

The Figure 4-6 below shows the distribution of magnetic flux density of the rotor and stator region for 200rpm speed. From the figure the value distribution of magnetic flux density around the stator and rotor region can be determine through the different colour shaded. The higher value magnetic flux density is 1.621Tesla while the lowest value is 5.045x10^{-3} Tesla.

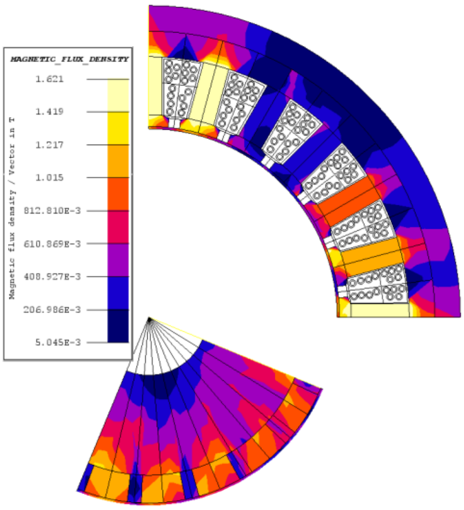

Figure 4-6: Distribution of Magnetic flux density of rotor and stator for 200rpm speed

For speed: 400rpm

Figure 4-7 below shows the magnetic flux density distribution of permanent magnet region for 400rpm speed. The value for magnetic flux density for permanent magnet region can be determined based on the colour shaded region. The highest value of magnetic flux is 1.317Tesla and the lowest value is 511.359×10^{-3} Tesla.

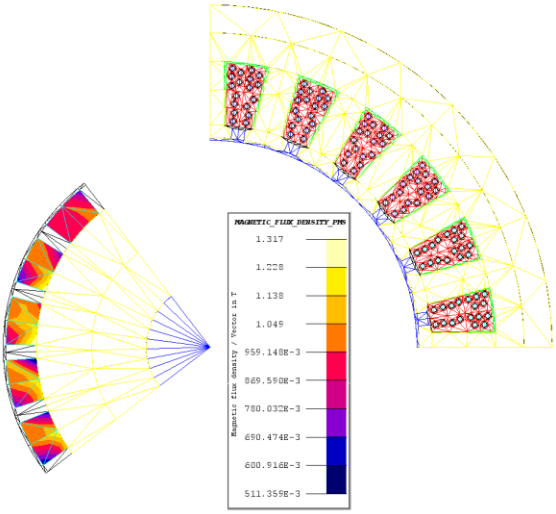

Figure 4-7: Distribution of Magnetic flux density of permanent magnet region for 400rpm speed

The Figure 4-8 below shows the distribution of magnetic flux density of the rotor and stator region for 400rpm speed. From the figure the value distribution of magnetic flux density around the stator and rotor region can be determine through the different colour shaded. The higher value magnetic flux density is 1.455Tesla while the lowest value is 699.309x10^{-3} Tesla.

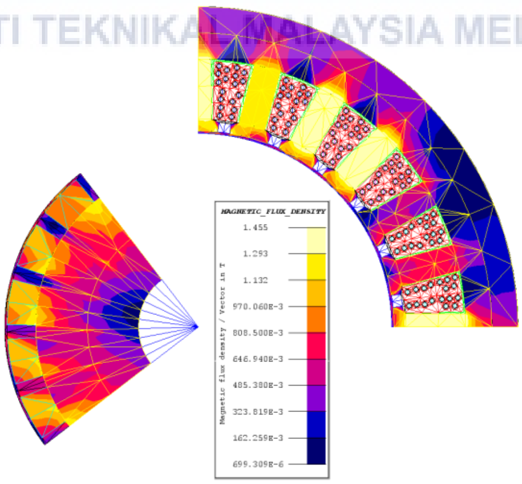

Figure 4-8: Distribution of Magnetic flux density of rotor and stator for 400rpm speed

4.3.2 Current Density of Motor

For speed:0rpm

The Figure 4-9 below shows the distribution of the current density of 2D computation domain for 0rpm speed which consist of permanent magnet simulated with 3 phase of stator conductor. The value can be determined based on the colour shaded region. The value of current density for permanent magnet region is 3.657M A/m^2. The value of current density of stator conductor for every phase are phase 1 is 17.307M A/m^2, phase 2 is -23.641M A/m^2 and phase 3 is -892.447M A/m^2.

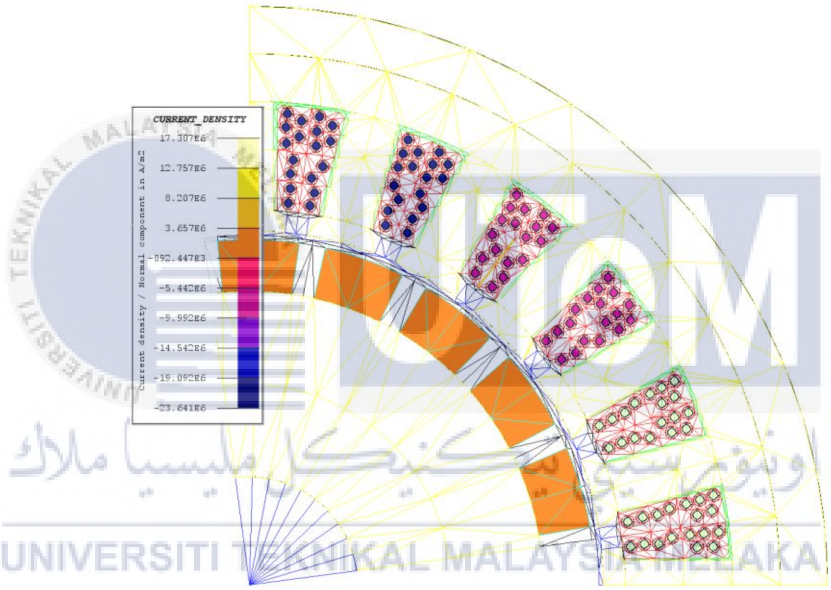

Figure 4-9: Distribution of current density of 2D Computation domain for 0rpm speed

The Figure 4-10 below shows the distribution of the current density of permanent magnet for 0rpm speed. This results obtained by simulating only permanent magnet region. The value of the current density is varied which can be determined based on the colour shaded region. The higher value of current density for permanent magnet region is 1.168x10^{-9} A/m^2 while the lowest is -1.303x10^{-9} A/m^2.

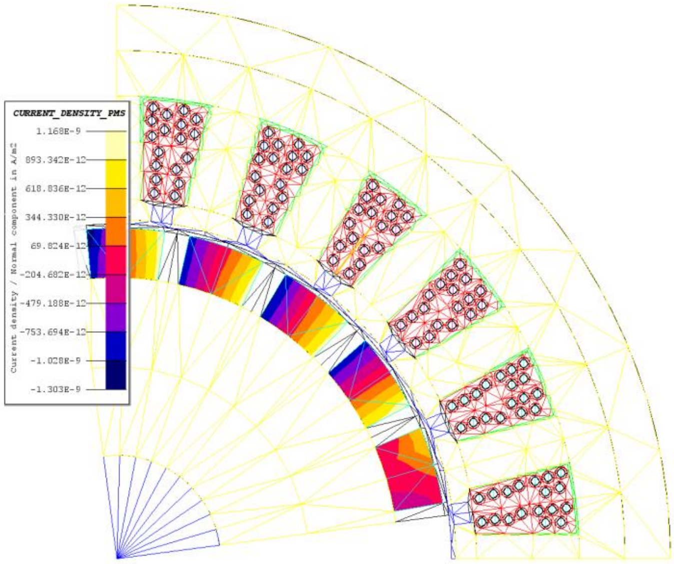

Figure 4-10: Distribution of current density of permanent magnet region for 0rpm speed

For speed:200rpm

The Figure 4-11 below shows the distribution of the current density of 2D computation domain for 200rpm speed which consist of permanent magnet simulated with 3 phase of stator conductor. The value can be determined based on the colour shaded region. The value of current density for permanent magnet region is 2.588M A/m^2. The value of current density of stator conductor for every phase are phase 1 is -23.642M A/m^2, phase 2 is 6.335M A/m^2 and phase 3 is -19.895M A/m^2.

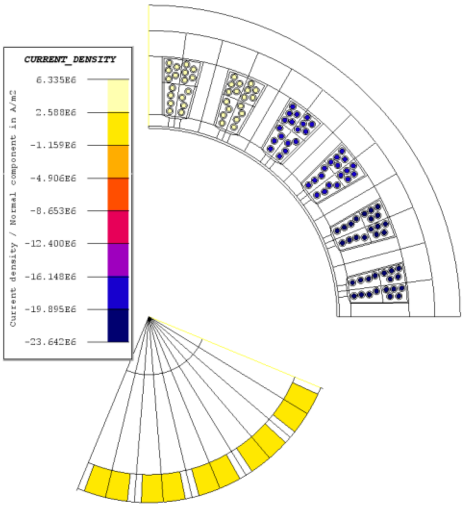

Figure 4-11: : Distribution of current density of 2D Computation domain for 200rpm speed

The Figure 4-12 below shows the distribution of the current density of permanent magnet for 200rpm speed. This results obtained by simulating only permanent magnet region. The value of the current density is varied which can be determined based on the colour shaded region. The higher value of current density for permanent magnet region is 774.198 A/m^2 while the lowest is -662.964 A/m^2.

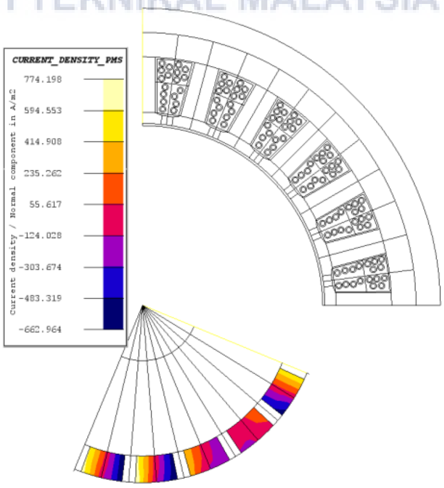

Figure 4-12: Distribution of current density of permanent magnet region for 200rpm speed

For speed 400rpm

The Figure 4-13 below shows the distribution of the current density of 2D computation domain for 400rpm speed which consist of permanent magnet simulated with 3 phase of stator conductor. The value can be determined based on the colour shaded region. The value of current density for permanent magnet region is -725.565 A/m^2. The value of current density of stator conductor for every phase are phase 1 is 2.626M A/m^2, phase 2 is 18.388M A/m^2 and phase 3 is 23.641M A/m^2.

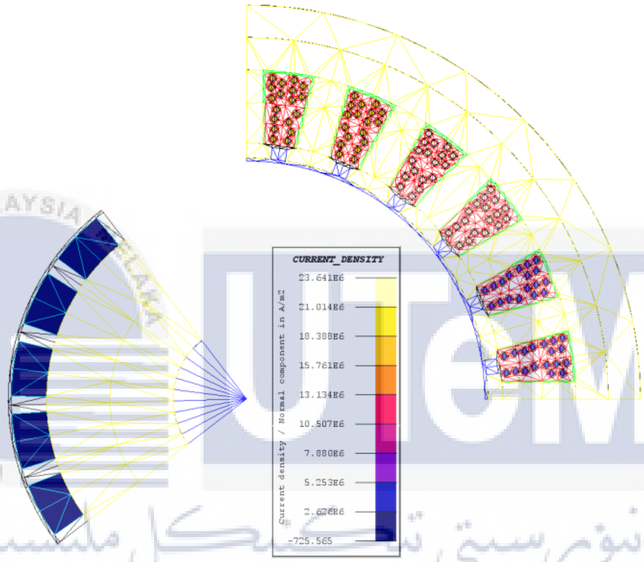

Figure 4-13: Distribution of current density of 2D Computation domain for 400rpm speed

The Figure 4-14 below shows the distribution of the current density of permanent magnet for 400rpm speed. This results obtained by simulating only permanent magnet region. The value of the current density is varied which can be determined based on the colour shaded region. The higher value of current density for permanent magnet region is 696.112 A/m^2 while the lowest is -725.565 A/m^2.

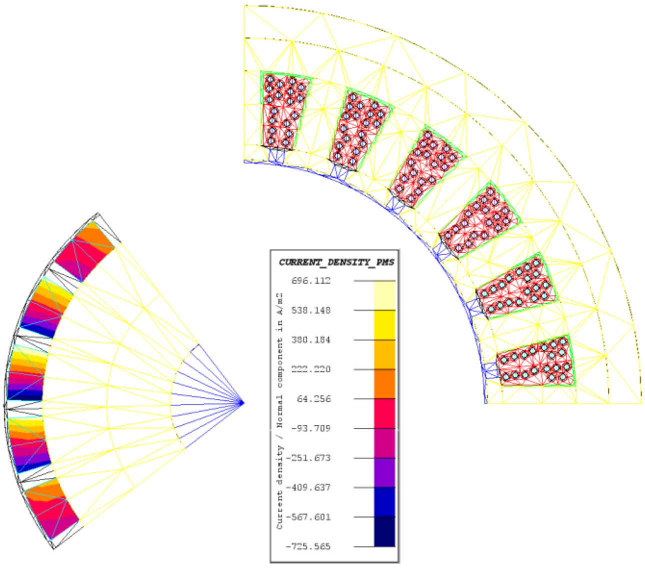

Figure 4-14: Distribution of current density of permanent magnet region for 400rpm speed

4.3.3 Joule Losses of Motor

For speed:0rpm

Figure 4-15 below shows the graph for the total of joule losses which consist of total joule of rotor and stator for 0rpm speed. The value of the losses is not consistent but increase and decrease due the time. The losses slightly increase from 0sec to 1sec with value $52.18\text{x}10^{-27}$ but decrease to $8.09\text{x}10^{-80}$ at time 2sec. The highest losses is $52.18\text{x}10^{-27}$ at 1sec.

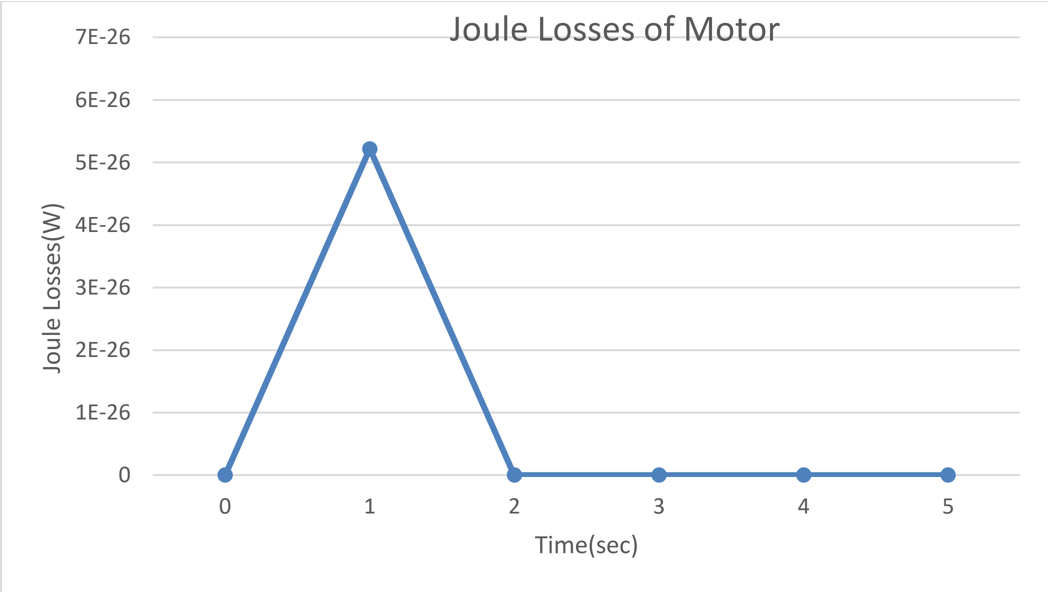

Figure 4-15: *The of Graph Total Joule Losses of Motor for 0rpm*

Figure 4-16 below shows the graph for total joule losses of the end winding resistor for 0rpm speed that had been simulate in the simulation model. The value of total joule losses of end winding resistor is 284.603Watt. The value is constant from 0ses to 5sec.

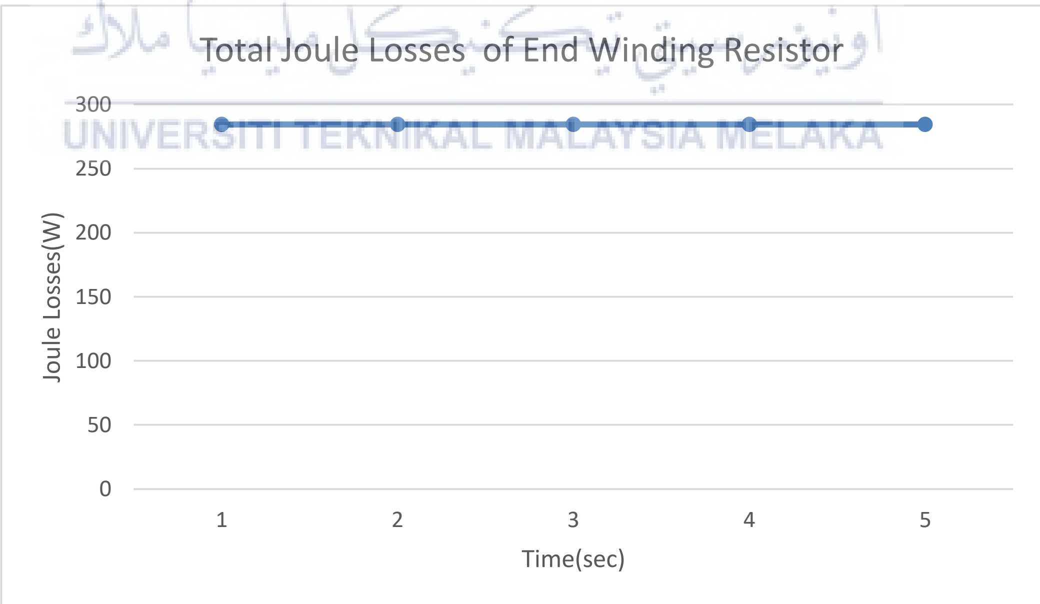

Figure 4-16: *The of Graph Total Joule Losses of End Winding Resistor for 0rpm speed*

For speed: 200rpm

Figure 4-17 below shows the graph for the total of joule losses which consist of total joule of rotor and stator for 200rpm speed. The value of the losses is not consistent but increase and decrease due the time. The losses slightly increase from 0sec to 1sec with value 2.15x10^{-6} but decrease to 2.13x10^{-6} at time 4sec. The highest losses is 2.48x10^{-6} at 3sec.

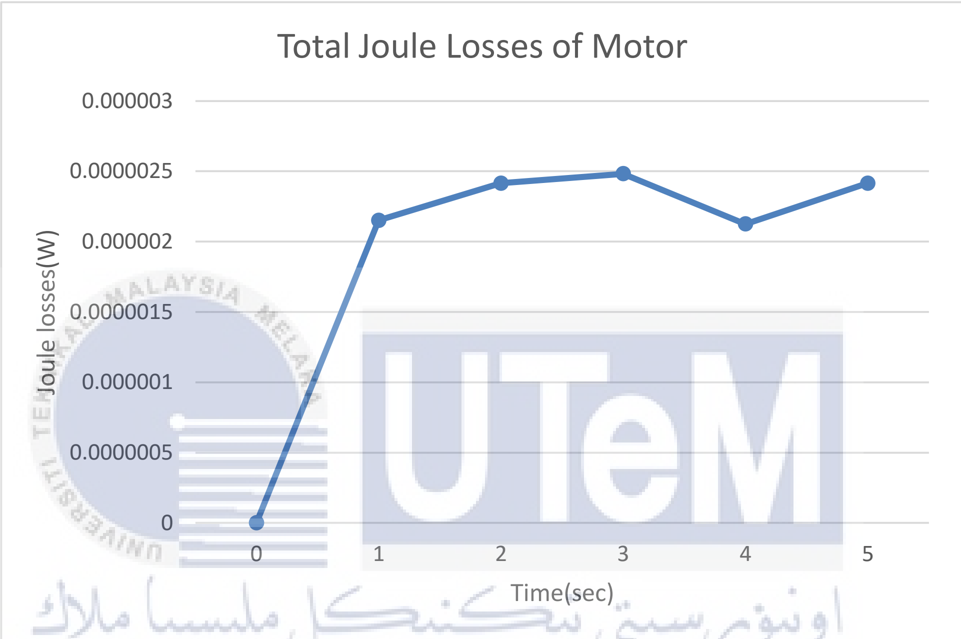

Figure 4-17: *The of Graph Total Joule Losses of Motor for 200rpm*

Figure 4-18 below shows the graph for total joule losses of the end winding resistor for 200rpm speed that had been simulate in the simulation model. The value of total joule losses of end winding resistor is 284.603Watt. The value is constant from 0ses to 5sec.

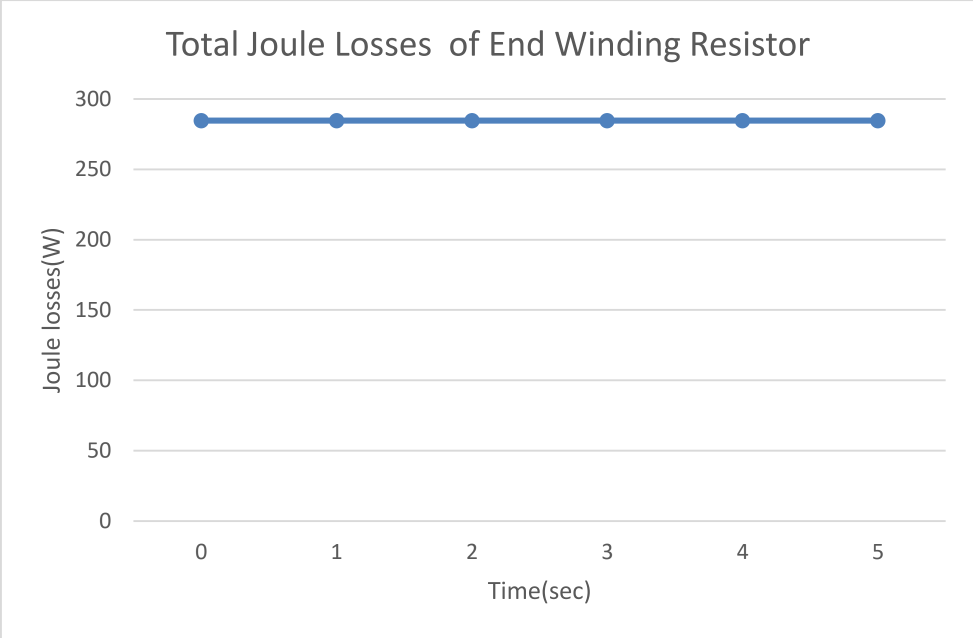

Figure 4-18: *The of Graph Total Joule Losses of End Winding Resistor for 200rpm speed*

For speed: 400rpm

Figure 4-19 below shows the graph for the total of joule losses which consist of total joule of rotor and statorfor 400rpm speed. The value of the losses is not consistent but increase and decrease due the time. The losses slightly increase from 0sec to 1sec with value $2.32x10^{-6}$ but decrease to $2.24x10^{-6}$ at time 2sec. The highest losses is $2.51x10^{-6}$ at 3sec.

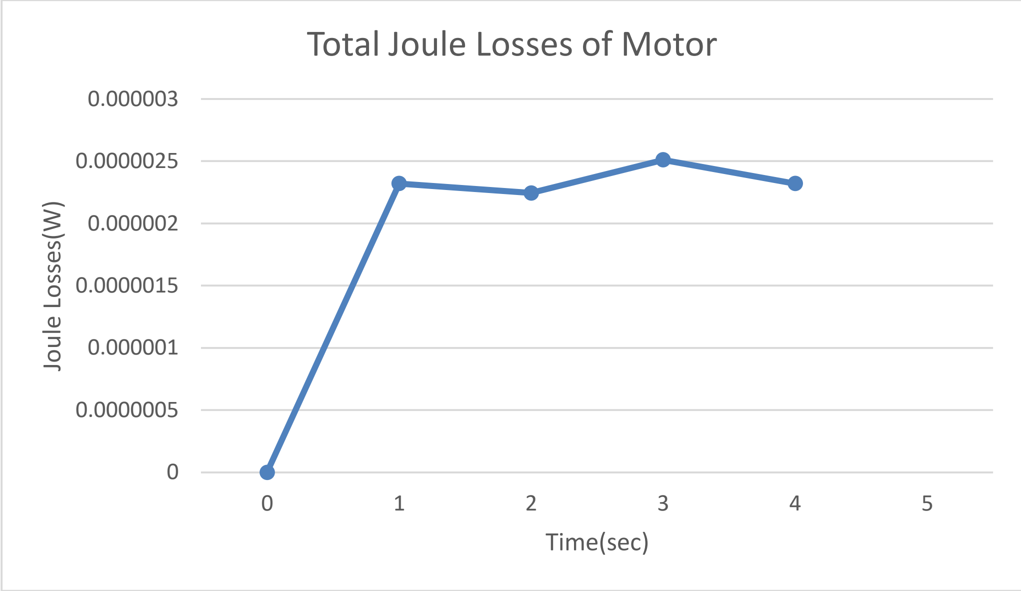

Figure 4-19: *The of Graph Total Joule Losses of Motor for 400rpm*

Figure 4-20 below shows the graph for total joule losses of the end winding resistor for 400rpm speed that had been simulate in the simulation model. The value of total joule losses of end winding resistor is 284.603Watt. The value is constant from 0ses to 5sec.

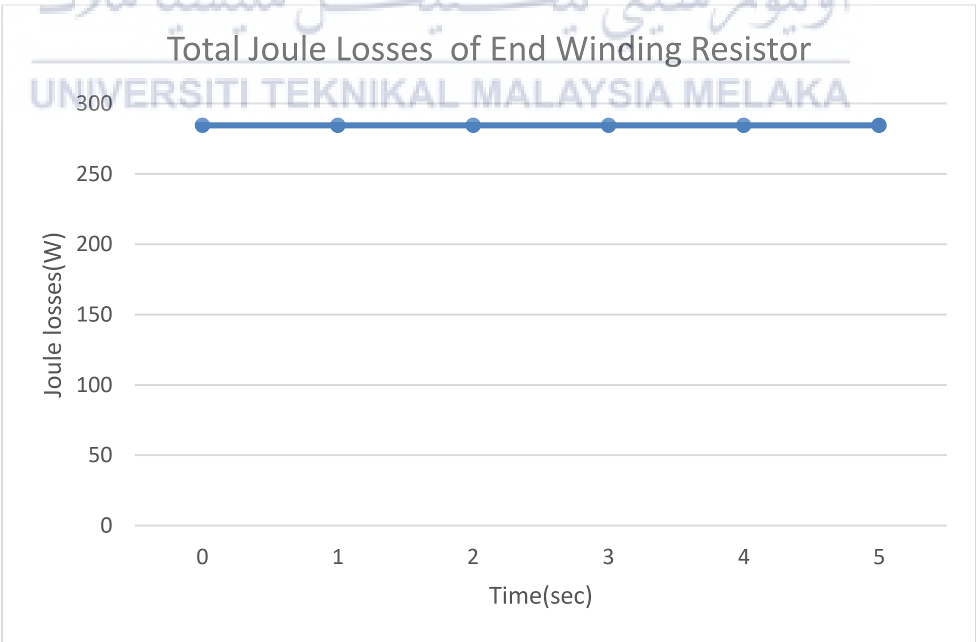

Figure 4-20: The of Graph Total Joule Losses of End Winding Resistor for 400rpm speed

4.3.4 Iron Losses of Motor

For speed: 0rpm

The Figure 4-21, Figure 4-22 and Figure 4-23 below show the total iron losses for rotor, stator and total for both of rotor and stator. This results are simulated through the Bertotti losses in the simulation with 0rpm speed.

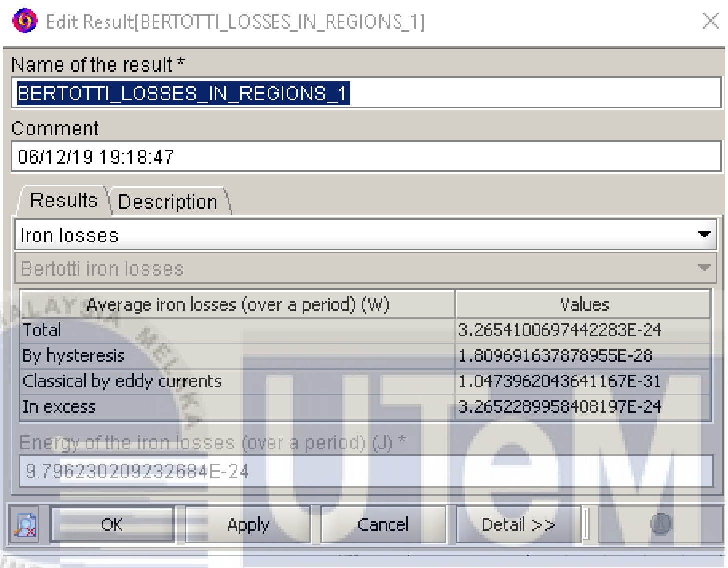

Figure 4-21: *Iron Losses of The Rotor for 0rpm speed*

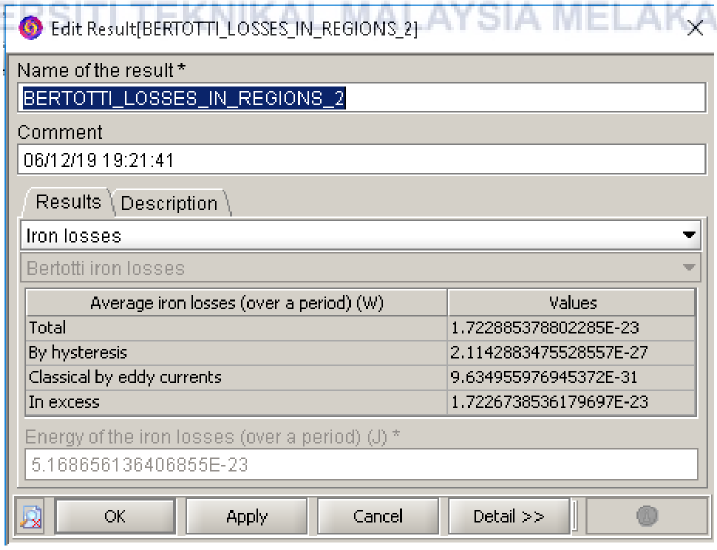

Figure 4-22: *Iron Losses of The Stator for 0rpm speed*

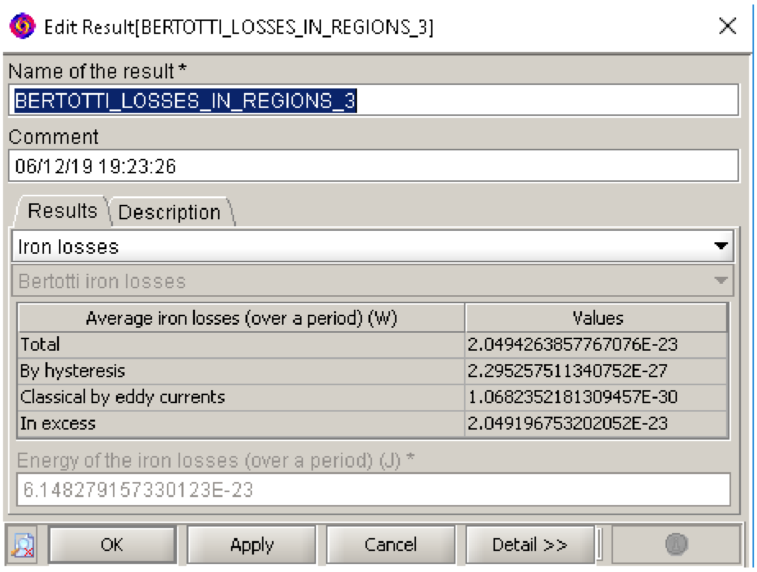

Figure 4-23: *Total of Iron Lossesfor 0rpm speed*

The Table 4-1 below shows the result of total iron losses which consist of rotor and stator magnetic core with 0rpm speed. This result will be used for the thermal analysis. The result of iron losses presented below correspond to the computation domain which quarter of the whole motor. In order to compute the total iron losses for the whole motor need to be multiply the result with 4 as shown in Table 4-2 below.

For peak current, I_{max}= 19.49 A

Table 4-1: *Result of Total Losses for Quarter Motorfor 0rpm speed*

Rotor core losses (W)	Stator core losses (W)	Total core losses (W)
$3.26541x10^{-24}$	$1.72289x10^{-23}$	$2.04943x10^{-23}$

Table 4-2: *Result of Total Losses for Whole Motor for 0rpm speed*

Rotor core losses (W)	Stator core losses (W)	Total core losses (W)
$1.30616x10^{-23}$	$6.89156x10^{-23}$	$8.19772x10^{-23}$

For speed :200rpm

The Figure 4-24, Figure 4-25 and Figure 4.26 below show the total iron losses for rotor, stator and total for both of rotor and stator. This results are simulated through the Bertotti losses in the simulation with 200rpm speed.

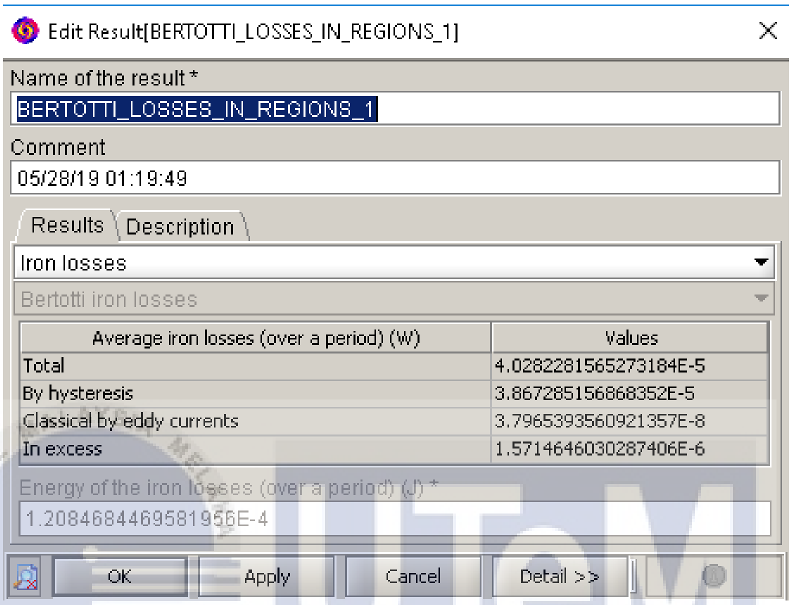

Figure 4-24: *Iron Losses of The Rotor for 200rpm speed*

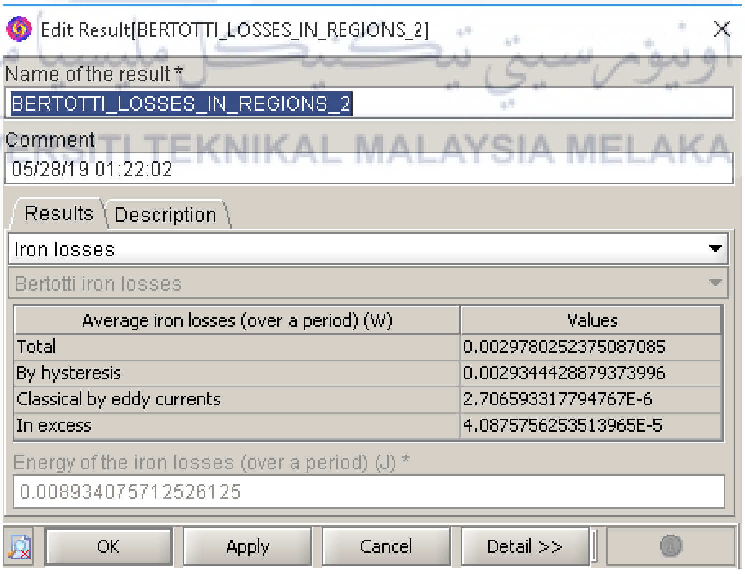

Figure 4-25: *Iron Losses of The Stator for 200rpm speed*

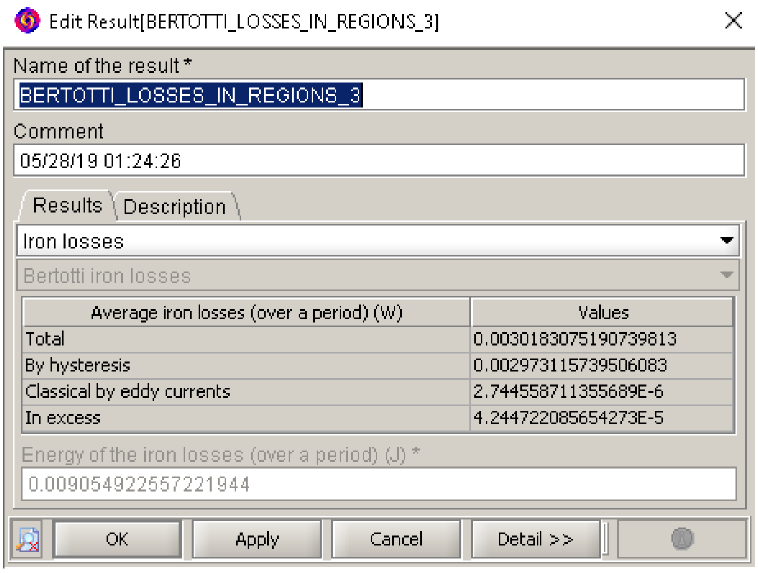

Figure 4-26: *Total of Iron Losses for 200rpm speed*

The Table 4-3 below shows the result of total iron losses which consist of rotor and stator magnetic core with speed 200rpm speed. This result will be used for the thermal analysis. The result of iron losses presented below correspond to the computation domain which quarter of the whole motor. In order to compute the total iron losses for the whole motor need to be multiply the result with 4 as shown in Table 4-4 below.

For peak current, I_{max}= 19.49 A

Table 4-3: *Result of Total Losses for Quarter Motorfor20 0rpm speed*

Rotor core losses (W)	Stator core losses (W)	Total core losses (W)
$4.02823x10^{-5}$	0.00298	0.00302

Table 4-4: *Result of Total Losses for Whole Motor for200rpm speed*

Rotor core losses (W)	Stator core losses (W)	Total core losses (W)
$1.61130x10^{-5}$	0.01192	0.01208

For speed:400rpm

The Figure 4-27, Figure 4-28 and Figure 4-29 below show the total iron losses for rotor, stator and total for both of rotor and stator. This results are simulated through the Bertotti losses in the simulation with 400rpm speed.

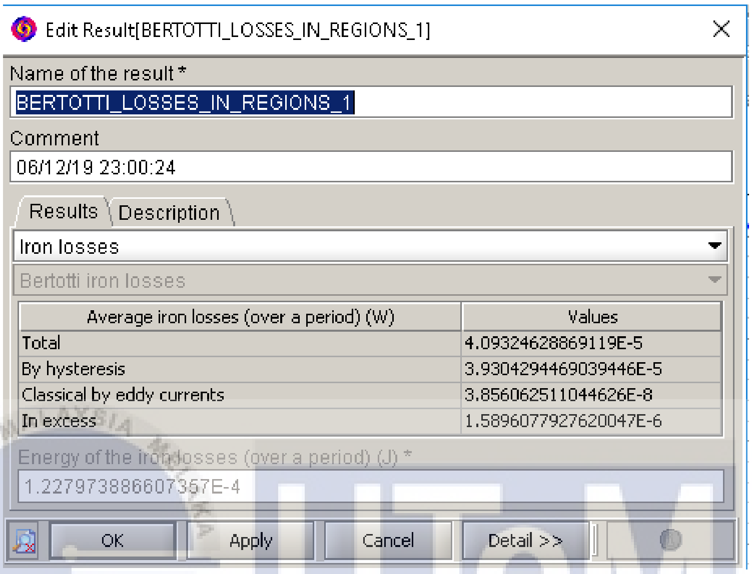

Figure 4-27: *Iron Losses of The Rotor for 400rpm speed*

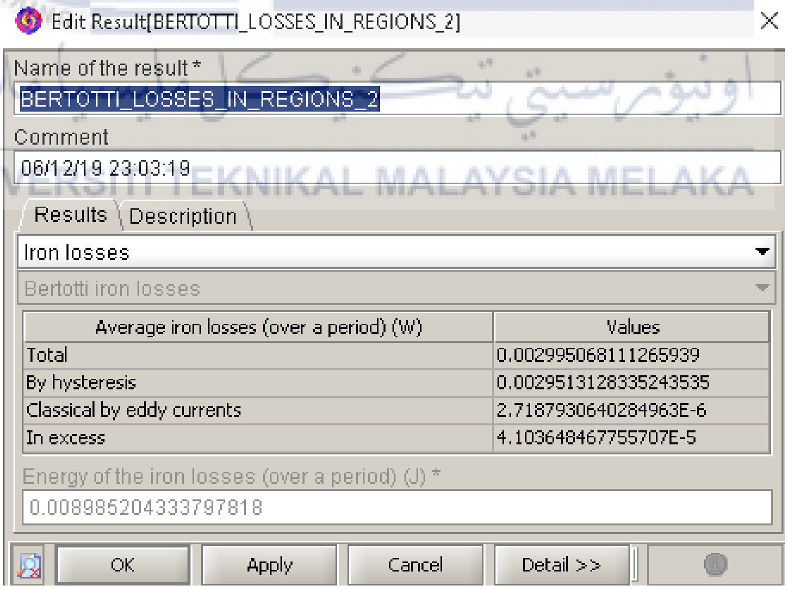

Figure 4-28: *Iron Losses of The Stator for 400rpm speed*

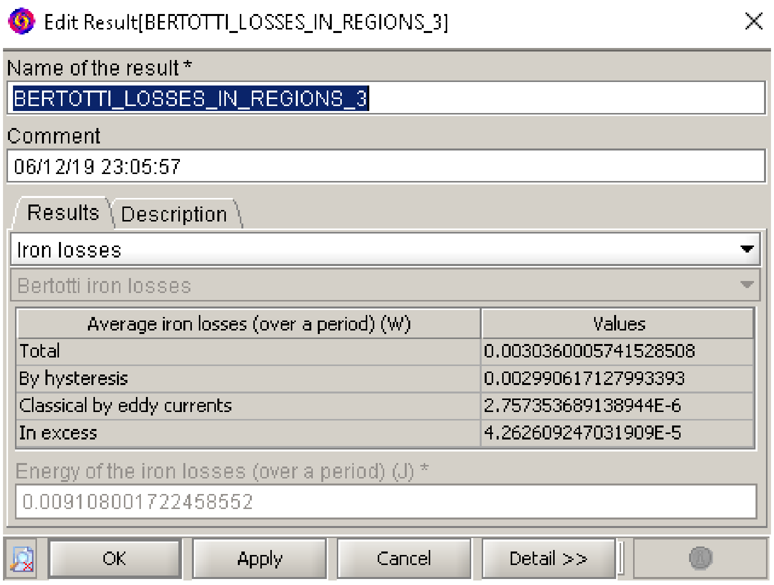

Figure 4-29: *Total of Iron Losses for 400rpm spee*

The Table 4-5 below shows the result of total iron losses which consist of rotor and stator magnetic core with 400rpm speed. This result will be used for the thermal analysis. The result of iron losses presented below correspond to the computation domain which quarter of the whole motor. In order to compute the total iron losses for the whole motor need to be multiply the result with 4 as shown in Table 4-6 below.

For peak current, I_{max}= 19.49 A

Table 4-5: *Result of Total Losses for Quarter Motorfor 400rpm speed*

Rotor core losses (W)	Stator core losses (W)	Total core losses (W)
$4.09325x10^{-5}$	0.00300	0.00304

Table 4-6: *Result of Total Losses for Whole Motor for 400rpm speed*

Rotor core losses (W)	Stator core losses (W)	Total core losses (W)
$1.6373x10^{-4}$	0.01200	0.01216

4.4 CASE 3: Steady State Thermal Analysis

In Case 3, the simulation done to determine the value of temperature for the motor region after steady state is reached. Some of the result obtained from the Case 2 used to run this simulation and the application from steady state thermal is convert to the transient thermal so that the result can be obtained based on the losses gained from the case 2.

4.4.1 Simulation Results

Temperature of rotor and stator of motor

The Figure 4-30 Figure 4-31 and Figure 4-32 below show the temperature distribution of rotor and stator region for different value of speed. The temperature for the rotor region is 2213Kelvin while for the stator region, there is varies value and can be determined based on the colour shaded. The highest value is 2167Kelvin for yellow colour in stator tooth region and decrease to 1422Kelvin for blue colour toward the stator bore.

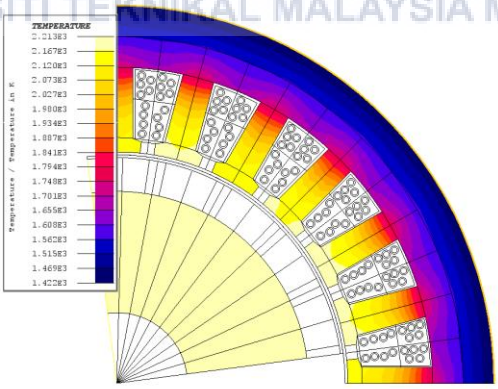

Figure 4-30: *Distribution of temperature for rotor and stator region for 0rpm speed*

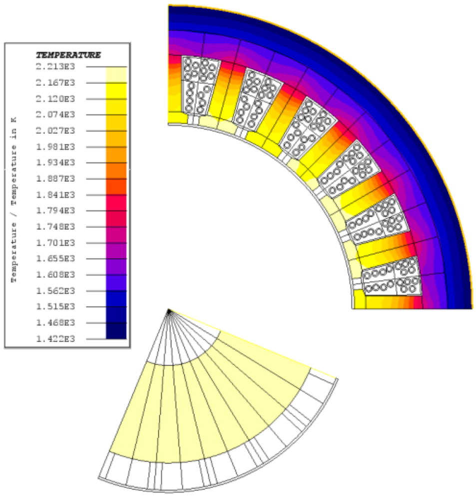

Figure 4-31: Distribution of temperature for rotor and stator region for 200rpm speed

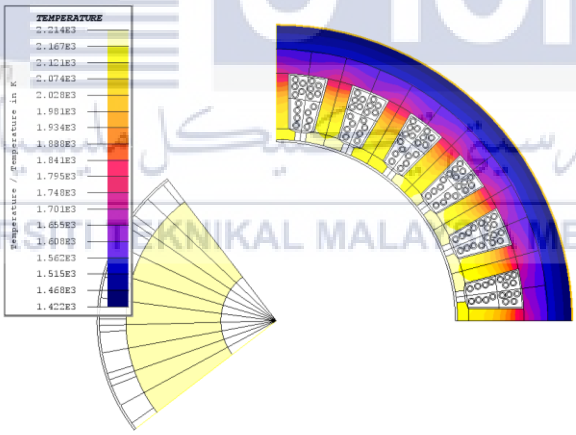

Figure 4-32: Distribution of temperature for rotor and stator region for 400rpm speed

Figure 4-33 and Figure 4-34 below show the graph of temperature in stator and rotor for different speed which are 0rpm, 200rpm and 400rpm. The temperature is measured at one of the point of the motor region. The motor with speed 400rpm has the highest temperature in stator compared to the motor with 0rpm and 200rpm speed. In rotor the motor with speed 200rpm and 400rpm has same temperature, 2460Kelvin which higher than the motor with 0rpm speed.

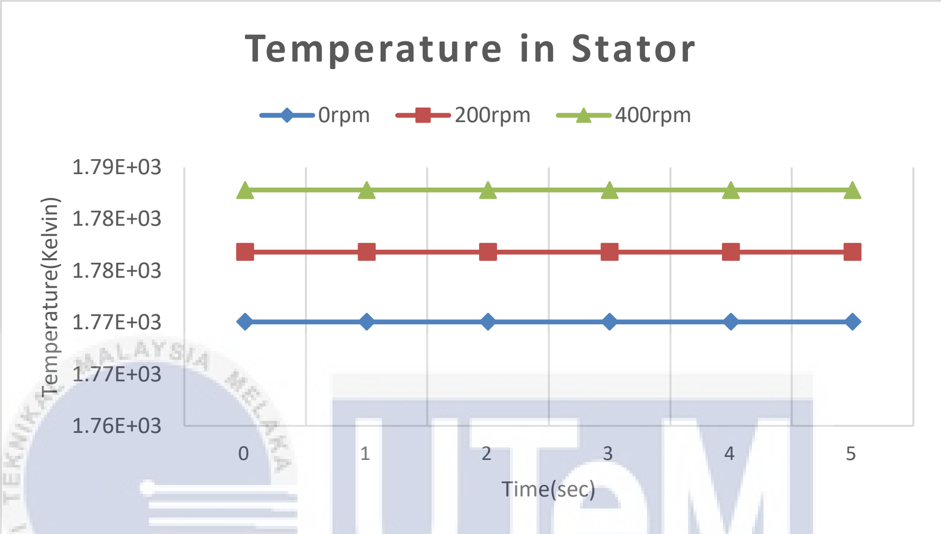

Figure 4-33: The Graph of temperature in stator for different speeds

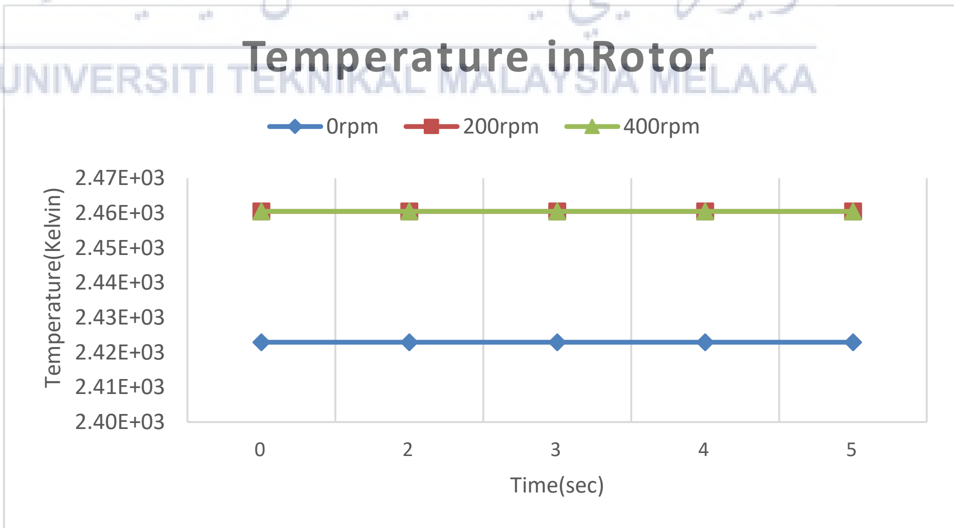

Figure 4-34: The Graph of temperature in Rotor for different speeds

Temperature of permanent magnet

The Figure 4-35, Figure 4-36 and Figure 4-37 below show the temperature distribution of permanent magnet region for different value of speed. The temperature for the magnet 2214Kelvin. This value is different compared to the experimental value due to the incorrect heat coefficient of material that assign during the simulation.

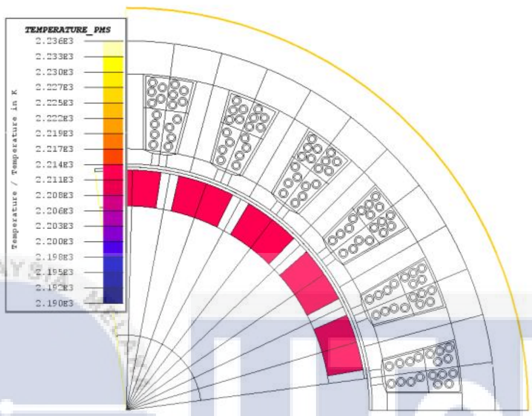

Figure 4-35: *Distribution of temperature for permanent magnet region for 0rpm*

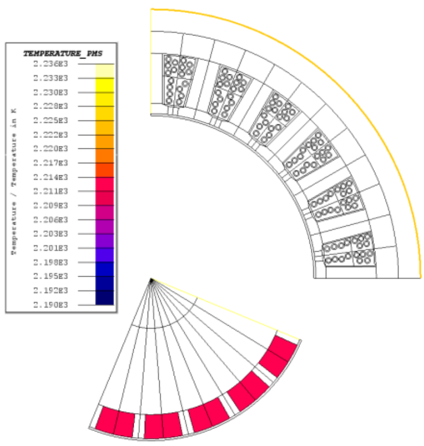

Figure 4-36: Distribution of temperature for permanent magnet region for 200rpm

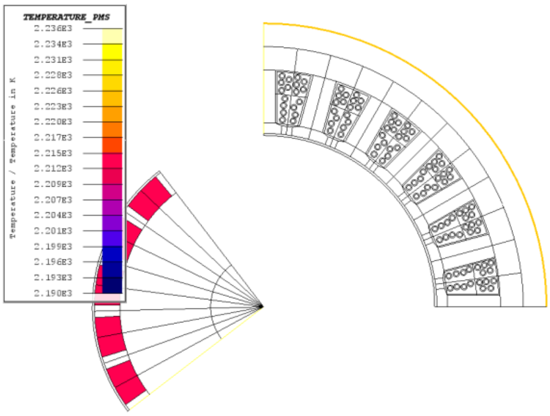

Figure 4-37: Distribution of temperature for permanent magnet region for 400rpm

Figure 4-38 below shows the graph of temperature in permanent magnet of motor for different speed which are 0rpm, 200rpm and 400rpm. The temperature is measured at one of the point of the motor region. The motor with speed 400rpm and 200rpm has the same temperature in permanent magnet region, 2460Kelvin which higher than motor with speed 0rpm, 2420Kelvin.

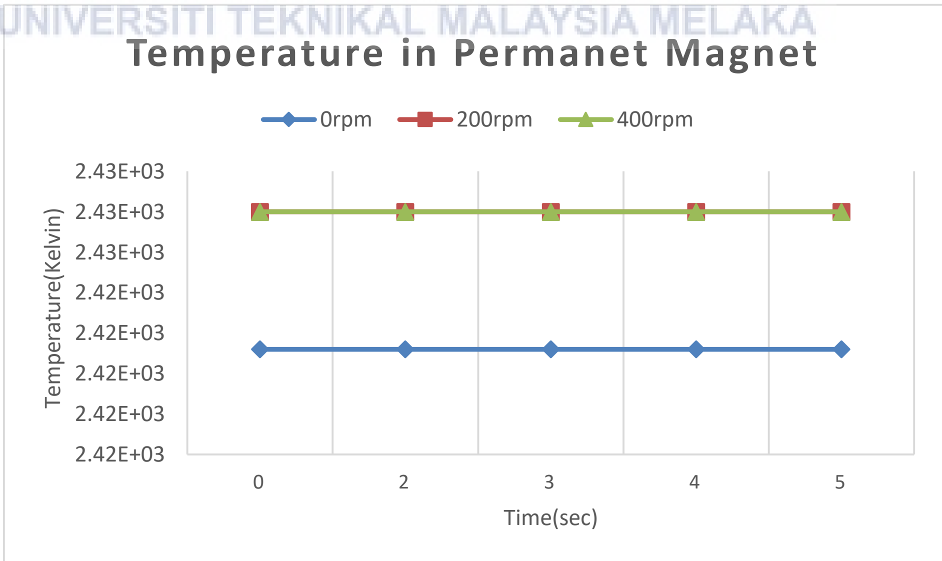

Figure 4-38: The Graph of temperature in Permanent Magnetfor different speed

Temperature of motor conductors

The Figure 4-39, Figure 4-40 and Figure 4-41 below show the temperature distribution of stator conductor region for different value of speed. The stator conductor consist of 3 phase and every phase has 36 conductors. Every phase has different value of temperature and can be determined based on the colour shaded region. The range of the conductor temperature are from 4301Kelvin to 8988Kelvin.

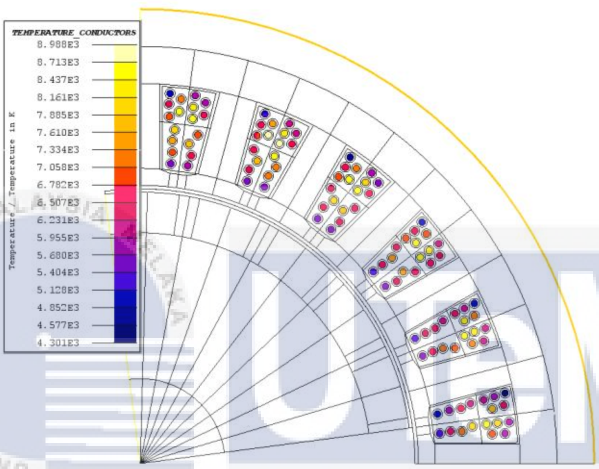

Figure 4-39: Distribution of temperature of conductors region for 0rpm speed

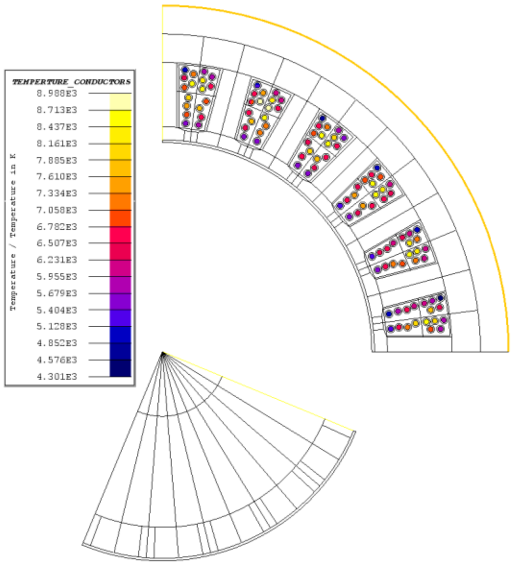

Figure 4-40: Distribution of temperature of conductors region for 200rpm speed

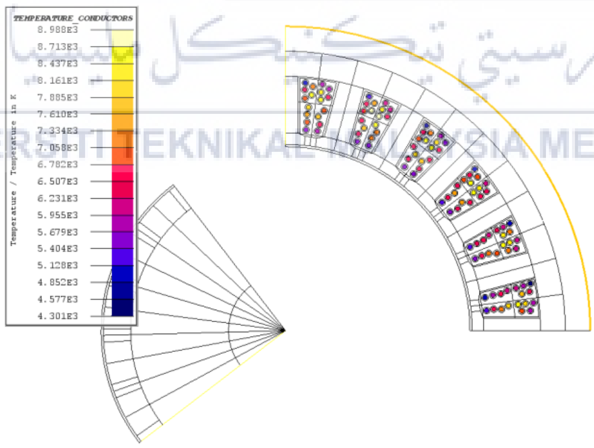

Figure 4-41: Distribution of temperature of conductors region for 400rpm speed

Figure 4-42 below shows the graph of temperature in motor conductors for different speed which are 0rpm, 200rpm and 400rpm. The temperature is measured at one of the point of the motor region.All the motor with different speed has the same value of temperature in motor conductors region, 5370Kelvin.

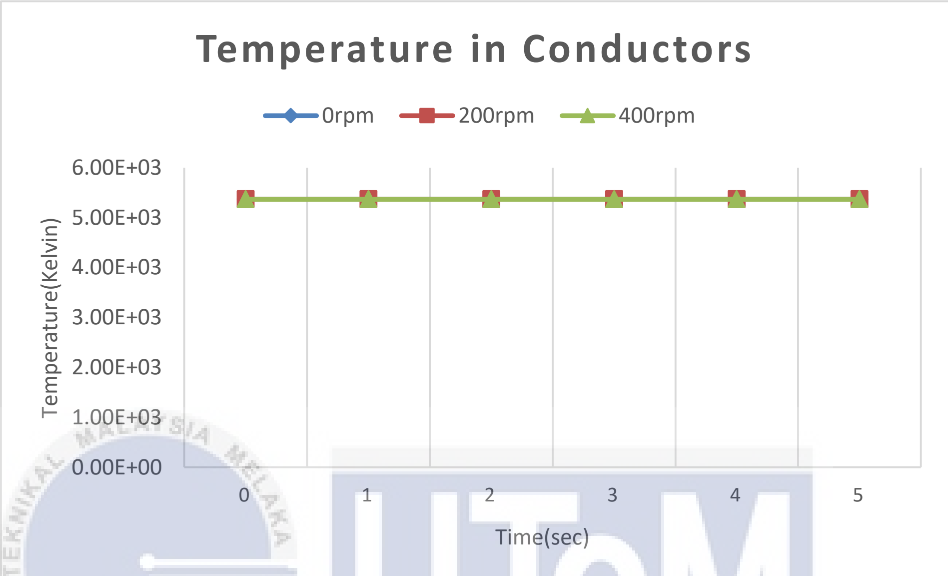

Figure 4-42: The Graph of Temperature in Motor Conductors for Different Speed

4.4.2 Experimental Data

Figure 4-39 below shows the experimental result of temperature for end winding and magnet region with 200rpm speed for two hours. Both temperature are slightly increase due to the time. The temperature of the end winding is higher than the magnet region.

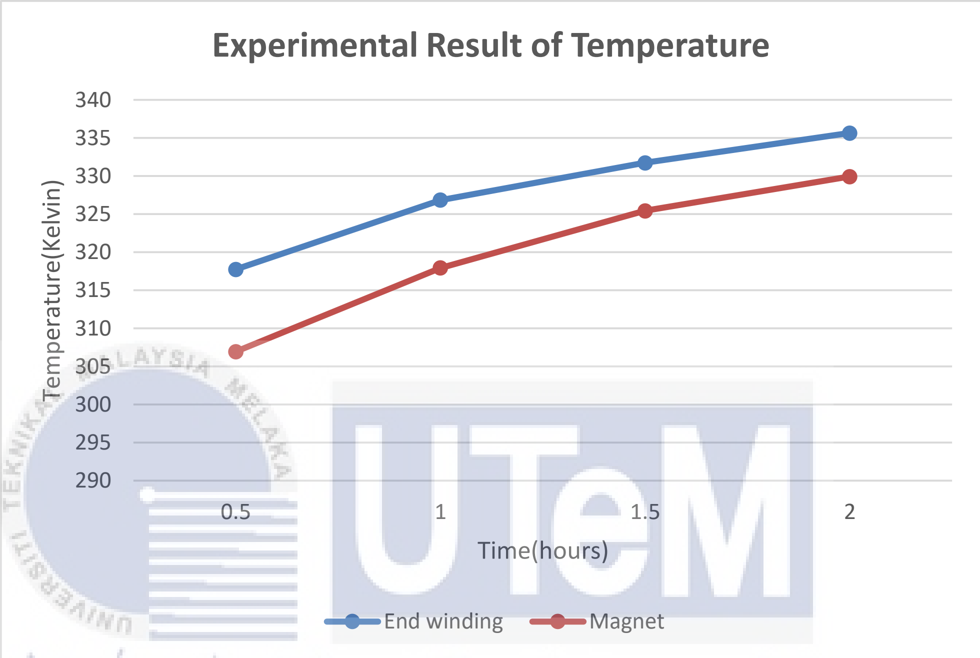

Figure 4-43: *Experimental Result of Temperature with Speed 200rpm*

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Overview

In this chapter will discuss about the conclusion of the work done in Projek Sarjan 2 (PSM 2) about thermal in electric motor and future work for upgrade the motor.

5.2 Conclusion

In conclusion, the thermal behaviour in the electric motor is depends on the heat sources and motor geometry. Flux 2D Altair software is used to design the thermal generated in electric motor by using thermal motor parameter. The simulation is done by divided into three cases which are Case 1 is design permanent magnet motor, Case 2 is simulated transient/time magnetic dependent and Csase 3 is steady state thermal analysis. In Case 1 the model of permanent magnet motor successfully design based on the motor parameter. The model is simulated by various value of speed which are 0rpm, 200rpm and 400rpm with same maximum number of current, 19.49A For Case 2, the result of magnetic flux density, current density, joule losses and iron losses are determined for the different values of speed. For Case 3 which steady state thermal analysis the temperature distribution in the electric motor for different value of speed is obtained. The temperature also measured based on one of the point of motor region through the simulation. The experimental result for 200rpm speed is plotted to compared with the simulation results. Based on analysis from the simulated results, the results is not achieved as the experimental results where the temperature value obtained in simulation is higher than the experimental value. This scenario happen due to the problem of heat coefficient for material and the parameter of the motor. The inaccurate value of heat coefficient for the material may caused the temperature of the motor region not accurate because the temperature of the motor depends on the value of the heat coefficient for the material that insert through the simulation. The temperature of the motor also depends on the parameter of the motor. Inaccurate value of the motor parameter between simulation and experimental also one of the reason caused the temperature of the motor in simulation is differ with the experimental. Thus, from this project, the temperature of the motor is influenced by the heat coefficient for the material and the parameter of the motor.

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5.3 Future work

The project will continue with determine the correct value of heat coefficient and correct value of motor parameter and simulated the model to obtaine the accurate results.

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APPENDICES

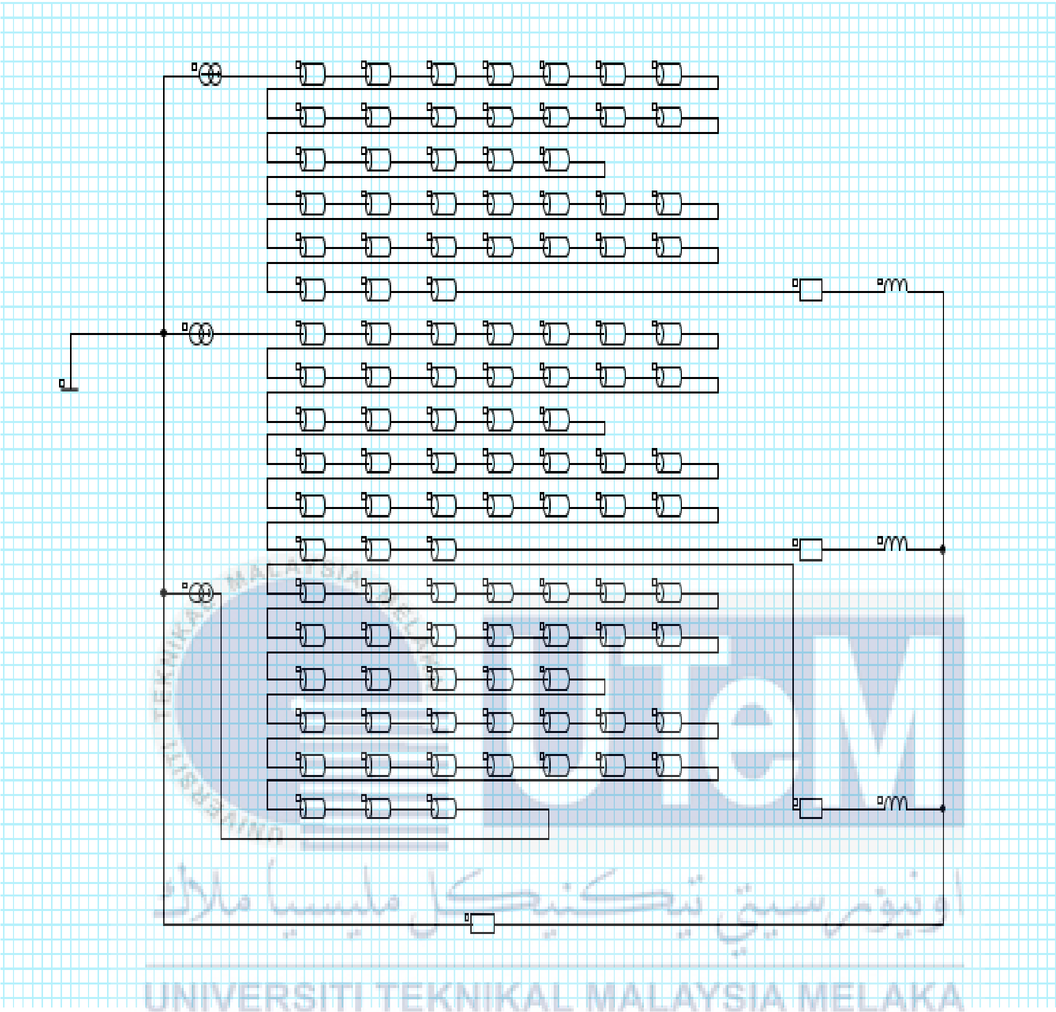
APPENDIX A: Gantt Chart

NO	ACTIVITY	PERIOD	WEEK													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	PSM 2 Briefing	1														
2	Discussing with supervisor	1														
3	Learn about 2D Flux Altair Software and Design the permanent magnet	4														
4	Simulate transient/time dependent magnet	3														
5	Simulate steady state thermal analysis	4														
6	PSM 2 Presentation	1														
7	Final report submission	1														

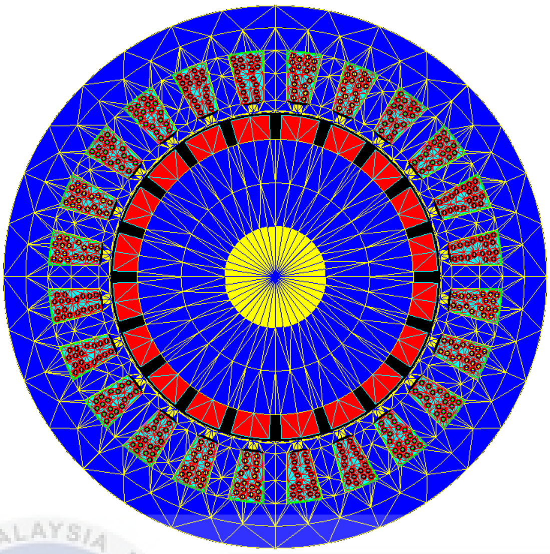
APPENDIX B: Motor Parameter

Air gap	1mm
Speed	0rpm, 200rpm, 400rpm
Rotor	
Shaft radius	12.5mm
Thickness of magnet	6mm
Magnet pole arc [Deg]	136.5
No. of pole	20
Rotor external radius	40mm
Stator	
Slot depth	17mm
Stator tooth width	5.62mm
Slot opening	3.6mm
Radial depth	2mm
Undercut angle [Deg]	15
No. of slot	24
Stator outer radius	67mm

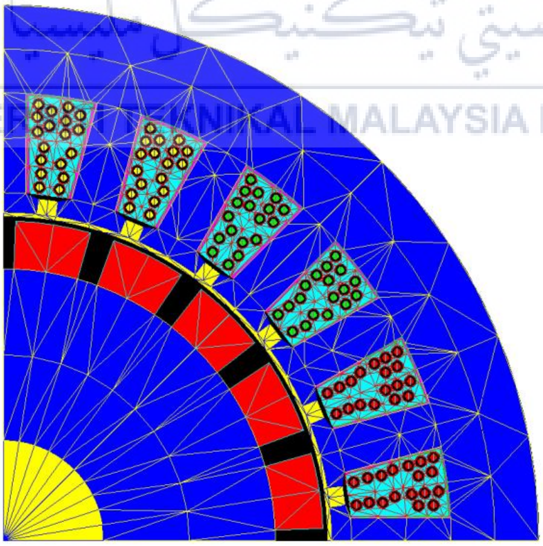
APPENDIX C: Electric Circuit



APPENDIX D: Mesh Geometry of Motor



Whole motor



Quarter of the motor

APPENDIX E: Data of Joule Losses

Speed: 0rpm

Time(sec)	Total Joule losses (W)
0	0
1	52.18E-27
2	8.09E-30
3	10.74E-30
4	2.76E-30
5	7.78E-30

Total joule losses of the motor

Time(sec)	Joule losses
0	284.603
1	284.603
2	284.603
3	284.603
4	284.603
5	284.603

Total joule losses of the end winding resistor

Speed: 200rpm

Time(sec)	Total Joule losses (W)
0	0
1	2.15E-06
2	2.42E-06
3	2.48E-06
4	2.13E-06
5	2.42E-06

Total joule losses of the motor

Time(sec)	Joule losses
0	284.603
1	284.603
2	284.603
3	284.603
4	284.603
5	284.603

Total joule losses of the end winding resistor

Speed: 400rpm

Time(sec)	Total Joule losses (W)
0	0
1	2.32E-06
2	2.24E-06
3	2.51E-06
4	2.32E-06
5	2.24E-06

Total joule losses of the motor

Time(sec)	Joule losses
0	284.603
1	284.603
2	284.603
3	284.603
4	284.603
5	284.603

Total joule losses of the end winding resistor

APPENDIX F: Temperature at the point of motor region

	Speed		
Time(sec)	0rpm	200rpm	400rpm
0	1.77E+03	1.78E+03	1.78E+03
1	1.77E+03	1.78E+03	1.78E+03
2	1.77E+03	1.78E+03	1.78E+03
3	1.77E+03	1.78E+03	1.78E+03
4	1.77E+03	1.78E+03	1.78E+03
5	1.77E+03	1.78E+03	1.78E+03

Temperature in Stator

	Speed		
Time(sec)	0rpm	200rpm	400rpm
0	2.42E+03	2.46E+03	2.46E+03
2	2.42E+03	2.46E+03	2.46E+03
3	2.42E+03	2.46E+03	2.46E+03
4	2.42E+03	2.46E+03	2.46E+03
5	2.42E+03	2.46E+03	2.46E+03

Temperature in Rotor

	Speed		
Time(sec)	0rpm	200rpm	400rpm
0	2.42E+03	2.43E+03	2.43E+03
2	2.42E+03	2.43E+03	2.43E+03
3	2.42E+03	2.43E+03	2.43E+03
4	2.42E+03	2.43E+03	2.43E+03
5	2.42E+03	2.43E+03	2.43E+03

Temperature in Permanent Magnet

	Speed		
Time(sec)	0rpm	200rpm	400rpm
0	5.37E+03	5.37E+03	5.37E+03
1	5.37E+03	5.37E+03	5.37E+03
2	5.37E+03	5.37E+03	5.37E+03
3	5.37E+03	5.37E+03	5.37E+03
4	5.37E+03	5.37E+03	5.37E+03
5	5.37E+03	5.37E+03	5.37E+03

Temperature in Motor Conductors

APPENDIX F: Experimental Data

Time (hours)	Temperature at End winding (Kelvin)	Temperature at Magnet (Kelvin)
0.5	317.75	306.95
1	326.85	317.95
1.5	331.75	325.45
2	335.65	329.95