SEGMENTED PERMANENT MAGNET SYNCHRONOUS MACHINES FOR WIND ENERGY CONVERSION SYSTEM

by

Wenying Jiang

A report submitted in partial fulfillment of the requirements for the degree of

Master of Science
(Electrical and Computer Engineering)

at the
UNIVERSITY OF WISCONSIN-MADISON

2010
SEGMENTED PERMANENT MAGNET
SYNCHRONOUS MACHINES
FOR
WIND ENERGY CONVERSION SYSTEM

by

Wenying Jiang

Under the supervision of Professor Thomas M. Jahns
at the University of Wisconsin-Madison

Approved by: _______________________
Professor Thomas M. Jahns
University of Wisconsin-Madison

Date: _______________________

Abstract

Direct drive generator is favorable in wind energy conversion system (WECS), as it eliminates the vibration, noise, and losses from the gear used in geared-drive wind generators. However, the direct drive wind generator suffers from the large size and heavy weight problem. The purpose of this research project is to design a generator with improved performance for the direct drive WECS.

A new concept segmented permanent magnet (PM) machine was introduced, whose proposed features show that it is very suitable for the application of direct drive wind generator. The analytical models for both single-airgap and double-airgap segmented PM machines were built for initial design. Then finite element models were created to further investigate the characteristics and performance of this type of machine.

To optimize the segmented PM machine, a finite element analysis based machine design optimization program was developed. This program use differential evolution, a powerful optimization algorithm, to provide outer shell, leading to fast convergence. And the adoption of FE analysis guarantees the accuracy of results. Compared to initial designs, the optimized segmented PM machine’s torque density has been significantly improved, along with reduction in total active material cost.
Acknowledgements

Financial support for this work was provided by Vestas Wind Systems. I am very thankful for the academic advice and counseling provided by Professor Thomas M. Jahns, and Professor Thomas A. Lipo. Technical support on the finite element analysis package JMag is provided by Yusaku Suzuki from JSOL Corp. And I am grateful for his help and his company's generous donation of JMag licenses. I sincerely appreciate the cooperation from my partners Patel Reddy and Li Zhu. Additional support and inspiration for this work stemmed from engineers in Vestas. Finally, I would like to thank my family and friends for their continuous support throughout my educational career.
Table of Contents

Abstract ................................................................................................................................. i
Acknowledgements ............................................................................................................. ii
Table of Contents .............................................................................................................. iii
List of Figures .................................................................................................................... vi
List of Tables ...................................................................................................................... ix
Nomenclature ..................................................................................................................... x

Chapter 1: Introduction .................................................................................................... 1

1.1 Background [1-7] ........................................................................................................ 1
1.2 Project overview ......................................................................................................... 2
1.3 Document organization ............................................................................................ 3

Chapter 2: State of the Art Review ................................................................................. 5

2.1 Direct-drive and geared-drive wind generator ......................................................... 5
2.2 Generator topologies and comparisons for direct drive wind generator ............... 8
  2.2.1 Asynchronous machines .................................................................................... 8
  2.2.2 Electrically excited synchronous generator (EESG) ........................................ 9
  2.2.3 Permanent magnet synchronous generator (PMSG) ..................................... 10
2.3 Optimization on machine design ........................................................................... 11
  2.3.1 Analytical model based vs. FE model based optimization .............................. 11
  2.3.2 Comparison of optimization algorithms ......................................................... 12
  2.3.3 Multi-physics machine design optimization .................................................... 13
Chapter 3: Segmented PM Machines ...................................................... 15

3.1 Segmented PM machine concept .................................................. 15
3.2 Segmented PM machine with double-airgap .................................. 16

Chapter 4: Analytical Designs for Segmented PM Machines ................. 20

4.1 Specifications and design assumptions ........................................... 20
4.2 Single rotor – single stator (SRSS) configuration .................................. 21
4.3 Double-airgap configurations ....................................................... 28
4.4 Comparisons .............................................................................. 30

Chapter 5: Finite Element Models for Segmented PM Machines .......... 32

5.1 Finite element analysis condition setup .......................................... 32
5.2 Comparison of analytical and FE model for SRSS machine .......... 36
5.3 Segmentation of segmented PM machine ........................................ 41
5.4 Comparison of SRSS topologies ................................................... 44
5.5 Double-airgap configurations ....................................................... 48

Chapter 6: Machine Design Optimization (Electromagnetic) ............... 53

6.1 Differential evolution (DE) algorithm ............................................. 53
6.2 Optimization technique ................................................................ 55
6.3 Objective function – Case definitions ............................................ 56
6.4 Nine-phase segmented configurations: single air-gap and double air-gap ...... 57
6.5 Definition of parameters and constraints ........................................ 62
6.6 Optimization results .................................................................... 66
6.6.1 Optimized cases ...................................................................... 66
List of Figures

Figure 2.1 - 1 Variable speed wind turbine system based on DFIG [3] ................................. 6
Figure 2.1 - 2 Direct drive wind turbine system based on voltage source inverter [3] .............. 7
Figure 2.2.1 - 1 Fixed speed wind turbine system base on induction generator [3] ............... 8
Figure 2.2.2 - 1 Illustration of the 10 m airgap diameter wind generator – Enercon E112 [9].... 10
Figure 2.3.3 - 1 Flow chart of electromagnetic-thermo-mechanical integrated design [23] ...... 14
Figure 3.1 - 1 Concept of single rotor single stator (SRSS) segmented PM machine .............. 15
Figure 3.1 - 2 Zoom-in plot of one segment in SRSS .......................................................... 16
Figure 3.2 - 1 Segmentation concept of double-airgap segmented PM machine ................. 17
Figure 3.2 - 2 Zoom-in plot of one segment in DRSS ......................................................... 18
Figure 3.2 - 3 Zoom-in plot of one segment in SRDS ......................................................... 19
Figure 5.1 - 1 Analysis control setup .................................................................................. 33
Figure 5.1 - 2 Iron loss calculation setup ............................................................................ 34
Figure 5.1 - 3 Circuit layout for rated load analysis ............................................................ 35
Figure 5.1 - 4 Sinusoidal current excitation setup ............................................................... 35
Figure 5.1 - 5 Mesh generation setup .................................................................................. 36
Figure 5.2 - 1 Cross section of baseline SRSS machine (base unit) ..................................... 37
Figure 5.2 - 2 Flux linkage of SRSS machine (base unit) ..................................................... 38
Figure 5.2 - 3 Cogging torque of SRSS machine (base unit) ................................................ 39
Figure 5.2 - 4 Torque waveform of SRSS machine (base unit) ............................................ 39
Figure 5.3 - 1 Cross section of three-phase SRSS machine ................................................. 42
Figure 5.3 - 2 Cogging torque of three-phase SRSS machine ............................................. 42
Figure 5.3 - 3 Torque waveform of three-phase SRSS machine ......................................... 43
Figure 5.4 - 1 Cross section of open slot SRSS machine .................................................... 45
Figure 5.4 - 2 Cross section of inset SRSS machine with 5 mm airgap ............................... 46
Figure 5.4 - 3 Cross section of inset SRSS machine with 10 mm airgap .......................... 47
Figure 5.5 - 1 Cross section of DRSS machine .......................................................... 48
Figure 5.5 - 2 Cross section of SRDS machine ......................................................... 48
Figure 5.5 - 3 Flux density contour of DRSS ............................................................. 49
Figure 5.5 - 4 Flux density contour of SRDS ............................................................. 49
Figure 5.5 - 5 Cogging torque of DRSS ................................................................. 50
Figure 5.5 - 6 Cogging torque of SRDS ................................................................. 50
Figure 5.5 - 7 Torque waveform of DRSS ............................................................... 50
Figure 5.5 - 8 Torque waveform of SRDS ............................................................... 50
Figure 6.1 - 1 Flow chart of DE’s generate and test loop [20] .................................. 54
Figure 6.2 - 1 Machine optimization routine ......................................................... 55
Figure 6.4 - 1 Machine cross sections for three types of segmented PM machines ........ 58
Figure 6.4 - 2 Winding configuration for nine-phase segmented PM machine .......... 60
Figure 6.4 - 3 Mechanical structure assumptions for the three types of segmented PM machines ................................................................. 61
Figure 6.5 - 1 Five adjustable parameters for segmented PM machine .................. 62
Figure 6.5 - 2 TD, TPD vs. No. of pole pairs ......................................................... 63
Figure 6.5 - 3 TD, TPD vs. magnet span ratio ......................................................... 63
Figure 6.5 - 4 TD, TPD vs. magnet thickness to airgap thickness ratio .................... 64
Figure 6.5 - 5 TD, TPD vs. stator yoke thickness to tooth width ratio ...................... 64
Figure 6.5 - 6 TD, TPD vs. rotor yoke thickness to pole pitch ratio ......................... 64
Figure 6.6.3 - 1 JMag and MagNet results comparison ......................................... 68
Figure 6.6.4 - 1 Design cross sections for Case 1 .................................................... 70
Figure 6.6.4 - 2 Design cross sections for Case 2 .................................................... 71
Figure 6.6.4 - 3 Design cross sections for Case 3 .................................................... 72
Figure 6.6.4 - 4 Design cross sections for TD only case ....................................... 73
Figure 6.6.4 - 5 Design cross sections for TPD only case ..................................... 74
Figure 6.6.5 - 1 Active mass trend with varying weighting factors in objective function .......... 75
Figure 6.6.5 - 2 Magnet mass trend with varying weighting factors in objective function ........ 76
Figure 6.6.5 - 3 Active material trend with varying weighting factors in objective function .... 76
Figure 7.1 - 1 Torque ripple for Case 1 machines ................................................................. 80
Figure 7.2 - 1 Normalized current and voltage waveforms .................................................... 81
Figure 7.2 - 2 Fourier spectrum of current .......................................................................... 81
Figure 7.2 - 3 Fourier spectrum of voltage .......................................................................... 81
Figure 7.3 - 1 Zoom-in cross section for six-segmented magnet model for Case 1 SRSS machine ................................................................................................................. 83
Figure 7.4 - 1 Demagnetization risk in Case 1 machines ....................................................... 84
Figure 8.2 - 1 Flow chart for future optimization in Condor ............................................... 89
List of Tables

Table 2.3.2 - 1 Comparison of optimization algorithms [20, 21] ...................................................... 12

Table 4.1 - 1 Segmented PM machine specifications ............................................................................ 20

Table 4.4 - 1 Comparisons of analytical models of SRSS, DRSS, and SRDS ................................. 30

Table 5.2 - 1 Comparison of analytical and FE model for SRSS machine ......................................... 40

Table 5.3 - 1 Comparison of baseline and three-phase SRSS machine ............................................. 44

Table 5.4 - 1 Comparisons of SRSS topologies .................................................................................... 47

Table 5.5 - 1 Comparison of DRSS and SRDS .................................................................................... 51

Table 6.5 - 1 Parameter variation range ............................................................................................... 65

Table 6.6.4 - 1 Segmented PM calculated metrics for 50% TD, 50% TPD case ....................... 70

Table 6.6.4 - 2 Segmented PM calculated metrics for 70% TD, 30% TPD case ....................... 71

Table 6.6.4 - 3 Segmented PM calculated metrics for 30% TD, 70% TPD case ....................... 72

Table 6.6.4 - 4 Segmented PM calculated metrics for TD only optimization (a = 1, b = 0) .... 73

Table 6.6.4 - 5 Segmented PM calculated metrics for TPD only optimization (a = 0, b = 1) .... 74

Table 7.3 - 1 Loss components of Case 1 optimized segmented machines .................................... 83

Table 7.3 - 2 Comparison of magnet loss for segmented magnet models .................................... 84
## Nomenclature

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>Permanent magnet</td>
</tr>
<tr>
<td>WECS</td>
<td>Wind energy conversion system</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
</tr>
<tr>
<td>SRSS</td>
<td>Single rotor single stator</td>
</tr>
<tr>
<td>DRSS</td>
<td>Double rotor single stator</td>
</tr>
<tr>
<td>SRDS</td>
<td>Single rotor double stator</td>
</tr>
<tr>
<td>DFIG</td>
<td>Doubly fed induction generator</td>
</tr>
<tr>
<td>$B_r$</td>
<td>Remanent flux density</td>
</tr>
<tr>
<td>$B_g$</td>
<td>Airgap flux density (peak)</td>
</tr>
<tr>
<td>$h_m$</td>
<td>Permanent magnet thickness</td>
</tr>
<tr>
<td>$g$</td>
<td>Airgap thickness</td>
</tr>
<tr>
<td>$P_e$</td>
<td>Rated power</td>
</tr>
<tr>
<td>$T_e$</td>
<td>Rated torque</td>
</tr>
<tr>
<td>$R_g$</td>
<td>Airgap radius</td>
</tr>
<tr>
<td>$l_g$</td>
<td>Machine iron length</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Shear stress</td>
</tr>
<tr>
<td>$B_{gavg}$</td>
<td>Average airgap flux density</td>
</tr>
<tr>
<td>A</td>
<td>Electrical loading (linear current density)</td>
</tr>
<tr>
<td>m</td>
<td>Number of phases</td>
</tr>
<tr>
<td>$N_{ph}$</td>
<td>Total number of turns per phase</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$I_{ph}$</td>
<td>Phase current (rms)</td>
</tr>
<tr>
<td>$k_w$</td>
<td>Winding factor of the torque producing component</td>
</tr>
<tr>
<td>$N_{pp}$</td>
<td>Number of pole pairs</td>
</tr>
<tr>
<td>$\omega_e$</td>
<td>Machine angular frequency</td>
</tr>
<tr>
<td>$f_e$</td>
<td>Nominal frequency</td>
</tr>
<tr>
<td>$\tau_p$</td>
<td>Pole pitch</td>
</tr>
<tr>
<td>$w_{tb}$</td>
<td>Tooth width</td>
</tr>
<tr>
<td>$w_s$</td>
<td>Slot width</td>
</tr>
<tr>
<td>$h_s$</td>
<td>Slot height</td>
</tr>
<tr>
<td>$w_{tt}$</td>
<td>Tooth tip width</td>
</tr>
<tr>
<td>$h_{sy}$</td>
<td>Stator yoke thickness</td>
</tr>
<tr>
<td>$h_{ry}$</td>
<td>Rotor yoke thickness</td>
</tr>
<tr>
<td>$R_{outer}$</td>
<td>Machine outer radius</td>
</tr>
<tr>
<td>$R_{inner}$</td>
<td>Machine inner radius</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume of machine active material</td>
</tr>
<tr>
<td>$W_c$</td>
<td>Copper mass</td>
</tr>
<tr>
<td>$W_i$</td>
<td>Iron mass</td>
</tr>
<tr>
<td>$W_m$</td>
<td>Magnet mass</td>
</tr>
<tr>
<td>$W$</td>
<td>Total mass</td>
</tr>
<tr>
<td>$C_m$</td>
<td>Total cost of machine active material</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Iron loss</td>
</tr>
<tr>
<td>$P_c$</td>
<td>Copper loss</td>
</tr>
</tbody>
</table>
η  Efficiency
ρ  Copper resistivity
$k_e$  Eddy current loss coefficient
$k_h$  Hysteresis loss coefficient
$\phi_p$  Flux from permanent magnet
$\phi_a$  Flux from armature winding
pf  Power factor
DE  Differential evolution
PSO  Particle swarm optimization
GA  Genetic algorithm
TD  Torque density
TPD  Torque per dollar
EESG  Electrically excited synchronous generator
PMSG  Permanent magnet synchronous generator
Chapter 1: Introduction

1.1 Background [1-7]

A wind turbine drive train including a generator constitutes an important component of the entire wind energy conversion system (WECS), and affects substantially its performance. Attention needs to be paid on the issue about the low rotating speed of the wind turbine, compared to the rotor speed of generator. The conventional way to solve this problem is using a speeding-up gearbox to couple the wind turbine with the generator, in order to reduce the generator size. Unfortunately, the gearbox generates vibration and noise, increases losses and needs lubrication as well as regular maintenance. For this reason, the direct drive technology, whose generator rotor is directly connected to the rotor blade hub, will be favorable in WECS.

However, because of the characteristics of the direct-drive generator as low speed, high torque operation, the direct drive machine turns out to be a heavy and very expensive machine with large air gap diameter. To deal with such a giant generator, the machine configuration with the feature of segmentation would be mostly desired for its advantages as easy for manufacturing, transporting, and assembling. Moreover, the segmented configuration could lead to good fault tolerant performance and improve the reliability of the overall system.

Even for a selected configuration with the property of segmentation, in order to realize it in the direct drive WECS, efforts need to be made on minimizing the machine, mass and total cost, and achieving high efficiency, power factor, and reliability. As a result, the approach of developing and applying certain machine design optimization mechanism to optimize machine design is required to be adopted for finding the most suitable generator for this application.
1.2 Project overview

The purpose of this research project is to design and optimize a direct drive wind generator, which could improve the system’s overall performance, i.e. higher efficiency, higher reliability, lower nacelle weight, and possibly lower overall cost.

This project was divided into two stages of study. In Stage 1 study, through literature review and internal discussion, a new concept segmented PM machine was brought up by Prof. Lipo, which is very suitable for the direct drive wind generator application. The analytical models for both single-airgap and double-aigap segmented PM machines were built for initial design. Then finite element models were created for understanding more about the characteristics of this type of machine. Certain variations were made on initial design configuration, and the effects of these variants were evaluated and compared based on finite element analysis.

In Stage 2 study, a finite element (FE) analysis based machine design optimization program was developed to optimize the segmented PM machines. This program use differential evolution (DE), a powerful optimization algorithm, to provide outer shell. The segmented PM machine designs were described with Visual Basic scripts and coupled into the DE shell. The resulted optimum segmented PM machine designs show significant improvement in torque density, as well as reduction in total active material cost. Post optimization analysis was also performed at the end of this stage study. The torque ripple, power factor, magnet loss, and demagnetization features of all the optimum designs were investigated, which prove that the nine phase segmented PM synchronous machine is suitable for being applied in direct drive WECS.
1.3 Document organization

Chapter 1 provides the background information about the direct drive wind energy conversion system, the desire for segmented machine configuration along with approach for optimizing machine designs. It also presents the research topics covered in this project and a discussion of the structure of this report.

Chapter 2 presents a state of the art review of merits of direct-drive wind generator compared to the geared-drive one, comparisons of different machine topologies used in the application of direct drive wind turbine, and the optimization techniques used in the field of machine design.

Chapter 3 introduces the concept of segmented PM machine, suitable for this application of direct drive wind generator, with the advantages of unity winding coefficient, high efficiency, short end winding, light weight, easily fabricated. Moreover the double-airgap segmented PM machine configuration is also proposed for the purpose of weight and radial force reduction.

Chapter 4 summarizes the specification and design assumptions for Stage 1 study. Then the analytical calculations for initial designs of the segmented PM machine are presented. Comparisons are made among the single-airgap and double-airgap segmented PM machines.

Chapter 5 compares the machine performances from analytical calculations and FE analysis results for the initial designs. According to concerns from mechanical aspects, modified designs are made, and effects of these changes are investigated. The behaviors of the single-airgap and double-gap segmented PM machines are compared based on FE analysis results.
Chapter 6 introduces optimization algorithm, optimization techniques used for Stage 2 study. The final nine-phase segmented configuration is describes. Then objective functions, parameter, constraints, evaluation criteria are defined. Finally, the performances of the optimum designs from each optimization case are presented.

Chapter 7 presents the torque ripple, power factor, magnet loss, and demagnetization characteristics of the optimum segmented inset PM machines designs. This type of machine has very good performance on torque ripple and demagnetization, while efforts need to be made on improving power factor and reducing the magnet loss.

Chapter 8 summarizes the key findings that are developed throughout this project report. Finally, it highlights areas in which future work is needed in order to optimize machines based on not only electromagnetic analysis, but also thermal and structural analysis.
Chapter 2: State of the Art Review

2.1 Direct-drive and geared-drive wind generator

As natural resources are drained and power consumption has been dramatically increased, it is necessary to develop renewable energy. As a clear and renewable energy source, wind power system technologies have been developed noticeably so that the cost of energy production using wind turbines has been getting declined. There are basically two kinds of wind generator from the point of view of driving mode between the wind turbine and generator. One is the indirect drive mode that the generator is driven by the turbine through a speedup gearbox. The other is the direct drive mode that the generator is driven directly by the turbine without speedup gearbox [1, 2].

Actually, most conventional wind power plants have the configuration such that the rotor of a wind turbine and the generator are coupled via a mechanical gearbox. Figure 2.1 – 1 shows a very popular geared-drive configuration in recent years, i.e. variable speed doubly fed induction generator (DFIG) system. The merit of this structure is that it can reduce the size of generator, which leads to low material cost. However, the gearbox itself makes big noise, suffers from considerable faults, and increases maintenance expenses. These drawbacks make a generation system with gearbox unsuitable to apply in hostile wind power generation environments [4].
There is currently a great deal of interest in directly driven WECS, whose generator rotor is directly connected to the rotor blade hub (Figure 2.1 – 2). It can eliminate noise and maintain cost of the gearbox, and increase the system efficiency and reliability. It is especially suitable for offshore applications, whose maintenance cost is relatively high [5, 6].

However, the direct drive generator also has its own drawbacks. For a generator, its power and torque can be expressed as

\[ P = T \omega_m \]  
\[ T = 2\pi R_g l_g \sigma \]

where \( \omega_m \) is the angular velocity of generator, \( R_g \) is the airgap radius, \( l_g \) is the axial length, and
\( \sigma \) is the sheer stress. Since the direct-drive generator operates at low speed, high torque is demanded. Generally, shear stress is fixed in generator, so high torque demands high tangential force and large air gap diameter. For this reason, the direct-drive generator is large and heavy. Consequently the direct-drive generator is expensive [7].

**Figure 2.1 - 2 Direct drive wind turbine system based on voltage source inverter [3]**

Compared to geared drive wind power generation system, direct drive system has the advantages of simplified drive train and increased energy yield, higher reliability and availability and less maintenance by omitting the gearbox. If a suitable generator topology can be designed, and optimized with high efficiency, low weight and cost, the direct-drive wind generator would be a better solution to wind energy conversion.
2.2 Generator topologies and comparisons for direct drive wind generator

2.2.1 Asynchronous machines

Induction generator is widely used in geared drive fixed speed wind turbine system. It is directly coupled to the grid, whose configuration is shown in Figure 2.2.1 – 1. The merits of using induction generator are simple and cheap configuration, no power converter requirement. However, the induction generator has to draw magnetizing reactive power from the grid, which leads to low power factor at the interface of the system [3, 7]. Besides, it is very sensitive to airgap thickness. If induction machine is used for direct drive wind application, where large airgap applies, it could ends up quite large, heavy and inefficient.

Figure 2.2.1 - 1 Fixed speed wind turbine system base on induction generator [3]
As previously mentioned, DFIG configuration is very popular nowadays in variable speed wind turbine system. A bidirectional power converter is used to control DFIG at the rotor side, as shown in Figure 2.1 – 2. Decouple control of active and reactive power can be easily done for the system, which leads to higher energy capture and higher power factor compared to induction generator. Another advantage of this DFIG configuration is that the power rating of the converter only needs to be approximately 30% of the rated power, which reduces the overall system cost. However, the DFIG has wearing components as brushes, which requires regular maintenance [3, 8]. In reference [9], a 10 MW DFIG is designed for direct drive wind turbine, which turns out to be very heavy, and low efficient.

2.2.2 Electrically excited synchronous generator (EESG)

The EESG appears to be the heaviest, and most expensive configuration for direct drive wind turbine. Since the rotor of EESG is excited by a DC source, slip rings and brushes, or brushless exciter with a rotating rectifier are necessary, which leads to large copper losses and low efficiency. The only commercially successful large direct-drive wind turbine manufacturer, Enercon, uses this system (Figure 2.2.2 – 1). It claims EESG has improved reliability including immunity to problems from voltage disturbances due to grid faults as a result of the use of a fully rated power converter [8, 10].
2.2.3 Permanent magnet synchronous generator (PMSG)

PMSG has a simple configuration by eliminating the DC excitation in the rotor winding with PM, which improves the efficiency. By using full scale power converter, the maximum wind power capture can be achieved in wide wind speed range. It also has high reliability due to the absence of mechanical components as slip rings and brushes. However, the expenditure of PM material is high, and PM suffers from demagnetization problem at harsh environment [10, 11].

As the performance of PM material is improving and the cost is decreasing in recent years [11], the direct drive PMSG will be more attractive for wind turbine market according to the brief comparison shown above. Particularly, surface-mounted PM synchronous generator is a
very attractive candidate for direct drive wind generator, which shows the distinctive advantages of the high efficiency, high torque density, and even the size effectiveness [1, 4].

2.3 Optimization on machine design

2.3.1 Analytical model based vs. FE model based optimization

For machine design optimization, there are two types of models used to evaluate objective function in optimization, i.e. analytical model and FE model. The advantage of analytical model is that it is extremely fast. It also gives much more insights in the physics of the system. However, considering the nonlinearity of the material, it is difficult to get accurate results from analytical model. On the other hand, FE analysis often is the preferred analysis tool for electric machines because it takes magnetic saturation effects into account. But FE analysis based optimization has been rarely adopted due to long computational time [12-14].

In developing design optimization algorithms, good accuracy is desired throughout the whole solution space along with fast analyzing speed. A computationally efficient – FE analysis is developed based on the symmetries of electric and magnetic circuits of AC machines in reference [15]. Additionally, the distributed parallel computing has been applied to FE based machine design optimization to loose excessive computation times, inherently based on the internet web service [16]. As a result, FE analysis based machine design optimization will be more favorable in the future.
2.3.2 Comparison of optimization algorithms

There are many different optimization algorithms used in the area of machine design optimization. Differential evolution (DE), particle swarm optimization (PSO), and genetic algorithm (GA) are the three optimization algorithms widely seen in publications [17-19]. The comparisons of these three algorithms are listed in Table 2.3.2 – 1. It shows that DE, PSO, and GA are all population based, stochastic function minimizers, which fulfill the requirements for machine design optimization, which is a nonlinear and constrained problem involving both continuous and discrete variables. Comparisons between DE and many other optimization algorithms have been done in reference [20]. The results show that DE may not always be the fastest method, it is usually the one that produces the best result, although the number of cases in which it is also faster is significant.

Table 2.3.2 - 1 Comparison of optimization algorithms [20, 21]

<table>
<thead>
<tr>
<th></th>
<th>DE</th>
<th>PSO</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Stochastic Generation based</td>
<td>Stochastic Generation based</td>
<td>Stochastic Generation based</td>
</tr>
<tr>
<td>Differentiability</td>
<td>Derivative-free</td>
<td>Derivative-free</td>
<td>Derivative-free</td>
</tr>
<tr>
<td>Modality</td>
<td>Multi-modal</td>
<td>Multi-modal</td>
<td>Multi-modal</td>
</tr>
<tr>
<td>Coding method</td>
<td>Floating point</td>
<td>Floating point</td>
<td>Binary string</td>
</tr>
<tr>
<td>Control coefficient</td>
<td>F, Cr</td>
<td>Initial particle positions, velocities, …</td>
<td>F, Cr</td>
</tr>
</tbody>
</table>
2.3.3 Multi-physics machine design optimization

Most existing design and optimization methods treat the electromagnetic, thermal and structural designs separately. As a result, the effects of power supply, machine control, load profile, thermal effects and materials are not fully integrated and accounted for, which often leads to over- or under- machine design [22]. An optimization system which integrates electromagnetic, thermal analysis is developed, the flowchart of which is shown in Figure 2.3.1 – 1. It stars from defining prime design variables. The electromagnetic design model is first run to design the active part of the machine from specifications and assumptions. The mechanical design is then run to determine the frame thickness of the machine. The machine performances then calculated. At the same time, the thermal model is applied and calculates the temperature distribution with the load profile of the mechanical load that this machine is expected to drive. The winding insulation life is estimated and whether the permanent magnets are subject to demagnetization damage. The performance of this trial design represented by the prime design variables is then evaluated against design objectives and constraints to decide how to modify these prime design variables [23].
Figure 2.3.3 - 1 Flow chart of electromagnetic-thermo-mechanical integrated design [23]
Chapter 3: Segmented PM Machines

3.1 Segmented PM machine concept

Thinking about the large size of the generator for direct drive wind turbine, the feature of segmentation becomes a very important requirement. The segmented PM machine idea was brought up by Prof. Lipo at the beginning of this project study. The concept of the single rotor single stator (SRSS) segmented PM machine can be described by Figure 3.1 – 1. The machine is evenly divided into 6 segments (or other multiples of three for three-phase machines). Each segment is occupied by a single phase with evenly cut teeth and slots, which is shown in Figure 3.1 – 2. The tooth width is equal to one pole pitch. In order to make a three-phase machine, an extra piece of iron, which is equivalent to 60 or 120 electrical degree spatial phase shift, should be added between two adjacent segments in the stator. Single layer concentrated winding are wound around every alternate tooth.

![Figure 3.1 - 1 Concept of single rotor single stator (SRSS) segmented PM machine](image)
In reference [24], Chen proposed a similar machine configuration. And he claimed that this type of segmented PM machine has the merits as unity winding coefficient, high efficiency and performance, short winding ends and motor axial length, saving copper and light weight, easily wound and fabricated [25], which make this configuration very suitable for the application of direct driven wind generators.

### 3.2 Segmented PM machine with double-airgap

Based on the single stator-rotor layer segmented PM machine configuration, the idea of double stator-rotor layers segmented PM machine with two airgaps is described in Figure 3.2 – 1. The machine is also evenly divided into six segments (or other multiples of three for three-phase machines). In each segment, two layers of stator-rotor configuration are occupied by a single phase. To make it a three-phase machine, the 60 or 120 electrical degree spatial phase shift is still required for the double-airgap segmented PM machine.
Figure 3.2 - 1 Segmentation concept of double-airgap segmented PM machine

There are two types of double-airgap configurations for this segmented PM machine, i.e. double rotor single stator (DRSS) and single rotor double stator (SRDS). The zoom-in plot of one segment in DRSS is shown in Figure 3.2 – 2. For each stator-rotor layer in DRSS, it has identical structure as that of SRSS, i.e. the tooth width is equal to one pole pitch, and each alternate tooth is wound with single layer concentrated windings. The stator yoke is shared by the two stator-rotor layers. According to the flux path shown in Figure 3.2 – 2, the fluxes from the two layers meet at the shared stator yoke, and cancel each other out. So ideally, the flux density in the shared stator yoke area should be close to zero, and this yoke can be eliminated without affecting the machine’s electromagnetic performance. Figure 3.2 – 3 shows the zoom-in plot of one segment in the SRDS. The two stator-rotor layers in SRDS are combined in an opposite way, compared with DRSS. The configuration in each stator-rotor layer still keeps the same as SRSS and DRSS. Instead of the stator yoke, the rotor yoke is shared by the two layers in SRDS. According to the flux path shown in Figure 3.2 – 3, there is no flux travel
circumferentially through the shared rotor yoke. In other words, the machine would behave the same electromagnetically no matter how thick the shared rotor yoke is.

Because of the double stator-rotor layers configuration, both of the airgap can closely carry the same amount of torque, which results in reduction in stack length (approximately half of the stack length of SRSS). From an electromagnetic point of view, the shared stator yoke in the DRSS and the shared rotor yoke in SRDS can be eliminated, which would leads to significant active mass reduction. However, this elimination needs to be verified by mechanical analysis based on if there is sufficient structural support to hold the airgaps in place. Moreover, another advantage about this double stator-rotor layer configuration is that the machine itself can cancel certain amount of unwanted effects, such as radial force, cogging torque, etc [26, 27]. Further study would help to understand more about the characteristics of this type of segmented PM machine.

Figure 3.2 - 2 Zoom-in plot of one segment in DRSS
Figure 3.2 - Zoom-in plot of one segment in SRDS
Chapter 4: Analytical Designs for Segmented PM Machines

4.1 Specifications and design assumptions

The specification for the project study was provided by Vestas, and listed in Table 4.1 – 1.

Table 4.1 - 1 Segmented PM machine specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Rating</td>
<td>6 MW</td>
</tr>
<tr>
<td>Corner Speed</td>
<td>11.3 rpm</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>15 rpm</td>
</tr>
<tr>
<td>Voltage</td>
<td>690 Vrms l-l</td>
</tr>
<tr>
<td>Air-gap (Inner) Diameter</td>
<td>10 m</td>
</tr>
<tr>
<td>Stator Length</td>
<td>&lt; 1 m</td>
</tr>
<tr>
<td>Airgap Length</td>
<td>10 mm</td>
</tr>
<tr>
<td>Cooling Method</td>
<td>Liquid OK</td>
</tr>
<tr>
<td>Coolant Temperature</td>
<td>60 to 80 degC</td>
</tr>
<tr>
<td>Current Density</td>
<td>4 A/mm^2</td>
</tr>
<tr>
<td>Copper Fill Factor</td>
<td>50%</td>
</tr>
<tr>
<td>Copper Temperature/Resistivity</td>
<td>150 degC; 25 nΩm</td>
</tr>
<tr>
<td>Steel laminations</td>
<td>M19, 0.35 mm</td>
</tr>
<tr>
<td>Steel flux density, maximum</td>
<td>1.8 T peak</td>
</tr>
<tr>
<td>Hysteresis loss coefficient, k_h</td>
<td>256 W/m^3/Hz</td>
</tr>
<tr>
<td>Core loss coefficient, k_e</td>
<td>0.37 W/m^3/Hz^2</td>
</tr>
<tr>
<td>Magnet Remanent Flux Density</td>
<td>1.1 T @ 150 degC</td>
</tr>
<tr>
<td>Magnet Resistivity</td>
<td>1.4 µΩm</td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>150 Hz</td>
</tr>
<tr>
<td>No. of Phases</td>
<td>3,9 (Baseline=3)</td>
</tr>
<tr>
<td>Cost laminination steel</td>
<td>US$1/kg</td>
</tr>
<tr>
<td>Cost copper</td>
<td>US$5/kg</td>
</tr>
<tr>
<td>Cost NdFeB magnets</td>
<td>US$55/kg</td>
</tr>
<tr>
<td>Demagnetization Threshold</td>
<td>&gt;3x rated current</td>
</tr>
</tbody>
</table>
The design assumptions for Stage 1 study are:

- Rated torque (6.03 MN\*m) is produced at corner speed
- The material densities are: Copper – 8940 kg/m^3, Steel – 7850 kg/m^3, Neo Magnet – 7450 kg/m^3
- Airgap flux density kept at 0.75 T (peak)
- Shear stress is 75 kPa
- Infinite permeability in steel
- Tooth tip thickness is 3 mm.

### 4.2 Single rotor – single stator (SRSS) configuration

**Magnet Operating Point**

Choose 120 degrees C to be the operating temperature. In this case, the remanent flux density 
\( B_r = 1.1 \) Tesla.

According to reference [28], the airgap flux density at this operating point can be expressed as

\[
B_g = \frac{B_r}{1 + \frac{g}{h_m}}
\]

(4.2.1)

The airgap flux density is assumed to be \( B_g = 0.75 \) \( T \) peak, airgap thickness is 7.5 mm (5 mm from specs plus 2.5 mm for banding to retain the magnets, solving for the magnet thickness \( h_m \)

\[
h_m = \frac{g}{\frac{B_r}{B_g} - 1} = \frac{7.5}{\frac{1.1}{0.75} - 1} = 16.07 \text{ mm}
\]

(4.2.2)

So that
\[ g + h_m = 23.57 \text{ mm} \] (4.2.3)

Assume the maximum \( NI \) per phase per pole pair is to be \( 3N_{I_{rated}} \) per phase per pole pair. To prevent demagnetization, the MMF applied to two gaps is set equal to the \( H \) at zero \( B \),

\[
3 \times (N_{phpp}I_{ph\text{-}rated}) = \frac{B_g}{\mu_0} \times 2 \times (h_m + g)
\] (4.2.4)

Thus

\[
N_{phpp}I_{ph\text{-}rated} = \frac{2 \times 0.75 \times (0.02357)}{3 \times 4\pi \times 10^{-7}} = 9,378 \text{ pk} = 6,632 \text{ rms}
\] (4.2.5)

Estimation of Machine Size

From specs, the desired power output \( P_e = 6 \text{ MW} \) and the rated speed is 9.5 rpm. Then, the torque can be expressed as

\[
T_e = \frac{P_e}{\omega_m} = \frac{6,000,000}{9.5 \times \frac{2\pi}{60}} = 6,030,000 \text{ N*m}
\] (4.2.6)

According to

\[
T_e = 2\pi \times \sigma \times R_g^2 \times l_g
\] (4.2.7)

where \( \sigma = 75 \text{ kPa} \), \( R_g = 4.5 \text{ m} \), the iron length is

\[
l_g = \frac{T_e}{2\pi \times \sigma \times R_g^2} = \frac{6,030,000}{2\pi \times 75,000 \times 4.5^2} = 0.632 \text{ m}
\] (4.2.8)

Rated Frequency

Magnet Loading = \( B_{gav\text{vg}} = \frac{B_g}{\sqrt{2}} = \frac{0.75}{\sqrt{2}} = 0.53 \text{ T} \) (4.2.9)
Shear = \( \sigma = \frac{\pi}{2\sqrt{2}} \cdot k_w \cdot B_{gav\:g} \cdot A = \frac{\pi}{2\sqrt{2}} \cdot k_w \cdot B_{gav\:g} \cdot \frac{2+m\cdot N_{ph\:l_{phrms}}}{2\pi\cdot R_g} \) \hspace{1cm} (4.2.10)

Electric Loading = \( A = \frac{2+m\cdot N_{ph\:l_{phrms}}}{2\pi\cdot R_g} = \frac{2+1\cdot1,800,850}{2\pi+4.5} = 127.38 \text{ kA/m} \) \hspace{1cm} (4.2.11)

Where \( N_{ph} \) = total number of turns per phase

\( I_{phrms} \) = RMS phase current

\( k_w \) = winding factor of the torque producing component \((k_w = 1\), full pitch winding\)

\( N_{ph\:l_{phrms}} = \frac{\sigma \cdot 2\sqrt{2} \cdot R_g}{B_{gav\:g} \cdot m} = \frac{75,000+2\sqrt{2} \cdot 4.5}{0.53+1} = 1,800,850 \text{ A} \) \hspace{1cm} (4.2.12)

The number of pole pairs is,

\( N_{pp} = \frac{N_{ph\:l_{phrms}}}{N_{ph\:pp\:l_{phrms}}} = \frac{1,800,850}{6,632} = 272 \) \hspace{1cm} (4.2.13)

The angular frequency of the machine will be

\( \omega_e = \omega_r \cdot N_{pp} = 9.5 \cdot \frac{2\pi}{60} \cdot 272 = 271 \text{ rad/sec} \) \hspace{1cm} (4.2.14)

The nominal frequency will be

\( f_e = \frac{\omega_e}{2\pi} = 43.1 \text{ Hz} \) \hspace{1cm} (4.2.15)

Calculation of Magnet Flux

The pole pitch is

\( \tau_p = \frac{2\pi\cdot R_g}{2\cdot N_{pp}} = \frac{2\pi\cdot 4.5}{2\cdot 272} = 51.97 \text{ mm} \) \hspace{1cm} (4.2.16)
Assume now the span of magnet is $0.8 \tau_p$. The flux per pole due to permanent magnet (PM) is

$$\phi_p = B_g \times (0.8 \tau_p) \times l_g = 0.75 \times (0.8 \times 0.05197) \times 0.632 = 0.0197 \text{ Wb} \quad (4.2.17)$$

The flux per pole due to the armature winding is

$$\phi_a = \frac{\mu_0 N_{phpp} l_{ph\text{-rated}}}{2 \times (g + h_m)} \times \tau_p \times l_g = \frac{4 \pi \times 10^{-7} \times 0.378}{2 \times (0.02357)} \times 0.05197 \times 0.632 = 0.0082 \text{ Wb} \quad (4.2.18)$$

Let the maximum flux in the iron to be 1.8 T, the tooth width is

$$w_{tb} = \frac{\phi_a + \phi_p}{1.8 + \tau_p} \times l_g = \frac{0.0197 + 0.0082}{1.8 + 0.05197} = 24.53 \text{ mm} \quad (4.2.19)$$

The width of slot is

$$w_s = \tau_p - w_{tb} = 51.97 - 24.53 = 27.44 \text{ mm} \quad (4.2.20)$$

From specs the maximum current density is 4 A/mm$^2$, and the window fill factor is 50 %, the area need to conduct the required current is

$$N_{phpp} l_{phrms} = 6.632 = 4 \times 0.5 \times w_s \times h_s \quad (4.2.21)$$

Thus, the height of a slot is

$$h_s = \frac{N_{phpp} l_{phrms}}{2 \times w_s} = \frac{6.632}{2 \times 27.44} = 120.85 \text{ mm} \quad (4.2.22)$$

Assume the tooth tip width $w_{tt} = 0.8 \tau_p$, and the teeth-tip height $h_t = 3$ mm. Thus,

$$w_{tt} = 0.8 \tau_p = 0.8 \times 51.97 = 41.58 \text{ mm} \quad (4.2.23)$$

The flux density in the teeth tip is
\[ B_t = \frac{\phi_a + \phi_p}{w_{te} \cdot l_d} = \frac{0.0197 + 0.0082}{0.04158 + 0.632} = 1.06 \text{ T} \]  \hspace{1cm} (4.2.24)

Assume the maximum flux density in the back iron is 1.8 T.

\[ h_{sy} = h_{ry} = \frac{\phi_a + \phi_p}{1.8 \cdot l_d} = \frac{0.0197 + 0.0082}{1.8 + 0.632} = 24.53 \text{ mm} \]  \hspace{1cm} (4.2.25)

**Volume of the Machine**

The outer radius of the machine is

\[ R_{outer} = R_g + h_t + h_s + h_{sy} = 4.5 + 0.003 + 0.12085 + 0.02453 = 4.648 \text{ m} \]  \hspace{1cm} (4.2.26)

The inner radius of the machine is

\[ R_{inner} = R_g - h_m - h_{ry} = 4.5 - 0.01607 - 0.02453 = 4.46 \text{ m} \]  \hspace{1cm} (4.2.27)

The active volume of the machine is (lamination factor is 95%)

\[ V = \pi \cdot (R_{outer}^2 - R_{inner}^2) \cdot l_d/0.95 = 3.579 \text{ m}^3 \]  \hspace{1cm} (4.2.28)

**Mass of the Machine**

The active area of the armature coil per phase per pole is

\[ A_c = 0.5 \cdot w_s \cdot h_s = 0.5 \cdot 0.02744 \cdot 0.12085 = 0.00166 \text{ m}^2 \]  \hspace{1cm} (4.2.29)

The copper length per phase is

\[ l_c = 2 \cdot (\tau_p \cdot \pi/2 + l_d/0.95) \cdot \frac{N_{pp}}{3} = 2 \cdot (0.08163 + 0.665) \cdot \frac{272}{3} = 135.39 \text{ m} \]  \hspace{1cm} (4.2.30)

The total volume of copper is
\[ V = 3 \times A_c \times l_c = 3 \times 0.00166 \times 135.39 = 0.674 \text{ m}^3 \]  
(4.2.31)

The mass of the copper is

\[ W_c = 8940 \times V_c = 8,940 \times 0.674 = 6,026 \text{ kg} \]  
(4.2.32)

The iron volume for one pole pair is (roughly)

\[ V_{ip} = \left[ 2 \times \tau_p \times (h_{sy} + h_{ry}) + 2 \times w_{tt} \times h_t + 2 \times w_{tb} \times h_s \right] \times l_g \]

\[ = \left[ 2 \times 0.05197 \times (0.02453 + 0.02453) + 2 \times 0.04158 \times 0.003 + 2 \times 0.02453 \times 0.12085 \right] \times 0.632 = 0.00713 \text{ m}^3 \]  
(4.2.33)

The total iron volume is

\[ V_i = N_{pp} \times V_{ip} = 272 \times 0.00713 = 1.939 \text{ m}^3 \]  
(4.2.34)

The total iron mass is

\[ W_i = 7,850 \times V_i = 7,850 \times 1.939 = 15,221 \text{ kg} \]  
(4.2.35)

The volume of the magnets is

\[ V_m = 2 \times N_{pp} \times l_g / 0.95 \times 0.8 \tau_p \times h_m = 0.242 \text{ m}^3 \]  
(4.2.36)

The total magnet mass is

\[ W_m = 7,450 \times V_m = 7,450 \times 0.242 = 1,803 \text{ kg} \]  
(4.2.37)

The total mass of the machine is

\[ W = 6,026 + 15,221 + 1,803 = 23,050 \text{ kg} \]  
(4.2.38)
Material Cost of the Machine

According to the price of the active material listed in Table 4.1. The estimated total active material cost is

\[
C_m = 1.0 \times 15,221 + 5 \times 6,026 + 55 \times 1,803 = 144,516
\]

(4.2.39)

Efficiency

Assumed loss coefficients

\[
k_e = 0.37 \text{ W/m}^3/\text{Hz}^2
\]

\[
k_h = 256 \text{ W/m}^3/\text{Hz}
\]

Iron loss (W/m^3) = \(k_h \times f \times B^2 + k_e \times f^2 B^2\)

(4.2.40)

Total iron loss is

\[
P_i = (k_h f_e + k_e f_e^2) \times N_{pp} \times l_g \left[1.8^2 \times 2 \tau_p \times (h_{sy} + h_{ry}) + B_t^2 \times 2 \times w_{tt} \times h_t + 1.8^2 \times 2 \times w_{tb} \times h_s\right] = (256 \times 43.1 + 0.37 \times 43.1^2) \times 272 \times 0.632 \times (1.8^2 \times 0.10394 \times 0.04906 + 1.06^2 \times 2 \times 0.04158 \times 0.003 + 1.8^2 \times 2 \times 0.02453 \times 0.12085) = 72,556 \text{ W}
\]

(4.2.41)

Assumed copper resistivity @ 150 degC

\[
\rho = 25 \text{ nohm/m}
\]

(4.2.42)

Resistance per pole pair is

\[
R_{phpp} = \rho \frac{2 \tau_p \pi / 2 + l_g / 0.95}{A_c} = 25 \times 10^{-9} \times \frac{2 \times (0.08135 + 0.665)}{0.00166} = 2.248 \times 10^{-5} \text{ ohm}
\]

(4.2.43)
The total copper loss (skin effect is not taken into account) is

\[ P_c = N_{pp} \times I_{phrms}^2 \times R_{phpp} = 272 \times 6,632^2 \times 2.248 \times 10^{-5} = 268,939 \text{ W} \]  \hspace{1cm} (4.2.44)

Efficiency of the machine (only considering iron and copper losses)

\[ \eta = \frac{P_e}{P_e + P_i + P_c} \times 100\% = \frac{6,000,000}{6,000,000 + 72,556 + 268,939} \times 100\% = 94.61\% \]  \hspace{1cm} (4.2.45)

4.3 Double-airgap configurations

As introduced before, there are two types of double-airgap machine configurations, i.e. double rotor single stator (DRSS) and single rotor double stator (SRDS). Compared to single-airgap machine, the torque carried by the double-airgap machine is shared by the two airgaps. Moreover, the two layers of stator in DRSS and the two layers of rotor in SRDS share the same back iron.

Analytical model for DRSS configuration:

Since the desired power output \( P_e = 6 \text{MW} \) and the rated speed is 9.5 rpm, the total torque is

\[ T_e = 6,030,000 \text{ N}\cdot\text{m} \] as calculated in (4.2.6)

The inner air-gap radius is still assumed to be \( R_{gi} = R_g = 4.5 \text{ m} \). According to previous calculations for single-airgap machine, the outer air-gap radius is

\[ R_{go} = R_{outer} + h_s + h_t = 4.648 + 0.12085 + 0.003 = 4.772 \text{ m} \]  \hspace{1cm} (4.3.1)

The torque from the inner and outer airgap can be expressed as
\[ T_{ei} = 2\pi * \sigma * R_{gi}^2 * l_g \]  
\[ T_{eo} = 2\pi * \sigma * (R_{go}^2) * l_g \]  
\[ T_e = T_{ei} + T_{eo} \]  

Solving for \( T_{ei} \) and \( T_{eo} \),

\[ T_{ei} = \frac{R_{gi}^2}{R_{gi}^2 + R_{go}^2} * T_e = \frac{4.5^2}{\frac{4.5^2}{4.5^2} + 4.782^2} * 6,030,000 = 2,838,258 \text{ N*m} \]  
\[ T_{eo} = T_e - T_{e2} = 6,030,000 - 2,831,969 = 3,191,742 \text{ N*m} \]  

As \( \sigma = 75 \text{ kPa} \), the iron length now becomes

\[ l_g = \frac{T_{ei}}{2\pi*\sigma*R_{gi}^2} = \frac{2,831,969}{2\pi*75,000*4.5^2} = 0.297 \text{ m} \]  

Since the flux in the shared stator back iron is almost zero, the thickness of it is now assumed to be equal to the stator back iron thickness of the single-airgap machine, i.e. \( h_{sy} = 24.53 \text{ mm} \).

Analytical model for SRDS configuration:

The inner air-gap radius is still assumed to be \( R_{gi} = R_g = 4.5 \text{ m} \). According to previous calculations for single-airgap machine, the outer air-gap radius is

\[ R_{go} = R_{outer} + h_m = 4.648 + 0.01607 = 4.664 \text{ m} \]  

In a similar way as DRSS machine, solving for \( T_{ei} \) and \( T_{eo} \),
As \( \sigma = 75 \text{ kPa} \), the iron length now becomes

\[
l_g = \frac{T_{ei}}{2\pi \sigma R^2_{gi}} = \frac{2,907,121}{2\pi \times 75,000 \times 4.5^2} = 0.305 \text{ m}
\] (4.3.11)

Again, since the flux of the shared rotor back iron in the circumferential direction is almost zero, the thickness of it is now assumed to be equal to the rotor back iron thickness of the single-airgap machine, i.e. \( h_{ry} = 24.53 \text{ mm} \).

The performance of the DRSS and the SRDS machines can be analytically evaluated in a similar way as the SRSS machine. The detailed calculation can be seen in Appendix.

### 4.4 Comparisons

According to the analytical designs of the SRSS, DRSS, and SRDS machines, their performances are compared in Table 4.4 – 1.

<table>
<thead>
<tr>
<th></th>
<th>Segmented SRSS</th>
<th>Segmented DRSS</th>
<th>Segmented SRDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (MW)</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Aig-gap (mm)</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Stator Type</td>
<td>Concentrated Wdg</td>
<td>Concentrated Wdg</td>
<td>Concentrated Wdg</td>
</tr>
<tr>
<td>Rotor Type</td>
<td>Surface PM</td>
<td>Surface PM</td>
<td>Surface PM</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>Stack Length (m)</td>
<td>0.665</td>
<td>0.313</td>
<td>0.329</td>
</tr>
<tr>
<td>Current Density (A/mm^2)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Air-gap Flux Density (T) peak</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Electrical Loading (kA/m)</td>
<td>127</td>
<td>127</td>
<td>127</td>
</tr>
<tr>
<td>PM Flux Linkage (Wh) peak</td>
<td>5.64</td>
<td>5.473</td>
<td>5.608</td>
</tr>
<tr>
<td>Shear (kPa)</td>
<td>75.0</td>
<td>75.0</td>
<td>75.0</td>
</tr>
<tr>
<td>Shear (psi)</td>
<td>10.88</td>
<td>10.88</td>
<td>10.88</td>
</tr>
<tr>
<td>Outer Diameter (m)</td>
<td>9.296</td>
<td>9.642</td>
<td>9.423</td>
</tr>
<tr>
<td>Machine Length (m)</td>
<td>0.717</td>
<td>0.365</td>
<td>0.381</td>
</tr>
<tr>
<td>Number of Pole Pairs</td>
<td>272</td>
<td>544</td>
<td>544</td>
</tr>
<tr>
<td>Number of Slots</td>
<td>544</td>
<td>1088</td>
<td>1088</td>
</tr>
<tr>
<td>Slots per Pole</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Nominal Frequency (Hz)</td>
<td>43.1</td>
<td>43.1</td>
<td>43.1</td>
</tr>
<tr>
<td>Active Volume (m^3)</td>
<td>3.598</td>
<td>3.376</td>
<td>3.432</td>
</tr>
<tr>
<td>Copper Weight (ton)</td>
<td>6.03</td>
<td>6.41</td>
<td>6.62</td>
</tr>
<tr>
<td>Iron Weight (ton)</td>
<td>15.22</td>
<td>12.93</td>
<td>13.38</td>
</tr>
<tr>
<td>Magnet Weight (ton)</td>
<td>1.80</td>
<td>1.75</td>
<td>1.79</td>
</tr>
<tr>
<td>Total Weight (ton)</td>
<td>23.05</td>
<td>21.08</td>
<td>21.79</td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>144,516</td>
<td>141,060</td>
<td>144,970</td>
</tr>
<tr>
<td>Copper Loss (kW)</td>
<td>269</td>
<td>287</td>
<td>296</td>
</tr>
<tr>
<td>Iron Loss (kW)</td>
<td>73</td>
<td>61</td>
<td>64</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>94.6</td>
<td>94.5</td>
<td>94.3</td>
</tr>
</tbody>
</table>
Chapter 5: Finite Element Models for Segmented PM Machines

5.1 Finite element analysis condition setup

The software package used for this stage of transient finite element analysis is JMag, developed by JSOL Corp. For setting up conditions for finite element analysis, the steps are as follows

- Draw base unit (one pole pair) machine cross section according to calculated dimensions.
- Define material properties, and assign them to specific regions.
- Assign periodic boundary, and specify the angle for the repetitive geometry, i.e. the angle of a base unit.
- Input the stack length in Analysis Control diagram, shown in Figure 5.1 – 1. The value of the stack length is initially calculated based on analytical model, and then modified to produce rated torque.
- For transient analysis, assign 180 steps for one electrical cycle.
- Assign coefficient values for iron loss calculation, as shown in Figure 5.1 – 2.
- Specify winding configuration in the coil material regions. Then create electrical circuit for the windings as shown in Figure 5.1 – 3. For the rated load analysis, a sinusoidal current excitation with rated amplitude and frequency is applied to the stator winding, shown in Figure 5.1 – 4. The current angle is adjusted in order to achieve maximum torque per ampere operation.
- The meshes are automatically generated, as shown in Figure 5.1 – 5. In the airgap region, there are 5 divisions along the radial direction, while there are 180 divisions along the
circumferential direction. For the coil, stator core, and rotor core regions, the element size is specified as 5 mm.

Figure 5.1 - 1 Analysis control setup
Figure 5.1 - 2 Iron loss calculation setup
Figure 5.1 - 3 Circuit layout for rated load analysis

Figure 5.1 - 4 Sinusoidal current excitation setup
5.2 Comparison of analytical and FE model for SRSS machine

According to the analytical model’s geometric dimensions, a base unit (one pole pair) FE model was build in JMag, whose cross section is shown in Figure 5.2 – 1. Since the pole pitch equals to the slot pitch in this case, this type of segmentation topology has unity winding factor
and can extract the most amount of torque. But at the same time, it acts as a single phase machine, which suffers from the problem of high torque pulsation.

Spinning the rotor at its rated speed without any electrical excitation, the flux linkage of the FE model from the no-load transient analysis is shown in Figure 5.2 – 2. Its peak value is 4.466 Wb, which is only 79.2% of the flux linkage calculated before. This might be caused by the low magnet span ratio of 0.8 and not taking iron saturation into account during the analytical calculation.

Then applying the rated sinusoidal current to the stator winding, the produced average torque is 66.9% of the rated torque. The discrepancy between the analytical and the FE model is mostly caused by not estimating flux linkage accurately in the analytical calculation. As a result, for the baseline SRSS FE model to produce the rated torque, the stack length needs to be extended from 0.665 m to 0.994 m.

Figure 5.2 - 1 Cross section of baseline SRSS machine (base unit)
Applying no-load analysis to the modified model, the cogging torque waveform is shown in Figure 5.2 – 3. As expected before, the single phase model has very high cogging torque, whose peak to peak value is 29.28 % of rated torque.

The torque waveform from the rated load analysis is shown in Figure 5.2 – 4. Even though the average torque now equals to the rated torque, the peak to peak torque ripple is about 1.77 times of the rated torque, which is too high to fulfill the requirement.
The performances of the baseline SRSS analytical and FE models are compared in Table 5.2 – 1. Both of the models produce rated torque. It can be easily seen that the FE model has
much worse performance than expected analytical calculation. Modification is required for the analytical model to better capture the machine performance.

Table 5.2 - 1 Comparison of analytical and FE model for SRSS machine

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Baseline SRSS (7.5 mm)</th>
<th>Baseline SRSS (7.5 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytical Model</td>
<td>FE Model</td>
</tr>
<tr>
<td>Airgap Thickness (mm)</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Slot Type</td>
<td>Semi-closed</td>
<td>Semi-closed</td>
</tr>
<tr>
<td>Rotor Type</td>
<td>Surface PM</td>
<td>Surface PM</td>
</tr>
<tr>
<td>Stack Length (m)</td>
<td>0.665</td>
<td>0.994</td>
</tr>
<tr>
<td>Iron Mass (ton)</td>
<td>15.23</td>
<td>22.76</td>
</tr>
<tr>
<td>Copper Mass (ton)</td>
<td>6.02</td>
<td>8.67</td>
</tr>
<tr>
<td>Magnet Mass (ton)</td>
<td>1.80</td>
<td>2.69</td>
</tr>
<tr>
<td>Total Mass (ton)</td>
<td>23.06</td>
<td>34.12</td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>144440</td>
<td>214200</td>
</tr>
<tr>
<td>Iron Loss (kW)</td>
<td>72.56</td>
<td>65.12</td>
</tr>
<tr>
<td>Copper Loss (kW)</td>
<td>269.47</td>
<td>388.10</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>94.6</td>
<td>93.0</td>
</tr>
</tbody>
</table>
5.3 Segmentation of segmented PM machine

As seen in previous section, the single-phase SRSS machine model suffers from high torque pulsation. To solve this problem, more phases needs to be introduced into this segmented PM machine. For instance, to realize a three-phase machine, each phase windings should belong to one or several segments as shown in Figure 5.2 – 1, and the connection between two adjacent phase segments is a 60 or 120 electrical degree spatial phase shift. There are many ways to segment this type of machine for the direct-drive wind application, whose machine structure contains sufficient amount of pole pairs to play with. Figure 5.3 – 1 shows the cross section of one extreme case of three-phase SRSS machine. Each segment has only one pole pair, which is the best way to reduce torque pulsation, while having the worst torque production capability. From intuition, compared to the baseline single-phase SRSS model shown before, with the same dimension, this three-phase SRSS machine could only produce around 75 % of rated torque.

The reduction in cogging torque is proved by Figure 5.3 – 2. The peak to peak value of the cogging torque is now only 4.12 %. Figure 5.3 – 3 shows the torque waveform of the three-phase SRSS machine. The peak to peak value of the torque ripple is reduced to 9.58 % of rated torque. As a result, by introducing more phases into the SRSS machine, the decrease in torque pulsation is significant.
Figure 5.3 - 1 Cross section of three-phase SRSS machine

Figure 5.3 - 2 Cogging torque of three-phase SRSS machine
The performances of the baseline single-phase and three-phase SRSS models are compared in Table 5.3 – 1. Both of the models can produce the rated torque. However the three-phase SRSS model is 33.4 % heavier and 34.9 % more expensive than the baseline single-phase SRSS model, even though it has much lower torque pulsation.

As a result, the number of pole pairs in each segment provides an opportunity for machine design optimization. A tolerable torque ripple and satisfactory torque production capability can be achieved at the same time by segmenting the machine into a proper number of pieces.
Table 5.3 - 1 Comparison of baseline and three-phase SRSS machine

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Baseline SRSS (7.5 mm) FE Model</th>
<th>Three-Phase SRSS (7.5 mm) FE Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airgap Thickness (mm)</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Slot Type</td>
<td>Semi-closed</td>
<td>Semi-closed</td>
</tr>
<tr>
<td>Rotor Type</td>
<td>Surface PM</td>
<td>Surface PM</td>
</tr>
<tr>
<td>Stack Length (m)</td>
<td>0.994</td>
<td>1.416</td>
</tr>
<tr>
<td>Iron Mass (ton)</td>
<td>22.76</td>
<td>32.61</td>
</tr>
<tr>
<td>Copper Mass (ton)</td>
<td>8.67</td>
<td>9.06</td>
</tr>
<tr>
<td>Magnet Mass (ton)</td>
<td>2.69</td>
<td>3.83</td>
</tr>
<tr>
<td>Total Mass (ton)</td>
<td>34.12</td>
<td>45.50</td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>214200</td>
<td>288870</td>
</tr>
<tr>
<td>Iron Loss (kW)</td>
<td>65.12</td>
<td>62.16</td>
</tr>
<tr>
<td>Copper Loss (kW)</td>
<td>388.10</td>
<td>405.32</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>93.0</td>
<td>92.8</td>
</tr>
</tbody>
</table>

5.4 Comparison of SRSS topologies

Besides the electro-magnetic performance of the SRSS, some suggestions from the manufacturing side were taken into account on the generator design, i.e. changing from semi-
closed slot to open slot, replacing magnet banding with inset PM configuration [29, 30],
increasing airgap thickness.

To evaluate how these changes affect the machine performance, the modified FE models
were created (to keep consistent comparison, only one base unit model was analyzed):

- Open slot with windings 5 mm away from airgap (Figure 5.4 – 1)
- Inset PM configuration with 5 mm airgap (Figure 5.4 – 2)
- Inset PM configuration with 10 mm airgap (Figure 5.4 – 3)

![Figure 5.4 - 1 Cross section of open slot SRSS machine](image)

The open slot, 5 mm inset, 10 mm inset, along with the baseline SRSS FE machine
models are compared in Table 5.4 – 1. By opening the slot, to produce the rated torque, the stack
length has to increase by 2.9 %, which leads to same amount of increase in total mass and cost.

Replacing the banding material with inset PM configuration can reduce the airgap
thickness by 2.5 mm, which helps to improve the machine performance. The total mass and the
cost of the Inset SRSS model is only 91.9 % and 92.23 % of the open slot SRSS model. Because of the inset PM configuration, there is around 5 % rated torque coming from reluctance for the 5 mm air-gap.

Increasing the airgap thickness of inset SRSS machine from 5 mm to 10 mm has deteriorated the machine performance in almost every aspect. The reluctance of the inset PM configuration is now only around 2 % of the rated torque. The total mass increases by 40.5 %, while the cost goes up by 40.6 %. As a result, the inset SRSS machine performance is sensitive to change in airgap thickness. To achieve good performance for certain airgap thickness, the inset SRSS machine should be designed and optimized for that specific airgap.

Figure 5.4 - 2 Cross section of inset SRSS machine with 5 mm airgap
Figure 5.4 - 3 Cross section of inset SRSS machine with 10 mm airgap

Table 5.4 - 1 Comparisons of SRSS topologies

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Baseline SRSS (7.5 mm) FE Model</th>
<th>Open Slot SRSS (7.5 mm) FE Model</th>
<th>Inset SRSS (5 mm) FE Model</th>
<th>Inset SRSS (10 mm) FE Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airgap Thickness (mm)</td>
<td>7.5</td>
<td>7.5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Slot Type</td>
<td>Semi-closed</td>
<td>Open slot</td>
<td>Open slot</td>
<td>Open slot</td>
</tr>
<tr>
<td>Rotor Type</td>
<td>Surface PM</td>
<td>Surface PM</td>
<td>Inset PM</td>
<td>Inset PM</td>
</tr>
<tr>
<td>Stack Length (m)</td>
<td>0.994</td>
<td>1.023</td>
<td>0.920</td>
<td>1.300</td>
</tr>
<tr>
<td>Iron Mass (ton)</td>
<td>22.76</td>
<td>23.43</td>
<td>21.61</td>
<td>30.53</td>
</tr>
<tr>
<td>Copper Mass (ton)</td>
<td>8.67</td>
<td>8.91</td>
<td>8.08</td>
<td>11.14</td>
</tr>
<tr>
<td>Magnet Mass (ton)</td>
<td>2.69</td>
<td>2.77</td>
<td>2.57</td>
<td>3.63</td>
</tr>
<tr>
<td></td>
<td>34.12</td>
<td>35.11</td>
<td>32.26</td>
<td>45.31</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>Total Mass (ton)</td>
<td>34.12</td>
<td>35.11</td>
<td>32.26</td>
<td>45.31</td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>214200</td>
<td>220500</td>
<td>203370</td>
<td>286000</td>
</tr>
<tr>
<td>Iron Loss (kW)</td>
<td>65.12</td>
<td>64.03</td>
<td>59.91</td>
<td>77.00</td>
</tr>
<tr>
<td>Copper Loss (kW)</td>
<td>388.10</td>
<td>498.82</td>
<td>361.48</td>
<td>498.60</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>93.0</td>
<td>92.8</td>
<td>93.4</td>
<td>91.3</td>
</tr>
</tbody>
</table>

### 5.5 Double-airgap configurations

According to the analytical designs made for DRSS and SRDS machines in Appendix, the modified open slot, inset PM FE models were set up with both airgap thicknesses kept at 5 mm, shown in Figure 5.5 – 1 and Figure 5.5 – 2.

For both of the models, spinning the rotors at the rated speed and apply the rated sinusoidal current excitation. The flux density contour plots from rated load transient FE analysis for the DRSS and SRDS models are shown in Figure 5.5 – 3 and Figure 5.5 – 4 respectively. It
can be observed that the flux density in the shared stator yoke of the DRSS model is almost zero. The shared stator yoke can be eliminated without deteriorating the machine performance, if there is some way to hold the stator in place. The flux density in the shared rotor yoke of the SRDS model is equal to the flux density in the magnet region no matter how thick the shared rotor yoke is. As a result the shared rotor yoke is also redundant from electromagnetic point of view.

![Flux density contour of DRSS](image1)
![Flux density contour of SRDS](image2)

Figure 5.5 - 3 Flux density contour of DRSS    Figure 5.5 - 4 Flux density contour of SRDS

Figure 5.5 – 5 and Figure 5.5 – 6 show the cogging torque waveform of DRSS and SRDS machines respectively. The torque produced by the DRSS machine is from two parts, i.e. the inner rotor and the outer rotor. Adding the peak to peak cogging torque values from different rotors together is 105.6 % of the rated torque. The cogging torque for the SRDS machine is 105.7 % of the rated torque. Both of the cogging torques are very large, when the two stator-rotor layers are aligned. If shift the two stator-rotor layers for the DRSS and SRDS machines for certain degree, the torque pulsation could come down due to force cancellation. However, in this case, the two stator-rotor layers would have separate flux paths, and the shared stator/rotor yoke would play a role and can’t be eliminated.

The torque waveforms of the DRSS and SRDS machines are shown in Figure 5.5 – 7 and Figure 5.5 – 8 respectively. For the DRSS machine torques from the inner and outer rotors added
together equals to the rated torque, while the shared rotor for the SRDS machine also produces rated torque. Because of the base unit (single phase) segmented configuration, they show very large torque ripples for this two double-airgap machines. Introducing more phases, adding shift between two stator-rotor layers, and applying proper segmentation could help to minimize the torque pulsation [26].

**Figure 5.5 - 5 Cogging torque of DRSS**

**Figure 5.5 - 6 Cogging torque of SRDS**

**Figure 5.5 - 7 Torque waveform of DRSS**

**Figure 5.5 - 8 Torque waveform of SRDS**
Table 5.5 – 1 compares the inset DRSS and SRDS models. The performances of the two double-airgap configurations look very close to each other, while the DRSS model is a little bit lighter and cheaper compared to the SRDS model. This is because the outer airgap diameter of the DRSS machine is larger than the SRDS machine. The thickness of the shared stator yoke in DRSS and shared rotor yoke in the SRDS is assumed to be equal to the yoke thickness in SRSS configuration. Compared with the SRSS’s total mass of 32.26 tons and total cost of $ 203370, the double-airgap configurations can achieve better performance based on the yoke thickness assumption. However, this assumption has not been proved by structural analysis yet.

### Table 5.5 - 1 Comparison of DRSS and SRDS

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Inset DRSS (5/5 mm) Analytical Model</th>
<th>Inset SRDS (5/5 mm) FE Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airgap Thickness (mm)</td>
<td>5/5</td>
<td>5/5</td>
</tr>
<tr>
<td>Slot Type</td>
<td>Open slot</td>
<td>Open slot</td>
</tr>
<tr>
<td>Rotor Type</td>
<td>Inset</td>
<td>Inset</td>
</tr>
<tr>
<td>Stack Length (m)</td>
<td>0.428</td>
<td>0.453</td>
</tr>
<tr>
<td>Iron Mass (ton)</td>
<td>18.19</td>
<td>18.79</td>
</tr>
<tr>
<td>Copper Mass (ton)</td>
<td>8.26</td>
<td>8.63</td>
</tr>
<tr>
<td>Magnet Mass (ton)</td>
<td>2.46</td>
<td>2.54</td>
</tr>
<tr>
<td>Total Mass (ton)</td>
<td>28.92</td>
<td>29.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>195040</td>
<td>201880</td>
</tr>
<tr>
<td>Iron Loss (kW)</td>
<td>53.12</td>
<td>58.39</td>
</tr>
<tr>
<td>Copper Loss (kW)</td>
<td>369.37</td>
<td>385.93</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>93.4</td>
<td>93.1</td>
</tr>
</tbody>
</table>
Chapter 6: Machine Design Optimization (Electromagnetic)

6.1 Differential evolution (DE) algorithm

Machine design optimization is a nonlinear and constrained problem involving both continuous and discrete variables. The dependency of the objective function and its gradients on the design parameters is unknown. DE is a very simple population based, stochastic function minimizer, which fulfills all the requirements for machine design optimization.

To realize the optimization, DE go through the steps as initialization, mutation, crossover and selection, which are described in Figure 6.1 – 1 [20].

- Initialization: Specify bother upper and lower bounds for each parameter; assign each parameter of every vector from within the prescribed range.
  \[ x_{j,i,0} = rand_j(0,1) \ast (b_{j,U} - b_{j,L}) + b_{j,L} \]  
  \[ (6.1.1) \]

- Mutation: Add a scaled, randomly sampled, vector difference to a third vector.
  \[ v_{i,g} = x_{r0,g} + F \ast (x_{r1,g} - x_{r2,g}) \]  
  \[ F \in (0,1+) \]
  \[ (6.1.2) \]

- Crossover: Build trial vectors out of parameter values that have been copied from two different vectors.
  \[ u_{i,g} = u_{j,i,g} = \begin{cases} v_{j,i,g} & \text{if } (rand_j(0,1) \leq Cr \text{ or } j = j_{rand}) \\ x_{j,i,g} & \text{otherwise}. \end{cases} \]  
  \[ Cr \in [0,1] \]
  \[ (6.1.3) \]

- Selection: Trial vector replaces the target vector in the next generation if it has an equal or lower objective function value than that of its target vector.
  \[ x_{i,g+1} = \begin{cases} u_{i,g} & \text{if } f(u_{i,g}) \leq f(x_{i,g}) \\ x_{i,g} & \text{otherwise}. \end{cases} \]  
  \[ (6.1.4) \]
Once the new population is installed, the process of mutation, recombination and selection is repeated until the optimum is located, or a prespecified termination criterion is satisfied.

DE is capable of optimizing machine design. Moreover it’s simple to implement, easy to use, reliable and fast, which is the reason for choosing DE as the optimizer to optimize the segmented PM machine for this project.
6.2 Optimization technique

For this machine design optimization problem, the first thing is to decide parameters that can be varied and parameters that need to be fixed. The second thing is to define the range for each variable parameter, and the actual value for each fixed parameter. After that, all the parameters are transferred to part of the modified code, in order to create the finite element script. Then the finite element script is executed either in MagNet or JMag to estimate performance of each design. The FE analysis results are written in an excel file and used by the main DE code to evaluate the cost function. If the design is the optimum, the optimization run will end, otherwise, the whole process will be repeated again until the optimum is found [31]. The flow chart describing the machine optimization routine is shown in Figure 6.2 – 1.

Figure 6.2 - 1 Machine optimization routine
In this Stage 2 study, all the optimization runs were carried out in a single computer environment. Because of the computing capability limit, the number of variable parameters and the evaluation criteria concerned in the cost functions were limited. Since DE is a population based optimizer, it is suitable for evaluating all the designs in the same generation simultaneously. In order to realize this computation intensive FE analysis based machine design optimization, a high throughput parallel computing environment is favorable in the future.

6.3 Objective function – Case definitions

The two key optimization metrics used to define the objective function (cost function) are

Torque Density (TD): [Nm/kg]

Torque-per-Dollar (TPD): [Nm/$US]

The objective function is expressed as a combination of TD and TPD.

\[ Q_{\text{cand}} = a \cdot \frac{TD}{TD_{\text{Base}}} + b \cdot \frac{TPD}{TPD_{\text{Base}}} \]

where \( Q_{\text{cand}} = \) Total Candidate Score
\( 0 < a < 1 \) and \( b = 1 - a \)

\( TD_{\text{Base}} \) and \( TPD_{\text{Base}} \) are base values

In order to select base value and normalize the two evaluation metrics, initial optimization runs were launched. For all the inset segmented PM configurations, the base values are the TD and TPD values shown mostly in initial runs. The based values used in Stage 2 optimization are
- TD Base = 250 Nm/kg
- TPD Base = 30 Nm/$

6.4 Nine-phase segmented configurations: single air-gap and double air-gap

At the beginning of the stage 2 study, certain changes in the specifications and assumptions were brought up based on the results from Stage 1 study. The changes in specifications are

- Corner speed is changed from 9.5 rpm to 11.3 rpm.
- Airgap (or inner airgap) diameter is changed from 9 m to 10 m.
- Airgap thickness is changed from 5 mm to 10 mm

The design assumptions for Stage 2 study are

- Rated torque (5.07 MN*m) is produced at corner speed.
- The machine is operated at maximum torque per ampere mode (MTPA), i.e. current vector is aligned with q-axis.
- Electrical loading is kept at 110 kA/m.
- Copper loss and iron loss are considered when calculating the efficiency.
- Demagnetization is verified when three times rated current is applied and aligned with d-axis. And this requirement is used to determine the minimum thickness of magnets.
- Minimum stator tooth thickness is 15 mm.
- Minimum rotor inset tooth thickness is 8 mm.
- Copper conductors are 5 mm away from airgap.
Three types of inset segmented PM machines were analyzed in Stage 2 study, i.e., Single Rotor Single Stator (SRSS), Double Rotor Single Stator Inset PM (DRSS), and Single Rotor Double Stator (SRDS) segmented PM machines. Their cross sections are shown in Figure 6.4 - 1. The stator yoke is shared for DRSS, while the rotor yoke is shared by SRDS.

The features for the segmented inset PM configuration are:

- Magnet-dominant design
- Dovetail tooth structure on rotor to hold magnets
- Nine phase machine with low torque ripple, and high torque production capability (smaller space phase shift)

Figure 6.4 - 1 Machine cross sections for three types of segmented PM machines
Complicate design structure required to support the double-stator and double-rotor configurations.

The winding configuration for this nine-phase segmented PM machine is shown in Figure 6.4–2. The characteristics of this type of winding configuration can be described as follows:

- The whole machine is divided into 27 arc segments on the stator. And each segment is around 1 m in arc circumference. On the rotor, the structure is a basic Inset Surface PM with 192 pole pairs.

- The windings in each segment are for a single phase, and they are concentrated windings. So each segment acts like a single phase machine.

- There is 40 degree electrical degree phase shift between every two phase belt.

- There are 192 rotor pole pairs in this machine, which means there are totally 384 magnet pieces on the rotor. But for the stator, there are 7 active pole pairs in each segment, meaning there are 7*27 = 189 active pole pairs in total. In addition, there are 3 pole pairs (40*27/360 = 3) in the stator for the entire machine dedicated for phase shift. Counting everything together on the stator, there would also be 189+3 = 192 pole pants.

- There are 7 active pole pairs in each segment, which means 14 slots. So the total number of slots for the entire machine would be 14*27 = 378.

- Between consecutive slots of a single phase, the phase shift is 180 degrees. Hence coil sides 1 and 2 form a single coil, i.e. single layer winding. In each segment, all seven coils are in a consecutive fashion, forming a single phase belt and hence the voltages in all coils are in phase.
This machine is not as any other conventional machine, where the phase sequence based on the slot/phase/pole combination. Instead all the coils in the phase belt are in phase due to the number of poles being (nearly) equivalent to the number of coil sides.

\[
(7 \text{ pole-pairs per phase-belt} \times 9 \times 3) + (3 \text{ interstitial pole pairs}) = 192 \text{ pole-pairs}
\]

**Figure 6.4 - 2 Winding configuration for nine-phase segmented PM machine**

In order to create different machine designs and launch the optimization, the mechanical structure assumptions need to be made, which are shown in Figure 6.4 – 3. (Note: these assumptions have not yet been verified by structural analysis)

- The magnet span ratio is defined as the bottom width of magnet to pole pitch ratio. And to fulfill the minimum 8 mm rotor inset tooth thickness requirement, the maximum
magnet span ratio is set as 0.9. The top width to the pole pitch ratio is assumed to be equal to magnet span ratio minus 0.05.

- For DRSS segmented PM machine, the lower thickness limit of the shared stator yoke = 0.1*tooth width.
- For SRDS segmented PM machine, the lower thickness limit of the shared rotor yoke = 0.1*pole pitch.

Figure 6.4 - 3 Mechanical structure assumptions for the three types of segmented PM machines
6.5 Definition of parameters and constraints

To optimize the single/double airgap segmented PM machine, five parameters can be adjusted. The five variable parameters are listed in red in Figure 6.5 – 1, i.e. tooth width, stator yoke thickness, rotor yoke thickness, magnet height, and magnet span.

Figure 6.5 - 1 Five adjustable parameters for segmented PM machine

In order to limit the computational time used for finite element analysis of each design, only base unit (single pole pair) structure is used for optimization. The average torque is one of the important outputs from each FE analysis during the optimization process. It is defined as the average value of maximum torque and minimum torque values from static analysis.

Initial (manual) variation of those adjustable parameters is performed, in order to identify the required parameter range variation for launching the optimization. To save computing time, the number of pole pairs of all the segmented PM machines was defined as a fixed parameter instead of a variable. Considering it is a nine phase segmented machine, the number of pole pairs in each phase belt need to be integer, and the space phase shift between each two adjacent phases has to be 40 electrical degrees. Moreover, taking structural support into account, each segment is
assumed to be around 1 m in arc circumference. As a result, the initial inset surface PM machine designs with 138, 165, 192, 219, and 246 as pole-pair number were created based on the same machine specification and design assumptions, in order to find the pole pair number close to optimum. The machine performance (TD and TPD) varies as a function of pole-pair number, and is shown in Figure 6.5 – 2. It can be observed that TPD decreases as the number of pole pairs increases, while TD increases until the number of pole pairs reaches 192, then keeps almost constant. Considering about the trade-off between TD and TPD, 192 was chosen as the pole-pair number for all the segmented PM machine designs (i.e., SRSS, DRSS, SRDS) during various optimization runs.

Magnet span ratio (bottom magnet width to pole pitch ratio) was the second parameter checked for variation range. The result is shown in Figure 6.5 – 3. It shows that as the magnet span ratio increases, TD increases significantly, while there is only a trivial decrease in TPD, which looks like higher magnet span ratio can lead to better machine performance. However, the maximum magnet span ratio is set as 0.9, because of the manufacturing limit.

![Figure 6.5 - 2 TD, TPD vs. No. of pole pairs](image1)

![Figure 6.5 - 3 TD, TPD vs. magnet span ratio](image2)
Magnet thickness to airgap thickness ratio is the third parameter checked to find out how it affects machine performance, which is shown in Figure 6.5 – 4. It can be observed that TD increases rapidly until magnet thickness is 1.6 times of the airgap thickness, and increases slowly...
after. On the other hand, TPD decreases dramatically as magnet thickness increases. To satisfy the demagnetization requirement, the minimum magnet thickness to airgap thickness ratio is conservatively set at 1.1. And 3.0 was selected as the upper limit to make sure the optimum point of the machine design is within the variation range.

The relationship between stator yoke thickness to tooth width ratio and TD, TPD is shown in Figure 6.5 – 5. As stator yoke thickness increases, TD decreases, while TPD first increases, then decreases. And when the stator yoke thickness decreases, the machine becomes more and more saturated. The similar result applies to the relationship between rotor yoke thickness to pole pitch ratio and machine performance, shown in Figure 6.5 – 6. Again, to make sure the optimum is within the variation range, the range for stator yoke thickness to tooth width ratio is set to be 0.1 to 1, and the range for rotor yoke thickness to pole pitch is set to be 0.1 to 0.5.

As length of one phase belt was factored into choices, and it is a nine phase machine, the machine is defined with 27 segments, and has 192 pole-pair number. Finally, all five variable parameter ranges have been identified based on effects of parameter variations on design performance, which are also summarized in Table 6.5 – 1.

<table>
<thead>
<tr>
<th>Sl.no</th>
<th>Symbol</th>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tau_th</td>
<td>Ratio of stator teeth width to rotor pole pitch</td>
<td>0.3-0.5</td>
</tr>
<tr>
<td>2</td>
<td>Tau_dsy</td>
<td>Ratio of stator yoke width to rotor teeth width</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>3</td>
<td>Alpha_p</td>
<td>Ratio of magnet span (at air-gap) to pole pitch</td>
<td>0.7-0.9</td>
</tr>
<tr>
<td>4</td>
<td>Tau_dyr</td>
<td>Ratio of rotor yoke width to pole pitch</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>5</td>
<td>Tau_hm</td>
<td>Ratio of magnet height to air-gap thickness</td>
<td>1.1-3</td>
</tr>
</tbody>
</table>
6.6 Optimization results

6.6.1 Optimized cases

As mentioned before, there are two key elements included in the objective function for optimization, which are:

- Torque Density (TD): Torque/Mass [N-m/kg]
- Torque Per Dollar (TPD): Torque/Cost [N-m/$US]

Initial runs were carried out with emphasis on torque density \((a=1, b=0)\) and torque per dollar \((a=0, b=1)\). Subsequently, FE analysis optimization runs were made with different objective functions:

- Case 1 – 50% normalized torque density and 50% normalized torque per dollar (i.e., \(a = 0.5; b = 0.5\))
- Case 2 – 70% normalized torque density and 30% normalized torque per dollar (i.e., \(a = 0.7; b = 0.3\))
- Case 3 – 30% normalized torque density and 70% normalized torque per dollar (i.e., \(a = 0.3; b = 0.7\))

6.6.2 Performance metrics

The optimum designs were further investigated based on the following calculated performance metrics:

- Active Mass
- Active Material Cost
- Magnet Mass
- Efficiency – Copper loss and iron loss are included @ corner speed
Terminal Power Factor – Calculated based on terminal current and voltage waveforms, however, end winding effects are not taken into account.

Torque Ripple – (Maximum – Minimum)/Average @ corner-speed torque

Stack Length

Radial/Tangential Force

6.6.3 JMag and Magnet comparisons

In order to save computational time, MagNet static analysis was used during optimization. When optimum design was found, its performance was verified by JMag transient analysis to guarantee the accuracy of the FE analysis result. Magnet static analysis and JMag transient analysis results are compared for final optimum machine designs from different optimization runs. The comparison results are shown in the Excel sheet named “Inset_SPM_Dimensions”, and attached to this document. It shows that their results agree with each other very well for SRSS and DRSS. However, there are some discrepancies for SRDS. The worst case for SRDS (Single Rotor Double Stator Case 2), the difference between the two FE analysis is around 25%. For this case, the JMag transient analysis was compared with MagNet transient analysis, shown in Figure 6.6.3 – 1. It shows that JMag and MagNet transient analysis results are very close. So JMag transient analysis results are trustworthy. All the optimum designs’ performance base on JMag transient FE analysis results are listed in the following tables.
6.6.4 Optimized machine designs

The results of SRSS, DRSS, and SRDS for Case 1 Optimization: 50% Torque Density, 50% Torque Per Dollar are shown in Table 6.6.5 – 1. It can be observed that most of metrics are similar among these three types of machines. However the single-airgap machine is around 2 tons heavier than the double-airgap machines. And single-airgap machine has almost twice the stack length of the double airgap machines. The design cross-sections for Case 1 are shown in Figure 6.6.4 – 1. It can be seen that both the shared rotor yoke in SRDS machine and the shared stator yoke in DRSS machine are very thin, which is close to the lower limit that was set before launching the optimization, since there is almost no flux going through those area. This scenario is good for reducing active material mass. But from mechanical point of view, there still need to have certain amount of passive mass in order to support the machine structure.

Figure 6.6.3 - 1 JMag and MagNet results comparison
The results of SRSS, DRSS, and SRDS for Case 2 Optimization: 70% Torque Density, 30% Torque Per Dollar are shown in Table 6.6.4 – 2. It can be seen that most of metrics look similar with Case 1 results. But compared to Case 1 machines, the Case 2 machines have lower mass and higher power factor, while the total cost is higher. The design cross-sections for Case 2 are shown in Figure 6.6.4 – 2.

The results of SRSS, DRSS, and SRDS for Case 3 Optimization: 30% Torque Density, 70% Torque Per Dollar are shown in Table 6.6.4 – 3. Still, it can be seen that most of metrics look similar with Case 1 and Case 2 results. But compared to Case 1 and Case 2 machines, the Case 3 machines have lower magnet mass, lower cost, and lower power factor, while the total mass is higher. The design cross-sections for Case 3 are shown in Figure 6.6.4 – 3.

To observe the SRSS and DRSS machine performance in the two extreme cases, i.e., TD Only Case and TPD Only Case, the weighting factor $a = 1$, $b = 0$ and $a = 0$, $b = 1$ were assigned in the objective function, respectively. The performance results of TD Only Case ($a = 1$, $b = 0$) is shown in Table 6.6.4 – 4, and their cross sections are shown in Figure 6.6.4 – 4. The results of TD Only Case suggest that with all the emphasis on TD, the machine can achieve low total mass, but having high magnet mass and cost.
Table 6.6.4 - 1 Segmented PM calculated metrics for 50% TD, 50% TPD case

<table>
<thead>
<tr>
<th>MACHINF GFOMFTRY</th>
<th>5050_Inset_SR</th>
<th>5050_Inset_DS</th>
<th>5050_Inset_DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Mass [ton]</td>
<td>22.07</td>
<td>20.46</td>
<td>20.72</td>
</tr>
<tr>
<td>Active Material Cost [$]</td>
<td>189440</td>
<td>179970</td>
<td>169660</td>
</tr>
<tr>
<td>Magnet Mass [ton]</td>
<td>2.55</td>
<td>2.55</td>
<td>2.36</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>93.11</td>
<td>94.3</td>
<td>94.76</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>0.595</td>
<td>0.593</td>
<td>0.564</td>
</tr>
<tr>
<td>Torque Ripple [%]</td>
<td>&lt;0.07%</td>
<td>&lt;0.06%</td>
<td>&lt;0.06%</td>
</tr>
<tr>
<td>Stack length [m]</td>
<td>0.866</td>
<td>0.406</td>
<td>0.395</td>
</tr>
</tbody>
</table>

Figure 6.6.4 - 1 Design cross sections for Case 1
Table 6.6.4 - 2 Segmented PM calculated metrics for 70% TD, 30% TPD case

<table>
<thead>
<tr>
<th>MACHINE GEOMETRY</th>
<th>7030_Inset_SR</th>
<th>7030_Inset_DS</th>
<th>7030_Inset_DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Material Cost [$]</td>
<td>190150</td>
<td>198980</td>
<td>195850</td>
</tr>
<tr>
<td>Magnet Mass [ton]</td>
<td>2.549</td>
<td>2.938</td>
<td>2.888</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>93.09</td>
<td>94.49</td>
<td>94.97</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>0.595</td>
<td>0.641</td>
<td>0.633</td>
</tr>
<tr>
<td>Torque Ripple [%]</td>
<td>&lt;0.07%</td>
<td>&lt;0.06%</td>
<td>&lt;0.06%</td>
</tr>
<tr>
<td>Stack length [m]</td>
<td>0.9</td>
<td>0.386</td>
<td>0.374</td>
</tr>
</tbody>
</table>

Figure 6.6.4 - 2 Design cross sections for Case 2
Table 6.6.4 - 3 Segmented PM calculated metrics for 30% TD, 70% TPD case

<table>
<thead>
<tr>
<th>MACHINE GEOMETRY</th>
<th>3070_Inset_SR</th>
<th>3070_Inset_DS</th>
<th>3070_Inset_DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Mass [ton]</td>
<td>23.753</td>
<td>21.543</td>
<td>22.089</td>
</tr>
<tr>
<td>Active Material Cost [$]</td>
<td>169890</td>
<td>164590</td>
<td>160640</td>
</tr>
<tr>
<td>Magnet Mass [ton]</td>
<td>2.118</td>
<td>2.24</td>
<td>2.121</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>93.23</td>
<td>94.37</td>
<td>94.25</td>
</tr>
<tr>
<td>Displacement Power Factor</td>
<td>0.529</td>
<td>0.539</td>
<td>0.498</td>
</tr>
<tr>
<td>Torque Ripple [%]</td>
<td>&lt;0.07%</td>
<td>&lt;0.06%</td>
<td>&lt;0.06%</td>
</tr>
<tr>
<td>Stack length [m]</td>
<td>0.94</td>
<td>0.408</td>
<td>0.437</td>
</tr>
</tbody>
</table>

Figure 6.6.4 - 3 Design cross sections for Case 3
Table 6.6.4 - 4 Segmented PM calculated metrics for TD only optimization (a = 1, b = 0)

<table>
<thead>
<tr>
<th>MACHINE GEOMETRY</th>
<th>Single Rotor</th>
<th>Double Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Active Mass [ton]</td>
<td>20.96</td>
<td>19.55</td>
</tr>
<tr>
<td>Total Material Cost [$]</td>
<td>251890</td>
<td>232110</td>
</tr>
<tr>
<td>Magnet Mass [ton]</td>
<td>3.783</td>
<td>3.567</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>92.86</td>
<td>94.92</td>
</tr>
<tr>
<td>Stack length [m]</td>
<td>0.763</td>
<td>0.374</td>
</tr>
</tbody>
</table>

Figure 6.6.4 - 4 Design cross sections for TD only case

The performance results of TPD Only Case (a = 0, b = 1) is shown in Table 6.6.4 – 5, and their cross sections are shown in Figure 6.6.4 – 5. The results of TPD Only Case suggest that with all the emphasis on TPD, the machine can achieve low magnet content and cost, but having high total mass.
Table 6.6.4 - 5 Segmented PM calculated metrics for TPD only optimization (a = 0, b = 1)

<table>
<thead>
<tr>
<th>MACHINE GEOMETRY</th>
<th>Single Rotor</th>
<th>Double Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Active Mass [ton]</td>
<td>33.63</td>
<td>29.13</td>
</tr>
<tr>
<td>Total Material Cost [$]</td>
<td>156030</td>
<td>149530</td>
</tr>
<tr>
<td>Magnet Mass [ton]</td>
<td>1.68</td>
<td>1.723</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>93.37</td>
<td>93.78</td>
</tr>
<tr>
<td>Stack length [m]</td>
<td>0.930</td>
<td>0.481</td>
</tr>
</tbody>
</table>

Figure 6.6.4 - 5 Design cross sections for TPD only case

In conclusion, the required machine lengths are higher based on transient FE analysis (JMag) compared to previous static FE analysis (MagNet) values, which leads to machine masses being higher than previous optimized designs made in MagNet. The total mass increases by approximately 10% to 20 tons instead of 18 tons previously for the double-airgap machines. And because of the more accurate loss calculations, the efficiency reduces modestly by less than 1%.
6.6.5 Trends

After finding all the optimum designs for TD Only, 0.7*TD+0.3*TPD, 0.5*TD+0.5*TPD, 0.3*TD+0.7*TPD, and TPD Only Cases, it is worthwhile to observe the trends in active mass, magnet mass, and active material cost while varying weighting factors in objective function. The bar charts for active mass, magnet mass, and active material cost of SR machines are shown in Figure 6.6.5 – 1, Figure 6.6.5 – 2, and Figure 6.6.5 – 3 respectively. It can be observed that as the weight factor of TD goes down, the active mass goes up, while the magnet mass and the active material cost go down.

![Active Mass Trend](image)

**High Torque Density** ↔ **Low Cost**

Figure 6.6.5 - 1 Active mass trend with varying weighting factors in objective function for SRSS machine
Figure 6.6.5 - 2 Magnet mass trend with varying weighting factors in objective function for SRSS machine

Figure 6.6.5 - 3 Active material trend with varying weighting factors in objective function for SRSS machine
To sum up, the segmented PM machines have advantages as

- Highest modularity with concentrated windings
- High efficiency
- High power density
- “Light” rotor structure

But, they also have disadvantages as

- Low power factor
- High magnet content
- Complex machine structure for double rotor, double stator designs

In order to catch the characteristics of this type of machine, the “Best of Class” segmented PM Machines are listed below:

- Low machine mass
  - SRSS (70-30 design) – mass ~ 21.8 tons
  - SRDS (70-30 design) – mass ~ 19.8 tons

- Low magnet content
  - SRSS (30-70 design) – magnet mass ~ 2.12 tons
  - SRDS (30-70 design) - magnet mass ~ 2.24 tons
High efficiency
  - SRSS (30-70 design) – efficiency ~ 93.2%
  - SRDS (70-30 design) – efficiency ~ 94.5%

Low torque ripple
  - SRSS (50-50 design) – torque ripple < 0.07%
  - SRDS (50-50 design) – torque ripple < 0.06%

Need power factor solutions
  - SRSS (50-50 design) – power factor of 0.60
  - DRSS (50-50 design) – power factor of 0.59

In conclusion, depending on objective priorities, segmented PM machines can be optimized for low mass, low magnet content, or high efficiency. It can also be designed to deliver very low torque ripple, but power factor is lower than desired.
Chapter 7: Post Optimization Analysis – Characteristics of Optimum Segmented Inset PM Machines

7.1 Torque ripple

The torque ripple waveforms for segmented PM machines was verified based on one third machine model (120 mechanical degrees) instead of the simplified base unit (one pole pair) model, which includes all the nine phase windings and space phase shift between adjacent phase belts. The one third machine model is the least repeating section of the whole machine, so the torque ripple of one third machine model can be used to represent the actual torque ripple for the entire machine. The torque ripple waveforms for Case 1 machines are shown in Figure 7.1 – 1. It can be observed that the torque ripple waveforms for all the three types of machines are all very low, which is less than 0.07% of rated torque. So the nine-phase machine with 27 segments is a very good configuration in limiting torque pulsating and keeping high torque production capability.
7.2 Power factor

The displacement power factor is calculated for each of the designs in the 50% torque density -50% cost density cases. The power factor calculation is based on the current regulated machine. With the amp-turns as an input to the finite element model, the voltage across the number of turns is the output. Fourier analysis of the per-unitized current and voltage waveforms yields the displacement angle between the two waveforms.

The single rotor single stator case is given here.
In the above case, the angle between the two voltage waveforms was 47.3°, which is equivalent to a displacement power factor of 0.67.
7.3 Magnet losses

All the previous efficiencies values were calculated only considering copper losses and iron losses. In order to see how much the magnet losses are, compared to copper losses and iron losses in these segmented inset PM machines, the Case 1 (50%TD, 50%TPD) SRSS, DRSS, and SRDS machines’ un-segmented magnet losses are checked in JMag based on one-third (120 mechanical degrees) machine models. The results are shown in the Table 7.3 – 1. It can be observed that the un-segmented magnet losses are relatively high. The efficiencies reduce by around 2% for all the three machines, when taking un-segmented magnet losses into account. So finding a method to reduce the magnet losses is crucial to the segmented machines.

Segmenting the magnets is a well-known method to reduce magnet losses. To understand how to segment magnets can most effective, and to what extent, the magnet losses can be reduced, the Case 1 SRSS machine’s magnets were segmented into two-segment and six-segment circumferentially (As only 2D FE analysis is performed at this stage, the radially segmented magnet model can be evaluated in 3D FE analysis in the future), i.e. segment each piece of permanent magnet into two pieces and six pieces respectively. Figure 7.3 – 1 shows a part of the six-segment magnet FE analysis model for Case 1 SRSS machine. The comparison of magnet loss for un-segmented, two-segment, and six-segment machine models is shown in Table 7.3 – 2. The magnet loss for six-segment model is only 4.5 kW, which is very small compared to the 148 kW for the un-segmented model. As a result, approach on segmenting the magnet needs to be taken, circumferentially or radially, in order to reduce the magnet loss, and increase the overall efficiency.
Table 7.3 - 1 Loss components of Case 1 optimized segmented machines

<table>
<thead>
<tr>
<th>Loss component</th>
<th>5050 Inset SRSS</th>
<th>5050 Inset DRSS</th>
<th>5050 SRDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet loss (kW)</td>
<td>148</td>
<td>174</td>
<td>156</td>
</tr>
<tr>
<td>(Un-segmented)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor iron loss (kW)</td>
<td>2.12</td>
<td>3.59</td>
<td>2.44</td>
</tr>
<tr>
<td>Stator iron loss (kW)</td>
<td>28</td>
<td>19.24</td>
<td>27.41</td>
</tr>
<tr>
<td>Copper loss (kW)</td>
<td>338</td>
<td>314</td>
<td>342</td>
</tr>
<tr>
<td>Generator efficiency (%)</td>
<td>92.1</td>
<td>92.2</td>
<td>91.9</td>
</tr>
<tr>
<td>Efficiency w/o magnet loss (%)</td>
<td>94.2</td>
<td>94.7</td>
<td>94.2</td>
</tr>
</tbody>
</table>

Figure 7.3 - 1 Zoom-in cross section for six-segmented magnet model for Case 1 SRSS machine
Table 7.3 - 2 Comparison of magnet loss for segmented magnet models

<table>
<thead>
<tr>
<th></th>
<th>Un-segmented</th>
<th>Two-segment</th>
<th>Six-segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet loss (kW)</td>
<td>148</td>
<td>38</td>
<td>4.5</td>
</tr>
</tbody>
</table>

7.4 Demagnetization

As mentioned previously, the lower limit for magnet thickness was set to make sure all the designs fulfill demagnetization requirement. To verify that, three times of rated current were applied in negative d-axis on Case 1 machines. The magnet flux density contour on the magnets areas of both SRSS and SRDS machines are shown in Figure 7.4 – 1. It can be seen that the lowest magnetic flux density in the bulk magnet is 0.4 T in the SRSS machine and 0.6 T in the SRDS machine, which leaves enough margin to prevent demagnetization. It can also be observed that regions closest to air-gap see higher demagnetizing effect compared to bulk magnet far away from the air gap.

![Figure 7.4 - 1 Demagnetization risk in Case 1 machines](image)
Chapter 8: Conclusion and Future Work

8.1 Summary of significant results

According to the state of the art review, direct drive wind turbine would be a more favorable solution in WECS as it eliminates the noise, losses, and regular maintenance from the gear in an indirect drive wind turbine. PMSG, especially surface-mounted PM generator, is a very attractive candidate for direct drive wind generator for its high efficiency, torque density and reliability. Since direct drive wind generator suffers from the problem of large size, heavy weight, and high overall cost problems, an accurate FE analysis based optimization is desired to improve its performance.

The segmented PM synchronous machine with either single airgap or double airgap turns out to be a great solution to the direct drive WECS. The segmented configuration is very beneficial for the purpose of manufacturing, transport and assembly. Besides, this configuration also offers flexibilities in choosing number of phases and number of segments. Finding a proper combination of phase, segment, and pole numbers can lead to very low torque pulsation.

According to the results from analytical calculation and finite element analysis, it shows that this type of machine has the merits as unity winding factor, high power density, short end winding, and hard to get demagnetized. Unfortunately, the segmented PM synchronous machines suffer from the problems as low power factor, and large magnet loss for un-segmented magnet. The magnet loss comes down significantly after segmenting the magnets into adequate amount of pieces.
Compared with single-airgap segmented PM machine, the double-airgap configuration is lighter, and has the capability of cancelling part of unwanted effects as radial force. However, to keep two airgap in place for the double-airgap configuration is a big challenge from manufacturing perspective.

The finite element analysis based machine design optimization program, which using differential evolution as the optimizer, is very effective in improving machine performance based on defined objective functions. By modifying the combination of torque density, and torque per dollar in the objective function, it shows the trend that increasing the weighting factor on torque density, while decreasing the weighting factor on torque per dollar, the total mass and magnet mass come down, but the machine becomes more expensive, vise versa.

By checking the performance of the optimum designs in finite element transient analysis with one third machine (120 mechanical degrees) model, it proves that the optimized nine-phase segmented inset PM machine with 27 segments and 192 pole pairs is very suitable for the direct drive wind application.

8.2 Research contributions

The major new technical contributions developed during the research project can be summarized into two principal areas: analysis of segmented PM synchronous machine, and development of finite element analysis based machine design optimization program.

The configuration of the single airgap and double airgap segmented PM synchronous machines was developed by Prof. Lipo, for the direct drive wind generation application.
Analytical models for the segmented PM machines were created for initial design. Their characteristics, such as segmentation, open slot, inset PM, airgap sensitivity, were investigated through finite element analysis. The performances of the segmented PM machines, like torque ripple, mass, volume, efficiency, power factor, etc, were evaluated as well.

The procedure for finite element analysis based machine design optimization was properly defined. Comparison among different optimization algorithms was conducted based on reviewing literature. And a powerful optimization algorithm, differential evolution (DE) is picked as the outer shell. Visual Basic scripts, used for describing segmented PM machine designs, were written and coupled into the DE shell. Fixed and variable parameters for the machine design are specified. And the variation ranges for the variable parameters were assigned according to previous analysis results on this type of machine. A mechanism for defining the objective functions is initiated to investigate the trends of optimum machine designs. Finally, the finite element analysis based machine design optimization program was completed and capable of optimizing the segmented PM machines.

8.3 Future work

There is still a great deal of work that remains in order to further understand the segmented PM synchronous machine not just from electromagnetic perspective, but also from thermal and structural point of view. During the electromagnetic optimization, there still are some parameters, the variation of which could affect the overall machine performance, such as the number of segments, number of phases, and number of pole pairs, set as fixed value rather than variables because of the computational constraints based on a single computer. Fortunately,
Condor, a high throughput computing environment, which harnesses the parallel processing capability of more than a thousand workstation computers, is available in UW-Madison [32]. Moreover, JSOL Corp. has generously donated 100 JMag licenses, making it possible to analyze up to 100 candidate machines at the same time. The framework for coupling JMag, DE optimizer, and Condor is being built. In the near future, machine designs would be able to be optimized more thoroughly in a much shorter period of time. The flow chart for future Condor based optimization is shown in Figure 8.2 – 1.

Furthermore, the optimization program so far can only optimize machine designs electromagnetically, which leaves the effects of power supply, machine control, load profile, thermal effects and materials not being taken care of. So the optimum designs from the study of this project can’t be truly addressed as the final “optimums”. The future goal for this project is to develop an optimization system which integrates electromagnetic, thermal and structural analysis to realize the multi-physics machine design optimization.
Figure 8.2 - 1 Flow chart for future optimization in Condor
Bibliography


Appendix

A.1 Double rotor – single stator analytical design

Magnet Operating Point

Choose 120 degrees C to be the operating temperature. In this case, the remanent flux density $B_r = 1.1$ Tesla.

The airgap flux density at this operating point can be expressed as

$$B_g = \frac{B_r}{\frac{1}{g} + \frac{1}{h_m}}$$  \hspace{1cm} (A.1.1)

The airgap flux density is assumed to be $B_g = 0.75 \ T peak$, airgap thickness is 7.5 mm (5 mm from specs plus 2.5 mm for banding to retain the magnets, solving for the magnet thickness $h_m$

$$h_m = \frac{g}{\frac{g}{B_g} - 1} = \frac{7.5}{0.75 - 1} = 16.07 \ mm$$  \hspace{1cm} (A.1.2)

So that

$$g + h_m = 23.57 \ mm$$  \hspace{1cm} (A.1.3)

Assume that the maximum $NI$ per phase per pole pair is to be $3NI_{rated}$ per phase per pole pair.

To prevent demagnetization, the MMF applied to two gaps is set equal to the H at zero B,

$$3 \times (N_{ppp}I_{ph-rated}) = \frac{B_g}{\mu_0} \times 2 \times (h_m + g)$$  \hspace{1cm} (A.1.4)

Thus
\[ N_{\text{phrms}} l_{\text{ph-rated}} = \frac{2 + 0.75 \times (0.02357)}{3 \times 4\pi \times 10^{-7}} = 9,378 \text{ pk} = 6,632 \text{ rms} \] (A.1.5)

**Estimation of Machine Size**

As calculated before, the total torque is

\[ T_e = \frac{P_e}{\omega_m} = \frac{6,000,000}{9.5 \times \frac{4\pi}{60}} = 6,030,000 \text{ N}\cdot\text{m} \] (A.1.6)

The inner air-gap radius is still assumed to be \( R_{gi} = R_g = 4.5 \text{ m} \). According to previous calculation, the outer air-gap radius is

\[ R_{go} = R_{outer} + h_s + h_t = 4.648 + 0.12085 + 0.003 = 4.772 \text{ m} \] (A.1.7)

Solving for \( T_{el} \) and \( T_{eo} \),

\[ T_{el} = \frac{R_{gi}^2}{R_{gi}^2 + R_{go}^2} \times T_e = 2,838,258 \text{ N}\cdot\text{m} \] (A.1.8)

\[ T_{eo} = T_e - T_{el} = 3,191,742 \text{ N}\cdot\text{m} \] (A.1.9)

Assuming \( \sigma = 75 \text{ kPa} \), the machine length now becomes

\[ l_g = \frac{T_{el}}{2\pi \sigma R_{gi}^2} = 0.297 \text{ m} \] (A.1.10)

**Rated Frequency**

Magnet Loading = \( B_{gavg} = \frac{B_g}{\sqrt{2}} = \frac{0.75}{\sqrt{2}} = 0.53 \text{ Tesla} \) (A.1.11)

Electric Loading = \( A = \frac{2 \times m \times N_{\text{phrms}}}{2\pi \times (R_{gi} + R_{go})} = 123.85 \text{ kA/m} \) (A.1.12)
\[ N_{phr} I_{phrms} = N_{phpp} I_{ph-rated} * N_{pp} = 1,803,800 \text{ A} \]  
\text{(A.1.13)}

The number of pole pairs for each rotor is,

\[ N_{pp} = 272 \]  
\text{(A.1.14)}

The angular frequency of the machine will be

\[ \omega_e = \omega_r * N_{pp} = 9.5 * \frac{2\pi}{60} * 280 = 270.6 \text{ rad/sec} \]  
\text{(A.1.15)}

The nominal frequency will be

\[ f_e = \frac{\omega_e}{2\pi} = 43.1 \text{ Hz} \]  
\text{(A.1.16)}

Calculation of Magnet Flux

The pole pitch is

\[ \tau_{pi} = \frac{2\pi * R_{gi}}{2 * N_{pp}} = 52 \text{ mm} \]  
\text{(A.1.17)}

\[ \tau_{po} = \frac{2\pi * R_{go}}{2 * N_{pp}} = 55.1 \text{ mm} \]  
\text{(A.1.18)}

Assume now the span of magnet is \(0.8\tau_p\). The flux per pole due to permanent magnet (PM) is

\[ \phi_{pi} = B_g * (0.8\tau_{pi}) * l_g = 0.0093 \text{ Wb} \]  
\text{(A.1.19)}

\[ \phi_{po} = B_g * (0.8\tau_{po}) * l_g = 0.0098 \text{ Wb} \]  
\text{(A.1.20)}

The flux per pole due to the armature winding is

\[ \phi_{ai} = \frac{\mu_0 N_{phpp} I_{ph-rated}}{2*(g+h_m)} * \tau_{pi} * l_{gi} = 0.0039 \text{ Wb} \]  
\text{(A.1.21)}
\[ \phi_{ao} = \frac{\mu_0 N_{phpp}\text{ph-rated}}{2\pi (g + h_m)} \ast \tau_{po} \ast l_g = 0.0041 \text{ Wb} \]  
(A.1.22)

Let the flux in the iron to be 1.8 T

\[ w_{tbi} = \frac{\phi_{ai} + \phi_{pl}}{1.8 l_g} = 24.5 \text{ mm} \]  
(A.1.23)

\[ w_{tbo} = \frac{\phi_{ao} + \phi_{po}}{1.8 l_g} = 26.0 \text{ mm} \]  
(A.1.24)

The width of slot is

\[ w_{si} = \tau_{pl} - w_{tbi} = 27.4 \text{ mm} \]  
(A.1.25)

\[ w_{so} = \tau_{po} - w_{tbo} = 29.1 \text{ mm} \]  
(A.1.26)

The area needs to conduct the required current is

\[ N_{phpp}l_{phrms} = 6,632 = 4 \ast 0.5 \ast w_s \ast h_s \]  
(A.1.27)

Thus, the height of a slot is

\[ h_{si} = \frac{N_{phpp}\text{phrms}}{2 \ast w_{si}} = 120.9 \text{ mm} \]  
(A.1.28)

\[ h_{so} = \frac{N_{phpp}\text{phrms}}{2 \ast w_{so}} = 114.0 \text{ mm} \]  
(A.1.29)

Assume the \( w_{tt} = 0.8r_p \), and the teeth-tip height \( h_t = 3 \text{ mm} \). Thus,

\[ w_{tti} = 0.8r_{pl} = 41.6 \text{ mm} \]  
(A.1.30)

\[ w_{tto} = 0.8r_{po} = 44.1 \text{ mm} \]  
(A.1.31)
The flux density in the teeth tip is

\[ B_{ti} = \frac{\phi_{ai} + \phi_{pi}}{w_{tti} \times l_g} = 1.06 \, \text{T} \]  
(A.1.32)

\[ B_{to} = \frac{\phi_{ao} + \phi_{po}}{w_{tto} \times l_g} = 1.06 \, \text{T} \]  
(A.1.33)

Assume the flux density in the backing iron is 1.8 T.

\[ h_{r yi} = \frac{\phi_{ai} + \phi_{pi}}{1.8 \times l_g} = 24.5 \, \text{mm} \]  
(A.1.34)

\[ h_{r yo} = \frac{\phi_{ao} + \phi_{po}}{1.8 \times l_g} = 26.0 \, \text{mm} \]  
(A.1.35)

**Volume of the Machine**

The outer radius of the machine is

\[ R_{outer} = R_{go} + h_m + h_{r yo} + 0.0075 = 4.822 \, \text{m} \]  
(A.1.36)

The inner radius of the machine is

\[ R_{inner} = R_{gi} - h_m - h_{r yi} - 0.0075 = 4.452 \, \text{m} \]  
(A.1.37)

The active volume of the machine is

\[ V = \pi \times (R_{outer}^2 - R_{inner}^2) \times l_g / 0.95 = 3.376 \, \text{m}^3 \]  
(A.1.38)

**Weight of the Machine**

The active area of the armature coil per phase per pole is

\[ A_{ci} = 0.5 \times \omega_{st} \times h_{si} = 0.0017 \, \text{m}^2 \]  
(A.1.39)
\[ A_{co} = 0.5 \ast w_{so} \ast h_{so} = 0.0017 \text{ m}^2 \]  

(A.1.40)

The length per phase is

\[ l_{ci} = 2 \ast \left( \tau_{pi} \ast \pi / 2 + l_g / 0.95 \right) \ast \frac{N_{pp}}{3} = 71.58 \text{ m} \]  

(A.1.41)

\[ l_{co} = 2 \ast \left( \tau_{po} \ast \pi / 2 + l_g / 0.95 \right) \ast \frac{N_{pp}}{3} = 72.48 \text{ m} \]  

(A.1.42)

The total volume of copper is

\[ V_c = 3 \ast (A_{ci} \ast l_{ci} + A_{co} \ast l_{co}) = 0.7166 \text{ m}^3 \]  

(A.1.43)

The weight of the copper is

\[ W_c = 8940 \ast V_c = 6,406 \text{ kg} \]  

(A.1.44)

The iron volume for two pole pair is (roughly)

\[ V_{ip} = \left[ 2 \ast \tau_{pi} \ast \left( h_{giy} + h_{oky} \right) + 2 \ast w_{tti} \ast h_t + 2 \ast w_{tbi} \ast h_{si} + 2 \ast \tau_{po} \ast h_{ryo} + 2 \ast w_{tto} \ast h_{tto} + 2 \ast w_{tso} \ast h_{so} \ast l_g \right] = 0.0061 \text{ m}^3 \]  

(A.1.45)

The total iron volume is

\[ V_i = N_{pp} \ast V_{ip} = 1.647 \text{ m}^3 \]  

(A.1.46)

The total iron weight is

\[ W_i = 7,850 \ast V_i = 12,925 \text{ kg} \]  

(A.1.47)

The volume of the magnets is

\[ V_m = 2 \ast N_{pp} \ast l_g / 0.95 \ast 0.8 \ast (\tau_{pi} + \tau_{po}) \ast h_m = 0.2345 \text{ m}^3 \]  

(A.1.48)
The total magnet weight is

\[ W_m = 7,450 \times V_m = 1,747 \text{ kg} \]  \hspace{1cm} (A.1.49)

The total weight is

\[ W = 6,406 + 12,925 + 1,747 = 21,078 \text{ kg} \]  \hspace{1cm} (A.1.50)

**Material Cost of the Machine**

The estimated material cost is

\[ C_m = 1.0 \times 12,925 + 5 \times 6,406 + 55 \times 1,747 = $141,060 \]  \hspace{1cm} (A.1.51)

**Efficiency**

Total iron loss is

\[ P_i = (k_h f_e + k_e f_e^2) \times N_p p \times l_g \left[ 1.8^2 \times 2 \tau_{pi} \times (h_{syi} + h_{ryi}) + B_{ti}^2 \times 2 \times w_{tti} \times h_t + 1.8^2 \times 2 \times w_{tbi} \times h_{ti} + 1.8^2 \times 2 \times w_{tbo} \times h_{so} \right] \]

\[ = 61,446 \text{ W} \]  \hspace{1cm} (A.1.52)

Resistance per pole per phase is

\[ R_{phppi} = \rho \frac{2^{\times (\tau_{pi} \cdot \pi/2 + l_g/0.95)}}{A_{ci}} = 1.191 \times 10^{-5} \text{ ohm} \]  \hspace{1cm} (A.1.53)

\[ R_{phppo} = \rho \frac{2^{\times (\tau_{po} \cdot \pi/2 + l_g/0.95)}}{A_{ci}} = 1.205 \times 10^{-5} \text{ ohm} \]  \hspace{1cm} (A.1.54)

The total copper loss (skin effect is not taken into account) is
\[ P_c = N_{pp} * I_{phrms}^2 * (R_{phppi} + R_{phppo}) = 286,620 \text{ W} \]  \hspace{1cm} (A.1.55)

Efficiency of the machine

\[ \eta = \frac{P_e}{P_e + P_i + P_c} * 100\% = 94.5\% \]  \hspace{1cm} (A.1.56)

A.2 Single rotor – double stator analytical design

Solving for \( T_{ei} \) and \( T_{eo} \),

\[ T_{ei} = \frac{R_{gi}^2}{R_{gi}^2 + R_{go}^2} * T_e = 2,977,800 \text{ N*m} \]  \hspace{1cm} (A.2.1)

\[ T_{eo} = T_e - T_{ei} = 3,053,300 \text{ N*m} \]  \hspace{1cm} (A.2.2)

The machine iron length becomes

\[ l_g = \frac{T_{ei}}{2\pi * \sigma * R_{gi}^2} = 0.312 \text{ m} \]  \hspace{1cm} (A.2.3)

Magnet Loading = \( B_{avg} = \frac{B_g}{\sqrt{2}} = \frac{0.75}{\sqrt{2}} = 0.53 \text{ Tesla} \)  \hspace{1cm} (A.2.4)

Electric Loading = \( A = \frac{2 * m * N_{ph} I_{phrms}}{(R_{gi} + R_{go})^2} = 126.8 \text{ kA/m} \)  \hspace{1cm} (A.2.5)

\[ N_{ph} I_{phrms} = N_{phpp} I_{phrms} * N_{pp} = 1,803,800 \text{ A} \]  \hspace{1cm} (A.2.6)

The number of pole pairs for each rotor is,

\[ N_{pp} = 272 \]  \hspace{1cm} (A.2.7)
The angular frequency of the machine will be

\[ \omega_e = \omega_r \times N_{pp} = 9.5 \times \frac{2\pi}{60} \times 276 = 270.6 \text{ rad/sec} \]  

(A.2.8)

The nominal frequency will be

\[ f_c = \frac{\omega_e}{2\pi} = 43.1 \text{ Hz} \]  

(A.2.9)

**Calculation of Magnet Flux**

The pole pitch is

\[ \tau_{pi} = \frac{2\pi \cdot R_{gi}}{2 \times N_{pp}} = 52.0 \text{ mm} \]  

(A.2.10)

\[ \tau_{po} = \frac{2\pi \cdot R_{go}}{2 \times N_{pp}} = 52.6 \text{ mm} \]  

(A.2.11)

Assume now the span of magnet is 0.8\( \tau_p \). The flux per pole due to permanent magnet (PM) is

\[ \phi_{pi} = B_g \times (0.8 \tau_{pi}) \times l_g = 0.0097 \text{ Wb} \]  

(A.2.12)

\[ \phi_{po} = B_g \times (0.8 \tau_{po}) \times l_g = 0.0099 \text{ Wb} \]  

(A.2.13)

The flux per pole due to the armature winding is

\[ \phi_{ai} = \frac{\mu_0 \times N_{phpp} \times l_{ph\text{-rated}}}{2 \times (g + h_m)} \times \tau_{pi} \times l_{gi} = 0.0041 \text{ Wb} \]  

(A.2.14)

\[ \phi_{ao} = \frac{\mu_0 \times N_{phpp} \times l_{ph\text{-rated}}}{2 \times (g + h_m)} \times \tau_{po} \times l_{gi} = 0.0041 \text{ Wb} \]  

(A.2.15)

Let the flux in the iron to be 1.8 T, the tooth width is
\[ w_{tbi} = \frac{\phi_{ai} + \phi_{pl}}{1.8 + l_g} = 24.5 \text{ mm} \]  \hspace{1cm} (A.2.16)

\[ w_{tbo} = \frac{\phi_{ao} + \phi_{po}}{1.8 + l_g} = 24.9 \text{ mm} \]  \hspace{1cm} (A.2.17)

The width of slot is

\[ w_{si} = r_{pi} - w_{tbi} = 27.4 \text{ mm} \]  \hspace{1cm} (A.2.18)

\[ w_{so} = r_{po} - w_{tbo} = 27.8 \text{ mm} \]  \hspace{1cm} (A.2.19)

The area needs to conduct the required current is

\[ N_{phpp}l_{phrms} = 6,632 = 4 \times 0.5 \times w_s \times h_s \]  \hspace{1cm} (A.2.20)

Thus, the height of a slot is

\[ h_{si} = \frac{N_{phpp}l_{phrms}}{2 \times w_{si}} = 120.9 \text{ mm} \]  \hspace{1cm} (A.2.21)

\[ h_{so} = \frac{N_{phpp}l_{phrms}}{2 \times w_{so}} = 119.4 \text{ mm} \]  \hspace{1cm} (A.2.22)

Assume the \( w_{tt} = 0.8r_p \), and the teeth-tip height \( h_t = 3 \text{ mm} \). Thus,

\[ w_{tti} = 0.8r_{pi} = 41.6 \text{ mm} \]  \hspace{1cm} (A.2.23)

\[ w_{tto} = 0.8r_{po} = 42.1 \text{ mm} \]  \hspace{1cm} (A.2.24)

The flux density in the teeth tip is

\[ B_{tt} = \frac{\phi_{ai} + \phi_{pi}}{w_{tti} \times l_g} = 1.06 \text{ T} \]  \hspace{1cm} (A.2.25)
\[ B_{t0} = \frac{\phi_{ao} + \phi_{pa}}{w_{tto} l_g} = 1.06 \text{ T} \]  

(A.2.26)

Assume the flux density in the backing iron is 1.8 T.

\[ h_{syi} = \frac{\phi_{ai} + \phi_{pi}}{1.8 l_g} = 24.5 \text{ mm} \]  

(A.2.27)

\[ h_{sys} = \frac{\phi_{ao} + \phi_{pa}}{1.8 l_g} = 24.9 \text{ mm} \]  

(A.2.28)

**Volume of the Machine**

The outer radius of the machine is

\[ R_{outer} = R_{go} + h_{so} + h_{sys} + 0.0075 + 0.003 = 4.711 \text{ m} \]  

(A.2.29)

The inner radius of the machine is

\[ R_{inner} = R_{gi} - h_{yi} - h_{si} - 0.0075 - 0.003 = 4.344 \text{ m} \]  

(A.2.30)

The active volume of the machine is

\[ V = \pi \times (R_{outer}^2 - R_{inner}^2) \times l_g/0.95 = 3.432 \text{ m}^3 \]  

(A.2.31)

**Weight of the Machine**

The active area of the armature coil per phase per pole is

\[ A_{ci} = 0.5 \times w_{si} \times h_{si} = 0.0017 \text{ m}^2 \]  

(A.2.32)

\[ A_{co} = 0.5 \times w_{so} \times h_{so} = 0.0017 \text{ m}^2 \]  

(A.2.33)

The length per phase is
\[ l_{cl} = 2 \left( \tau_{pi} \pi/2 + l_g/0.95 \right) \frac{N_{pp}}{3} = 74.37 \text{ m} \quad (A.2.34) \]

\[ l_{co} = 2 \left( \tau_{po} \pi/2 + l_g/0.95 \right) \frac{N_{pp}}{3} = 74.56 \text{ m} \quad (A.2.35) \]

The total volume of copper is

\[ V_c = 3 \left( A_{cl} * l_{cl} + A_{co} * l_{co} \right) = 0.741 \text{ m}^3 \quad (A.2.36) \]

The weight of the copper is

\[ W_c = 8940 * V_c = 6,622 \text{ kg} \quad (A.2.37) \]

The iron volume for two pole pair is (roughly)

\[ V_{ip} = \left[ 2 * \tau_{pi} \left( h_{siy} + h_{ry} \right) + 2 * w_{tti} * h_c + 2 * w_{tbi} * h_{si} + 2 * \tau_{po} * h_{syo} + 2 * w_{tto} * h_{to} + 2 * w_{ts} * h_{so} * 0.0063 \right] \text{ m}^3 \quad (A.2.38) \]

The total iron volume is

\[ V_i = N_{pp} * V_{ip} = 1.705 \text{ m}^3 \quad (A.2.39) \]

The total iron weight is

\[ W_i = 7,850 * V_i = 13,382 \text{ kg} \quad (A.2.40) \]

The volume of the magnets is

\[ V_m = 2 * N_{pp} * l_g/0.95 * 0.8 \left( \tau_{pi} + \tau_{po} \right) * h_m = 0.2403 \text{ m}^3 \quad (A.2.41) \]

The total magnet weight is

\[ W_m = 7,450 * V_m = 1,790 \text{ kg} \quad (A.2.42) \]
The total mass is

\[ W = 6,622 + 13,382 + 1,790 = 21,794 \text{ kg} \]  \hfill (A.2.43)

Material Cost of the Machine

Thus the estimated material cost is

\[ C_m = 1.0 \times 13,382 + 5 \times 6,622 + 55 \times 1,790 = 144,970 \]  \hfill (A.2.44)

Efficiency

Total iron loss is

\[
P_i = (k_h f_e + k_e f_e^2) \times N_{pp} \times l_g \left[ 1.8^2 \times 2 \tau_{pl} \times (h_{syl} + h_{r_y}) + B_{ti}^2 \times 2 \times w_{tti} \times h_t + 1.8^2 \times 2 \times \right.
\]

\[
w_{tbi} \times h_{si} + 1.8^2 \times 2 \tau_{po} \times h_{syo} + B_{co}^2 \times 2 \times w_{tto} \times h_t + 1.8^2 \times 2 \times w_{tbo} \times h_{so}
\]

\[ = 63,630 \text{ W} \]  \hfill (A.2.45)

Resistance per pole per phase is

\[
R_{phpi} = \rho \frac{2 \times (\pi \times 10^5 \times l_g / 0.95)}{A_{ci}} = 1.237 \times 10^{-5} \text{ ohm} \]  \hfill (A.2.46)

\[
R_{phpno} = \rho \frac{2 \times (\pi \times 10^5 \times l_g / 0.95)}{A_{ci}} = 1.24 \times 10^{-5} \text{ ohm} \]  \hfill (A.2.47)

The total copper loss (skin effect is not taken into account) is

\[ P_c = N_{pp} \times I_{phrms}^2 \times (R_{phpi} + R_{phpno}) = 296,290 \text{ W} \]  \hfill (A.2.48)

Efficiency of the machine \[ \eta = \frac{P_e}{P_e + P_i + P_c} \times 100 = 94.3\% \]  \hfill (A.2.49)