DESIGN OF OUTER ROTOR BLDC MOTOR FOR HIGH VOLUME LOW SPEED FAN

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This Report is submitted in Partial Fulfillment of Requirements for the Degree of Bachelor in Electrical Engineering

(Power Electronic & Drives)

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I hereby declare that this report entitle work 'Design Of Outer Rotor BLDC Motor For High Volume Low Speed Fan' is my own work. This report is a presentation of my original research work. All contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions. Written and submitted for the purpose of fulfillment of the requirements for the degree of Bachelor of Electrical Engineering (Power Electronic & Drives). The work was done under the supervision and guide from Prof. Madya Dr. Kasrul bin Abdul Karim of the Universiti Teknikal Malaysia Melaka.

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APPROVAL

" I hereby declare that I have read through this report entitle 'Design Of Outer Rotor BLDC Motor For High Volume Low Speed Fan' and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Power Electronic & Drives)"

Signature : ……………………………………

Supervisor Name : Prof Madya Dr. Kasrul bin Abdul Karim

Date :

DEDICATION

To my beloved father and mother, and all the lectures and my friends that had help me all the time…

ABSTRACT

Nowadays, due to the rapid advance of power electronic controller technology, the used of Brushless Permanent Magnet (BLPM) motor for electric fan application had become a trend due to its advantages in term of power efficiency than induction motor. This is because the rotor speed of BLPM motor is equal to the synchronous speed of the motor, compared to the rotor speed of induction motor that has a slight different of slip speed from the synchronous speed. BLPM motor has two types of motor, which is Brushless DC (BLDC) motor and Brushless AC (BLAC) motor. BLDC motor has trapezoidal back EMF criteria, while the BLAC motor has sinusoidal back EMF criteria. So, in term of speed control, BLDC motor is much simpler to control its speed compared to BLAC. This project will cover about designing an outer rotor BLDC motor for high volume and low speed motor fan that has rated power of 200W, torque of 13N.m and 150 rpm rated speed using Asys Maxwell Rmxprt software. The design steps are started by validating the feasibility of the combination of poles and slot numbers that are used for the motor design. Then, other parameters such as tooth width, tooth height and the tooth pitch of the stator part are designed with appropriate calculation, to be a suitable design based on the fixed desired design parameter of the motor such as the rotor outer diameter, the airgap of the motor and the size of the magnet used. The analysis of the motor performance has been simulated using Ansys Maxwell 2D software. As the result, the design of the motor that has closed value as the desired performance with desired motor dimension is achieved.

ABSTRAK

Pada masa kini, teknologi kawalan dengan penggunaan kuasa elektronik semakin berkembang. Justeru, selari dengan perkembangan ini, penggunaan Brushless Permanent Magnet Motor (BLPM) sebagai aplikasi untuk kipas elektrik turut menjadi pilihan dalam industri kerana motor BLPM mempunyai kecekapan kuasa yang lebih tinggi berbanding dengan induction motor, kerana berbanding induction motor, motor BLPM mempunyai kelajuan rotor yang selari dengan kelajuan sinkronisasi berbanding kelajuan rotor induction motor yang mempunyai sedikit perbezaan kelajuan dengan kelajuan sinkronisasi dengan nilai gelinciran. Motor BLPM terbahagi kepada dua jenis, iaitu motor Brushless DC (BLDC) dan motor Brushless AC (BLAC). Perbazaan antara keduanya ialah, motor BLDC mempunyai kriteria Back EMF berbentuk trapezoidal, manakala motor BLAC pula mempunyai kriteria back EMF berbentuk sinusoidal. Jadi,dari segi kawalan motor, motor BLDC lebih mudah dikawal berbanding dengan motor BLAC. Projek ini merangkumi dalam mereka bentuk motor BLDC yang mempunyai rotor luaran sebagai motor kipas gergasi yang mempunyai tork yang tinggi. Spesifikasi reka bentuk motor menggunakan kuasa sebanyak 200W, dan mempunyai nilai tork sebanyak 13N.m dan kelajuan 150 rpm menggunakan perisian komputer Ansys Maxwell Rmxprt. Proses mereka bentuk motor dimulakan dengan mengesahkan kesesuaian kombinasi bilangan pole dan slot yang akan digunakan dalam rekabentuk motor. Kemudian, nilai parameter seperti kelebaran gigi, ketinggian gigi dan saiz mulut gigi bagi bahagian statik motor direka dengan pengiraan yang sesuai, untuk menjadi reka bentuk yang sesuai berdasarkan parameter reka bentuk yang telah ditetapkan pada motor seperti diameter luar rotor, jarak udara pada motor dan saiz magnet yang digunakan. Simulasi untuk menganalisa prestasi motor telah dibuat menggunakan perisian komputer Ansys Maxwell 2D Analysis. Hasilnya, reka bentuk motor yang mempunyai nilai yang hampir sama dengan prestasi motor dengan dimensi motor yang dikehendaki telah dicapai.

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LIST OF ABBREVIATION

BLDC	-Brushless Direct Current
HVAC	-High Voltage Alternate Current
CNC	-Computer Numerical Control
HVLS	-High Volume Low Speed
DC	-Direct Current
BLPM	-Brushless Permanent Magnet
BLAC	-Brushless Alternate Current
2D	-2 Dimension
3D	-3 Dimension
RMF	-Rotating Magnetic Field
EMF	-Electromotive Force
FEA	-Finite Element Method
NdFeB	-Neodium Iron Boron

CHAPTER 1

INTRODUCTION

1.1) Overview

Nowadays, as the technology of power electronic controller had growing more advanced, the use of brushless DC (BLDC) motor had been widely used in the industry instead of the used of brushed DC motors and induction motor, as it has many advantages over the other motor types because of its efficiency, easy to control, smooth torque delivery, and high-speed operation. In the past time, the application of BLDC motor has been limited in factor of the additional cost of the complex motor controller needed to operate these motors. Consequently, right now, the controller costs have cut off in recent years as it keep evolving, so the application of brushless dc motors had become a trend in the industry. From the limited application of BLDC motor at past as it is applied limitedly in the automotive, HVAC, electronic, computer, semiconductor and medical industries sector, now BLDC motors have long been used in industrial applications such as actuators, feed drives for CNC machines, industrial robots and HVLS fan.

Brushless DC motors are controlled by a motor controller with DC source using inverter. The motor controller is used to control inverter and phase voltage that supply to the electric motor. The switching sequence of the power switches is referred from the output of the Hall Effect sensor, which is placed at the stator and near the rotor. Hall Effect sensors are needed to sense the location of the South and North poles of the Permanent Magnet and send the feedback to the motor controller. The controller will determine the current flow of the three phases from the Hall Effect sensor output and provide the power switching sequence.

1.2) Project Motivation

Nowadays, the economy of Malaysian had become much more challenging as all the cost of living had been increased. One of the way to reduce life economic cost is to save the electricity power consumption in one usage per time. So, in order to solve this problem as an engineer view, instead of the usage of high power consumption of air conditioner in a certain place, people can use low power consumption fan. Also, it is much more better to use one big fan that can cover all the area instead of using many small fans. By doing this, not only we can reduce electrical power consumption and cost of electrical bill, but it is also eco-friendly as fan will not let out greenhouse gases that trap heat and lead to depletion of the ozone layer and contribute to global warming.

1.3) Problem Statement

The technology of large fan in industry had been introduced a long time ago. Mainly, the construction of large fan are using induction motor as main motor for the fan. Nowadays, as the technology of power electronic controller are becoming more advance, the usage of Brushless Permanent Magnet (BLPM) motor as main motor for large fan had become a trend because it has simpler speed control criteria and is more efficient in term of power consumption.

BLPM motor has two types of motor, which is Brushless DC (BLDC) motor and Brushless AC (BLAC) motor. BLDC motor has trapezoidal back EMF criteria, while the BLAC motor has sinusoidal back EMF criteria. So, in term of speed control, BLDC motor is much simpler to control its speed compared to BLAC. Based on this criteria, BLDC motor is chosen to be further analyzed for the fan motor application.

BLDC motor has two types of construction, that is outer rotor and inner rotor. In this project, BLDC outer rotor is chosen to be analyzed because it will produce higher torque compared to BLDC inner rotor while its design is suitable for fan motor application.

So, it is concluded that it is better to choose BLDC outer rotor to be designed for high volume low speed fan motor.

1.4) Objectives

1.4.1) To design an outer rotor BLDC motor and simulate its performance in RMxprt

1.4.2) To analyze the BLDC motor using Finite Element Method(FEM) in Ansys Maxwell 2D in term of its electromagnetic performance.

1.5. Scope of Research

This project is focused on designing and analyzing the outer rotor BLDC motor for high volume and low speed motor. The outer diameter of the rotor, air gap of the motor, motor speed, motor rated power and the magnet thickness is being fixed and specified based on commercial and availability of HVLS fan, while the other parameters such as no. of poles, no. of slots and tooth width are varied and being analyzed.

1.6. Report Outline

A brief description of this report is described in this section. Generally, this report contains five chapters in total, and all these chapters will deliver the overall information about this report, consequently.

The first chapter of this report will contain the introduction of this project. The overall idea of the project is briefly explained in this chapter.

The second chapter in this report will deliver the information on literature review of this project. The previous work related to the project will be analyzed in detail as guideline to improve the current project so that it will be much better.

The third chapter in this report will explain about the methodology that is being implemented to execute this project. All the formulas and theory used will be explained in this chapter.

The fourth chapter in this report will show the early results of the progress from the methodology used for this project. The data obtained from the results will be analyzed further to verify either the desired outcome of this project is achieved or not, and the results gain will be used for the next phase of the project.

Lastly, the fifth chapter in this report will summarize the overall conclusion obtained by from this project. The further work will be planned for the next step of this project, and all the references source will be cited in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1) Theory

2.1.1) General Structure of Motor Classification

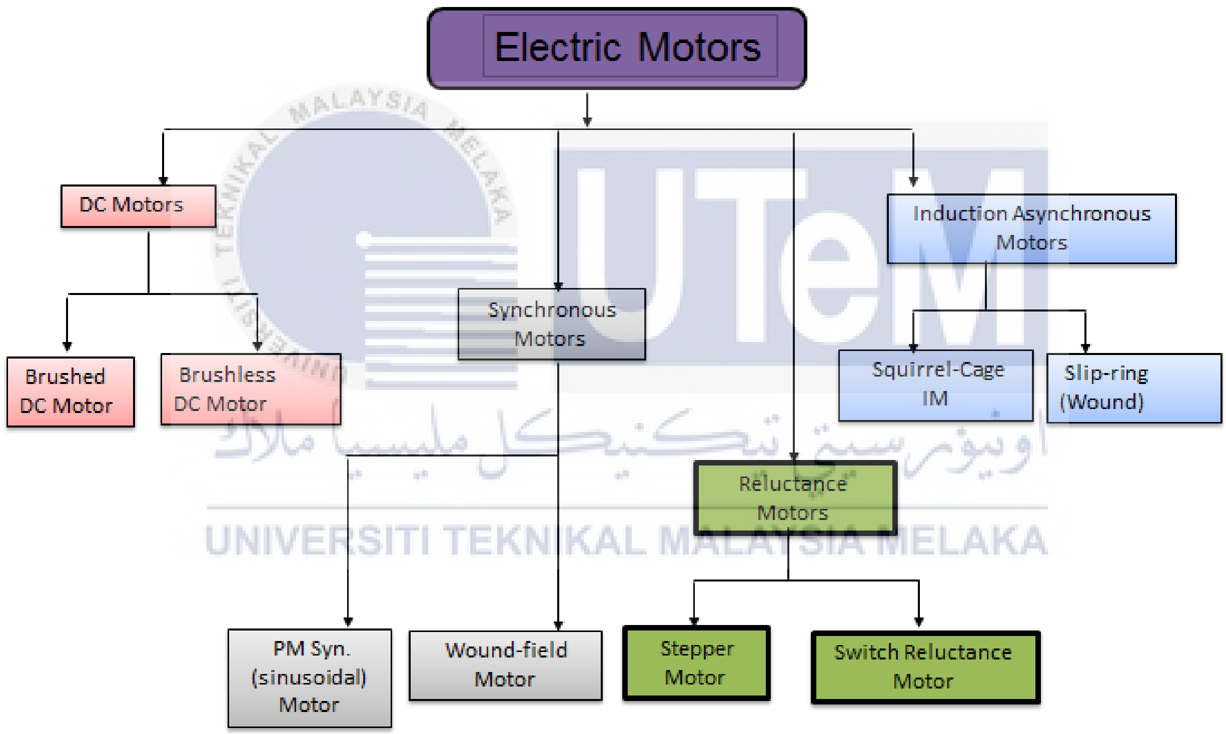


Figure 2.1: General classification of electrical motors type

Figure 2.1 shows the general classification of electrical motor type that is being used in current industry. All these motors have their own pros and cons, that make each of them are being used in the industry, according to the justification of the industrial player and the purpose of the usage of the motor.

For the large fan of motor application, the type of motor used in industry are induction motor. As the technology of the power electronic control are becoming more advance, the usage of brushless permanent magnet (BLPM) motor are becoming a new trend, since the efficiency of the BLPM motor is higher than induction motor.

As the BLPM motor is a motor that use permanent magnet as rotor, it has a numerous advantages rather than the induction motor that does just use a non-magnetic material as rotor such as squirrel cage and wound rotor, mainly about its performance. Table 2.1 below is a shortlist of the advantages and disadvantages between both induction and permanent magnet motor.

Table 2.1: Advantages and disadvantages of induction and permanent magnet motor

	Induction motor	Permanent magnet motor
Efficiency	-high I^2R losses -lower efficiency compared to synchronous motors	-Higher than induction motor -no conductor losses(I^2R) on rotor, thus more efficient than induction motor
Power	3-phase induction motors need 3 power supply lines	higher power density because it has higher magnetic flux compared to induction motor due to the permanent magnet rotor.
Speed	rotor speed is always less than the synchronous speed by slip	Speed constant regarding any load

2.1.2) BLPM motor

There are two types of BLPM motor, that is BLAC and BLDC. BLAC motor has a back emf shape of a sine wave, due to its stator winding is distributed winding, so it has sinusoidal phase currents in order to get in ripple-free torque operation. The BLDC motor has a back emf of a trapezoidal wave due to its concentrated stator winding, so its phase current at the stator is injected with quasi- square currents in order to get ripple-free torque operation.

The sinusoidal back emf characteristic of BLAC motor require high resolution position sensor because the rotor position need to be detected at particular instant time for optimal operation. This requires more complex controller circuit. This makes the BLDC motor is easier to be controlled compared to the BLAC motor because of its trapezoidal shape waveform.

2.1.3) BLDC motor

BLDC motor is same like brushed DC motor, that has internal shaft position feedback that has roles of determining which windings need to be energized (switch on) at the particular moment. This characteristic makes the BLDC motor has linear speed-torque curves, and make it easy to control the speed and has high torque.

BLDC motor is a part of permanent magnet AC motor that has same torque-speed characteristic like DC motor. The BLDC is using electronic commutation, instead of using brush as commutator in brush DC motor. The flux position of the rotor is detected by Hall Effect position sensors, usually by 3 Hall sensors that are placed 120° apart from each other. Those three hall sensors will determine the position of the rotor field. So, it is like the using of permanent magnet synchronous motor, but it much lower in cost and savvy because it only requires simple and cheap converter to control it.

Brushless DC motor, or known as an electronically commutated motor, is a synchronous motor feed by a DC source connected with an inverter as switching power supply, which converts DC to AC signal to control the motor. Here, AC signal from inverter does not represented as sinusoidal shape of the wave, but as a bi-directional current with no restriction on its waveform.[3]

Same like other types of motors, a BLDC motor consists of a stator and a rotor. Permanent magnets are mounted on the rotor, while the stator is made of the stacking slotted steel laminations. The stator can also be either slotted or slotless. A slotless core has lower inductance, and results in the motor operate in high speed.[4]

The inverter is responsible for commutation, which will triggered the motor phase currents at the appropriate time and switching to create a rotating magnetic field (rmf) at the stator, which will producing rotational torque. The rmf is maintained by using the appropriate phase switching sequence to supply the stator phases. While one pair slot of the stator is energized, stator electromagnet will attracts one of the rotor poles, while the second pair of the slots is energized, stator phase repels the corresponding pole of the rotor. This action of the rotor chasing the electromagnet poles on the stator makes the rotor speed has same speed as the synchronized speed.

The BLDC motor can be classified as,

a) Inner Rotor operation- The rotor that is embedded with permanent magnets is located in the center of the machine, while the windings of the stator surround the rotor.

b) Outer Rotor operation- The stator coils is form at the center (core) of the motor while the rotor embedded with permanent magnets spin around the stator. [5]

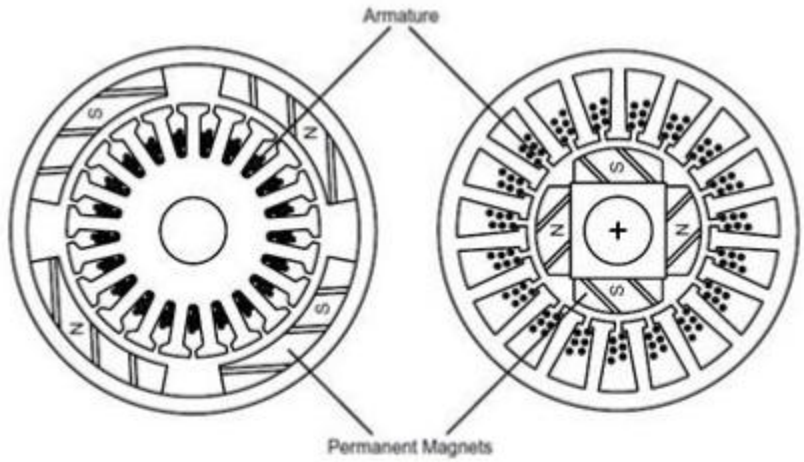


Figure 2.2: Outer Rotor Motor (Left), Inner Rotor Motor (Right) [6]

The BLDC motor's control is based on the information of position of its rotor. The detection of rotor position in brushless DC motors can be done by using sensor or sensorless.

For the sensor based control, a Hall-effect position sensor detects the position of the rotating magnet in the rotor and gives the corresponding windings through appropriate switching. The rotating permanent magnet moving across the front of the sensor causes it to change state. The sensor operates when each South Pole approaches the sensor. [7]

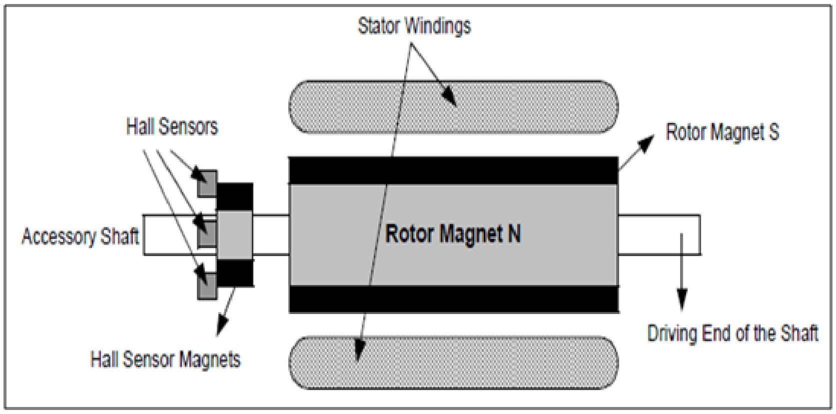


Figure 2.3: Hall Effect sensor at BLDC motor

For sensorless control, the concept used for rotor position estimation and control is the analysis of the Back Electromotive Force (back EMF) from the motor. Back EMF is the voltage value induced in the stator winding of the motor because of a rotating magnetized of the rotor. The magnitude of back EMF is accordance to the speed of the motor. [8] A BLDC motor has trapezoidal back EMF waveform shape, while the sinusoidal back EMF waveform shape found in permanent magnet synchronous motor.[9]

BLDC motor also can be design as axial flux or radial flux.

a) Axial Flux – Has a flux that runs parallel to the output shaft characteristic, (along the axis of the shaft)

b) Radial Flux – Has its flux running in and out from the center of the shaft, on the peripheral radius.

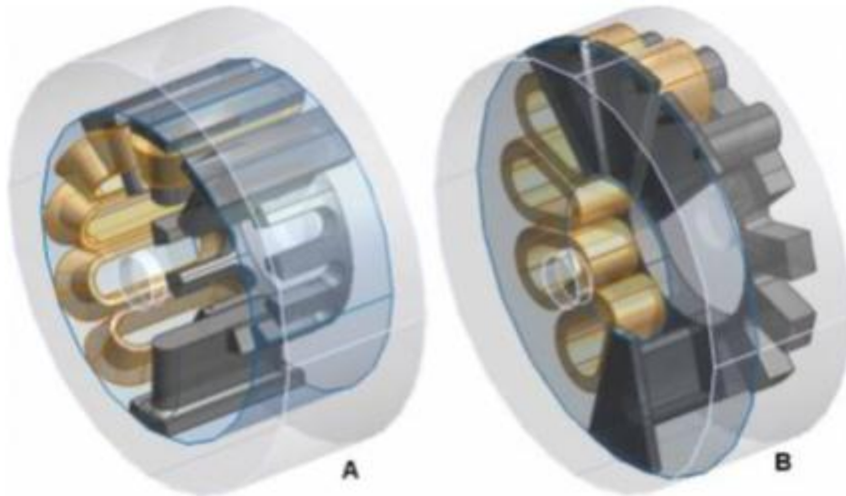


Figure 2.4 : A radial flux motor, B axial flux motor

2.1.4) Ansys RMxprt

(RMxprt) Rotating Machine Expert is a template-based design tool of the ANSYS – Maxwell suite used to create a customized machine design flow to meet demand for higher efficiency. Using classical analytical motor theory and equivalent magnetic circuit methods, RMxprt can calculate machine performance, make initial sizing decisions and perform numerous analyses. RMxprt is able to automatically set up a complete Maxwell project (2-D/3-D) including geometry, materials and boundary conditions. The set up includes the appropriate symmetries and excitations with coupling circuit topology for electromagnetic transient analysis. [11] [12]

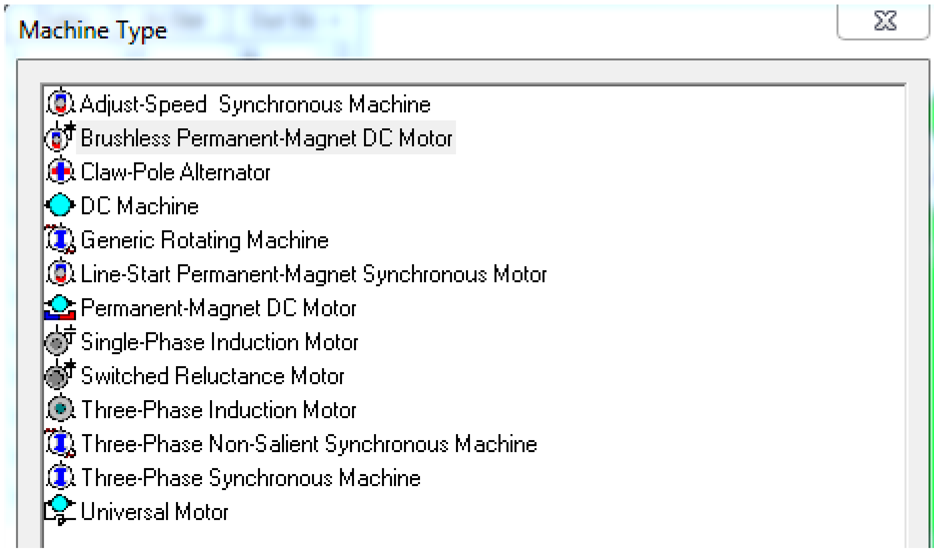


Figure 2.5: Machine selection interface in RMxprt

2.1.5) Ansys Maxwell Software

ANSYS Inc is an American Computer-aided engineering software developer headquartered south of Pittsburgh in Pennsylvania, United States. Ansys develops engineering software for various of analysis purpose like finite element analysis, structural analysis, computational fluid dynamics, and heat transfer.

ANSYS Maxwell is a high performance and low frequency electromagnetic field simulation software that provides finite element analysis (FEA) to solve electromagnetic problems by using Maxwell's equations in a finite region of space with appropriate boundary and user-specified initial conditions for electromagnetic and electromechanical devices either in 2D or 3D design, simulating motors, actuators, transformers and coils. Maxwell provide the accurate finite element method to solve static, frequency-domain, and time-varying electromagnetic and electric fields. The software use a triangular(2D analysis) and tetrahedral(3D analysis) elements to mesh the domain and linear interpolation functions to get the solution. [13]

The equations that represent the electromagnetic field given by James Clerk Maxwell are [14],

Gauss' Law for Electricity $\nabla . \boldsymbol{D} = \boldsymbol{p}$ ………………1

Gauss' Law for Magnetism $\nabla . \boldsymbol{B} = \boldsymbol{0}$ ………………2

Faraday's Law of Induction $\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B} \partial \boldsymbol{t}$ ………………3

Amperes' Law $\nabla \times \boldsymbol{H} = \boldsymbol{J} + \partial \boldsymbol{D} \partial \boldsymbol{t}$ ………………4

2.2) Related Previous Work

2.2.1) Authors in paper [15] is designing and analysis parameter that is majorly affect the BLDC machine performance like selection of pole number, winding, drive circuit, field weakening and cooling. The scope of the paper is limited to radial flux motors. Apart from discussing some ratings to dimension the motor, the paper also explain the difference between AC & DC control. In this paper, the authors have also mentioned strategies in designing the slot to reduce cogging torque. The authors highlight the importance on choosing the number of slots & poles along with the number of coil sides in a slot for AC winding design, and the authors concluded that a fully pitched concentrated winding is necessary for DC winding design. Then, they also brief about the selection of magnets type and the appropriate dimensioning in designing the rotor. As the authors concern about the importance of not letting the magnets to operate in their non-linearity zone, they also prioritized on the thermal loading of the magnets. The authors also warned about having high stator slot fill percentages and advised caution. The paper content also discussed about thermal considerations for selecting current density in the winding along with some appropriate cooling methods. The last section of the paper write about I-Psi & Efficiency plots of a Permanent Magnet DC machine to observe its torque and performance. The paper also mentioned about effect of phase angle setting of the converter on the efficiency of the machine. Overall, the authors have presented a comprehensive design analysis of a brushless permanent magnet machine with many reliable references.

2.2.2) The paper [16], write by Srivastava and Brahmin focused on designing and simulating a 3-phase double layer coil BLDC motor (Hub Drive Machine) for Electric Vehicles (EV) using ANSYS software. Performance of two 15 kW brushless BLDC motors are designed, simulated and compared, one has motor combination of 36 slots and 24 poles, while the other one has motor combination of 36 slots and 16 Poles. FEM is used by the authors to resolve the electromagnetic field using Variational Calculus of Poisson’s type from the basic Magneto-Static Maxwell’s equations. The authors have graphically depicted their observations of Torque v/s Rotation Angle for all three phases. 2D mesh analysis in ANSYS - Maxwell revealed that the rated torque requirement is achieved from configuration - II (36S/16P). They concluded that with reduced number of poles high speed of rotation could be achieved easily.

2.2.3) For the paper[3], the authors design an optimal outer rotor BLDC motor for low cogging torque. They used ANFOT – Maxwell to model the rotor & stator of the motor and also verify its Pole/Slot combinations. The authors concluded that cogging torque was lowest in 26 Slot motors and was heavily influenced by slot aperture, wider slot openings leading to higher cogging torque, the authors also suggest that, the number of poles have a significant influence of the cogging torque of the machine, lower number of poles produced lower cogging torque.

2.2.4) The paper[17] published by IEEE Transactions in Magnetics present an efficiency study of a 1.5kW 2 & 6 Pole Induction Motor converted to 1.5kW 2 & 6 Pole BLDC Motor, they have modified the rotor of an induction motor to a PM rotor (NdFeB) and reported a higher average efficiency of 14% and consequent increase in speed and torque range. Afterwards, the authors have replaced the stator steel of the IM with M253-35A steel type in the BLDC motor with the same geometric design and reported a further 2% increase in efficiency.

2.2.5) The author of journal paper[18] study the effect of stator slot structure and switching angle on a cylindrical single-phase brushless direct current motor (BLDC). Three types of default slot designs are compared in RMxprt of Ansys – Maxwell, then the motor is analyzed in Maxwell 3D electromagnetically using FEM, and at the end with the use of MATLAB the author the examined influence of switching angle on motor performance. The author indicates that with correct choosing of stator slots & its structure along with switching angle, maximum efficiency can be obtained. The results shows that motors operate better when the windings are switched ON earlier respective to the emfs induced in them, which means, the applied voltage to the inverters will result in an advanced switching angle for maximum efficiency (β = - 45deg). The slot structure type 3 of RMxprt was found to have largest flux density and the smallest inductance leakage.

2.2.6) Paper[19] analyzes the best selection for phase , rotor poles and stator slots that can be made before the actual motor design is fabricated. The author has analyzes and compared various phase, pole and slot configurations. It is shown by the author that when number of phases is increases, the ripple content in the machine's torque will decreases, but the number of switches & sensors needed for commutation will increases and increase the system cost. The author also summarized the effect of number of poles towards a machine. The higher the number of poles, the lower the motor speed and vice a versa. Regarding the number of slots, the author had advised that for low cost sinusoidal motor, then Slots/Pole configuration of 3.75 is the best. The author had also listed numerous Slot/Pole configurations along with the number of slots & poles respectively. The author also has analyzed the back EMF of the slot/pole groups using Fourier series on an IBM PCAT computer for star and delta connections.

2.3) Summary Of Literature Review

Based on the literature review, all the formulas and ideas had been identified in this project, so that the design of the outer rotor BLDC motor executed as described in the next chapter.

CHAPTER 3

METHODOLOGY

3.0) Introduction

For this project, a BLDC outer rotor need to be designed and its performance is simulated in RMxprt. Then, its electromagnetic performance is analyzed with Finite Element Method (FEM) using simulation in Ansys Maxwell 2D software. The flowchart of the project is as shown in Figure 3.1.

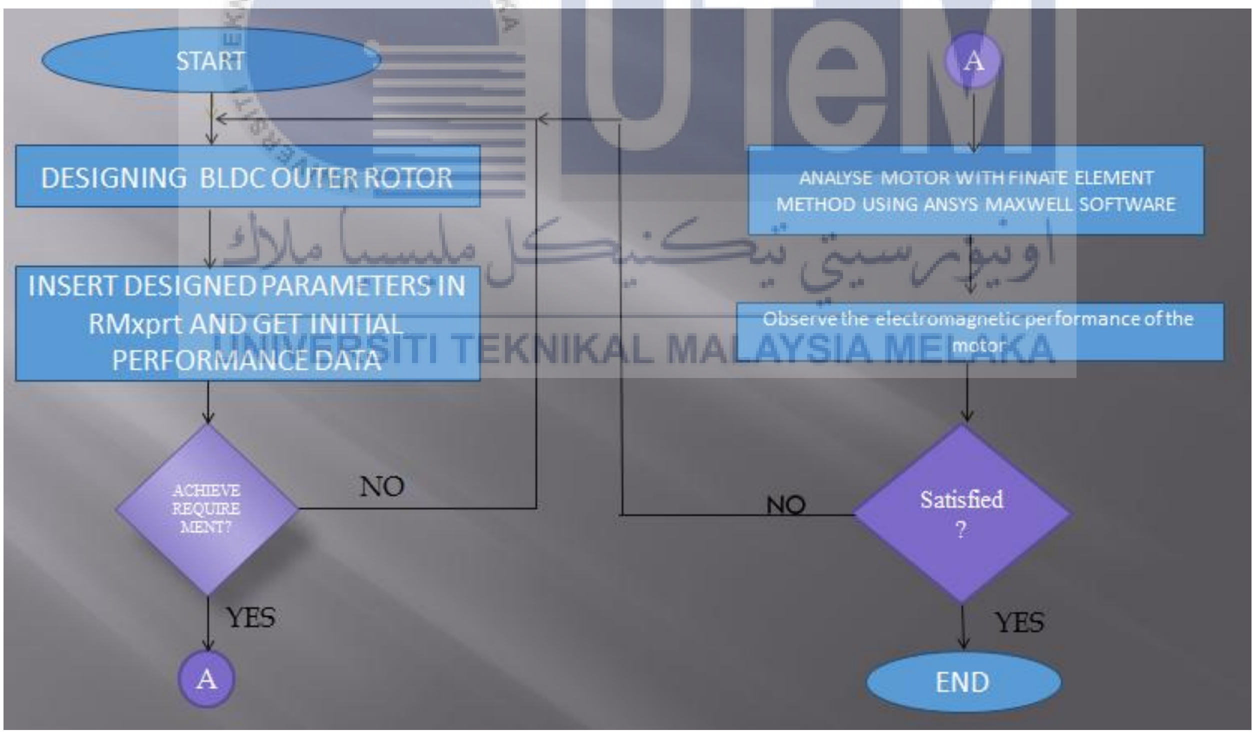


Figure 3.1 : The project implementation flowchart

3.1) Aspects of Designing Outer Rotor BLDC Motor

In accordance to the future-planning of installation of HVLS fan in the Masjid Sayyidina Abu Bakar, UTeM, this project is chosen because FKE had be chosen to do Memorandum of Understanding (MOU) to design the motor for this HVLS fan. So, this project will eventually give a little contribution to the UTeM back, and also apart from adapting a design project that is equivalent to the industrial demand. Figure 3.2 shows the donation box for HVLS fan installation.

Figure 3.2 :Future-installed HVLS fan in Masjid Sayyidina Abu Bakar UTeM

For the design of the outer rotor BLDC motor, a model of BLDC fan from Kale Environmental Technology(Shanghai) corporation had been referred as the design base value for its mechanical construction, according to its physical appearance and its nameplate as shown in Figure 3.3 and Figure 3.4.

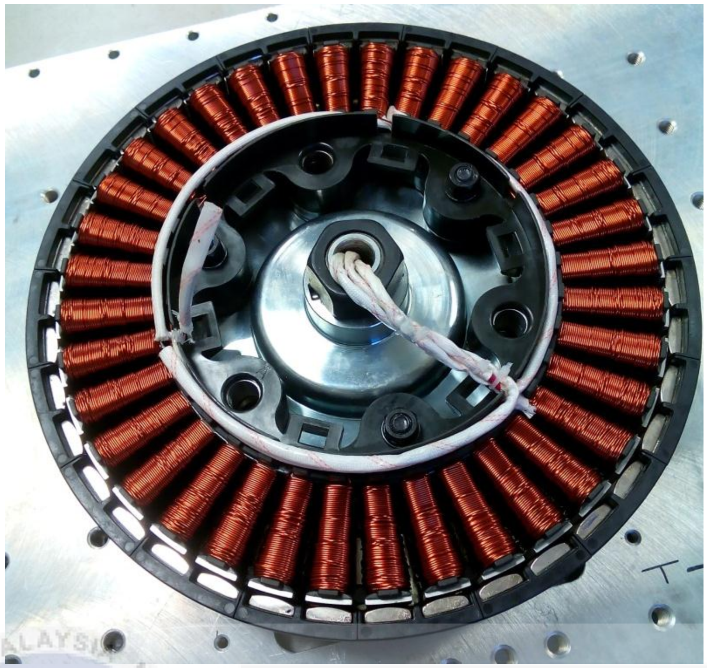


Figure 3.3: Mechanical structure of HVLS fan

Figure 3.4 : Nameplate of the HVLS fan

With the aid of the HVLS fan from above, a few parameter for the designed motor are being taken and set as the base value of the design, in accordance of the availability of the commercial fan and also there are a few of the value that need to be changed to suit the power ratings in Malaysia. The motor parameter that had been decided to be fixed are summarized as in Table 3.1. The speed is chosen to be slightly higher than that stated in Figure 3.4 in order to deliver more air to surrounding area.

Table 3.1 : Fixed motor parameter for design

Outer rotor diameter	300mm
Magnet length	6mm
Air gap	0.5mm
Rated speed	150rpm
Rated voltage	230V
Rated power	0.2Kw

3.2) Designing Step of The Motor

With the pre-determined motor parameters, the other parameters of the motor is being calculated based on the BLDC motor dimension formula[20] and with the aid of the Figure 3.5.

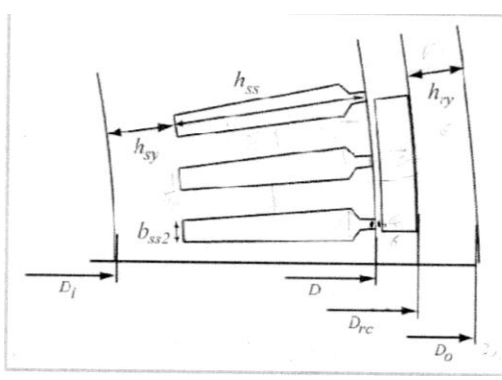


Figure 3.5: Basic dimensioning of outer rotor BLDC motor

3.2.1) Outer diameter of the BLDC rotor is fixed at 300mm, the air gap is of the motor is fixed at 5mm, and the magnet thickness is set at 6mm. Designing the back iron depth of the rotor is the same as the magnet thickness, stator outer diameter is then being calculated by the formula

$$D = D_{rc} - 2l_m - 2\delta \qquad \text{…………………..5}$$

Where;

D= stator outer diameter

D_{rc}= Rotor inner diameter

l_m= magnet thickness

δ= air gap length of the motor

3.2.2) Upper slot opening parameter is calculated by:

$$b_{s1} = \pi\frac{D-2h_{sw}}{Q_s} - b_{ls} \qquad \text{………………..6}$$

Where;

b_{s1}= upper slot opening

Q_s=Stator slot no.

h_{sw}= tooth thickness of stator core

b_{ls}= tooth width of the core

3.2.3) Lower slot opening parameter is calculated by:

$$b_{s2} = \pi \frac{D-2h_{ss}}{Q_s} s - b_{ls} \qquad \text{……………….7}$$

Where;

b_{s2}= lower slot opening

h_{ss}= slot length

3.2.4) Effective core thickness is calculated by:

$$h_{sy} = \frac{1}{2} (D - D_i - 2h_{ss}) \qquad \text{………………..8}$$

Where;

h_{sy} = effective core thickness

3.2.5) Thickness of back iron core is calculated by :

$$h_{ry} = \frac{1}{2} (D_o - D_{rc}) \qquad \text{……………….9}$$

Where;

h_{ry} = back iron core thickness

D_o = rotor outer diameter

3.2.6) Total slot area is calculated by:

$$A_{sl} = ½ (b_{ss1} + b_{ss2})*(h_{ss} – h_{sw}) \qquad \text{……………..10}$$

Where;

A_{sl} = Total slot area

3.2.7) Ratio of stator slot opening to slot width is calculated by:

$$k_{open} = \frac{b_{so}}{b_{ss1}} \qquad \text{……………11}$$

Where;

k_{open}= Ratio of stator slot opening to slot width

3.2.8) Maximum value of magnetic flux is calculated by:

$$B_m = \frac{B_r k_{leak}}{1+\frac{\mu_r \, \delta k_c}{l_m}} \qquad \text{…………………12}$$

Where;

B_m = max. value of magnetic flux

B_r = permanent flux density of magnet

μ_r= relative magnet permeability

k_c = Carter factor

3.2.9) Carter factor is calculated by:

$$k_c = \frac{T_s}{T_s - \frac{(k_{open} b_{ss1})^2}{b_{s1} k_{open} + 5\delta}} \qquad \text{…………………13}$$

Where;

T_s = stator tooth opening

k_c = Carter factor

3.2.10) Stator tooth opening is calculated by:

$$T_s = \pi \frac{D}{Q_s} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 14$$

By using the above equations, the parameter of the BLDC outer rotor had been determined. Table 3.2 shows all the parameters that had been calculated to be transferred to the RMxprt.

Table 3.2 : BLDC motor parameters

Rated power	0.2kW
Rated speed	150 rpm
Rated voltage	230V
No. of poles	26
No. of slots	24
Magnet thickness	6mm
Rated torque	13 Nm
Stator outer diameter	275mm
Stator inner diameter	137.5mm
Rotor outer diameter	300mm
Rotor inner diameter	294mm
Air gap length	5mm
Hs0 (As in Figure 3.10)	2mm
Hs2 (As in Figure 3.10)	48mm
Bs0 (As in Figure 3.10)	2mm
Bs1 (As in Figure 3.10)	18mm
Bs2 (As in Figure 3.10)	9mm

3.3) Transfering The Calculated Design Parameter To The RMxprt

After calculating the parameters of the motor, the motor is then being analysed using RMxprt.

3.3.1) First, from the Ansys Maxwell software, open the ‘insert RMxprt design’ and a pop up window will appear as Figure 3.6, to let us choose the type of motor that we want to analyze. For this project, Brushless Permanent Magnet DC Motor is chosen.

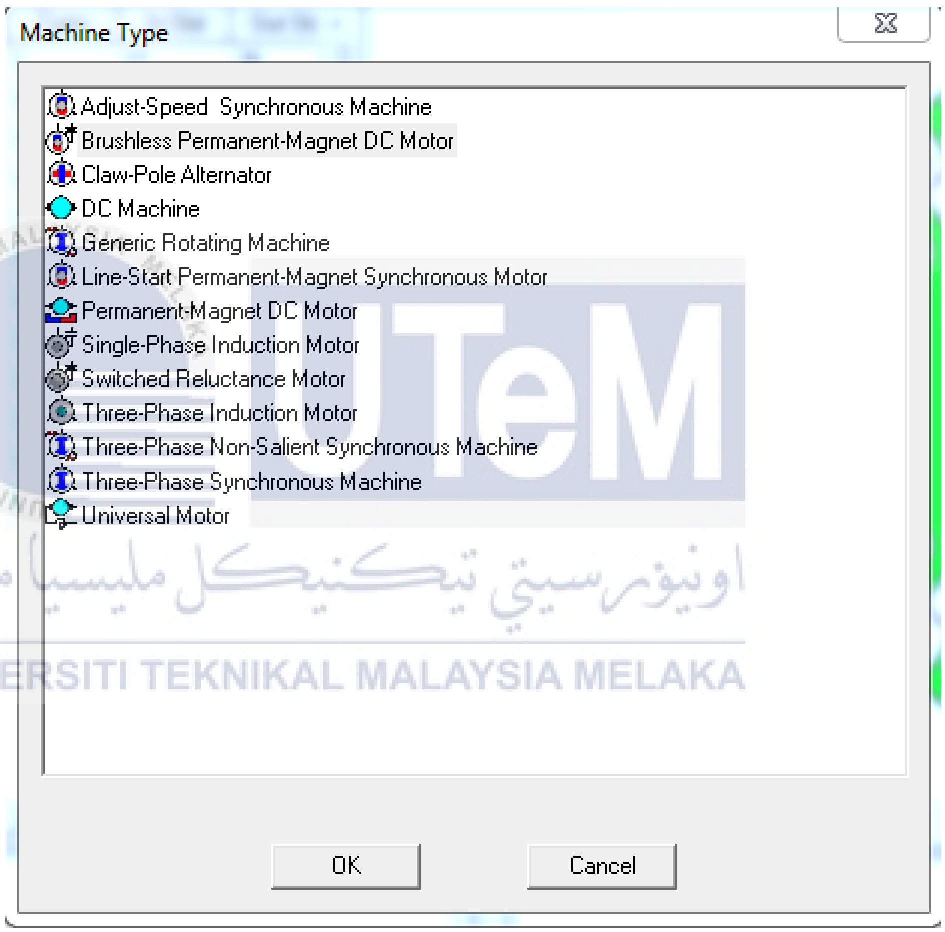


Figure 3.6 : RMxprt motor type selection windows

3.3.2) After selecting the BLDC motor type, the Project Manager as in Figure 3.7 will appear. From here, the machine parameter is inserted to each of the respective dropped tool list.

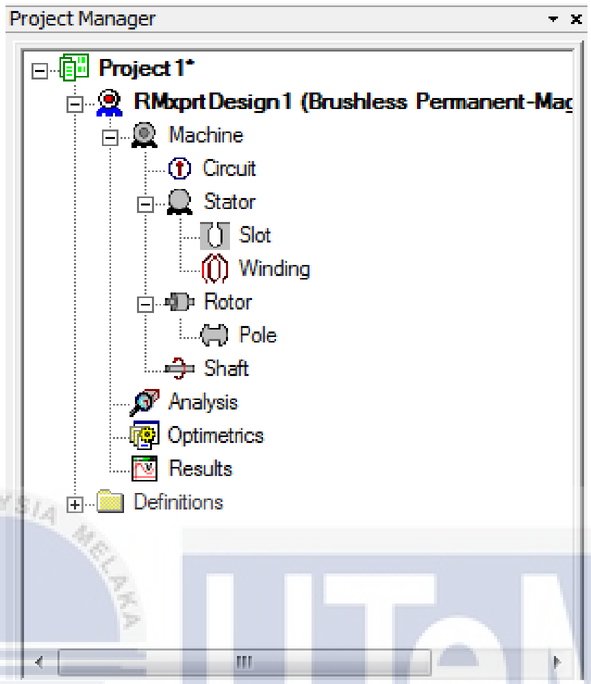
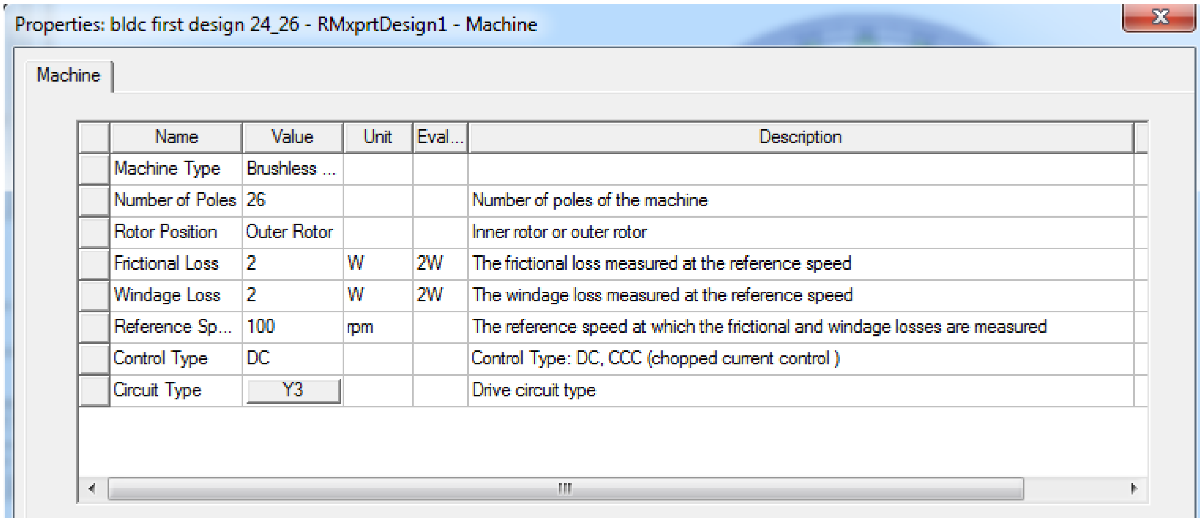


Figure 3.7 : Project Manager

3.3.3) The Machine Properties Window includes general information as in Figure 3.8. The number of poles has to be an even number integer, the position of the rotor can be either inner or outer rotor, the frictional & winding (air-resistance) loss along with reference speed are user defined quantities. The control type can be DC or CCC (Current Chopped Control). The data inserted for the RMxprt are as in the Figure 3.8:



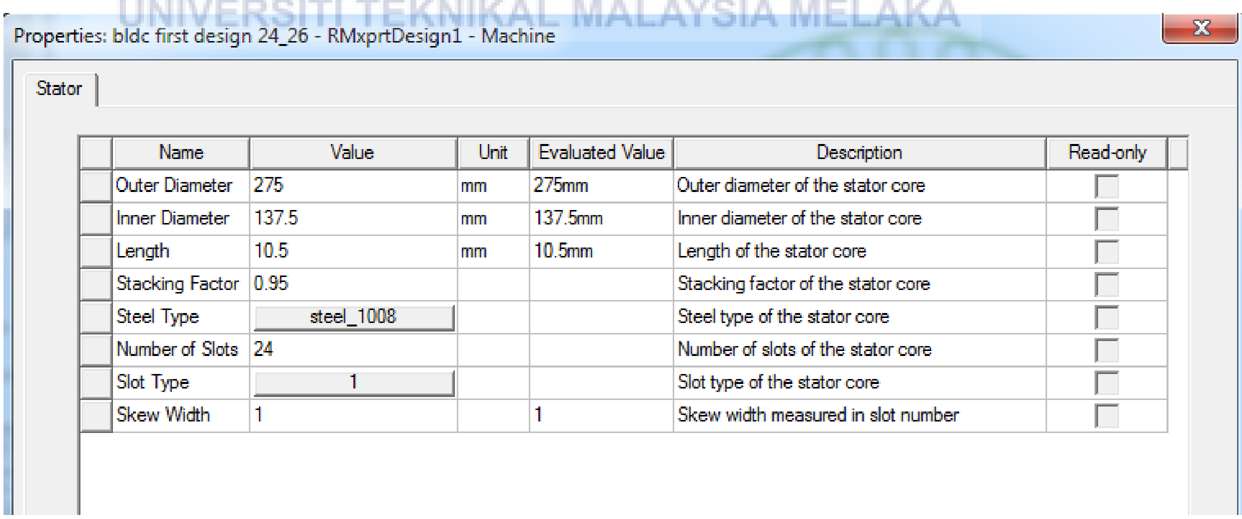
Properties: bldc first design 24_26 - RMxprtDesign1 - Machine

Machine

Name	Value	Unit	Eval...	Description
Machine Type	Brushless ...			
Number of Poles	26			Number of poles of the machine
Rotor Position	Outer Rotor			Inner rotor or outer rotor
Frictional Loss	2	W	2W	The frictional loss measured at the reference speed
Windage Loss	2	W	2W	The windage loss measured at the reference speed
Reference Sp...	100	rpm		The reference speed at which the frictional and windage losses are measured
Control Type	DC			Control Type: DC, CCC (chopped current control)
Circuit Type	Y3			Drive circuit type

Figure 3.8: Machine properties Window

3.3.4) The Stator properties window is shown in Figure 3.9. The stator outer & inner diameters, length and slot number can be inserted according to the calculation. Stacking factor is to quantify the total stator steel area to the area covered by lamination. Various types of steel can be described by the software. There are six types of slots provided in RMxprt for rotating machines. Skew Width quantifies the skew angle of a slot defined as in slot width unit.



Properties: bldc first design 24_26 - RMxprtDesign1 - Machine

Stator

Name	Value	Unit	Evaluated Value	Description	Read-only
Outer Diameter	275	mm	275mm	Outer diameter of the stator core	
Inner Diameter	137.5	mm	137.5mm	Inner diameter of the stator core	
Length	10.5	mm	10.5mm	Length of the stator core	
Stacking Factor	0.95			Stacking factor of the stator core	
Steel Type	steel_1008			Steel type of the stator core	
Number of Slots	24			Number of slots of the stator core	
Slot Type	1			Slot type of the stator core	
Skew Width	1		1	Skew width measured in slot number	

Figure 3.9: Stator properties Window

3.3.5) Slot dimensions design: the Stator option in RMxprt for BLDC motors includes slot properties and Winding Properties, the calculated slot dimensions are inserted as in Figure 3.10, while a slot model is shown in Figure 3.11.

Hs0	2	mm	2mm
Hs2	48	mm	48mm
Bs0	2	mm	2mm
Bs1	18	mm	18mm
Bs2	9	mm	9mm

Figure 3.10 : Slot dimensions

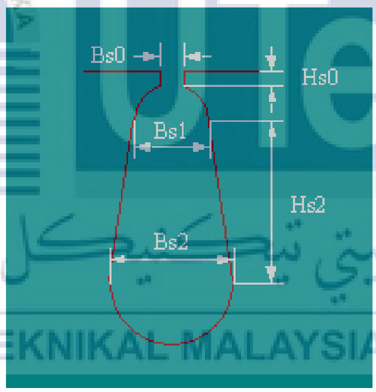
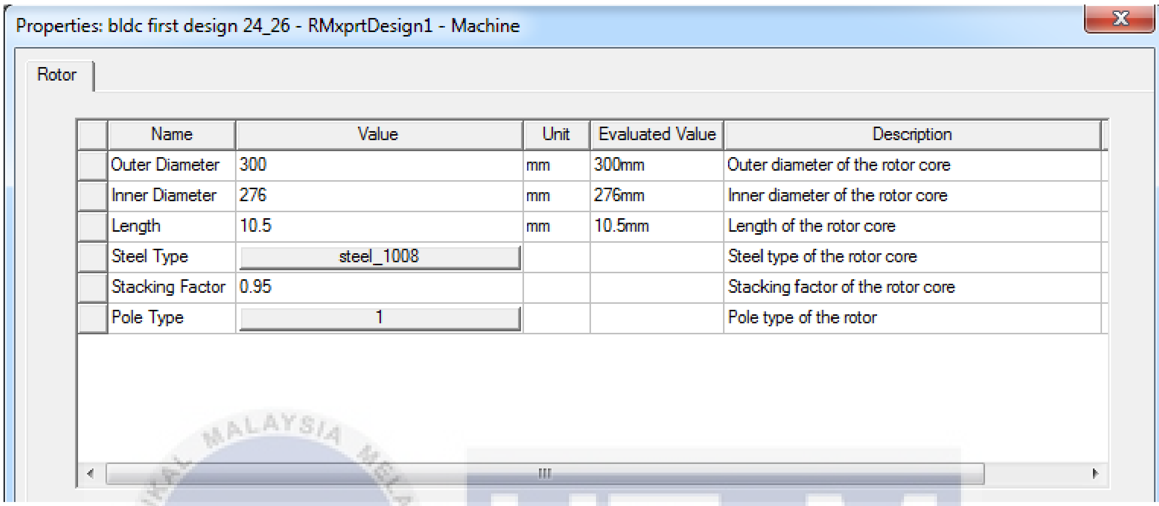


Figure 3.11: Slot model

3.3.6) The Rotor of a BLDC machine is a stack of laminated steel with permanent magnets on the periphery or embedded inside. The magnetic field of the stator coils react to the field of the rotor thereby resulting in a force causing rotary motion. The Rotor Data Properties Window is depicted in Figure 3.12. The general properties like Outer & Inner Diameter along with Length are user defined fields. The software describes various Steel Types and also has the option for user defined additions. The Stacking Factor is the measure of ratio of cross sectional area of all laminations to the area of steel that is stacked as a rotor. RMxprt provides five different types of pole selection, depending on the design.



Name	Value	Unit	Evaluated Value	Description
Outer Diameter	300	mm	300mm	Outer diameter of the rotor core
Inner Diameter	276	mm	276mm	Inner diameter of the rotor core
Length	10.5	mm	10.5mm	Length of the rotor core
Steel Type	steel_1008			Steel type of the rotor core
Stacking Factor	0.95			Stacking factor of the rotor core
Pole Type	1			Pole type of the rotor

Figure 3.12: Rotor properties Window

3.3.7) The Pole Properties Window is shown in Figure 3.13. Embrace is defined as the ratio of actual pole arc distance to the maximum possible arc distance, and the value is between 0 & 1 and is illustrated in Figure 3.14. Offset is the pole arc center offset from the rotor center (0 for uniform air gap). Magnet thickness is the maximum thickness of the magnet for all pole types.

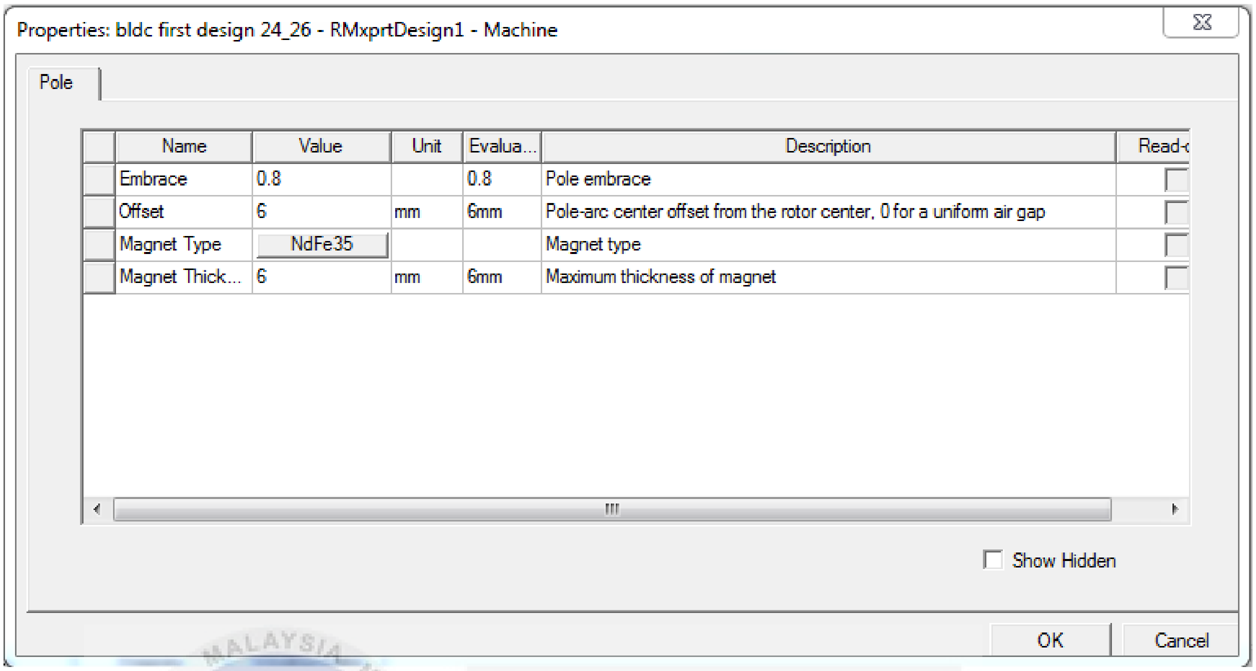


Figure 3.13 : Pole properties Window

Pole embrace=1 Pole embrace=8

Figure 3.14: Pole embrance

3.3.8) Analysis setup windows shows the electrical parameters that can be set up to the motor. Operation type can be set either as a motor or a generator. Load type can be selected from five choice, that is fan load, constant speed, constant power, constant torque and linear torque.

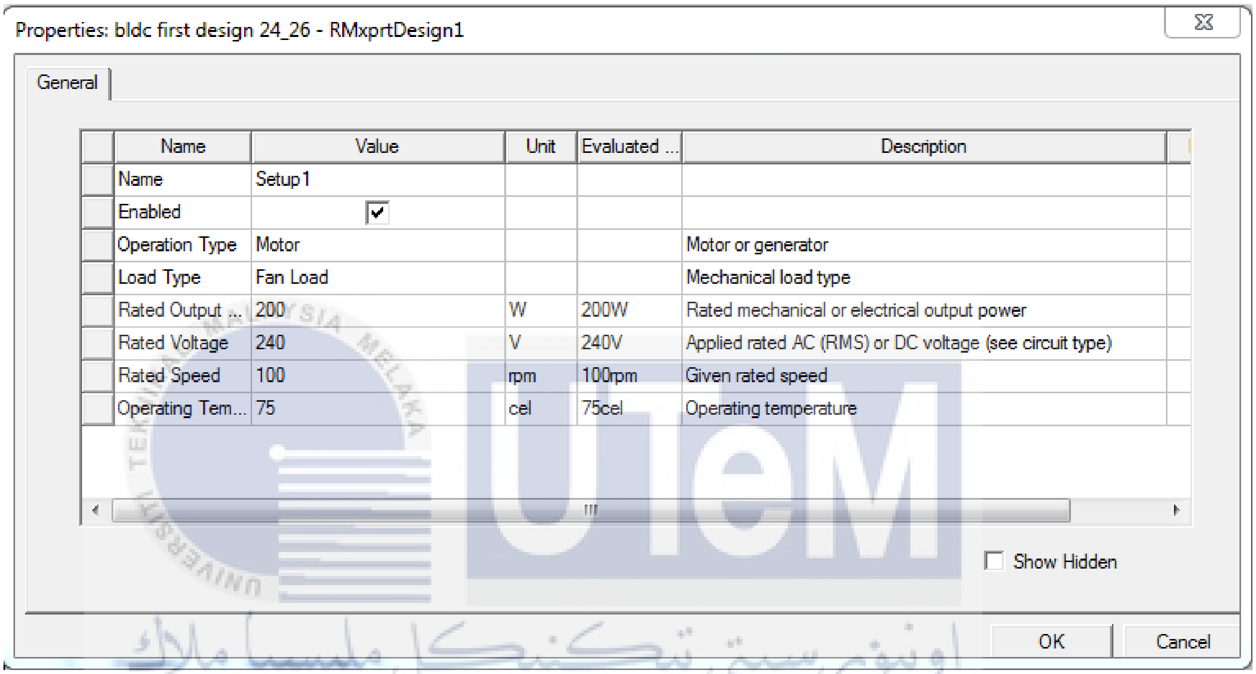


Figure 3.15 : Analysis setup Windows

3.3.9) After all the data had been inserted, the design of the motor is shown as in Figure 3.15. The rotor is designed to have 26 poles while the stator is designed to have 24 slots. The motor is then being analyzed to get its performance data.

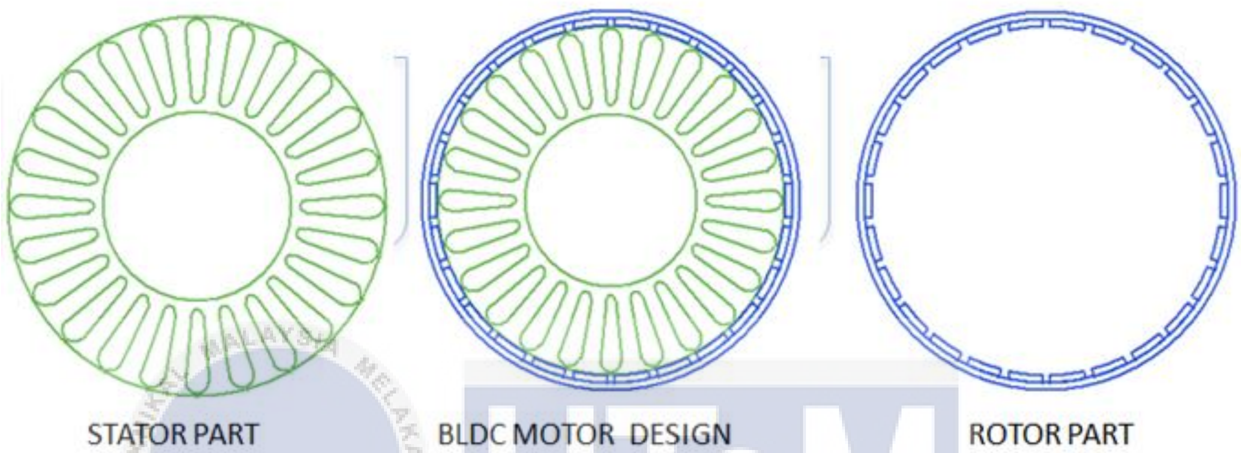


Figure 3.16: Design of 24/26 BLDC outer rotor motor

3.4) Redesigning Parameter Considerations

After analyzing the motor design in the Rmxprt, there are a few of motor parameter results that are not meet the optimum criteria for the motor such as low efficiency, unfeasibility of the slot fill factor and low torque requirement.

Low efficiency means that the motor efficiency are below than optimal efficiency of a motor which is below than 93%.

Unfeasible of slot fill factor is that the ratio between cross-sectional areas of all conductors in one slot to the whole area of the slot is more than one, which means that the conductors winding will exceed the slot area in order to achieve the machine required operation, thus will not be practical to be done for the real application.

So, a few of the motor parameter need to be adjusted, as well as some of the theories need to be revised so that the machine design will operate more efficiently. Those machine parameters considerations to be redesign and revised are as below:

3.4.1) Feasibility of the motor design.

The ideal selection of poles and slots numbers combination set for a machine plays a vital role in determining the winding factor for the machine, that will thus determining its back emf.

Checking the 24 slots 26 poles feasibility, given the formula of:

$$\text{Winding feasibility: } q_{ph} = Q/mt \qquad \ldots\ldots\ldots\ldots\ldots\ldots 15$$

Where

Q= no. of slots

m = no. of phase

t= greatest common divisor (GCD) of no. of slots and no. of poles

t = GCD(24,26)

= 2

m =3 (phase A, B and C)

Q =24

So, q_{ph} =24/(3x2)

= 4…… (feasible, since it is an integer number without remainder .)

3.4.2) Determining winding layout of the machine

Determining the winding layout of a machine is important so that the phase voltage of the machine is distributed equally. This is to ensure the stability of the machine and thus, producing less torque ripple.

Mechanical slot angle, $\alpha_s = \frac{360°}{24}$ ……………………16

= 15°

Electrical slot angle, $\alpha_s^e = 2p \times \alpha_s$ ……………………..17

= 13 x 15°

= 195°

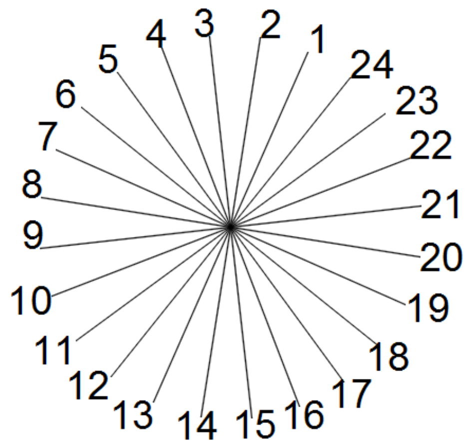


Figure 3.17 Mechanical degree of the slot angle

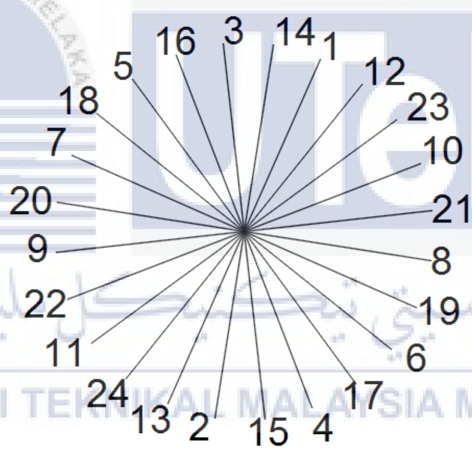


Figure 3.18 Electrical degree of the slot angle

The coil is then merged with its adjacent 180° phase shift and being grouped with 120°phase shift star configuration for each phase A,B and C as in Figure 3.19

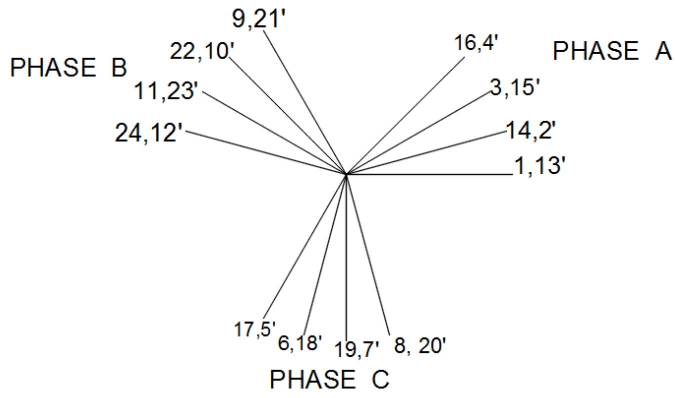


Figure 3.19: Phase coil arrangement

The winding configuration of the motor in the Rmxprt is shown as in Figure 3.20

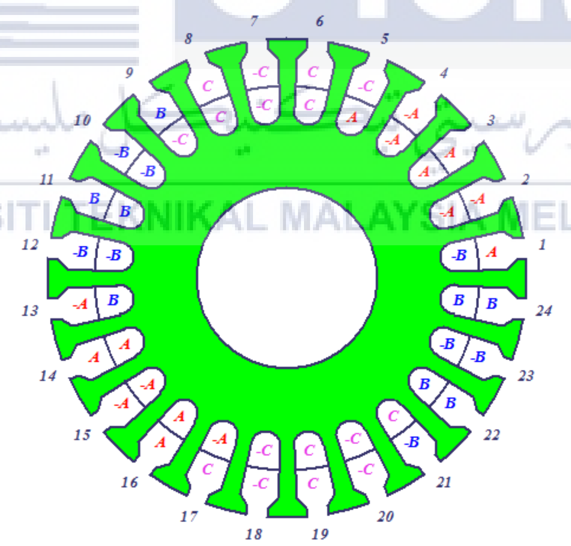


Figure 3.20: Winding configuration of motor in Rmxprt

3.4.3) Distribution factor, k_d pitch factor, k_p and winding factor, k_w

Winding factor will determine the back emf value of the motor. The better value of winding factor will be a value that is near unity.

Distribution factor,

$$k_d = \frac{\sin(\frac{q_{ph}}{2} \times \frac{\alpha_{ph}}{2})}{\frac{q_{ph}}{2}\sin(\frac{\alpha_{ph}}{2})} \qquad q_{ph} = \text{even} \qquad \ldots\ldots\ldots\ldots\ldots 18$$

$$k_d = \frac{\sin(q_{ph}\,\frac{\alpha_{ph}}{2})}{q_{ph}\sin(\frac{\alpha_{ph}}{4})} \qquad q_{ph} = \text{odd} \qquad \ldots\ldots\ldots\ldots\ldots 19$$

Angle between two spokes, $\alpha_{ph} = \frac{2\pi}{Q/t}$ 20

$$= \frac{360}{24/2}$$

$$= 30°$$

Since the calculated q_{ph} =4, so

$$K_d = 0.97$$

Pitch factor,

$$k_p = \cos(2p \times \frac{\alpha_p}{2} \qquad \ldots\ldots\ldots\ldots\ldots 21$$

$$\alpha_p = \frac{2\pi}{p} - \frac{2\pi}{Q} \qquad \ldots\ldots\ldots\ldots\ldots 22$$

$$\alpha_p = \frac{360°}{26} - \frac{360°}{24}$$

$$|\alpha_p| = 1.15°$$

$$k_p = \cos(13 \times \frac{1.15}{2})$$

$$=0.99$$

Where:

2p = no. of pole pairs

$\alpha_p = coil\ pitch$

Winding factor,

$$k_{wn} = k_d \times k_p \qquad \ldots\ldots\ldots\ldots\ldots\ldots.23$$

$$=0.97 \times 0.99$$

= 0.96 (near to unity, so good winding factor

3.4.4) Stator volume and size optimization

Given that the volume of a motor, V_o can be defined as

$$V_o = \frac{D^2 l}{T} \qquad \ldots\ldots\ldots\ldots\ldots\ldots.24$$

Where D= stator diameter

l= axial length of the motor

T = Torque

For air cooled motor, the design of the motor volume need to be in between 8~9in^3

Rearrange the equation,

$$l = \frac{TV_o}{D^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots.25$$

Therefore, the calculated range of l are as follows:

Table 3.3: Range of l in inch

V_o (inch)	8	9
l (inch)	1.3	1.5

Where D= 275mm = 10.83 inch,

T= 19N

So, range of l in mm, are

$33 < l < 38$

Therefore, for the motor design, $l = 35mm$ is chosen

3.4.5) Stator slot design

In the previous method, the stator slot design are determined by taking the slot area into account. In order to get the unsaturated flux , the design of optimum parallel tooth width is important, as narrow tooth width will limit the maximum flux that go through the tooth width, thus limit the motor performance, while wider tooth width will provide good flux linkage, but will reduce the slot area, resulting in not enough room for winding and will limit the mmf value.

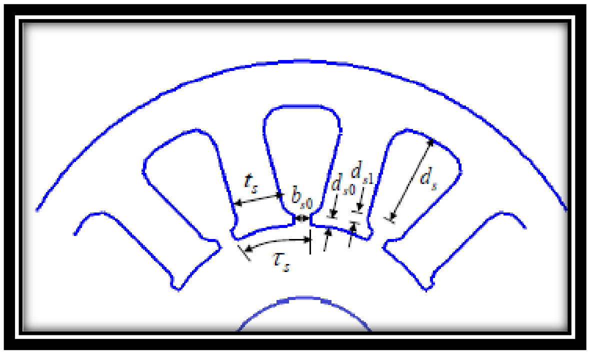


Figure 3.21: Stator slot parameter

3.4.5.1) Slot pitch

$$\tau_s = \frac{\pi D}{Q} \qquad \ldots\ldots\ldots\ldots\ldots..26$$

Where Q= no. of slots,(24slots)

D= stator outer diameter (275mm)

τ_s= slot pitch

Therefore, τ_s= 36mm

3.4.5.2) Stator tooth width, t_s

Typical stator tooth width, t_s ratio with slot pitch, τ_s are between 0.4 to 0.6.

$$0.4\tau_s \leq t_s \leq 0.6\tau_s \qquad \ldots\ldots\ldots\ldots\ldots\ldots27$$

Choosing t_s as $0.4\tau_s$,

Therefore, t_s= 14.4mm

3.4.5.3) Stator tooth length, d_s

Typical stator tooth length, d_s ratio with stator tooth width, t_s are between 3 to 7.

$$3\,t_s \leq d_s \leq 7\,t_s \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots28$$

Choosing $d_s = 5t_s$,

Therefore, d_s = 72mm

3.4.5.4) Stator slot opening, b_{so},

$$\text{Define } b_s = \tau_s - t_s \qquad \ldots\ldots\ldots\ldots\ldots\ldots...29$$

Therefore, b_s = 21.6mm

Typical stator slot opening, b_{so} ratio with b_s are between 0.1 to 0.5.

$$b_{so} \approx (0.1 \sim 0.5)\ b_s \qquad \ldots\ldots\ldots\ldots\ldots..30$$

$$d_{so} \approx (0.1 \sim 0.5)\ b_s \qquad \ldots\ldots\ldots\ldots\ldots..31$$

$$d_{s1} \approx (0.1 \sim 0.5)\ b_s \qquad \ldots\ldots\ldots\ldots\ldots32$$

Choosing $b_{s0,}$ d_{so} and d_{s1} as $0.1b_{s,}$

Therefore, $b_{s0} = d_{so} = d_{s1} = 2.16$mm

3.4.5.5) Inner back iron core depth, d_e

As the field is distributed radially, the inner back iron core depth, d_e ratio with tooth width, t_s is between 0.5 to 0.6.

$$d_e \approx (0.5 \sim 0.6) \qquad \ldots\ldots\ldots\ldots\ldots.33$$

Therefore, range of d_e are $7.2\text{mm} \leq d_e \leq 8.64\text{mm}$

For this motor design, $d_e = 8.18$mm is chosen

3.4.5.6) Inner diameter of stator core, D_i

Inner diameter of stator formula is derived as follows

$$D_i = ((D/2) - d_{s0} - d_{s1} - d_s - d_e)2 \qquad \ldots\ldots\ldots\ldots\ldots..34$$

Therefore, D_i=106mm

3.4.6) Slot type

For the slot type used to redesign, the slot type 3 is chosen, as the slot type 3 is much more easier to design by specifying the parameter of the tooth width over the slot width. The slot type 3 is as in Figure 3.22

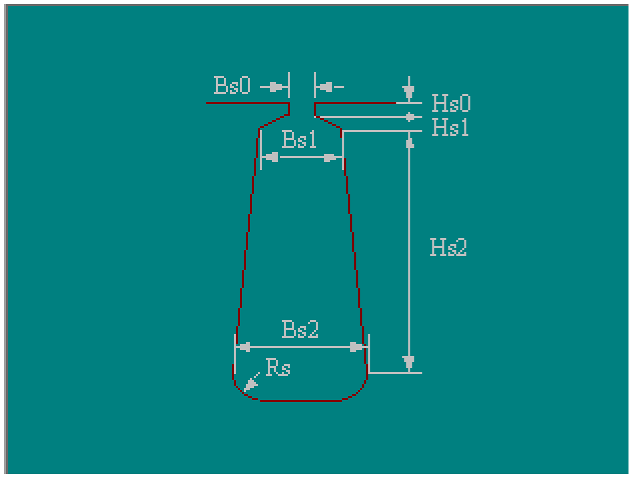


Figure 3.22: Slot type 3

3.4.7) New redesign BLDC motor parameter

The new redesign BLDC motor parameter are as follows:

3.4.7.1) Slot dimension

Table 3.4 : Slot dimension of redesign BLDC outer rotor motor

Name	Value	Unit	Evaluated Value	Description
Auto Design	☐			Auto design Hs2, Bs1 and Bs2
Parallel Tooth	☑			Design Bs1 and Bs2 based on Tooth Width
Tooth Width	14.4	mm	14.4mm	Tooth width for parallel tooth
Hs0	2.16	mm	2.16mm	Slot dimension: Hs0
Hs1	2.16	mm	2.16mm	Slot dimension: Hs1
Hs2	70	mm	70mm	Slot dimension: Hs2
Bs0	2.16	mm	2.16mm	Slot dimension: Bs0
Rs	2	mm	2mm	Slot dimension: Rs

3.4.7.2) Stator dimension

Table 3.5: Stator dimension of redesign BLDC outer rotor motor

Name	Value	Unit	Evaluated Value	Description
Outer Diameter	275	mm	275mm	Outer diameter of the stator core
Inner Diameter	100	mm	100mm	Inner diameter of the stator core
Length	35	mm	35mm	Length of the stator core
Stacking Factor	0.95			Stacking factor of the stator core
Steel Type	steel_1010			Steel type of the stator core
Number of Slots	24			Number of slots of the stator core
Slot Type	3			Slot type of the stator core
Skew Width	1		1	Skew width measured in slot number

3.4.7.3) Rotor dimension

Table 3.6: Rotor dimension of redesign BLDC outer rotor motor

Name	Value	Unit	Evaluated Value
Outer Diameter	300	mm	300mm
Inner Diameter	276	mm	276mm
Length	55.3	mm	55.3mm
Steel Type	steel_1010		
Stacking Factor	0.95		
Pole Type	1		

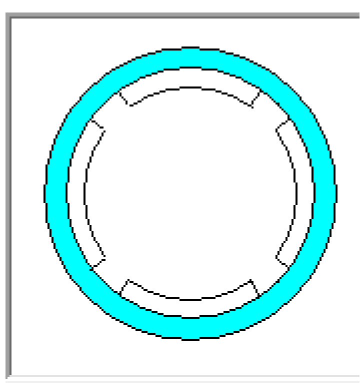
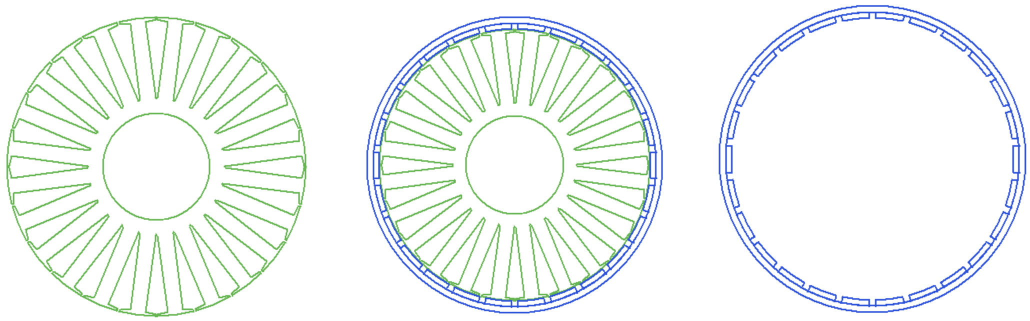


Figure 3.23: Type 1 pole

3.4.8) New BLDC outer rotor motor

The new motor configuration is as shown in Figure 3.24



Stator part BLDC motor redesign Rotor part

Figure 3.24 :Redesigned of BLDC outer rotor

The performance of the redesigned BLDC motor will be analysed in the Rmxprt and the parameter of the motor, such as the number of turns, winding diameter, and number of wire strand will be varied to observe and analyse the effect of varying those parameters towards the motor performance.

3.5) Transferring the machine design from Rmxprt to Ansys Maxwell 2D for electromagnetic analysis.

3.5.1)Simplorer excitation circuit

The analyzed motor model of RMxprt can be exported to create Maxwell 2D models that has Finite Element mesh modeling algorithms to solve the machine's Magneto Static and Transient equations along with an external electronic circuit editor called Simplorer, to integrate the machine & the power convertor, which decides its excitation and its operating performance.

Shown below *(Figure 3.25)* is the external excitation circuit which is modeled automatically in the software and is used for magneto static and transient analysis. The solid state diodes and switches are considered by a modeling window where the user can input data like contact resistance, emission coefficient, barrier height, reverse breakdown voltage and current. The switch model includes variable inputs like on/off state resistance and control voltages.

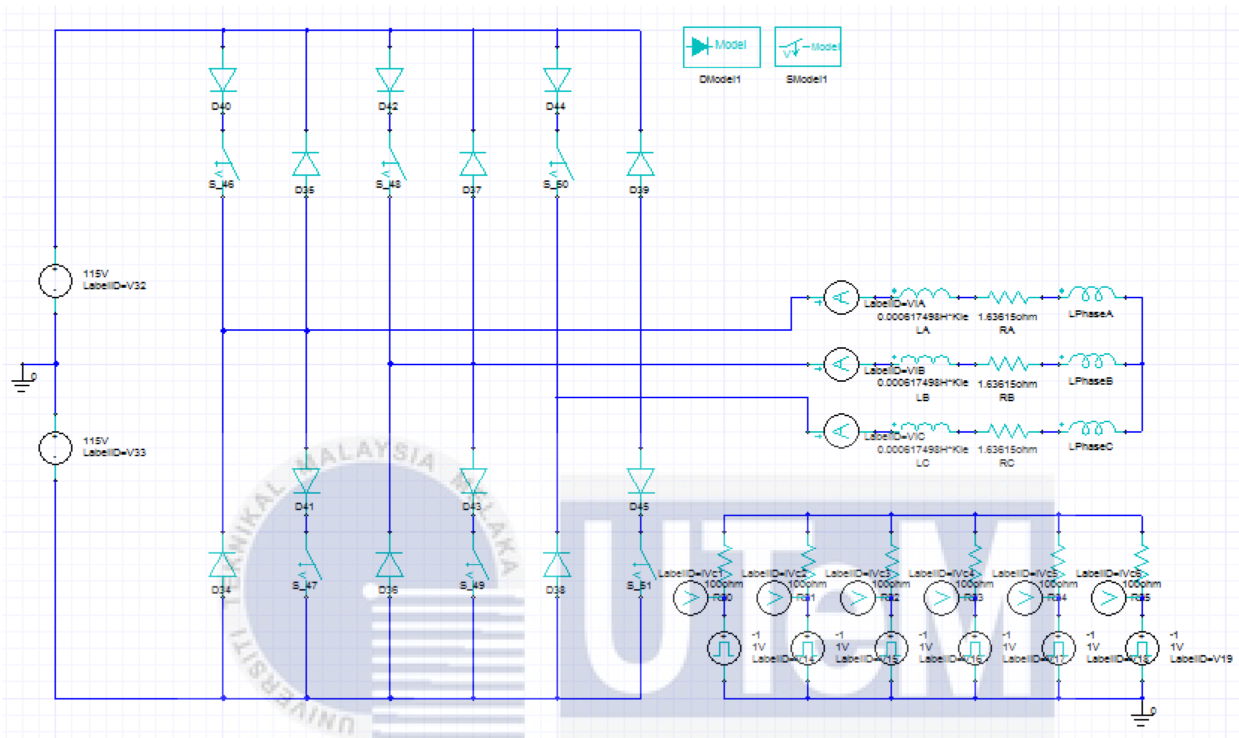


Figure 3.25: ANSYS – Simplorer Excitation Circuit

3.5.2)Time step of solver setup.

The step size of the solve setup save fields are set as Figure 3.26 for the analysis.

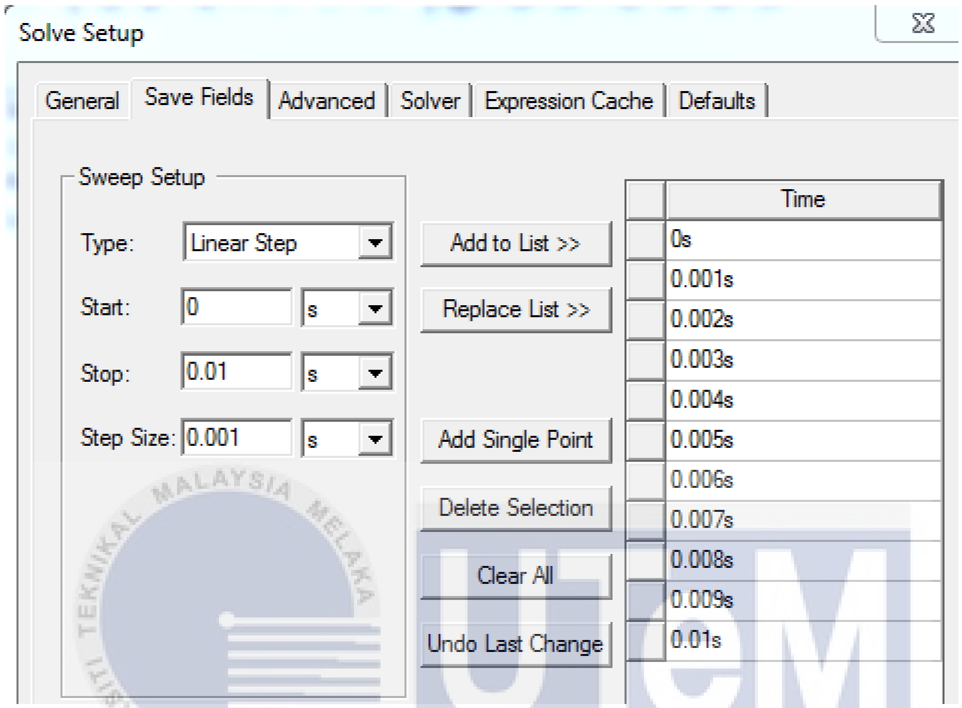


Figure 3.26: Time step size for the Maxwell 2D analysis

CHAPTER 4

RESULTS & DISCUSSION

From the proposed methodology, all the results of the motor performance is analyzed using Ansys Maxwell software of RMxprt. Below are all the data extracted from the software.

4.1) Result of The First Design of BLDC Outer Rotor Motor.

Table 4.1 : Results of the first BLDC motor design

No. of winding turns	Wire diameter (mm)	No. of strand	Efficiency (%)	Rated speed (rpm)	Rated torque (N)	Feasibility (Slot fill factor >100%)	Stator fill factor (%)
525	1	1	55.35	115.7	25.57	NO	104.335

From the result above, it is known that the designed BLDC motor stator fill factor is unfeasible. Also, the efficiency of the motor is not good enough. Thus, adjustment of the motor design need to be done.

4.2) Result of The Redesigned BLDC Outer Rotor Motor in RMxprt

From the Rmxprt machine design, the parameter of the motor is varied and been analyzed. All the simulation is being simulated with the setting of constant power, so the performance of the BLDC motor in term of its efficiency, rated speed and rated torque can be observed while maintaining the power output while adjusting the motor parameter. The results of the effect of the adjustment made are analyzed and summarized as follows:

Table 4.2: Comparison of the motor performance from its varied parameters

No. of winding turns	Wire diameter (mm)	No. of strand	Efficiency (%)	Rated speed (rpm)	Rated torque (N)	Feasibility (Slot fill factor <100%)	Stator fill factor (%)
440	1.369	1	95.8	105.468	18.1089	NO	150.0
220			98.3	213.265	8.9554	YES	75.2
110			99.2	495.343	3.8535	YES	37.6
292			97.6	171.272	11.1505	YES	99.8
450			95.7	102.581	18.6189	NO	153.8
460			95.5	99.820	19.1340	NO	157.2
	1.219		94.8	91.791	20.8805	NO	128.5
	1.369	5	99.2046	95.7717	19.9383	NO	786.2
	0.724		97.1065	93.8925	20.3410	NO	272.7
		1	83.5383	81.5187	23.4371	NO	54.5
	1.151		94.1241	91.1866	20.9476	NO	116.58
296			96.6347	152.4790	12.5268	YES	75
632	0.724		71.3458	48.5938	39.3174	YES	74.923

From the data simulated above, increasing the no. of strand of the conductor will results in significant increase of the motor efficiency, but on the other hand, it will increase the unfeasibility of the winding greatly. So it is applicable for improving the motor performance only if the previous slot fill factor design is low. From this project observation, the optimum slot fill factor of a machine is in a range of 70%-80%.

One of the counter measure to decrease the slot fill factor is by using the thinner diameter of the wire, so that the same number of winding turns that is unfeasible, can be feasible for the motor winding. But, the drawback of this measure is that the size of the diameter of the wire that being used must be in a range that can handle the maximum current flow in the winding. Other than that, the usage of thinner diameter of the wire can let the more winding turns per slot per phase, but the drawback is that the current density for the slot will increase and thus will make the motor to become hot quickly. This will result in demagnetization rate of the magnet to be more quickly, and colder cooling method, such as using water or air-cond instead of air will be needed to compensate with this problem.

Decreasing the number of turns will result in decreasing the torque value and thus, increasing the rated speed value because the output power is constant.

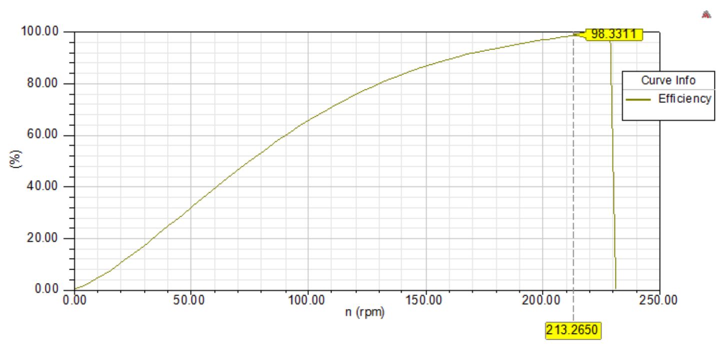
4.3) Comparing results

From all the simulated design in Rmxprt, three designs are being selected to be compared on its performance. The selection of the three designs are based on the feasibility of the slot fill factor, which is feasible, and the rated speed and torque are closed to the desired rated speed and torque for this project design scope. The selected design are as shown in Table 4.3.

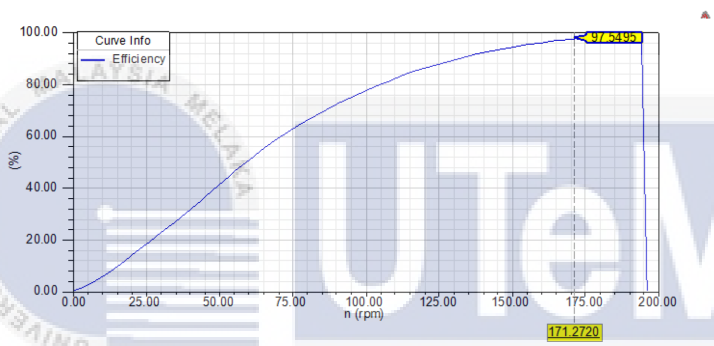
Table 4.3: The selected design to be compared.

No. of winding turns	Wire diameter (mm)	No. of strand	Efficiency (%)	Rated speed (rpm)	Rated torque (N)	Feasibility (Slot fill factor <100%)	Stator fill factor (%)
220	1.369	1	98.3	213.265	8.9554	YES	75.2
292			97.6	171.272	11.1505	YES	99.8
296	1.151		96.6347	152.4790	12.5268	YES	75

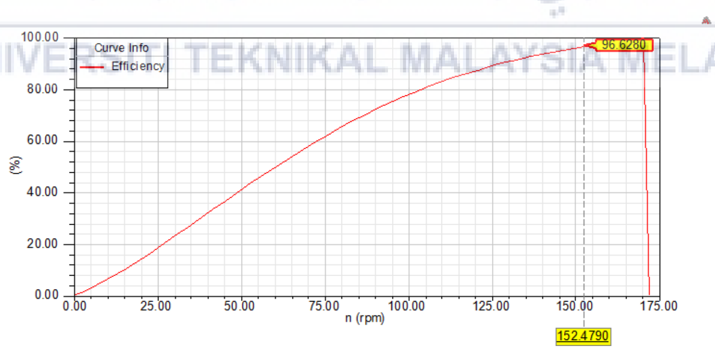
4.3.1)Efficiency VS Speed graph



220T



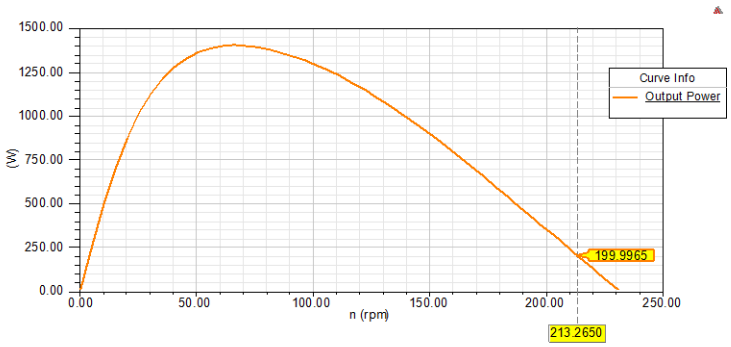
292T



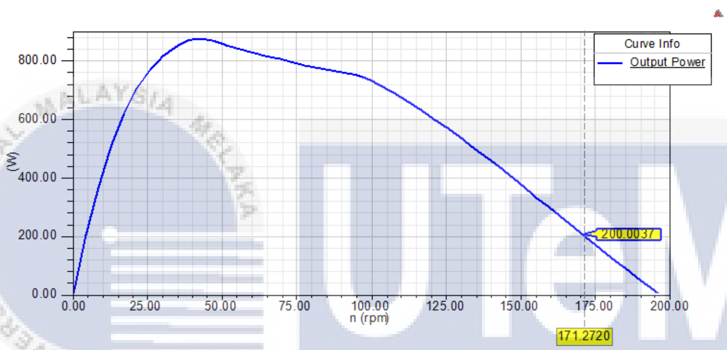
296T

Discussion: For each of the motor design, the efficiency VS speed graph was plotted when the motor operated with 200W power. The efficiency more that 95% and the rated speed of which is closed to the desired rated speed design will be prioritized to be chosen as the best design

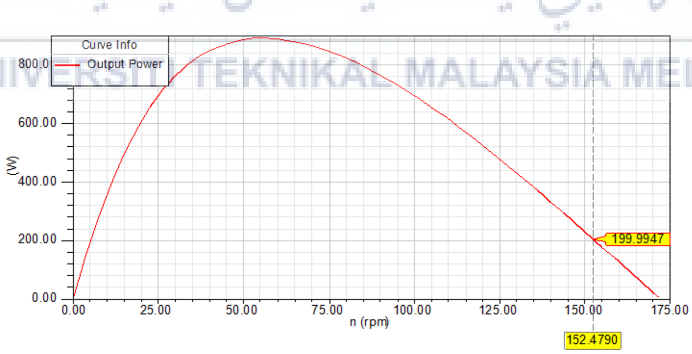
4.3.2) Output power VS speed graph



220T



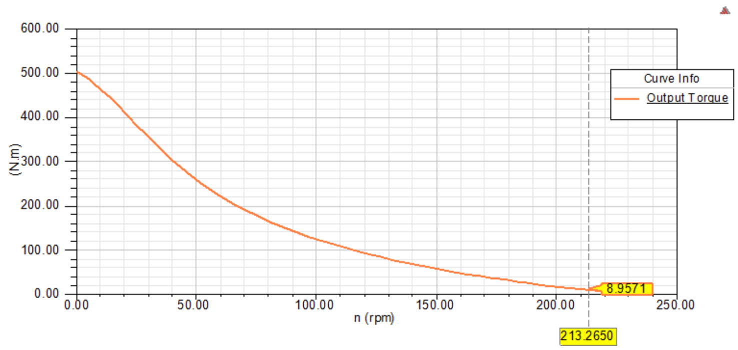
292T



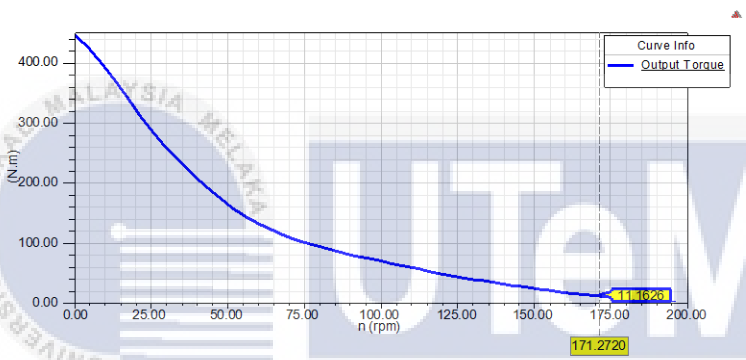
296T

Discussion: The graph of same rated output power of the motor, which is 200W is plotted against its speed. The value of the motor speed is being taken for each motor when it running with 200W power. The closest speed to the desired speed, which is 150rpm will be chosen for the best design.

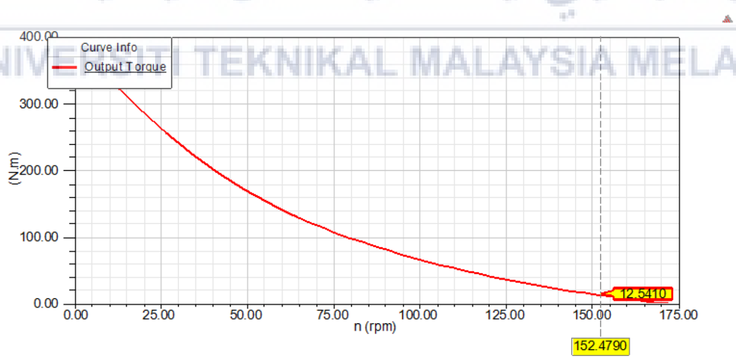
4.3.3)Output torque VS speed graph



220T



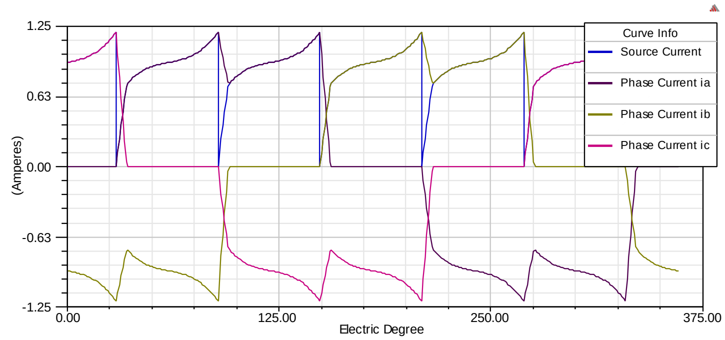
292T



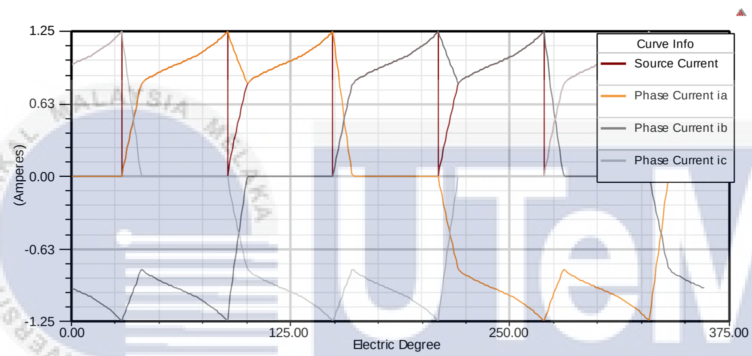
296T

Discussion: Output torque VS speed graph was plotted for each motor design, when it is operated with 200W power. The rated speed for each motor when operated with 200W is chosen as reading point and the corresponding torque is observed. The closest rated speed of the motor to the desired speed and its most highest equivalent torque is chosen.

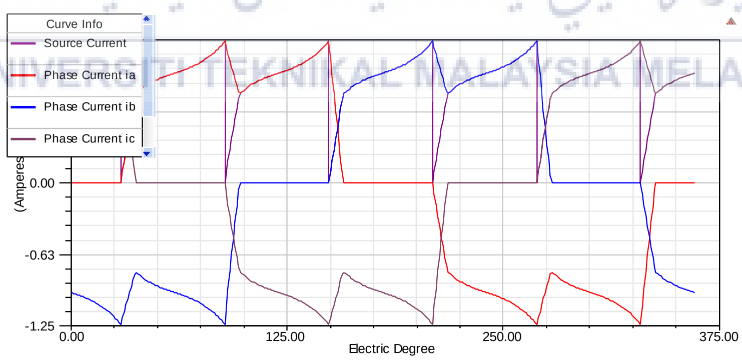
4.3.4) Winding current under load graph



220T



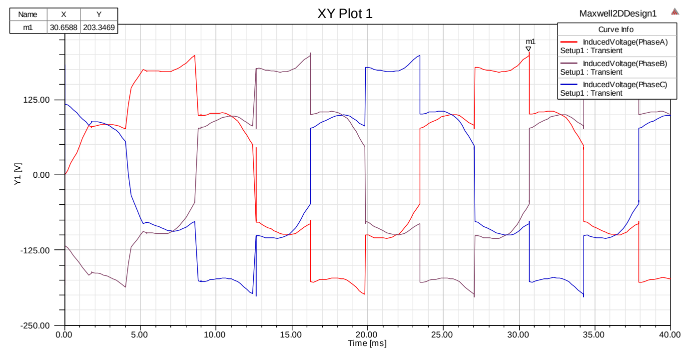
292T



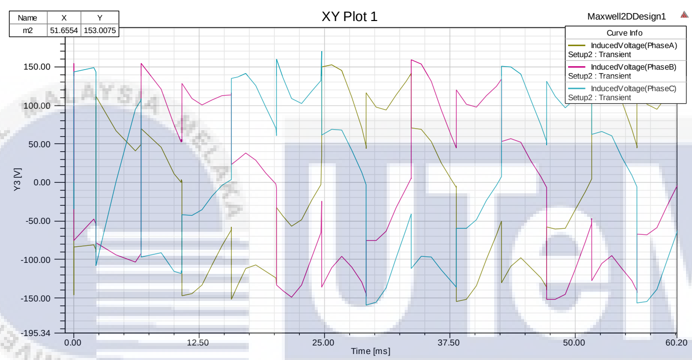
296T

Discussion: The current waveform for all the motor design is in similar regarding the differences of each of the motor design, which is, all the current waveform is in 120° phase shift from each phase A, B and C.

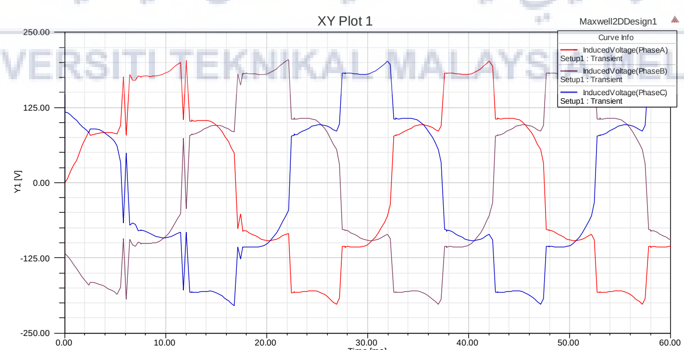
4.3.5) Back EMF of the BLDC motor



220T



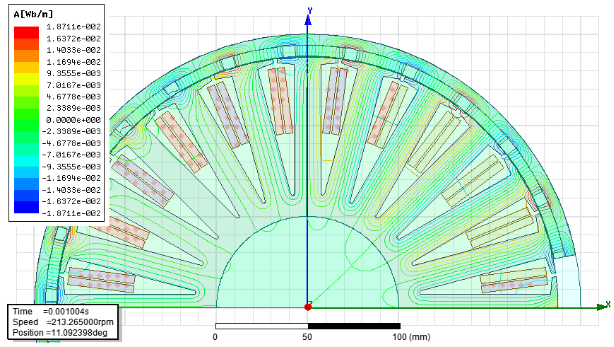
292T



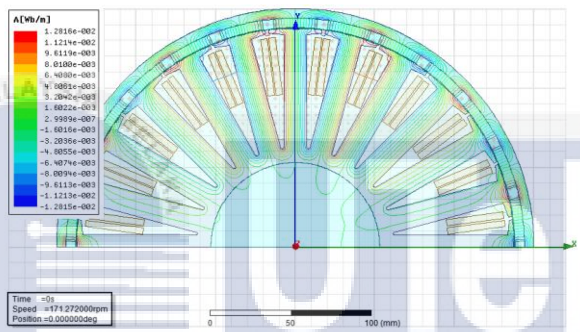
296T

Discussion: The back emf of the 220T and 296T is closer to the trapezoidal shape, different from the 292T design. This is because 220T and 292T design has slot fill factor of 75%, while the 292T design has slot fill factor of 99.8%.

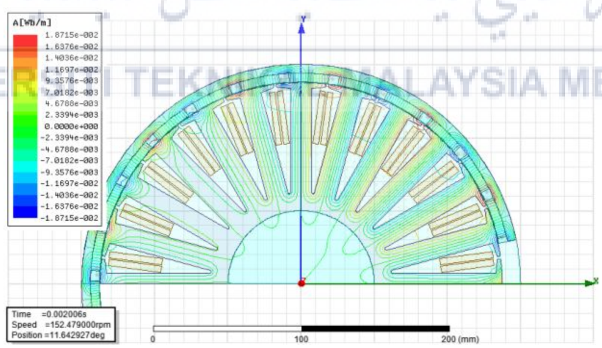
4.3.6) Flux lines (Wb/m)



220T



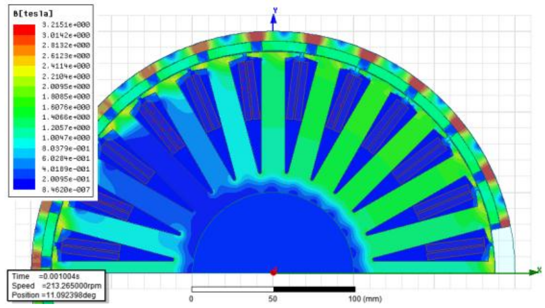
292T



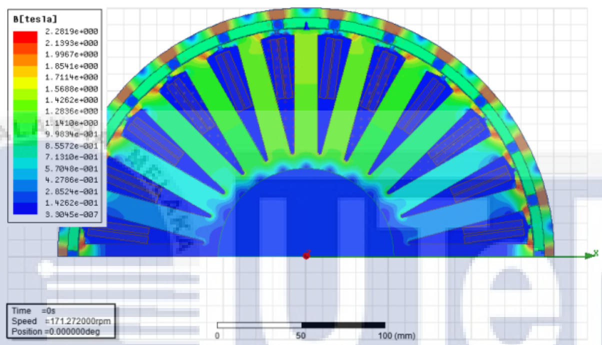
296T

Discussion: The flux lines graph shows the flux linkage movement when the motor start running. The higher value of flux lines are indicated with red colour and going lower values towards the blue colour. The saturation of flux lines can be observed so that the redesign of the motor mechanical parameter can be adjusted to get better motor performance.

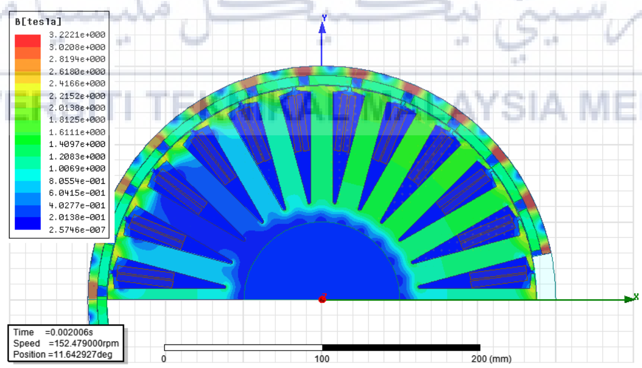
4.3.7) Flux density, B (Tesla)



220T



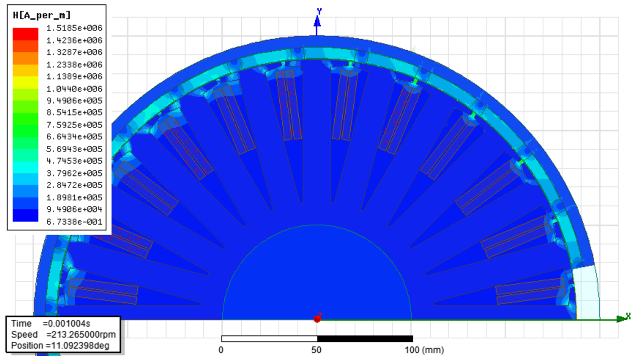
292T



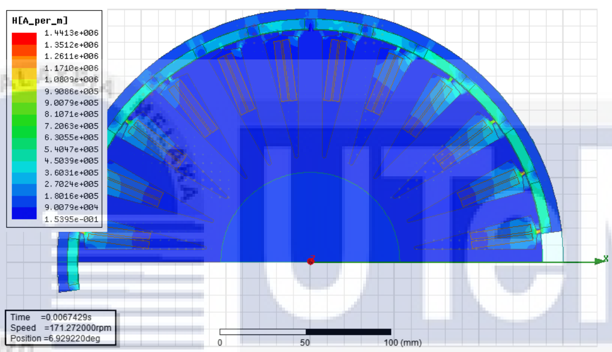
296T

Discussion: The flux density indicates the flux density position when the motor is running. The flux density of the stator is higher at its energized phase compared to its other phase, as the flux flows at the energized phase. 292T design has saturated flux density at its tooth because its slot fill factor is high, thus affecting its electrical and magnetic loading.

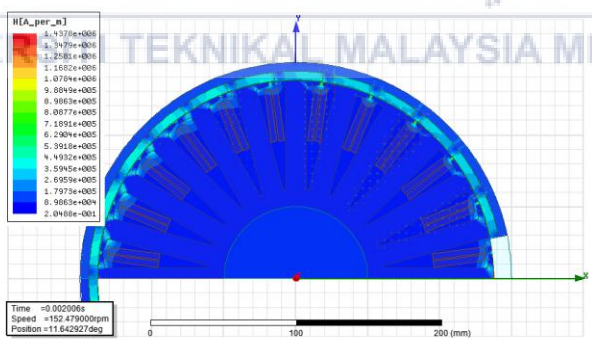
4.3.8) Flux intensity, H (A/m^2)



220T



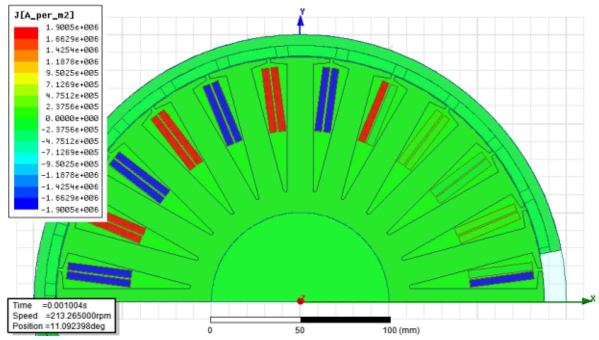
292T



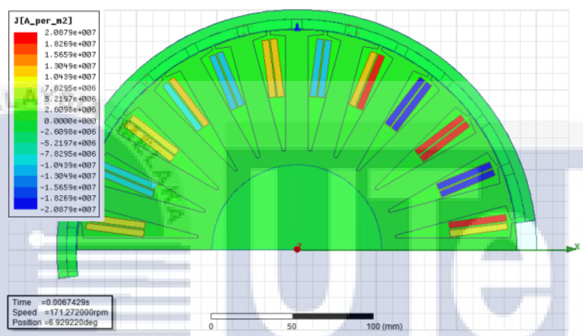
296T

Discussion: Flux intensity at 292T design is higher at its energized phase compared to the other two designs, due to its higher slot fill factor compared to the other two designs.

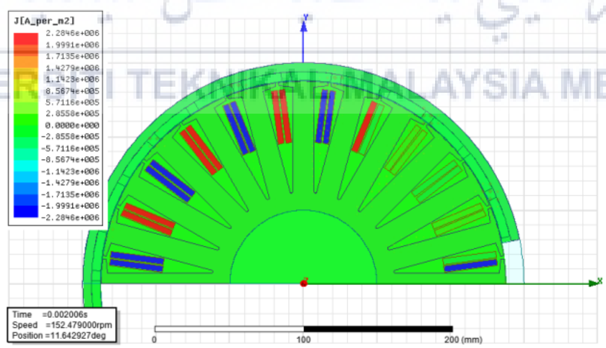
4.3.9)Current density, J (A/m^2)



220T



292T



296T

Discussion: The current density for both 220T and 296T are similar, which is the current density is maximum positive value (red colour) at positive phase and maximum negative value (blue colour) at negative phase of the energized winding. For 292T design, the other non energized phased also has medium positive (yellow) and medium negative (light blue) current density value.

CHAPTER 5

CONCLUSION

5.1 Conclusion

For the back emf, it is observed that the 292T design does not has the trapezoidal shape back emf. It is because the stator fill factor of the 292T design is 99.81%, which means that the slot is packed with the windings. When the winding energized at a particular phase, the other phase, which its winding is near to the previous phase, will be energized by the current density of high current density, as shown in 4.3.9. Thus, it will abrupt the induced voltage of each phase, and make the back emf of each phase is not achieving trapezoidal shape. 220T and 296T has a slot fill factor of 75%, which is the current density will just affecting the winding of the stator tooth, without effecting the other phase winding and thus, the behavior of the back emf remain in the shape of trapezoidal.

The observed flux density of the stator tooth for 292T design, which has stator fill factor of 99.81% as shown in 4.3.7 is saturated (has red colour) compared to the other two designs that has slot fill factor of 75%. This shows that the electrical loading of the motor is high, thus countermeasures such as limiting the slot fill factor by reducing the no. of turns of the design or using bigger tooth pitch as design is needed to avoid saturation.

Design parameters of the motor such as the tooth width can be redesign so that the flux lines that go through the stator tooth space is optimally used, which is not too narrow that will results in saturated flux lines to go through the stator teeth, and not too wide that there is still some space of the stator teeth that are not used when the maximum flux lines are going through the stator teeth, to avoid the waste of manufacturing cost of the motor by observing the simulation of the flux lines movement.

So, the design 296T is chosen as the best design as its speed and torque performance criteria met nearly to the desired motor specification for this project compared to the other two designs.

It is also concluded that, from the certain specification of the motor needed from the industry, such as the rated speed and torque demand of the motor, the geometry of the motor is then being designed and its performance is analyzed in order to fulfill the industrial demand product.

5.2 WORK OUTLINE

Table 5.1 below shows the working outline of this project.

Table 5.1: Working outline for the whole project

Project Activities	Weeks														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
FYP 1	Sept.	Sept.	Sept.	Oct.	Oct.	Oct.	Oct.	Nov.	Nov.	Nov.	Nov.	Dec.	Dec.	Dec.	Dec.
Selecting the project Title															
Identify Objective and Scope															
Doing Research, Start design															
Getting familiar with Ansys Maxwell software															
Transfer design to RMxprt Preliminary result															
Progress Report															
FYP 2	Feb.	March.	March.	March.	March.	April	April	April	April	May	May	May	May	June	June
Redesign the motor															
Getting familiar with Ansys Maxwell software															
Do FEM analysis in Maxwell 2D design															
Final Report															

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Appendix A

Wire Gauge and Current Limits Including Skin Depth and Strength

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Conductor cross section in mm^2	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper	Breaking force Soft Annealed Cu 37000 PSI
0000	0.46	11.684	107	0.049	0.16072	380	302	125 Hz	6120 lbs
000	0.4096	10.40384	84.9	0.0618	0.202704	328	239	160 Hz	4860 lbs
00	0.3648	9.26592	67.4	0.0779	0.255512	283	190	200 Hz	3860 lbs
0	0.3249	8.25246	53.5	0.0983	0.322424	245	150	250 Hz	3060 lbs
1	0.2893	7.34822	42.4	0.1239	0.406392	211	119	325 Hz	2430 lbs
2	0.2576	6.54304	33.6	0.1563	0.512664	181	94	410 Hz	1930 lbs
3	0.2294	5.82676	26.7	0.197	0.64616	158	75	500 Hz	1530 lbs
4	0.2043	5.18922	21.1	0.2485	0.81508	135	60	650 Hz	1210 lbs
5	0.1819	4.62026	16.8	0.3133	1.027624	118	47	810 Hz	960 lbs
6	0.162	4.1148	13.3	0.3951	1.295928	101	37	1100 Hz	760 lbs
7	0.1443	3.66522	10.6	0.4982	1.634096	89	30	1300 Hz	605 lbs
8	0.1285	3.2639	8.37	0.6282	2.060496	73	24	1650 Hz	480 lbs
9	0.1144	2.90576	6.63	0.7921	2.598088	64	19	2050 Hz	380 lbs
10	0.1019	2.58826	5.26	0.9989	3.276392	55	15	2600 Hz	314 lbs
11	0.0907	2.30378	4.17	1.26	4.1328	47	12	3200 Hz	249 lbs
12	0.0808	2.05232	3.31	1.588	5.20864	41	9.3	4150 Hz	197 lbs
13	0.072	1.8288	2.63	2.003	6.56984	35	7.4	5300 Hz	150 lbs
14	0.0641	1.62814	2.08	2.525	8.282	32	5.9	6700 Hz	119 lbs
15	0.0571	1.45034	1.65	3.184	10.4435	28	4.7	8250 Hz	94 lbs

					2				
16	0.0508	1.29032	1.31	4.016	13.17248	22	3.7	11 k Hz	75 lbs
17	0.0453	1.15062	1.04	5.064	16.60992	19	2.9	13 k Hz	59 lbs
18	0.0403	1.02362	0.823	6.385	20.9428	16	2.3	17 kHz	47 lbs
19	0.0359	0.91186	0.653	8.051	26.40728	14	1.8	21 kHz	37 lbs
20	0.032	0.8128	0.519	10.15	33.292	11	1.5	27 kHz	29 lbs
21	0.0285	0.7239	0.412	12.8	41.984	9	1.2	33 kHz	23 lbs
22	0.0253	0.64516	0.327	16.14	52.9392	7	0.92	42 kHz	18 lbs
23	0.0226	0.57404	0.259	20.36	66.7808	4.7	0.729	53 kHz	14.5 lbs
24	0.0201	0.51054	0.205	25.67	84.1976	3.5	0.577	68 kHz	11.5 lbs
25	0.0179	0.45466	0.162	32.37	106.1736	2.7	0.457	85 kHz	9 lbs
26	0.0159	0.40386	0.128	40.81	133.8568	2.2	0.361	107 kHz	7.2 lbs
27	0.0142	0.36068	0.102	51.47	168.8216	1.7	0.288	130 kHz	5.5 lbs
28	0.0126	0.32004	0.080	64.9	212.872	1.4	0.226	170 kHz	4.5 lbs
29	0.0113	0.28702	0.0647	81.83	268.4024	1.2	0.182	210 kHz	3.6 lbs
30	0.01	0.254	0.0507	103.2	338.496	0.86	0.142	270 kHz	2.75 lbs
31	0.0089	0.22606	0.0401	130.1	426.728	0.7	0.113	340 kHz	2.25 lbs
32	0.008	0.2032	0.0324	164.1	538.248	0.53	0.091	430 kHz	1.8 lbs
Metric 2.0	0.00787	0.200	0.0314	169.39	555.61	0.51	0.088	440 kHz	
33	0.0071	0.18034	0.0255	206.9	678.632	0.43	0.072	540 kHz	1.3 lbs
Metric 1.8	0.00709	0.180	0.0254	207.5	680.55	0.43	0.072	540 kHz	
34	0.0063	0.16002	0.0201	260.9	855.752	0.33	0.056	690 kHz	1.1 lbs
Metric 1.6	0.0063	0.16002	0.0201	260.9	855.752	0.33	0.056	690 kHz	
35	0.0056	0.14224	0.0159	329	1079.12	0.27	0.044	870 kHz	0.92 lbs
Metric 1.4	.00551	.140	0.0154	339	1114	0.26	0.043	900 kHz	
36	0.005	0.127	0.0127	414.8	1360	0.21	0.035	1100 kHz	0.72 lbs
Metric 1.25	.00492	0.125	0.0123	428.2	1404	0.20	0.034	1150 kHz	
37	0.0045	0.1143	0.0103	523.1	1715	0.17	0.0289	1350 kHz	0.57 lbs

Metric 1.12	.00441	0.112	0.00985	533.8	1750	0.163	0.0277	1400 kHz	
38	0.004	0.1016	0.00811	659.6	2163	0.13	0.0228	1750 kHz	0.45 lbs
Metric 1	.00394	0.1000	0.00785	670.2	2198	0.126	0.0225	1750 kHz	
39	0.0035	0.0889	0.00621	831.8	2728	0.11	0.0175	2250 kHz	0.36 lbs
40	0.0031	0.07874	0.00487	1049	3440	0.09	0.0137	2900 kHz	0.29 lbs