Design and Analysis of PM BLDC Generator For Wind Power Generation

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the

Degree of

Master of Technology

In

Electrical Engineering

(Electrical Power Systems)

By

Madhuri Mishra

12MEEE34

DEPARTMENT OF ELECTRICAL ENGINEERING

INSTITUTE OF TECHNOLOGY

NIRMA UNIVERSITY

AHMEDABAD-382481

May 2014

Undertaking for Originality of the Work

I, **Madhuri Mishra(Roll No:12MEEE34)**, give undertaking that the Major Project entitled" **Design and Analysis of PM BLDC Generator For Wind Power Generation"** submitted by me, towards the partial fulfillment of the requirement for the degree of Master of Technology in Electrical Power Systems, Electrical Engineering,under Institute of Technology, Nirma University, Ahmedabad is the original work carried out by me and I give assurance that no attempt of plagiarism has been made.I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere, it will result in severe disciplinary action.

....

Signature of Student

Date:

Place:Ahmedabad

....

Endorsed by:

Prof. S. C. Vora

Department of Electrical Engineering,

Institute of Technology,

Nirma University,

Ahmedabad.

CERTIFICATE

This is to certify that the Major Project Report entitled"**Design and Analysis of PM BLDC Generator For Wind Power Generation**"submitted by **Ms. Madhuri Mishra (Roll No: 12MEEE34)**towards the partial fulfillment of the requirements for the award of degree in Master of Technology(Electrical Engineering)in the field of Electrical Power System of Nirma University is the record of work carried out by her under our supervision and guidance.The work submitted has in our opinion reached a level required for being accepted for examination.The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or institution for award of any degree or diploma.

Date:.......................

....

Project Guide:
Prof. S. C. Vora
Department of Electrical Engineering,
Institute of Technology,
Nirma University,
Ahmedabad.

Head Of Department
Department of Electrical Engineering,
Institute of Technology,
Nirma University,
Ahmedabad.

Director
Institute of Technology,
Nirma University,
Ahmedabad.

I dedicate this thesis to........

My loving daughter ”Samara”

&

my family

ACKNOWLEDGEMENT

I would like to express my deep gratitude to my project guide Dr. Santosh Vora for his valuable guidance, direction, support, enduring patience and firm support for carrying out the project work.

I would also like to convey my sincerest gratitude and appreciation to all other faculty members and the staff of Department of Electrical Engineering who conferred their great effort and guidance at appropriate times without which it would have been very difficult on our project work.

Working on this project has been one of the most significant academic challenge i have ever had to face.Without the support,patience and guidance of the kind friends around me and all other batchmates ,this would not have been completed.

I owe my deepest gratitutde to my husband and my daughter,without whom this effort would have been worth nothing.Their love,support and constant patience have taught me so much about sacrifice,discipline and compromise.

Also, i would like to thank my family members, who have always supported, encouraged and believed in me, in all my endeavours.

Also, I would like to thank to Mr. Pratik Jani for his invaluable advice and lab support which were very helpful and are very much appreciated.

Finally, I am thankful to Entuple Technologies for their sustenance support in providing us the eval version of ANSYS-Maxwell to carry out our project work.

ABSTRACT

Numerous applications, significantly different than the conventional requirements, lead to conceptualizing of newer type of electrical rotating machines. To realize these newer machines with different behaviours, demands continous exploration of material science and think beyond routine theoretical concepts. One of the such realization is of Permanent Magnet machines. This technological advancement in development of new materials have placed permanent magnet machines in a prominent position.However, a biggest emphasis in the project has been put on the design of Permanent Magnet Brushless DC generator (PMBLDC) suitable for a small scale Wind Energy Conversion System (WECS), the different topologies of electrical generators have also been investigated for small scale wind turbines. A Permanent magnet generator is proposed as a solution with respect to the cost of other systems. After a detailed literature study on PM BLDC topologies,axial flux machines have found to be suitable for the desired application, because of its lighter weight, high power to weight ratio, high torque to weight ratio, their low speed suitability. This has led to focus the project work on the use of axial flux PMBLDC generators and has carried out the designing, modelling and analysis of an AFPM BLDC and the design is assessed by means of Finite Element Method (FEM) which includes its electrical and magnetostatic behaviour. To accomplish this purpose model was prepared in the CAD packaged software CREO, and then FE analysis has been carried out .A 250 W AFPM BLDC dual rotor and single rotor generator is designed and analysed .Also,the design parameters have been calculated for 5 kW model and due to paucity of time the analysis could not be performed.To validate the designed model, a simulation is performed in Matlab Simulink and the performance outputs have been presented.

Contents

List of Figures

List of Tables

Abbreviations

BLDC .... **Brushless Direct Current Generator**
DFIG .... **Doubly Fed Induction Generator**
PM .... **Permanent Magnet**
PMWG .... **Permanent Magnet Wind Generator**
FEM .... **Finite Element Method**
WECS .... **Wind Energy Conversion System**
PMSG .... **Permanent Magnet synchronous Generator**
RFPM .... **Radial Flux Permanent Magnet**
AFPM .... **Axial Flux Permanent Magnet**
PMSM .... **Permanent Magnet Synchronous Machine**
MMF .... **Magneto- Motive Force**
TFPM .... **Transverse Flux Permanent Magnet**
MVP .... **Magnetic Vector Potential**
MSP .... **Magnetic Scalar Potential**
DOF .... **Degree Of Freedom**

Dissertation Delineation

This thesis is written to accomplish the project work aimed to design a BLDC generator for wind power applications. This dissertation starts with an introduction in Chapter I to the wind power generation and the need for the PM BLDC generator. The research objective to design, model and analyze a BLDC generator is explained.

The fundamental characteristics advantages and disadvantages of a PM BLDC generator are presented in Chapter II. Mechanical structure and the electromagnetic behavior of the PM BLDC generator, and the advantages and disadvantages of PM BLDC generators over DFIG (conventional method) are presented.The conventional and probable configurations methods of the PM BLDC generator are reviewed. The drawbacks of the existing topology are investigated so as to develop a new topology that can solve those problems.

The basics related to FEM, electrostatic and magnetostatic behaviour of the generator is explained in Chapter III.

The theory of designing aspects of BLDC generator is presented in Chapter IV.Introduction to Finite Element analysis, electrostatic and magnetic analysis is also included. Also, the details of simulation work and electrostatic analysis are presented.

The Model prepared and its magnetostatic analysis are cited in Chapter V.

Chapter VI will conclude this dissertation/thesis and describes contribution of this work,its limitations as well as the future scope of work for this project.

Chapter 1

Project Facet

Wind energy is gaining a pivotal role in the inception of an environmentally sustainable low carbon economy.Traditionally,permanent magnet synchronous machines and doubly fed induction machines have been used for small scale wind power generation.In virtual each can be run at fixed or variable speed.Due to the wavering nature of wind power, it is beneficial to operate the wind turbine generator at variable speed which reduces the physical stress on the turbine structure.But the requirement of gearboxes and external excitation make their use limited for small scale wind power generation.

Permanent magnet brushless DC generators proved to be as the best consummate for wind power generation industry.Thus, nowadays, because of the neccessity of stand-alone generators, these are getting common not only in remote areas but also in urban areas.Considering its usage for small scale wind power generation capacity, its cost, power to weight ratio, torque to weight ratio does plays an important role. In other words, minimal sizing, lighter weight and highest efficiency in the same rated machine are the most important factors.Thus before manufacturing the generators its study for the electrical, magnetic and mechanical behaviour has to be studied and analysed so as to increase the life span of the machine

and serve uninterrupted power supply.

Among several kinds of generators, the permanent magnet brushless DC (PM BLDC) generator is the best candidate for improving power density. As compared with other generators, the PM BLDC generator has lots of benefits; it is lightweight, it has a compact design and low maintenance because it has a magnetic source inside itself. With the inherent advantages of the PM BLDC generator, additional increases in power density can be expected by the advanced control techniques, resulting in considerable reduction of weight and volume.

In the conventional wind power generation system, doubly fed induction generator is used. Such systems use a multistage gearbox, a DFIG, and a power electronic converter.

1.1 Historical Review

Growing interest in new topologies of permanent magnet (PM) brushless machines has prompted the researchers and scientists to update the technologies for wind power generation. The importance of PM brushless machines technology and its impact on energy conversion systems are receiving increasing attention each year. While D.C. brush machines production is shrinking, PM brushless machines are replacing D.C. brush and sometimes induction motors in consumer electronics, kitchen and bath equipment, public life, instrumentation and automation system, clinical engineering, industrial electromechanical drives, automobile manufacturing industry, electric and hybrid electric vehicles, marine vessels, toys, more electric aircrafts and many other applications on larger scale. New applications have emerged in distributed generation systems (wind turbine generators, high-speed micro turbine generators), miniature power supplies, flywheel energy storages, aircraft and rotorcraft actuators, missile fin actuators, naval integrated motor-propellers (rim driven thrusters). The role of PM brushless machines is increasing especially in applications where integration of motors with other mechanical parts is imperative.

1.2 Literature Survey

In context to the objective, the work requires to check for available PM BLDC generators and various configurations and taking this into a view the approach is to make possible changes in the design improving the performance. The present scenario notices that there is a need for PM BLDC generators to improve the overall efficiency of stand alone (small scale wind power) generators.The literature survey shows the same as below:

L. Somerlund J-T. Eriksson,J. Salonen, H. Vihriala and R. Perill- A Permanent-Magnet Generator for Wind Power Applications - [1]The author has cited the advantages of permanent magnet wind power generator (PMWG) . A construction having no teeth and the stator core wound directly from tape has been shown. The PMs used in this model were rectangular, while in the traditional radial-flux machines they would have a shape of an arc. Due to the magnets there is no need for the external magnetization, which is important especially in stand-alone wind power applications and also in remote areas where the grid cannot easily supply the reactive power required to magnetize the induction generator. Due to the small resistance, losses are small. Iron losses are also small, due to the laminated stator core and the absence of the armature reaction. The overall axial length of the deigned generator is small and correspondingly the nacelle of the wind power plant becomes simpler than with the traditional drive. On the other hand the diameter is large which should not exceed 10The author has presented a PM synchronous generator for

slow speed applications. It easily facilitates a large number of poles using an algorithm combined with FEM,an axial-field permanent-magnet synchronous wind power generator (PMWG) mainly from the magnetic viewpoint. Both mechanical and electromagnetic designs are described as well as some primary test results concerning the model generators having nominal power of 5 and 10 kW.

L. Somerlund J-T. Eriksson,J. Salonen, H. Vihriala and R. Perill - Design of an Axial Flux Permanent Magnet Wind Power Generator [2] In this paper author has presented optimum design based on minimizing the sum of investment and energy loss costs for a 100 kW prototype generator is searched.Also, he presented the advantages of gearless system.Traditionally the gearbox is required to increase the low rotational speed of the turbine (typically 20-40 rpm) up to a speed suitable for a common 4-pole generator (1500 rpm). The removal of the gearbox increases system availability and reduces its weight, losses and the need for maintenance. However, the low rotational speed calls for a generator with a very large number of poles. Due to the variable speed scheme a frequency converter is required to supply the power to a grid. The requirement of a large pole number can be met with permanent magnets which allow small pole pitch.A simple and effective generator structure is realized by the disc type axial flux configuration.

Jianyi Chen, Chemmangot V. Nayar, and Longya Xu -Design and Finite-Element Analysis of an Outer-Rotor Permanent-Magnet Generator for Directly Coupled Wind Turbines-[3] In this paper author presents the design and finite-element (FE) analysis of a permanent-magnet generator. A novel PM generator was designed with an innovative outer-rotor structure to cope with various difficulties in designing a directly coupled wind turbine generator. In a normally designed inner-rotor PM generator for gearbox-coupled applications, the pole number is low and the magnets

can be arranged on the rotor. In order to produce normal frequencies at very low speeds for direct coupling to the wind turbine, the PM generator needs a very large pole number, resulting in a design of substantially enlarged diameter and high cost. To be economically competitive, the design of low-speed, large-diameter generators has to be optimized in terms of cost, power density, and efficiency. The FE method is applied to analyze the details of the outer-rotor PM generator. A comparison between the theoretical work and testing results is presented to demonstrate the effectiveness of design principles and methodologies.

Yicheng Chen, Azeem Khan -PM Wind Generator Comparison of Different Topologies-[4] In this paper the author has presented the designs of large number of prototypes of permanent magnet (PM) wind generators.The criteria used for comparison are torque density, active material weight, outer radius, total length, total volume and efficiency as these are identified as being critical for the efficient deployment of generators in wind turbines.He included the conventional inner rotor radial-flux construction, outer rotor radial-flux construction, double stator axial-flux construction, double rotor axial-flux construction, single sided axial-flux constructions with force balance stator and force balance rotor, and torus toothless axial-flux construction. All the machines compared are built with surface mounted magnets, Nd-Fe-B, and grouped into two categories. One has direct-driven generators operating at low speeds of 50 rpm or 100 rpm, the other has the machines rotating at a high speed of 1200 rpm, where gearboxes are needed.

Guoliang Yang and Huiguang Li -Design and Analysis of a Newly Brushless DC Wind Generator-[5] In this paper the author has presented the brushless DC generator has been chosen as generator for WECSs. The proposed generator is a 27-phase, 8-pole generator. This has the advantages of not only voltage smooth like dc generator but also long life period

and high efficiency as PM synchronous generator (PMSG). And the voltage adjustment rate is lower than PMSGs. The design and optimization of the generator was done with the aid of the well-established computerized design procedures and electromagnetic field analysis. Also, the author has cited the disadvantage of high adjustment rate and many ripples for PM synchronous generator in wind power generation system, presents a newly brushless dc wind generator, whose rotor adopts tangential structure and Ferrite material in permanent magnet to increase flux .

B. J. Chalmers and W Wu-An axial flux permanent magnet generator for a gearless wind energy system-[6] The paper discuses the development of an axial flux permanent-magnet generator for a gearless wind energy system which aim to demonstrate the feasibility of integrating wind and photovoltaic energy converters for the generation of electricity and to achieve optimum exploitation of the two energy sources. The merits of an axial-flux generator topology are discussed with reference to the particular requirements of an electrical generator for a direct-coupled wind turbine application. The design, construction and test results of a 5 kW, 200 rev/min permanent-magnet generator, to form a 10 kW pilot power plant with a 5 kW photovoltaic array, are presented.

J.R. Bumby, N. Stannard, J. Dominy and N Mc Leod-A Permanent magnet generator for small scale wind and water turbines -[7] The paper discusses the development of an axial flux permanent-magnet generator for a gearless wind energy system which aim to demonstrate the feasibility of integrating wind and photovoltaic energy converters for the generation of electricity and to achieve optimum exploitation of the two energy sources. The merits of an axial-flux generator topology are discussed with reference to the particular requirements of an electrical generator for a direct-coupled wind turbine application. The design, construction and test results of a 5 kW, 200 rev/min permanent-magnet generator, to form

a 10 kW pilot power plant with a 5 kW photovoltaic array, are presented.

David G. Dorrell-Design requirements for brushless permanent magnet generators for use in small renewable energy systems - [8] Through this paper author has illustrated simple steps that can be used to obtain a design for a suitable generator for a small wind turbine. The first section studies the performance of a brushless motor (designed for use in a water pump) when utilized in a generator application. This is a modern high-efficiency design with a low phase reactance and good power factor. The second section shows the design of a low-speed generator. Basic design principles are followed to realize the geometry and it is illustrated that an external rotor machine is more compact. An attempt was made to further compact the machine by reducing the diameter and increasing the electrical loading but it was found that this led to reduced efficiency and power factor. This was to the extent were a diode bridge rectifier load is inappropriate and a fully controlled rectifier would have to be used.

N. J. Stannard, J R Bumby-Energy yield and cost analysis of small scale wind turbines -[9] With this citation author seeks to explore the attractiveness of small-scale wind turbines in the current economic climate. In order to do this, three pieces of information must be known: (1) the cost of the system; (2) the annual energy yield of the system; (3)the value of that energy yield. The annual energy yield is more difficult to determine, and in this paper a Weibull probability distribution of wind speed, combined with the turbine's power characteristic, has been used to estimate it. This analysis has been carried out on a number of small-scale turbines that are currently on the market and the results have been compared to a family of generic turbines with ideal performance characteristics to assess whether the manufactures performance claims are accurate. The income generated and the level of CO2 abatement has also been calculated. It was found that a 2.5-3kW turbine could supply all the energy needs of an average

household, however the current cost of the system is expensive compared to the cost of buying the energy from the grid, leading to a payback period of similar length to the design life of the turbine.

Ronghai Qu, Metin Aydin, Thomas A Lipo-Performance comparison of dual rotor radial flux and axial flux permanent magnet BLDC machines -[10] The objective of the author in this paper was to provide a performance comparison between two major alternatives of BLDC machines; Surface mounted dual rotor radial flux PM machine and axial flux PM machine, the comparison was done on the basis of material weight ,magnet material effect,copper and iron losses,torque and power per unit active volume,losses per unit gap area and machine efficiency.Pole number effects on both machines are investigated as well.RFPM and AFPM machines have similar performance in terms of torque density,torque to mass ratio,losses and efficiency.However, the material cost of AFPM machine is much higher than that of RFPM machines due to more magnet requirement in AFPM machines.The effect of machine pole number,the ratio of length to diameter for RFPM, and the ratio of stator inner to outer diameter for AFPM were also investigated.Also, limitation of outer rotor configuration for an application of both RFPM and AFPM machines are presented.

Kartik Sitapati and R. Krishnan-Performance comparisons of radial flux and axial flux permanent magnet brushless machines - [11] The objective of this paper is to provide a comparison between the traditional radial field permanent-magnet brushless machine and four unique configurations of axial field permanent- magnet brushless dc machines. These consist of a single-gap slotted axial field machine, a dual-gap slotted axial field machine, a single-gap slotless axial field machine, and a dual-gap slotless axial field machine. The comparison is done at five power levels ranging from 0.25 to 10 kW. A rated speed of 2000 rev/min is chosen for the 0.25 kW

designs while 1000 rev/min is chosen for the rest of the designs.Also, it is inferred that axial field machines have a smaller volume for a given power rating, making the power density very high.For a given magnet material and air gap flux density, the rotor moment of inertia of the radial field motor tends to be larger than all of the axial field designs, making the active weight of the axial field machines smaller. The slotless axial field machine require more magnet material than the radial field machine.The copper loss in the slotless dual gap machines is higher than that of the slotted radial field machine.

V.V Vadher, J. G. Kettleborough,I R smith-Generalized model of brushless DC Generator - [12] The author has cited a generalized model for a brushless dc machine consisting of a multiphase synchronous machine with a full-wave bridge rectifier connected to its output terminal.The state-variable equations are used for the machine to investigate the effects of no. of armature phase windings and different winding connections.Comparisons presented between predicted and measured results illustrate the validity of the model and the mathematical techniques adopted, and confirm that accurate information on the performance of a brushless generator may be obtained prior to manufacture.

F. Caricchi, F. Crescimbini, E Santini, C Santucci-FEM Evaluation of performance of axial flux slotted permanent magnet machines -[13] The author has presented a work on axial-flux permanent magnet with slotted winding exhibit a significant cogging torque due to magnetic anisotropy of the stator which produces a harmonic content in machine back emf. This paper introduces and discusses a simple and powerful FEM algorithm that gives the numerical evaluation of both cogging torque and back emf. This parametric analysis leads to the machine design that most meets the requirements for low cogging torque and limited higher harmonic content in back emf.

1.3 Problem Identification

Using DFIG for small scale wind power application does not proved to be worth because of its installation and operation cost. It is now becoming ubiquitous to use PM machines for wind power generation because of inherent advantages of using PM instead of giving seperate excitation.Recently, PMSM have been largely adopted in low speed stand alone wind power application.The problem in using PMSM is that its excitation can't be regulated, output voltage has high adjustment rate and large fluctuations in the output, and the DC waves after rectification by bridge have many ripples.Problem in using PMSM is its larger size even for small scale power generation,its less torque to weight and power to weight ratio.

1.4 Objective of the project

The main objective of this research is to investigate conventional machines and explore the use of Permanent Magnet machine for small scale wind power generation.A permanent magnet brushless DC generator has to be designed, modeled and analyzed for wind power generation of small capacity. For the given rating of a machine our objective is so as to accomplish minimal sizing, lighter weight generator and to do the finite element analysis to study magnetic and electrical behaviour of the machine under steady state condition. Considering these aspects, before giving physical shape to the design it is essential to check its various implicable stress(i.e. Magnetic,Electrical and Mechanical)conditions in account of justifying its stability and at the end of simulation it can be concluded that some improvements are worth to reduce cost of the final product and the ultimate effect is good reliability approach and quality that is what Finite Element Technique suggests. So the whole generator assembly is to be modeled

and analysed to improve its performance and lifespan.

1.5 Scope of the Work

The work approaches its objective in following steps:

a. **Comparative study of different configuration of PM BLDC generators.**

b. **Design and develop model of axial flux PM BLDC generator and its configurations.**

c. **Magnetic and Electrical analysis using finite element analysis technique.**

d. **Validation of model using Matlab Simulink.**

1.6 Adopted Methodolgy

a. **The first step of this project is to compare the conventional topology (DFIG) and BLDC generator for wind power generation.**

b. **The second step of this project is to design and develop a model of a PM BLDC generator.**

c. **The third step is to verify the validity using Matlab Simulink and evaluate the performance of the proposed design and model in ANSYS and Maxwell-Rmxprt.[1]**

---

[1] **Eval version 15 for student project work of ANSYS Maxwell-Rmxprt has been provided by Entuple technologies for two months.**

Chapter 2

Wind Turbine Generator System

2.1 Introduction

The use of wind power is getting ubiquitous now a days because of its eco-friendly way of acting as an energy source with no fuel costs. The deployment of wind power is growing every year, more and more countries invest in large wind power generation for part of their energy supply. It is important that the technology and development of wind power generation keeps unfolding to increase the amount of wind power generation efficiently. There are several different types of electrical systems available for converting the wind power to electricity but no single technology is dominating the market.In regards to this inflation in demand of standalone renewable electrical energy generation wind energy conversion systems (WECSs) are becoming increasingly popular.

Permanent magnet (PM) machines are ideally suited for these applications, as they are inherently more efficient than wound-field machines. Moreover, PM machine rotors are easy to manufacture with the large number of poles required by low-speed, direct-drive WECSs. Recently, PM synchronous machines (PMSM) have been largely adopted in most of the

low-speed wind turbine generators system. These have the advantages of high efficiency and reliability since there is no need of external excitation and conductor losses are removed from the rotor. But because of its excitation cannot be regulated, output voltage has high adjustment rate and large fluctuation domain. The direct current waves after rectification by bridge have many ripples, the voltage adjustment rate has over 70 percent in terms of nominal voltage.

So the life period of storage battery must be shorted and whole system is not stabilized. Operational wind turbines as well as those available on the market today usually use Doubly fed Induction generators but PM machines are especially common in small wind turbines. A more extensive overview over different electrical conversion systems for wind turbines can be found. In the conventional wind power generation system, doubly fed induction generator is used. Such systems use a multistage gearbox, a DFIG, and a power electronic converter.

In this project the brushless DC generator has been chosen as generator for WECSs. For recent years, with the rapid development of power electronics and control technology, the brushless electric machine can replace the brushed electric machine, and solid state switch can replace mechanical switch, as a result, the brushless DC generator has been developed rapidly. This has the advantages of not only voltage smooth like dc generator but also long life period and high efficiency as PM synchronous generator (PMSG). And the voltage adjustment rate is lower than PMSGs. The design and optimization of the generator was done with the aid of the well-established computerized design procedures and electro-magnetic field analysis.

2.2 Disadvantages of Doubly Fed Induction Generators

Doubly Fed Induction Generators suffers from the following drawbacks[23]

a. Requirement of slip rings and brushes.

b. Separate excitation for field.

c. Limited capability of supplying reactive power to compensate the grid power factor. Moreover, when a fault occurs in the grid, it is difficult to clear it because of additional requirement of reactive power by induction generator.

d. Large torque and stator current peak of the generator under grid fault condition.

e. Vulnerability to grid side voltage sags and short circuits.

f. External circuit between stator and grid to limit the start up current is required.

Moreover, geared system has other issues such as short life span of gear box and frequent maintenance. Because of this gearless and brushless system with highly efficient permanent magnets is gaining interest in manufacturers. Such system can eliminate the limitation of DFIG for wind power generation for small systems.

2.3 Advantages of Brushless DC generators

,Figure 2.1 Courtesy:[22] PM BLDC Generators offers many advantages such as[23]

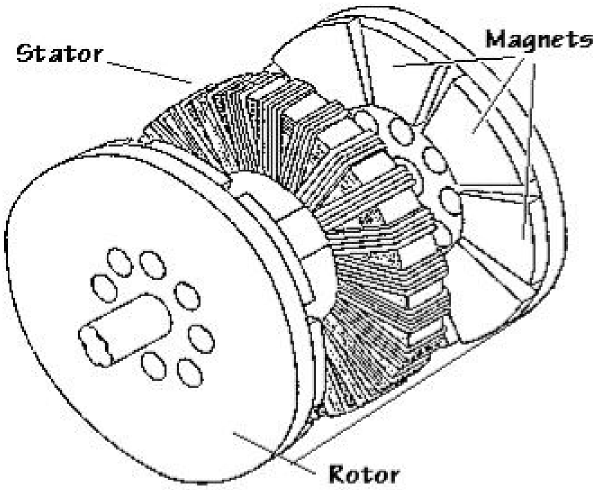

Figure 2.1: Brushless DC Generator

a. High efficiency: The PM BLDC machine is the most efficient of all electric machines since it has a magnetic source inside itself.

b. Use of permanent magnets for the excitation consumes no extra electrical power. Therefore, copper loss of the exciter does not exist and the absence of mechanical commutator and brushes or slip ring means low mechanical friction losses.

c. Compactness: The recent introduction of high-energy density magnets (rare-earth magnets) has allowed achievement of very high flux densities in the PM BLDC generator.Also, winding on the rotor is not required. These in turn allow the generator to be small, light and of rugged structure.

d. Ease of cooling: There is no current circulation in the rotor for magnetic field. Therefore, the rotor of a BLDC generator does not heat up. The only heat production is on the stator, which is easier to cool than the rotor because it is static and on the periphery of the generator.

e. Low maintenance, great longevity, and reliability: The absence of brushes, mechanical commutators and slip rings suppresses the need for associated regular maintenance and suppresses the risk of failure associated with these elements. The longevity refers only to the winding insulation, bearing, and magnet life length.

f. Low noise: There is no noise associated with the mechanical contact. The driving converter switching frequency is high enough so that the harmonics are not audible.

2.4 Disadvantages of PM Brushless DC generators

PM BLDC generators have certain limitations as follows[23]

a. Limited operating-speed range: The field-weakening operation for the PM BLDC machine is somewhat difficult due to the use of permanent magnets. Some accidental speed increase might damage the power electronic components above the rating of converter, especially for vehicle applications. In addition, the surface-mounted permanent magnet generators cannot reach high speeds because of the limited mechanical strength of the assembly between the rotor yoke and the permanent magnets. There is a possibility of permanent magnets to fly apart.

b. Demagnetization of the permanent magnet: Magnets can be demagnetized by large opposing magneto-motive-force (MMF) and high temperatures. The critical demagnetization force is different for each magnet material.

c. Cost: Permanent magnets are expensive parts in the machine and result in an increased motor cost. The cost of higher energy density magnets prohibits their use in applications where initial cost is a major concern

d. Extreme care must be taken to cool the generator, especially if it is compact

Hence, no research for a PM BLDC generator for greater than a few kW capacity has been done.

2.5 Comparison between various configuration of PM BLDC generator

There are many different permanent magnet machine configurations which can be used for wind power applications. According to direction of flux path PM machines can be subcategorized as:Figure 2.2 Courtesy[21]

a. Radial Flux permanent magnet machines(RFPM) Radial-flux PM synchronous machines (RFPM) are the most conventional PM machines. The flux flows radially in the machine while the current flows in the axial direction,the easiest and cheapest to manufacture among the PM machines,stators are similar to the ones of the induction machines.

b. Axial Flux permanent magnet machines(AFPM) Large diameter and a relatively short axial length compared to a radial-flux PM machine.The flux from the PMs flows axially while the current flows in the radial direction.Fig2.3 Courtesy:[21]

c. Transversal flux PM machines (TFPM)

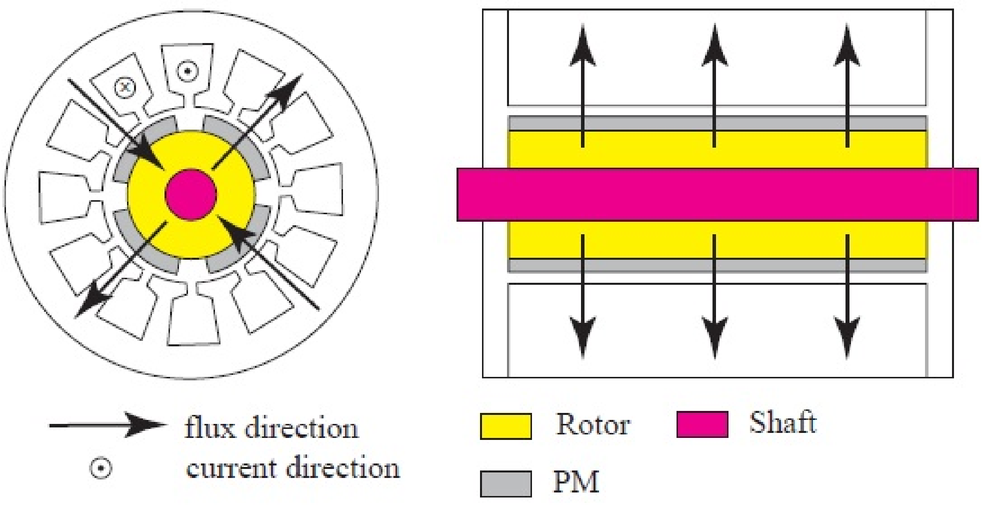

Figure 2.2: Radial flux PM BLDC generator configuration

A comparison is done between AFPM and RFPM which showed that AFPM have greater power density.

2.6 Advantages of AFPM over RFPM

Advantages of AFPM over RFPM are as follows[23]

a. High power density, hence require less core material.

b. They have planar and easily adjustable air gaps.

c. Noise and vibration are less.

d. Low cogging torque in the slot less structure.

NOTE: Major issue of AFPM machine includes structural instability with larger diameter discs, higher magnet cost in slot less design and requirement of large outer diameter makes it difficult to be used in large scale wind turbine.

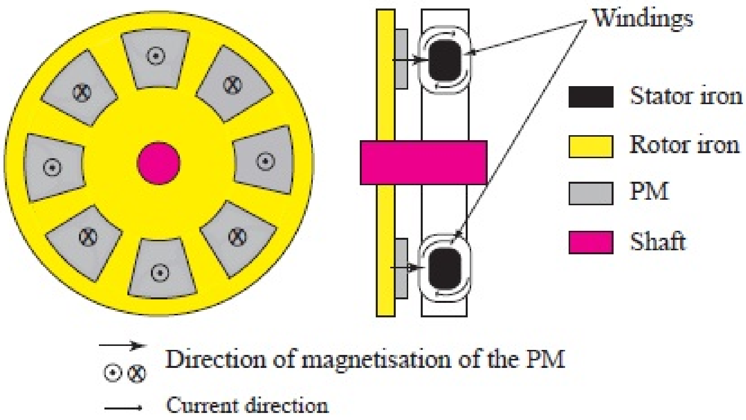

Figure 2.3: Axial flux BLDC generator configuration

2.7 Axial flux PM BLDC topologies

Following are the possible configuration for AFPM BLDC generators[11]

a. **Axial field single air gap-** In this machine, there is only one stator and one rotor.The rotor rotates besides the stator, flux crossing the air gap in the axial direction.For single gap machine rotor contains both magnet and back iron constitutes the return path for magnetic flux.In these type of generators the magnet width and area increases as generator diameter is increases for low speed applications.The disadvantage of using these type of machines is that there exists some axial attractive force between stator and rotor body, which may lead to vibration in the generator and hence can damage the generator.

b. **Axial field dual air gap-**This machine has two air gaps and may contain two stator assemblies around one rotor or two rotor assemblies around one stator. These type of generators provide cancellation of axial attractive forces between rotor and stator which exists between magnet and stator steel.

The other configuration possible for above two can be slotted and slotless.

The comparison for all the above mentioned configuration could be made in regards to their volume,moment of inertia, steel weight, and copper weight. Comparison based on above mentioned parameters for the different machine configurations is presented below:

a. **Volume:** Volume required by dual air gap machine is larger as compared to single air gap machine, due to the requirement of two rotor bodies.Slotless machine requires larger diameter due to more turns and end turns, copper requirement will also be more.In addition, the diameter of the slotless machine is larger when compared to slotted axial field machine. Slotted dual gap and slotless single gap machine have similar volumes.

b. **Moment of Inertia:** Radial field machines have has largest moment of inertia due to longer rotor length.An Axial field machine has fixed moment of inertia because of its shorter shaft length. For single air gap machine rotor contains both magnets and rotor back iron which constitutes return path for magnetic flux. For dual air gap , magnet thickness will be larger, but the densities of steel and magnet are similar. This makes moment of inertia of both the single and dual air gap machine constant. The dual air gap slotless machine has lowest moment of inertia, as it does not contain any steel in rotor and density of magnets is slightly lower than that of steel.

c. **Steel weight:** Lowest iron weight is in the single air gap slotless machine that does not have any teeth or tip. Then the next higher weight is of the single gap slotted machine followed by dual air gap slotless and then dual air gap slotted machine.

d. **Copper weight:**Maximum copper weight is required by the single air gap slotless machine.Flux density in air gap is low and there is space in only one stator of the winding.This machine also require a large no. of coils per phase so as to match the back emf constant value. For a given output power single gap slotless machine will experience largest copper loss. Copper weight is lowest in dual air gap slotted machine as the stator teeth help to guide flux across a small air gap, thus making a better utilization of air gap flux density.

2.8 Discussion and Implications

An overview of present scenario in wind power generation sysytem has been narrated in this chapter.The fringing benefit along with the limitations of using PM BLDC generators over the conventional sources of wind power generation like PM synchronous generators and doubly fed induction generators is presented.The use of AFPM BLDC generators proffers high power density, less weight, high torque, less maintenance, low cost over the use of RFPM BLDC and TFPM BLDC generators.Various axial flux topologies of PM BLDC generators are also discussed with their descriptions.

Chapter 3

FEM,Electrostatic and Magnetostatic analysis

The requirement of more and more accuracy during the process of design and analysis of electrical machines fostered the use of numerical models appropriate for computing electric and magnetic field.These numerical methods are essentially based on the determination of the distribution of electric and magnetic field in the structures,based on the solution of Maxwell's equations. The finite element method is a numerical technique that is suitable for the purpose. It allows a solution to be obtained, even with time variable fields and the materials that are non-homogeneous,anisotropic or non linear.Using finite element method, the whole geometry domain is divided in to elementary subdomains, which are called finite elements and the field equations are applied to them individually.

3.1 Steps for finite elements analysis

Finite element analysis is organized in following steps

a. Partition of the domain.

b. Choice of the interpolating functions.

c. Formulation of the system to resolve the field problem.

d. Solution of the problem.

3.2 Electrostatic field Analysis

[24]Electrostatic field analysis determines the electrical field distribution and electric scalar potential (voltage) distribution caused by the charge distribution due to applied electrical field. An electrostatic analysis is assumed to be linear.

Electrostatic boundary condition:

a. Natural boundary-The normal component of the D field at the boundary changes by the amount of surface charge density on the boundary.

b. Neumann boundary-The electric field is tangential to the boundary and flux cannot cross it.

c. Flux tangential (even symmetry)-It defines E to be tangential to the boundary.

d. Flux normal(odd symmetry)-It defines E to be normal to the boundary.

3.3 Magnetic field analysis

Magnetic fields may exist as a result of an electric current, a permanent magnet, or an applied external field.In general, parts/components of an electromagnetic analysis can be categorized by their electric and magnetic properties. Possible electric characteristics are:

a. No current exists in a body.

b. Solid conductor, current, no eddy current effects.

c. Stranded conductor, no eddy current.

d. Solid conductor, eddy current present (harmonic or transient analyses only).

Magnetic characteristics include:

a. Non-magnetic-typically air, Copper, Aluminum.

b. Soft magnetic- typically Iron or Steel.

c. Hard magnetic- typically Samarium cobalt, Alnico,NdFeB.

3.4 Magnetic analysis in ANSYS

The ANSYS program uses Maxwell's equations as the basis for electromagnetic field analysis. The primary unknowns (degrees of freedom) that the finite element solution calculates are magnetic and electric potentials. Other magnetic field quantities such as magnetic field flux density, current density, energy, forces, loss, inductance, and capacitance are derived from these degrees of freedom. Depending on the element type and element option we choose, the degrees of freedom may be scalar magnetic potentials, vector magnetic potentials, or edge flux, as well as non-time integrated and time integrated electric potential.

[24]ANSYS offers several formulations, depending on the type of analysis, the material properties in your analysis, and the overall physics of your analysis. Electromagnetic analysis may be coupled to circuit, heat transfer, mechanical, or fluid dynamics analysis.

3.5 Types of 3D magnetic analysis

a. 3-D Static Magnetic Analysis,analyzing magnetic field caused by DC or permanent magnet using Magnetic Scalar potential formulation

b. 3-D Static Magnetic Analysis,analyzing magnetic field caused by DC or permanent magnet using edge based formulation

c. 3-D Static Magnetic Analysis,analyzing magnetic field caused by low frequency alternating current using an edge based formulation.Permanent magnets are not permitted.The edge based formulation is recommended for most harmonic magnetic applications.

d. 3-D transient magnetic analysis, analyzing magnetic fields caused by arbitrary electric current or external field that varies over time,using an edge based formulation.Permanent magnet effects are also included.

e. 3-D static magnetic analysis,analyzing magnetic fields caused by direct current or permanent magnet using Magnetic vector potential formulation.

f. 3-D harmonic magnetic analysis, analyzing magnetic field caused by low frequency alternating current using a MVP formulation.Permanent Magnets are not permitted.

g. 3-D harmonic magnetic analysis, analyzing magnetic fields caused by arbitrary current or external field that varies over time,using a MVP formulation,Permanent magnet effects can also be included.

3.6 List of elements used in 3-D static scalar Magnetic analysis

Table I depicts the type of solid elements which can be used for magnetic analysis[24]

Table I: List of 3-D Solid Elements

Elements	Shape	DOF	Notes
SOLID5	Brick-eight nodes	UP to 6 at each node	Supported for cyclic symmetry
SOLID96	Brick-eight nodes	MSP	Supported for cyclic symmetry
SOLID 98	Tetrahedral,ten nodes	MSP,displacement, electric potential,temp	Supported for cyclic symmetry

Table II depicts the source elements used for magnetostatic analysis[24]

Table II: List of 3-D Source Elements

Elements	Dimensions	Shape	DOF
SOURCE36	3-D Bar,Arc,Coil	3 nodes	None

3.7 Discussion and Implications

This chapter discuss about the finite element methodology adopted for analyzing the behaviour of the machine in regards to its electrostatic and magnetostatic behaviour.The types of elements which can be used for the different type of analysis. For instance, for current carrying conductors source 36 can be used for magnetostatic analysis.Possible meshing attributes are also presented.

Chapter 4

Model and its Electrostatic Analysis

An AFPM dual rotor model has been designed using [11],the specifications and model of dual rotor axial flux permanent magnet generator are as follows.

a. Rated Power- 250 W

b. Rated Speed(in rpm)-150

c. No. of phases-3

d. No. of Magnet Pole pair-8

e. Rated current -11.20 amps

Main Dimensions

a. Outer rotor diameter-200mm

b. Outer stator diameter-196mm

c. Rotor inner diameter-45mm

d. Stator inner diameter-77mm

e. Air gap-0.75mm

f. Shaft diameter-20mm

g. Machine weight-14.7 Kg

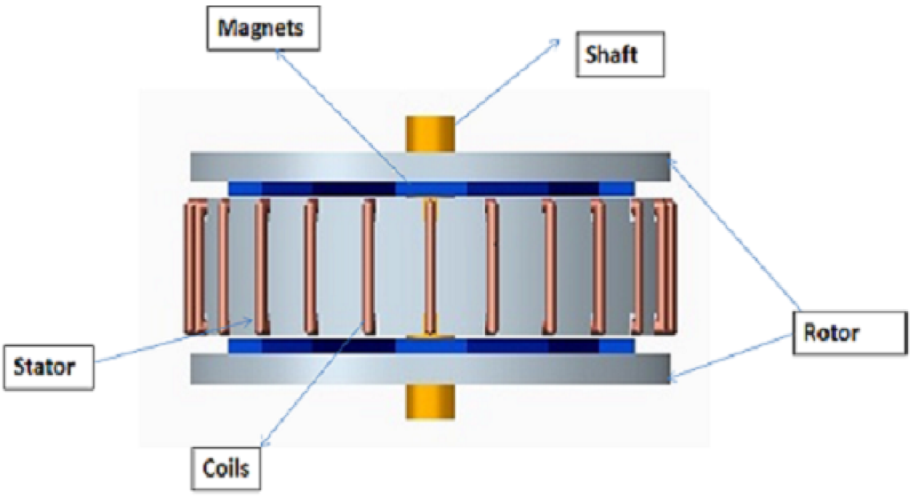

Figure 4.1: Axial Flux BLDC Generator Model

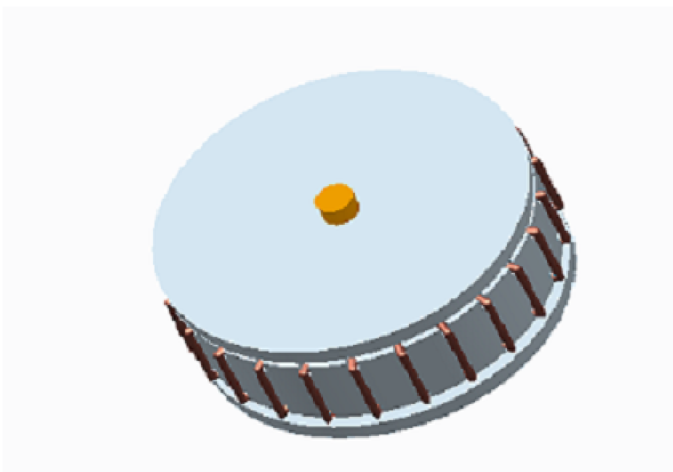

Figure 4.2: Axial Flux BLDC Generator Model

figure 4.1 and 4.2 shows the model which was prepared in a CAD packaged software after calculating parameters for the design and its isometric view respectively. A 3-D static magnetic analysis calculates the magnetic fields produced by one of the following:

- **Permanent magnets**
- **The steady flow of direct electric current (DC)**
- **An applied voltage**
- **An applied external field**

Static magnetic analyses do not consider time-dependent effects such as eddy currents. Figure 4.3 represents the meshed geometry in ANSYS Workbench, coarse tetrahedral meshing was selected.

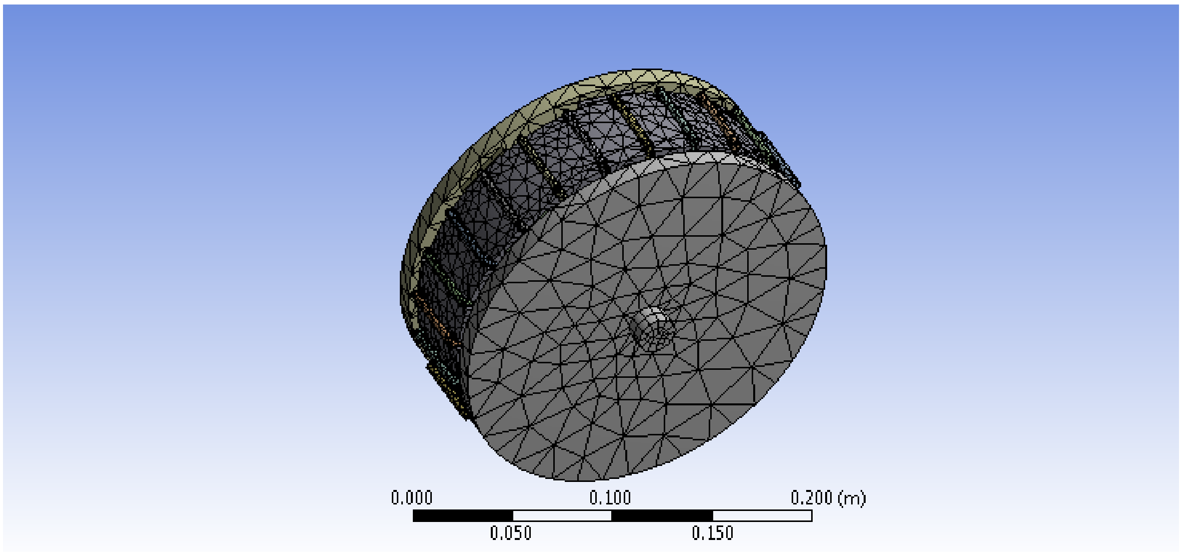

Figure 4.3: Model Meshing in ANSYS Workbench

4.1 Electrical Field Distribution of Generator Model

As the electric field at the end of generator windings is pockety, it can cause the stresses and lead to failures of the generator.Although this can be eliminated by introducing extra insulation in the form of tapes, paper insulation etc. Its virtue cannot be identified quantitatively.So its imperative to conduct and put forward a way to analyse distribution quantitatively.

4.1.1 Electrical field intensity at coil

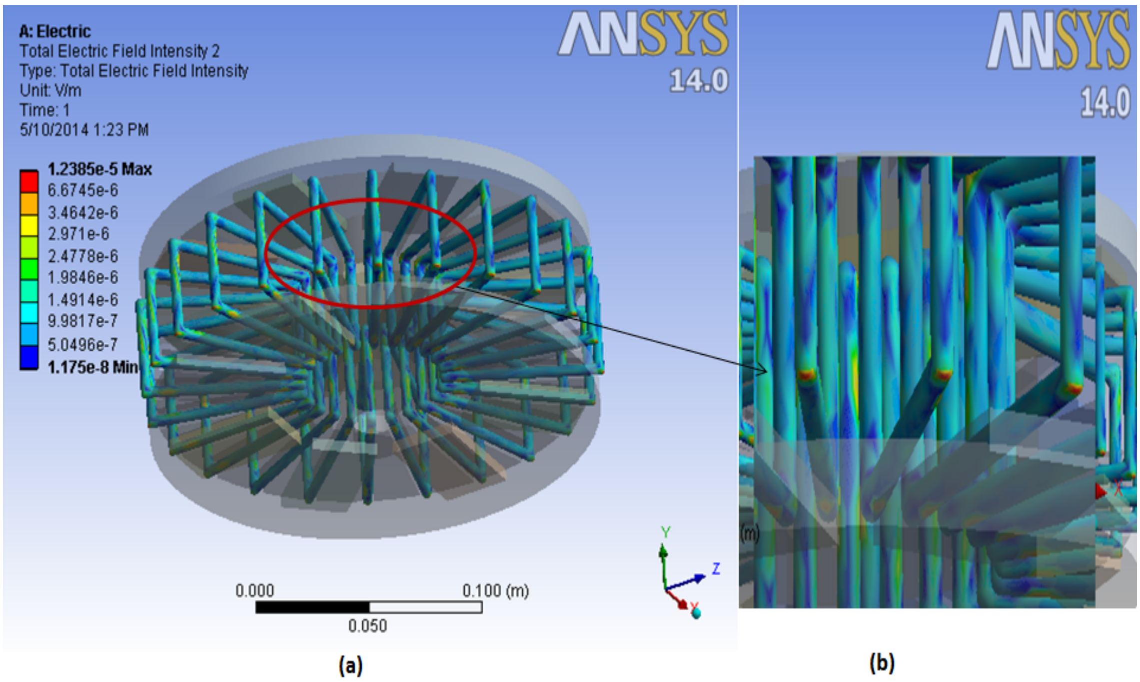

Figure 4.4: (a)Distribution of electric field at coils,(b) Enlarged view

Figure 4.4 shows the electrical field intensity at the coils of the generator which can be seen to be maximum at the corners of the coil part 1.2385e-5 V/m is comparable with that of the calculated one as 1.1387e-5V/m.As per the IEEE paper [20] which was for doing the FEM of high voltage

synchronous motor the airgaps or defects will make the local electrical field distorted, Also the location of maximum electric field is concentrated in the airgaps/defects. This paper also talks about the slot opening electric field which is not constant. The position where the insulation materials tend to produce maximum stresses or breakdown may be highlighted and electric field strength at this position is calculated. It is because of this reason it is suggested that coils near the slot opening may be wrapped by using the insulation tapes with different conductivities to improve the electrical field distribution.

4.1.2 Electrical field intensity at coils and stator body

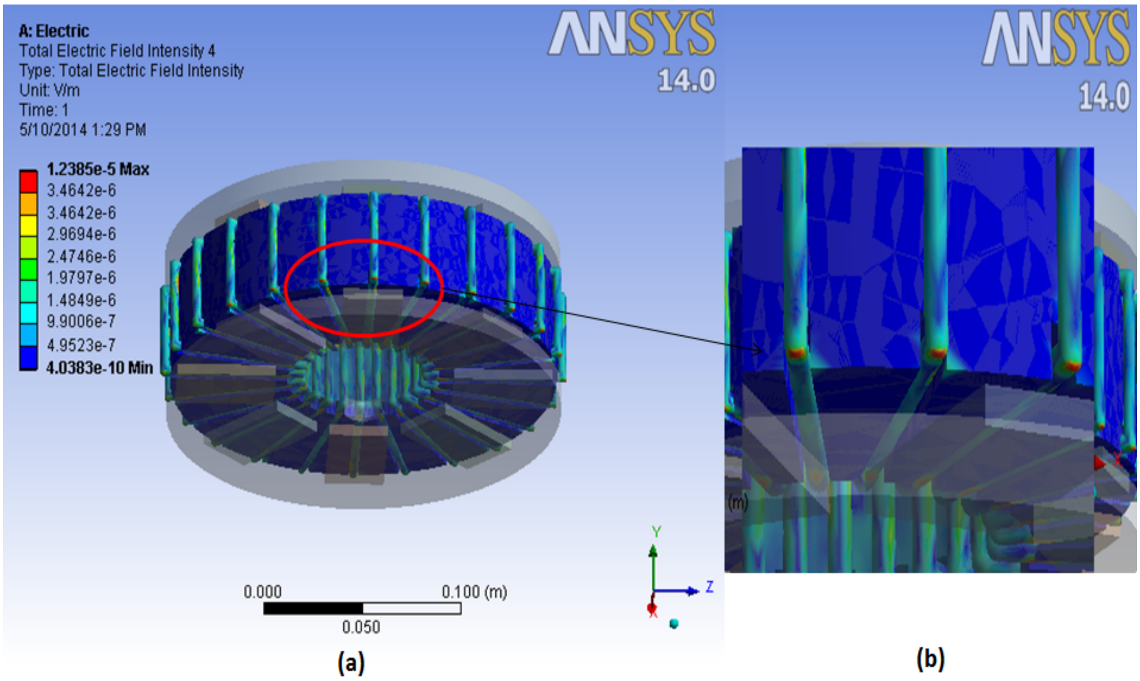

Figure 4.5: (a)Influence of electric field on coils and stator body,(b)Enlarged view

Fig. 4.5 Shows the electrical field intensity at coils and stator The size of air gap greatly affects the distribution of electrical field. The maximum of electric field strength in air gap is shown as the width of air gap is increased. The maximum electrical field strength is reduced as the width of air gap increasing.The shape of air gap also influences the distribution of electrical field. The distribution of electrical field in circular airgap is more uniform than that in flat air gap. If the air gap appears in the insulation material, the insulation strength may be decreased.

4.1.3 Current density at coils

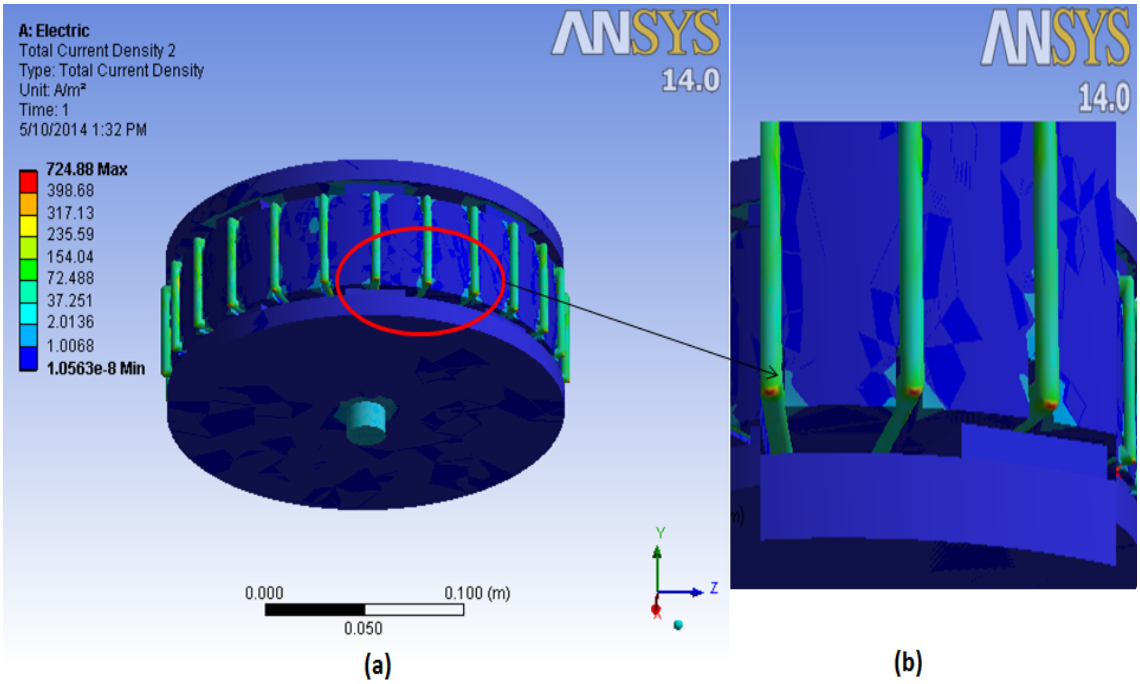

Figure 4.6: (a)Current density perceived at coils,(b)Enlarged view

Fig 4.6 shows the current density at coils which is maximum at the corners of the coils , because the area for the flow of current is minimum at the corners.The calculated value of current density is 4.58e-5 A/mm^2 of overall conductor area.As per the analysis is coming to be 7.24e-5A/mm^2 maximum at the corners.

4.1.4 Current density at stator slot end

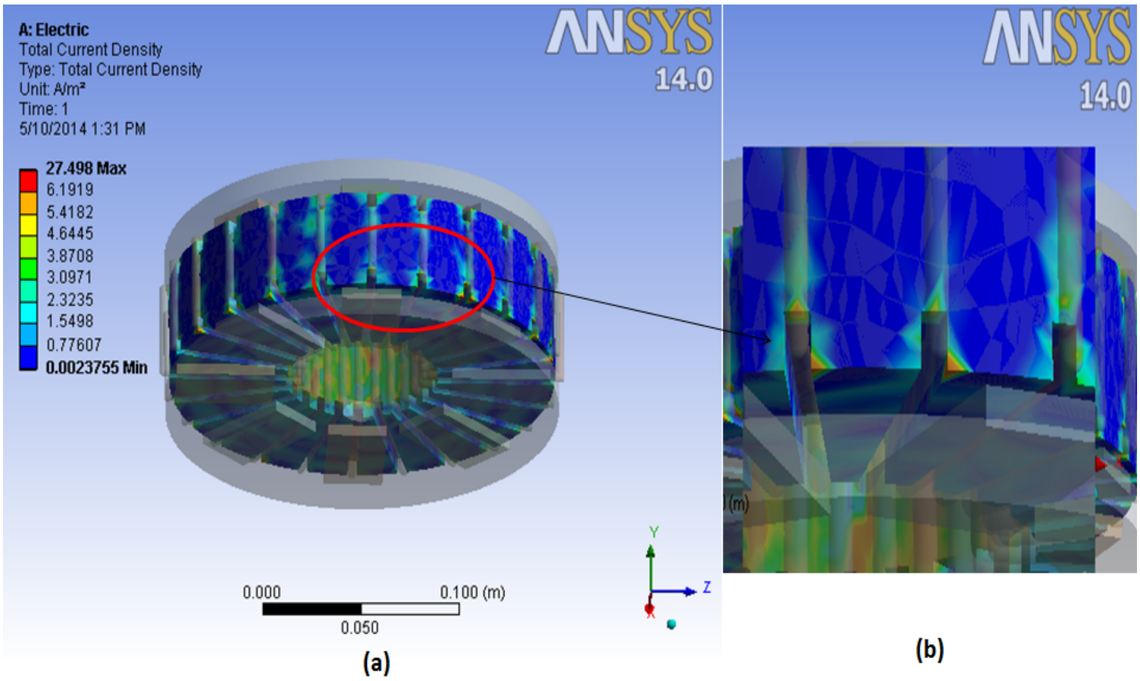

Figure 4.7: (a)Current density perceived at stator teeth,(b)Enlarged view

Fig 4.7 shows the current density at stator slot end which is maximum at the corners of the slot end,this is because of the eddy current flowing through the stator body.The analysed value of current density is 2.67e-5A/mm^2 (max at slot end). The calculated value is 2.41e-5 A/mm^2

4.1.5 Joule heat

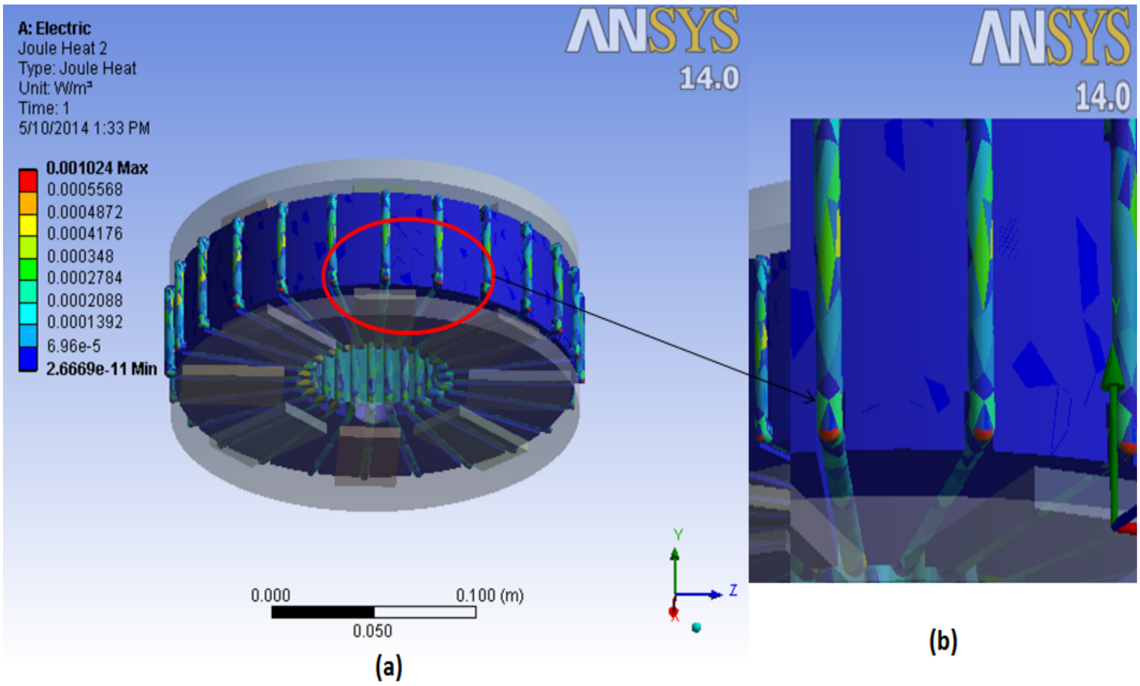

Figure 4.8: (a)Joule heat produced in generator,(b)Enlarged view

Fig 4.8 shows the joule heat generated, as the current density at the corners of the coils is maximum and hence the joule heat generation is also maximum at the same place (at 30 deg C)and the value is coming to be 0.001024 W/m^3 which is comparable with the calculated 0.000925W/m^3

4.2 Matlab Simulink Modelling

A simulation is performed in Matlab Simulink to see the performance of the designed PM BLDC generator which is simulated to be driven by a prime mover and see the driving torque requirement,current values and back emf generation.Fig 4.9 shows the model of the PM BLDC generator which is is driven by a prime mover (PMBLDC motor) where we are controlling the speed through a PI controller. The PM BLDC motor is giving the driving torque to the generator , hence we can see the back emf generated. The gate signal is generated with the help of Hall effect sensors and converting those signals in to the voltage signals.

4.2.1 Model Parameters

PM BLDC Motor-No. of Phases -3
Back emf waveform- Trapezoidal
Mechanical Input-Torque
PM BLDC Generator- No. of Phases-3
Back emf waveform-Trapezoidal
Mechanical input -Speed- 150 rpm
Stator phase resistance- 8.1 ohm
Stator phase inductance-11.23e-3 H
Pole Pair- 8 No.s

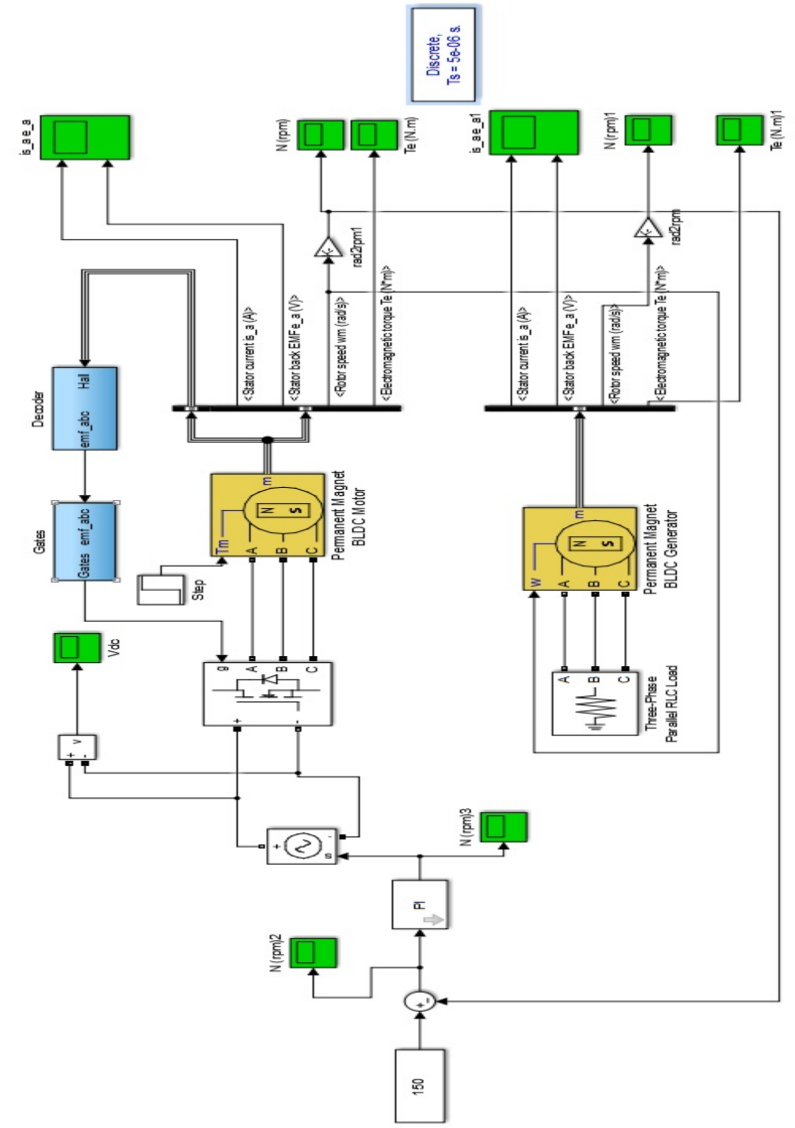

Figure 4.9: PM BLDC Generator Model

4.2.2 Voltage and stator currents at load

Fig 4.10 shows the peak value of current is coming about to be 14 Amp and Voltage is coming about 32V (peak-after connecting resistive load of 150 W).This time as the torque requirement to maintain the generator speed is higher the current drawn by the coils is higher. Also, as the permanent magnet field is getting affected with the load the flat top waveform of the voltages is not truly flat topped.The effect of fringing could be seen.

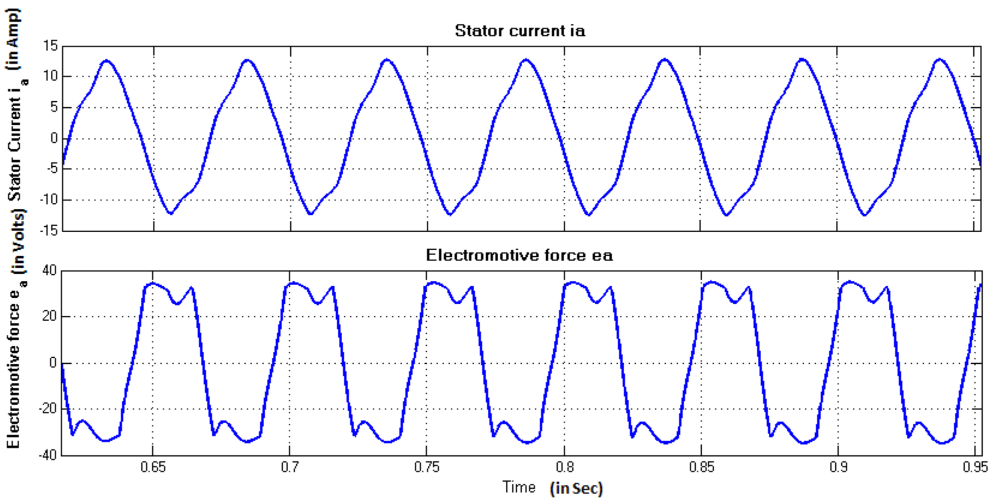

Figure 4.10: Stator current and voltages at load

4.2.3 Torque requirements

Fig 4.11 shows the driving torque required by the generator at load is 10Nm.Which seems to be good as per the data given in [23].As the machine is loaded the torque requirement is 10 Nm to maintain the speed of the generator.As any electrical load connected to the generator contributes to the torque at any rpm,including startup.

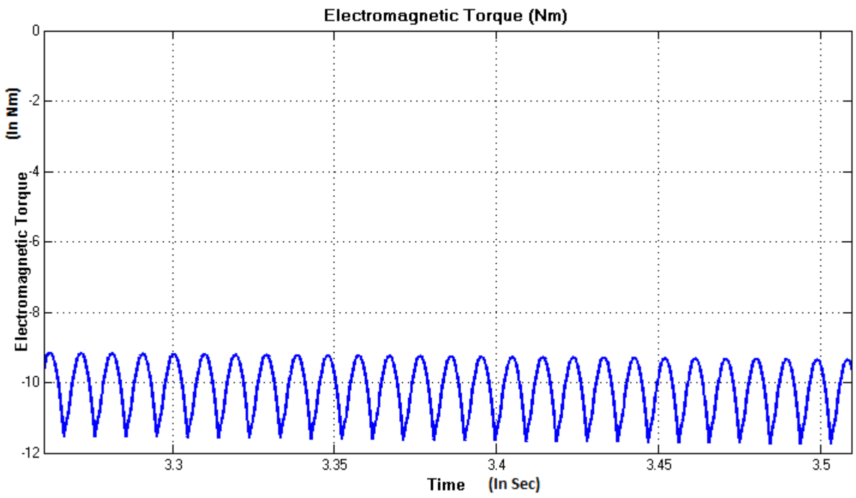

Figure 4.11: Torque at load

4.2.4 Back emf and stator currents at no load

Fig 4.12 shows the peak value of no load current is coming about to be 4 Amp and Back emf is coming about 29V (peak).Due to the use of permanent magnet the voltage ripple have been lessened to generate a flat topped wave. The expected flux density is 1.25 Tesla which would generate an EMF of 24.5V(rms) at a speed of 150 RPM.As the nominal torque of 4 Nm is applied to maintain the speed of the generator, the stator current remains at a low value of 4 Amp.

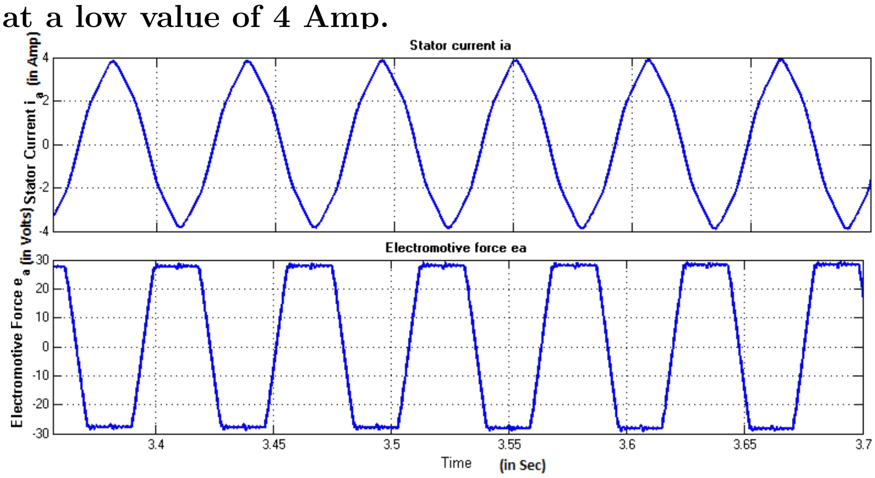

Figure 4.12: Stator current and voltages at no load

4.2.5 Torque requirements at no load

Fig 4.13 Torque at no load is coming around to be 4 Nm.To maintain the required speed of the generator, the low torque value seems to be justifiable with small valuse of no load current (4 Amps).

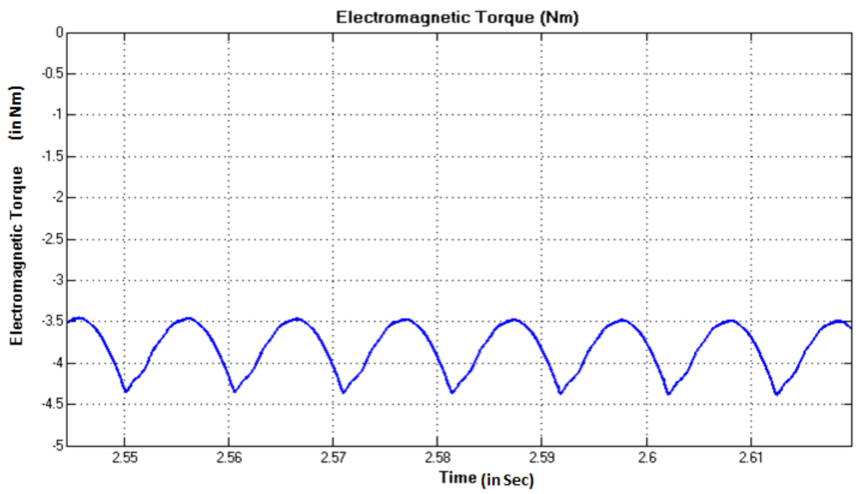

Figure 4.13: Torque at no load

4.3 Discussion and Implications

The chapter describes the analysed electrostatic performance parameters of the dual rotor axial flux PM BLDC generator designed for 250W and 24 V output in FEA software.The electrical field distribution of the machine, current density are found to be maximum at the corners of the coil and stator slot teeth.Also, the model output is validated in Matlab Simulink to the the back emf and torque requirement of the designed PM BLDC generator.

Chapter 5

Model and its Magnetostatic Analysis

A model is designed for single rotor configuration, the specification of single rotor axial flux permanent magnet generator is as follows:

a. **Rated Power- 250 W**

b. **Rated Speed(in rpm)-150**

c. **No. of phases-3**

d. **No. of Magnet Pole -8**

e. **Rated current -11.20 amps**

f. **Machine weight- 11.4 Kg**

Main Dimensions

a. **Outer rotor diameter-200mm**

b. **Outer stator diameter-196mm**

c. **Rotor inner diameter-45mm**

d. Stator inner diameter-77mm

e. Air gap-0.75mm

f. Shaft diameter-20mm

Model was prepared in a Rmxprt software after getting the hand calculated parameters for the design

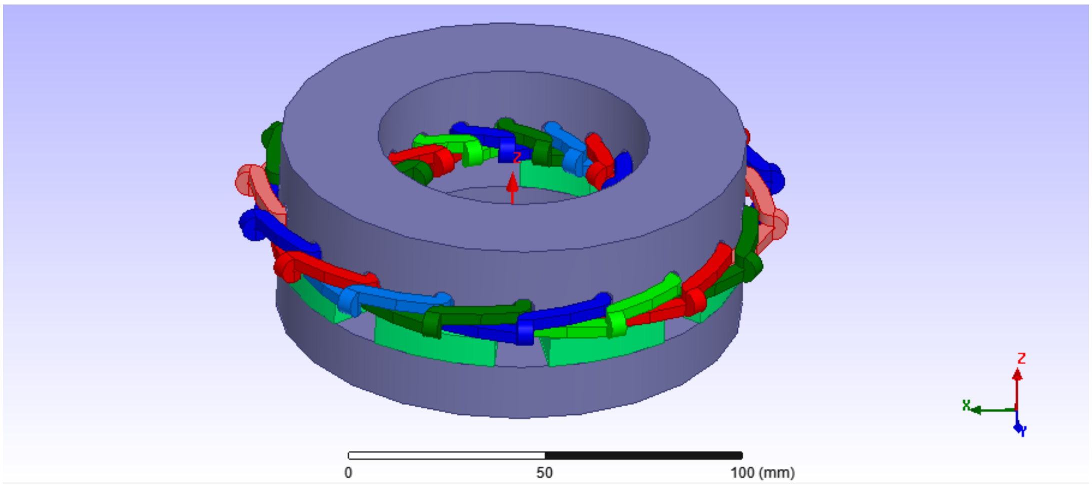

Figure 5.1: Axial Flux PM BLDC Generator Model -Single rotor

A 3-D static magnetic analysis calculates the magnetic fields produced by one of the following:

- Permanent magnets
- The steady flow of direct electric current (DC)
- An applied voltage
- An applied external field

Static magnetic analyses do not consider time-dependent effects such as eddy currents.

5.1 Flux Distribution of Generator Model

As the magnetic field at generator due to the effect of PM is established, it is necessary to see its distribution at generator different parts, to see any leakages and maximum flux density value.So while designing a machine consisting of PM its important to perform this analysis because it can lead to saturation of core.

5.1.1 Flux density distribution

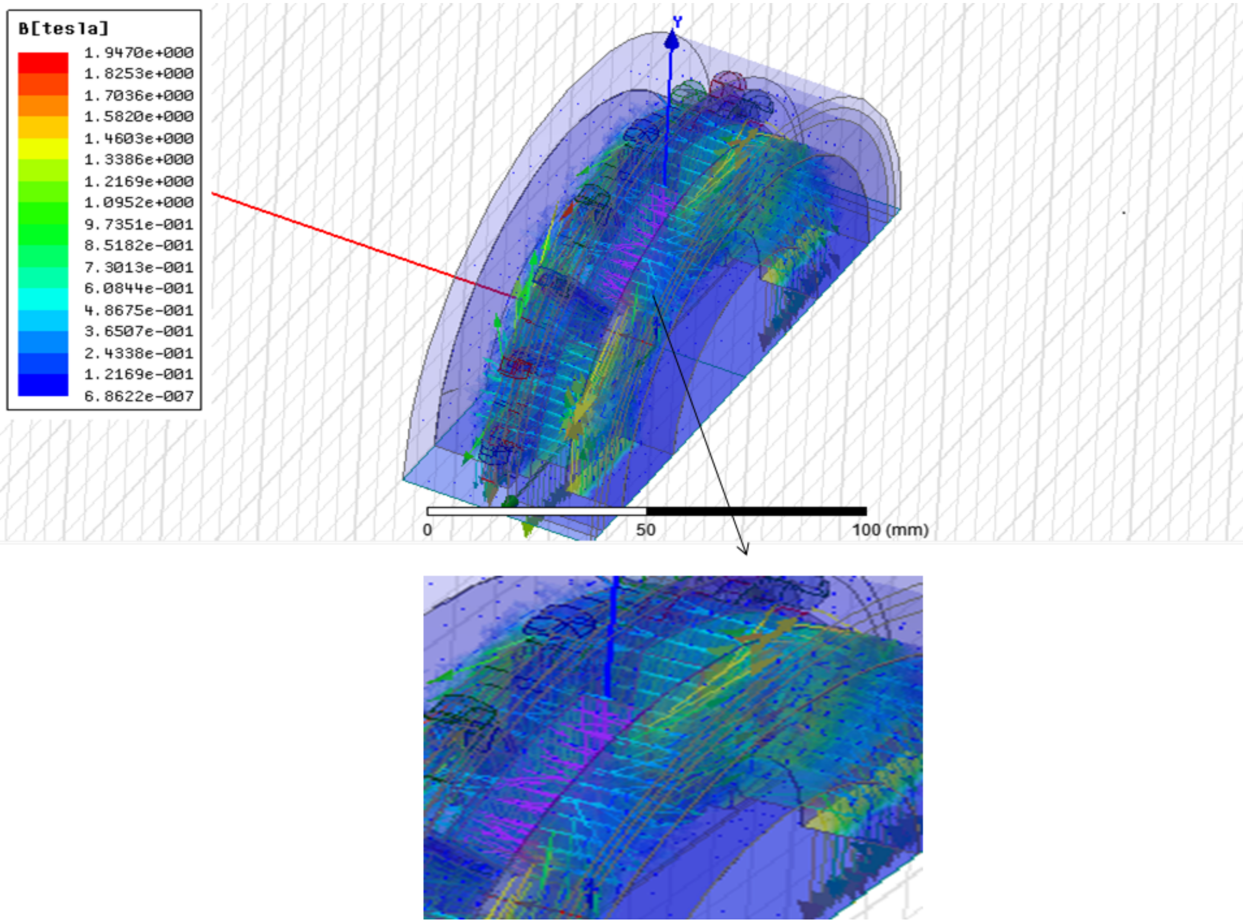

Figure 5.2: Flux density distribution at generator

Figure 5.2 shows the magnetic flux density at the generator which can be seen to be maximum at the corners of the coil part 1.94 Tesla and seems to be reasonable as the Br of permanent magnet NdFeB is taken as 1.25 Tesla and this lies under the limits [25]. Also the location of maximum manetic field is concentrated in the area of magnet edges.

5.1.2 Flux Path

Fig. 5.3 Shows the direction of flux vectors As the generator is an axial flux machine and the configuration of the magnet is N-S the direction of the flux seems to be expected as it has to be theoritically.

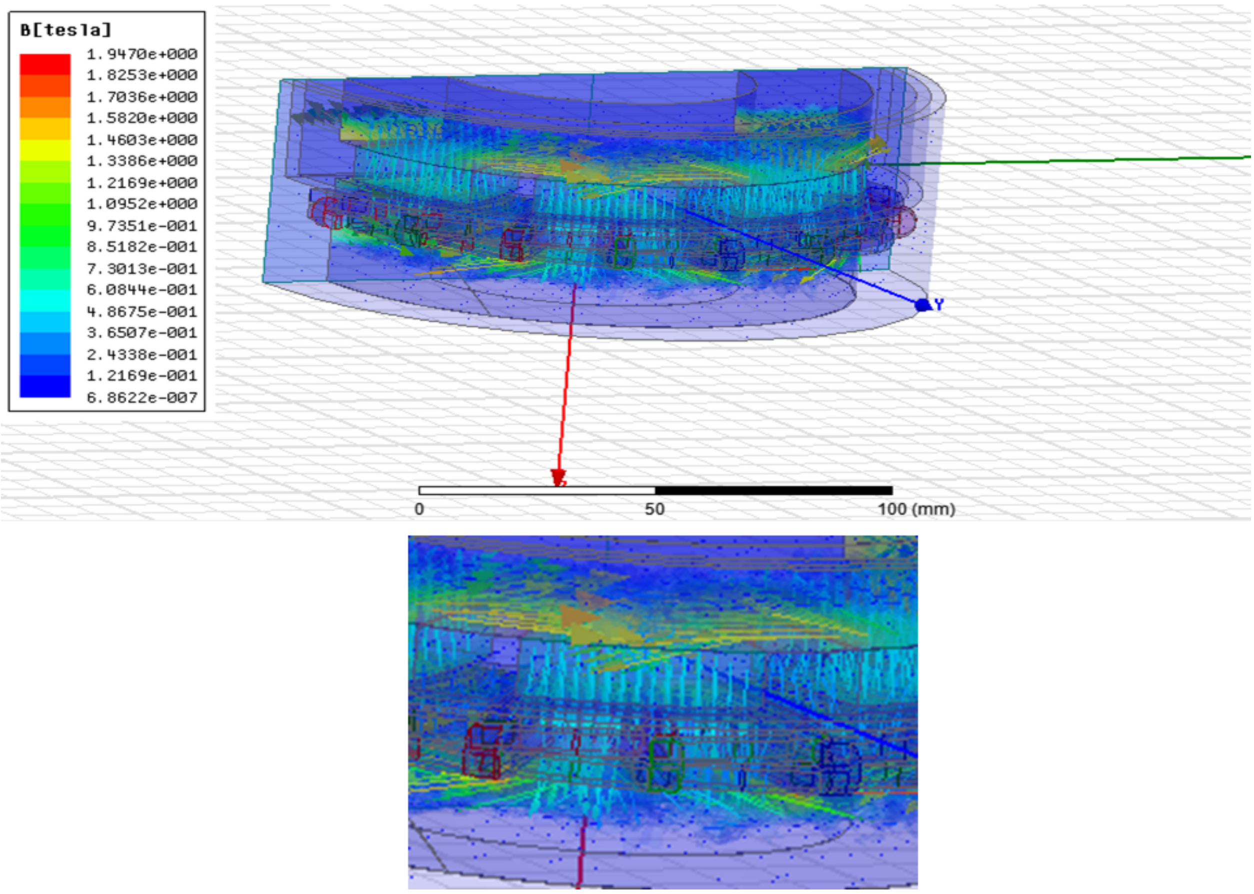

Figure 5.3: Direction of Flux Flow

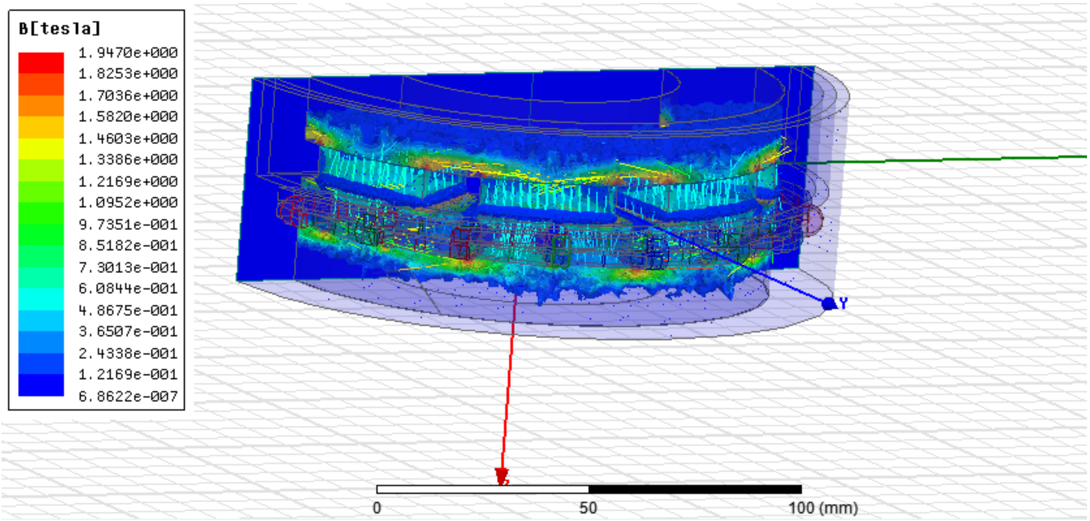

Figure 5.4: Direction of Flux Flow -another view

5.1.3 Current density

Fig 5.4 shows the current density at coils 1.40e-6 A/mm^2 , and at the corners of the stator slot seems to be maximum as 2.5e-6 A/mm^2.The vectors which are in front of the slots teeth shows the efect of eddy currents.

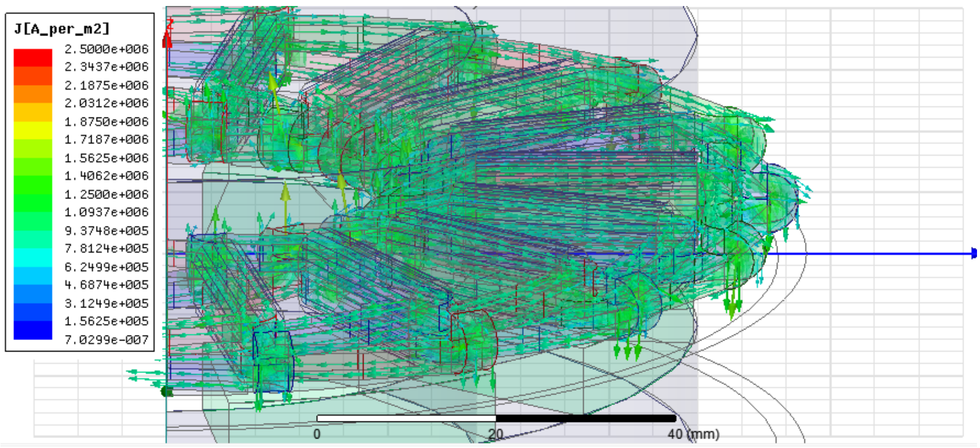

Figure 5.5: Current Density at coils

5.2 Result Validation

The table depicts the value as mentioned in[25] and the values achieved in analysis.

Table I: Result comparison

Sr. No.	Magnetic path section	Flux density (T)	Obtained Flux density (T)
1	Rotor back iron	$1.09 - 1.24$	$1.095 - 1.21$
2	Stator tooth tips	$0.78 - 1.09$	$0.73 - 0.85$
3	Stator teeth	$1.71 - 1.94$	$1.70 - 1.94$
4	Stator yoke section	$1.24 - 1.55$	$1.21 - 1.46$

5.3 Design-Dimensions and Parameters of 5 kW model

A design for a dual rotor model has been carried out, the specifications of double rotor axial flux permanent magnet generator for 5 kW rating is as follows

a. **Rated Power- 5000 W**

b. **Rated Speed(in rpm)-100**

c. **No. of phases-3**

d. **No. of Magnet Pole pair - 36**

e. **Rated current -36.5 amps**

Main Dimensions

a. **Outer rotor diameter-417mm**

b. **Outer stator diameter-410mm**

c. **Rotor inner diameter-85mm**

d. **Stator inner diameter-124mm**

e. **Air gap-0.75mm**

f. **Shaft diameter-46mm**

5.4 Discussion and Implications

The magnetostatic analysis of the dual rotor generator were tried in ANSYS software, but because of some limitation with the software to use it for axial flux PM BLDC generators it could not be performed.Also the same model was analysed in Maxwell-Rmxprt, but because of some inconsistencies found with the analysis, the analysis on single rotor axial flux PMBLDC generator has been done. The results were achieved for both electrostatic and magnetostatic behaviour for the model of same rating.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The analysis of various attributes of the proposed design and models are performed and the results are presented.There were some impediments in doing the magnetostatic analysis of dual rotor model.Also,design parameters for 5 kW model has been calculated.

For a dual rotor axial flux PM BLDC generator,electrical analysis was done in ANSYS workbench showing the results for electrical field intensity at stator body and coils, along with the current density.The result deduced for electrical field intensity at the coils of the generator which can be seen to be maximum at the corners of the coil part 1.2385e-5 V/m ,and that of the calculated one as 1.1387e-5 V/m. As the electric field stress developed is found to be maximum at the corners of the coils and stator teeth, to improve the electrical field distribution one may consider this at manufacturing stage for increasing the life span of the designed generator.

Along with above the results are acquired for current density and Joule heat generation as 2.7e-6A/mm^2 (max at slot end) and 0.00102 W/m^3 respectively.These values seems to be legitimate as calculated.

Matlab Simulink model was prepared for the generator showing the validity of the designed model, generating no load voltage of 29 V (peak),which seems to comensurate the expected 24 V (rms) designed level.

Because of certain limitation of doing 2D magnetostatic analysis of axial flux PM machine in ANSYS and also to compare the dual rotor model with single rotor electrostatic and magnetostatic analysis was done for the designed single rotor axial flux PM BLDC generator,Flux density was evaluated and is with in acceptable limits as per the limits mentioned in [25] Also,it can be seen throught the analysis of both the models that current density of single rotor confiuration is lower than that of the double rotor model because the copper used here is more as compared to dual rotor model, and weight of the single rotor (11.4 Kg) is less as compared to the double rotor(14.7 Kg) generator topology, as the rotor weight of single rotor model is less .This conclusion goes in line with the work presented in paper[11].

6.2 Future Work

There is a scope to analyse a model for 5 kW (ratings and dimensions mentioned in chapter 4). Also,other configurations like dual stator, slotless structure may also be investigated.In addition, there are possibilities of simulating the designed machine in simplorer Maxwell and see the actual performances.

6.3 Limitations

As the part of project work 2D analysis has to be performed, but for axial machines it can not be done as this machine has axial symmetry. Also, these generators can not be designed for higher kW ratings (limited to only

tens of kW) because at higher rating the PMs will loose their magnetism and also there are chances of magnet to fly apart for higher dimensions.

References

[1] L. Somerlund and J-T. Eriksson,J. Salonen, H. Vihriala and R. Perala "A Permanent-Magnet Generator for Wind Power Applications"IEEE transactions on Magnetics,Vol. 32, No.4, July 2006.

[2] L. Somerlund, A. Koski, H. Vihiriala, J-T. Eriksson and R. Perala"Design of an axial flux permanent magnet wind power generator"

[3] Jianyi Chen, Chemmangot V. Nayar, and Longya Xu"Design and Finite-Element Analysis of an Outer-Rotor Permanent-Magnet Generator for Directly Coupled Wind Turbines"IEEE transactions on Magnetics,Vol. 36, No.5, September 2000.

[4] Yicheng Chen, Azeem Khan" PM Wind Generator Comparison of Different Topologies"IEEE transactions on industry applications,Vol. 41, No.6, November/December2005.

[5] Guoliang Yang and Huiguang Li"Design and Analysis of a Newly Brushless DC Wind Generator"

[6] B.J Chalmers W Wu, E Spooner "An axial flux permanent magnet generator for a gearless wind energy system "

[7] J.R. Bumby, N. Stannard, J. Dominy and N Mc Leod"A Permanent magnet generator for small scale wind and water turbines "Pro-

ceedings of the 2008 International Conference on Electrical Machines,paper ID 733.

[8] David G. Dorrell"Design requirements for brushless permanent magnet generators for use in small renewable energy systems"

[9] N. J. Stannard, J R Bumby"Energy yield and cost analysis of small scale wind turbines "

[10] Ronghai Qu, Metin Aydin, Thomas A Lipo"Performance comparison of dual rotor radial flux and axial flux permanent magnet bldc machines "IEEE transaction,0-7803-7817-2/03,2003

[11] Kartik Sitapati and R. Krishnan,"Performance comparisons of Radial and Axial field permanent- magnet, brushless machines"IEEE transactions on industry applications,Vol. 37, No.5, September/October2001.

[12] V.V Vadher, J. G. Kettleborough,I R smith"Generalized model of brushless DC Generator"IEEE transactions on Aerospace and Electronic Systems, Vol. 25, No. 4 ,JULY 1989

[13] F. Caricchi, F. Crescimbini, E Santini, C Santucci-"FEM Evaluation of performance of axial flux slotted permanent magnet machines"IEEE transactions,0-7803-4943-1/98,1998.

[14] Brushless permanent magnet motor design by Dr. Duane Hanselman

[15] Brushless Permanent Magnet and reluctance motor drives By T J E Miller

[16] Wind and water by John Tabak

[17] Wind and Solar power systems by Mukund R Patel

[18] Wind power integration by Brendan Fox, Damian Flynn, Leslie Bryans, Nick Jenkins, David Milborrow, Mark OMalley, Richard Watson and Olimpo Anaya-Lara

[19] Permanent Magnet Brushless and synchronous motor drives by R.Krishnan.

[20] Jun Zhang,Shuhong Wang,Jie Qiu,Haibo Li,Qiu hui Zhang,Jian Guo Zhu,Youguang Guo"Finite Element Analysis and Evaluation of Stator Insulation in High Voltage Synchronous Motor"IEEE Transactions on Magnetics, Vol. 48, No. 2, February 2012

[21] www.diva-portal.org/smash/get/diva2:470664/FULLTEXT01.pdf

[22] www.googleimages.com/Axial-flux-permanent-magnet-brushless-dc-generator.png

[23] "Axial Flux Permanent Magnet Brushless Machines"written by Jacek F. Gieras,Rong-Jie Wang,Marten J. Kamper

[24] www.google.com/Ansys Maxwell 3D

[25] Electronically commutated motors by Duan C. Hanselman,Dan Jones,Douglas W. Jones,William H. Yeadon.

Appendix A

Equations for Design Calculations

The design equations are as follows

a. $\omega_m = (\pi/30)S_r$ ....**Mechanical speed rad/s**

b. $\omega_e = (N_m/2)\omega_m$ .... **Electrical speed rad/s**

c. $T = 745P_{hp}/\omega_m$ ....**Torque from horsepower rad/s**

d. $N_s = N_{sp}N_{ph}$ .... **No. Of Slots**

e. $N_{spp} = N_{sp}/N_m$ .... **No.of slots per pole per phase**

f. $N_{sm} = N_{spp}N_{ph}$ ....**No. of slots per pole**

g. $\alpha_{cp} = int(N_{spp})/N_{spp}$ .... **Coil pole fraction**

h. $\theta_p = 2\pi/N_m$ .... **Angular Pole pitch**

i. $\theta_s = 2\pi/N_s$ .... **Angular Slot pitch**

j. $\theta_{se} = \pi/N_{sm}$ .... **Slot pitch,electrical radian**

k. $\tau_{pi} = R_i\theta_p$ ....**Inside pole pitch**

l. $\tau_{po} = R_o\theta_p$ ....**Outside pole pitch**

m. $\tau_{ci} = \alpha_{cp}\tau_{pi}$ .... **Inside coil pitch**

n. $\tau_{co} = \alpha_{cp}\tau_{po}$ .... **Outside coil pitch**

o. $\tau_{si} = R_i\theta_s$ .... **Inside slot pitch**

p. $k_d = \frac{sin(N_{spp}\theta_{se}/2)}{N_{spp}sin(\theta_{se}/2)}$ .... **Distribution factor**

q. $k_p = \alpha_{cp}$ .... **Pitch factor**

r. $k_s = 1 - \theta_{se}/(2\pi)$ .... **Skew factor**

s. $\alpha_m = 1 - \frac{N_m\tau_f}{\pi(R_o - R_i)}$ .... **Magnet fraction**

t. $C_\phi = \frac{2\alpha_m}{1+\alpha_m}$ .... **Flux concentration**

u. $P_c = l_m/(2gC_\phi)$ .... **permeance coefficient**

v. $k_{ml} = 1 + \frac{2l_mN_m}{\pi^2\mu_r\alpha_m(R_i+R_o)}l_n(1+\pi\frac{g}{\tau_f})$ .... **Magntet leakage fac**

w. $g_c = 2g + l_m/\mu_r$ **Effective air gap for carter coefficient**

x. $k_c = (1 - \frac{1}{\frac{\tau_s i}{\omega_s}(5\frac{g_c}{\omega_s}+1)})^{-1}$ .... **Carter coefficient**

y. $A_g = \frac{\pi(1+\alpha_m)}{2N_m}(R_o^2 - R_i^2)$ .... **Air gap area**

z. $B_g = \frac{C_{phi}}{1+\mu_R k_c k_{ml}/P_c}B_r$ .... **Air gap flux density**

a. $\phi_g = B_gA_g$ .... **Air gap flux**

b. $\omega_{bi} = \frac{B_g\tau_{po}}{2B_{max}k_{st}}B_r$ .... **Back iron width**

c. $\omega_{tbi} = \frac{B_g\tau_{pi}}{N_{sm}B_{max}k_{st}}$ .... **Tooth width at inner radius**

d. $\omega_{sb} = \tau_{si} - \omega_{tbi}$ .... **Slot bottom width**

e. $\alpha_{si} = \frac{\omega_{sb}}{\omega_{tbi}+\omega_{sb}}$ .... **slot aspect ratio at inner radius**

f. $d_1 + d_2 = \alpha_{sd}\omega_{tbi}$ ..... **shoe depth split between**d_1 **and**d_2

g. $n_s = int(\frac{E_{max}}{N_m k_d k_p k_s B_g N_{spp}(R_o^2 - R_i^2)\omega_m})$ .... **no. of turns per slot**

h. $e_{max} = N_m k_d k_p k_s B_g N_{spp}(R_o^2 - R_i^2)\omega_m$ .... **Peak back emf**

i. $I_s = \frac{T}{N_m k_d k_p k_s B_g N_{spp}(R_o^2 - R_i^2)}$ .... **Peak slot current**

j. $I_p h = \frac{I_s}{N_{ph} n_s}$ .... **phase current**

k. $d_3 = \frac{I_s}{k_{cp}\omega_{sb}J_{max}}$ .... **conductor slot depth**

l. $A_s = \omega_{sb} d_3$ .... **conductor area**

m. $J_c = \frac{I_s}{k_{cp}A_s}$ ..... **Peak conductor current density**

n. $d_s = d_1 + d_2 + d_3$ .... **Total slot depth**

o. $L = d_s + \omega_{bi}$ .... **Stator axial length**

p. $B_{smax} = \frac{\mu_o I_s}{\omega_s}$ .... **Peak slot flux density**

q. $R_s = \frac{\rho n_s^2 (R_o - R_i)}{k_c p A_s}$ .... **Slot resistance**

r. $R_e = \frac{\rho n_s^2 \pi(\tau_{co} + \tau_{ci})}{4 k_{cp} A_s}$ .... **End turn resistance**

s. $R_{ph} = 2N_{sp}(R_s + R_e)$ .... **Phase resistance**

t. $L_g = \frac{n_s^2 \mu_R \mu_o \theta_c (R_o^2 - R_i^2) k_d}{4(l_m + 2\mu_R k_c g)}$ .... **Air gap inductance**

u. $L_s = n_s^2[\frac{\mu_0 d_3}{3\omega_{sb}} + \frac{\mu_0 d_2}{(\omega_s + \omega_{sb})/2} + \frac{\mu_0 d_1}{\omega_s}](R_0 - R_i)$ .. **Slot leakage inductance**

v. $L_e = \frac{n_s^2 \mu_o \tau_{co}}{16} l_n(\frac{\tau_{co}\pi}{4A_s}) + \frac{n_s^2 \mu_o \tau_{ci}}{16} l_n(\frac{\tau_{ci}\pi}{4A_s})$ ...... **End turn inductance**

w. $L_{ph} = 2N_{sp}(L_g + L_s + L_e)$ .... **Phase inductance**

x. $V_{st} = 2k_{st}[\pi(R_o^2 - R_i^2)(\omega_{bi} + d_s) - N_s A_s (R_o - R_i)]$ ... **stator steel volume**

y. $P_r = N_{ph} I_{ph}^2 R_{ph}$ **4** .... **ohmic power loss**

z. $P_{cl} = \rho_{bi} V_{st} \Gamma(B_{max}, f_e)$ .... **core loss**