

**ANALYTICAL MODELLING AND EFFICIENCY  
OPTIMISATION OF PERMANENT MAGNET  
SYNCHRONOUS MACHINE USING  
PARTICLE SWARM OPTIMISATION**

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**UNIVERSITI SAINS MALAYSIA**

**2018**

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PERMANENT MAGNET SYNCHRONOUS MACHINE USING  
PARTICLE SWARM OPTIMISATION**

**by**

**LING POH PING**

**Thesis submitted in fulfillment of the  
requirements for the degree  
of Master of Science**

**April 2018**

## ACKNOWLEDGEMENT

For a start, my utmost and sincerest appreciation goes to Assoc. Prof. Ir. Dr. Dahaman Ishak for the technical guidance, assistances and moral support under his supervision throughout my masters studies. His highly knowledgeable and professional insights on myriad problems encountered in the research studies were greatly valued. Amidst of his unending vigorous encouragement, it suddenly dawned on me that I have come to an end of my studies. It was indeed my greatest pleasure to have him to oversee the journey on achieving the next milestone in my life.

Next, I would like to convey my gratitude to Dr. Tiang Tow Leong, for all of the technical assistances in the research, and informative advices to achieve the quintessence of academic writing aesthetics.

Not forgetting my family for their unconditional love- pater and mater, for every wrinkle and silver hair gained over the years I am far away from home for studies, I am sure many were from me. And to my sisters who went polishing mermaid scales and burying treasures with me, whom have always wondered what mathematics and indices are for, this thesis is one of the WhyS.

I am grateful for Beh Khi Khim who always stood by my side through thick and thin, relentlessly made sure that I did not go into auto-photosynthesising. Not leaving the girls whom shared same fervour in the diminishing reading genre; Yvonne Loke and Jonathan Tan over endless bowls of Snowflakes; UMP H2-5, the irritating Mr. Chee and SMK Seafield Form 6 Amanah Batch 2010 for everything else which includes Reticulating Splines, Repairing Time Continuum, Predicting Predestined Path...

Last but not least, I would like acknowledge Universiti Sains Malaysia for partially funding my research through the Fundamental Research Grant Scheme (Grant No: USM-RU-FRGS 203/PELECT/6071328).

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## LIST OF ABBREVIATIONS

12s/8p	12-Slot/8-Pole
1D	1-Dimensional
2D	2-Dimensional
CAD	Computer-Aided Design
EMDS	Electrical Machines Driven Systems
EMF	Electromotive Force
EV	Electric Vehicles
FE	Finite Element
FEA	Finite Element Analysis
gbest	Global Best
GA	Genetic Algorithm
IEA	International Energy Agency
MEPS	Minimum Energy Performance Standards
MMF	Magnetomotive Force
Nd	Neodymium
NdFeB	Neodymium-Iron-Boron
pbest	Personal Best
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Machine
PSO	Particle Swarm Optimisation
S	South

## LIST OF SYMBOLS

$\alpha_p$	Magnet pole-pitch ratio
$\alpha_{ma}$	Angle between axes of magnetic field components due to phase MMF and magnet MMF
$A_0$	slotting effect function
$\theta_{end}$	End winding radius with respect to slot-pitch, ° mech.
$\theta_p$	Pole-pitch angle, ° mech.
$\theta_s$	Slot-pitch angle, ° mech.
$\theta_{so}$	Slot-opening angle, ° mech.
$\theta_{tb}$	Tooth body angle, ° mech.
$\mu_0$	Permeability of vacuum, H/m
$\mu_m$	Recoil permeability of magnet
$\varphi$	Scalar magnetic potential
$\varphi_I$	Scalar magnetic potential in air-gap region
$\varphi_{II}$	Scalar magnetic potential in permanent magnet region
$\phi_{sp}$	Total flux per stator tooth, Wb
$\phi_x$	Total flux crossing through tooth-tip height, Wb
$\omega_r$	Rotor rotational speed, rad/s
$\omega(t)$	Inertia coefficient in PSO

$A_{cu}$	Copper area, m <sup>2</sup>
$A_{cu}$	Copper area, m <sup>2</sup>
$A_{slot}$	Total slot area per slot-pitch, m <sup>2</sup>
$A_{slot1}$	Slot area on right of non-overlapping winding machine, m <sup>2</sup>
$A_{slot2}$	Slot area on left of non-overlapping winding machine, m <sup>2</sup>
$A_{slot3}$	Slot area on bottom slot of overlapping winding machine, m <sup>2</sup>
$A_{slot4}$	Slot area on top slot of overlapping winding machine, m <sup>2</sup>
$arc_i$	i-th magnet pole arc in PSO
$arc_{max}$	Upper boundary of magnet pole arc in PSO
$arc_{min}$	Lower boundary of magnet pole arc in PSO
$B$	Magnetic flux density, T
$B_g$	Average airgap flux density, T
$b_o$	Slot-opening angle, ° mech.
$B_{rm}$	Remanence of magnet, T
$B_{rI}$	Radial component of the magnetic flux density in air-gap region, T
$B_{\theta I}$	Tangential component of the magnetic flux density in permanent magnet region, T
$B_{smax}$	Maximum saturation level of flux density in stator iron, T
$c_1$	Cognitive coefficient in PSO
$c_2$	Social coefficient in PSO
$D_{ro}$	Rotor outer diameter, m
$D_s$	Stator bore diameter, m
$D_w$	Copper wire diameter, m
$e_b$	Induced back-emf per phase, V

$G$	Global best position in PSO
$g_{best}$	Global best solution in PSO
$H$	Magnetic field intensity vector, A/m
$H_{rl}$	Radial component of the magnetic field intensity in air-gap region, A/m
$H_{\theta l}$	Tangential component of the magnetic field intensity in air-gap region, A/m
$h_g$	Air-gap width, m
$h_{gi}$	i-th air-gap width in PSO, m
$h_{gmin}$	Upper boundary of air-gap width in PSO, m
$h_{gmax}$	Lower boundary of air-gap width in PSO, m
$h_m$	Magnet thickness, m
$h_{mi}$	i-th magnet thickness in PSO, m
$h_{max}$	Upper boundary of magnet thickness in PSO, m
$h_{min}$	Lower boundary of magnet thickness in PSO, m
$h_{rbi}$	Rotor back iron thickness, m
$h_{sbi}$	Stator back iron thickness, m
$i$	Particle position in PSO population
$I_{ph}$	RMS phase current, A
$j$	Variable in PSO
$K_{dn}$	Winding distribution factor
$K_{pn}$	Pitch factor
$k_{slot}$	Slotting opening factor
$l$	Length of copper wire inclusive of axial length, m

$l_a$	Axial length, m
$l_{end}$	Length of end winding, m
$M$	Residual magnet magnetisation, A/m
$M_r$	Radial component of magnet magnetisation vecor, A/m
$M_\theta$	Tangential component of magnet magnetisation vecor, A/m
$n$	Spatial harmonic number in winding slots
$N_{cph}$	Number of coil per phase, coil per phase
$N_{cs}$	Coil span number
$N_{layer}$	Number of winding layer configuration in the PM machine
$N_p$	Number of rotor pole
$N_s$	Number of slot in the stator
$N_{tpc}$	Number of turns per coil, turns per coil
$N_{tpph}$	Number of turn per phase, turn per phase
$p$	Number of pole-pair
$pbest$	Personal best solution in PSO
$P_{core}$	Core losses, W
$P_{cu}$	Copper winding losses, W
$P_{out}$	Ouput Power, W
$PF$	Packing factor, %
$P_j$	Present best position of j-th particle in PSO
$Q$	Number of slots per pole
$r$	Radial position of polar coordinate system, m
$r_{end}$	Radius of the end winding semicircle, m

$R_m$	Radius of PM surface, m
$R_{ro}$	Stator outer radius, m
$R_r$	Inner radius of rotor yoke, m
$R_{ph}$	Phase resistance for single core filament conductor, $\Omega$
$R_s$	Stator radius or the outer radius of slot openings, m
$R_{sy}$	Radius of stator yoke, m
$R_{shaft}$	Shaft radius, m
$R_t$	Outer radius of slot openings, m
$R_{tt}$	Tooth-tip bottom radius, m
$R_{tt\_slot}$	Inner radius of slot openings, m
$slot_i$	i-th slot opening width in PSO, m
$slot_{max}$	Upper boundary slot opening width in PSO, m
$slot_{min}$	Lower boundary slot opening width in PSO, m
$t$	Time, s
$THD_v$	Total harmonic distortion of back-EMF, %
$V_j$	Velocity vector of j-th particle
$W_{sy}$	Stator yoke width, m
$W_{tb}$	Tooth body width, m
$W_{tt}$	Tooth-tip height, m
$X_j$	Position vector of j-th particle

**PEMODELAN BERANALISIS DAN PENGOPTIMUMAN KECEKAPAN  
MESIN SEGERAK MAGNET KEKAL  
DENGAN MENGGUNAKAN PENGOPTIMUM KERUMUNAN ZARAH**

**ABSTRAK**

Reka bentuk mesin biasanya merupakan proses yang rumit dengan pembolehubah yang saling berkait dan juga bergantung pada faktor-faktor lain seperti hubungan tak linear antara parameter, sifat bahan, batas rekabentuk dan keperluan aplikasi. Pemodelan beranalisis masih diperbaiki secara berterusan untuk menghasilkan ramalan yang menyerupai analisis unsur terhingga (FEA) dan operasi mesin masa-nyata. Akan tetapi, kedua-dua pemodelan beranalisis serta FEA tidak dapat mengenal pasti parameter mesin diperlukan untuk pengoptimuman kecekapan mesin yang berbeza. Pemilihan pembolehubah secara stokastik juga tidak cekap dalam pengoptimuman mesin kerana hubungan-hubungan tak linear antara pembolehubah mesin PMSM. Lantaran itu, penyelidikan ini tertumpu kepada penggunaan pemodelan subdomain beranalisis medan magnetik dan sifat-sifat berkaitan untuk pengoptimuman tiga-fasa, 12-lubang alur/8-kutub PMSM lekap permukaan dengan topologi pemutar luaran. Teknik ini telah digunakan dengan mengubah nilai-nilai pembolehubah mesin terpilih seperti lengkung kutub magnet, ketebalan magnet, kelebaran sela udara, dan bukaan lubang alur. Selepas itu, suatu algoritma berkomputer pintar Pengoptimum Kerumunan Zarah (PSO) digunakan untuk mengubah pembolehubah mesin yang terpilih secara serentak, bagi mencari penyelesaian optimum berkrompomi untuk prestasi mesin yang tertinggi. Hasil prestasi mesin yang terbaik adalah berdasarkan indeks prestasi yang terpilih – kecekapan dan THDv. Hasil yang didapati daripada pemodelan beranalisis dan Pengoptimum Kerumunan Zarah (PSO) telah dsahkan dan dipersetujui dengan FEA. Daripada hasil penyelesaian PSO, keempat-empat pembolehubah reka bentuk mesin yang dioptimumkan berjaya mengoptimumkan prestasi mesin. Hasil penyelidikan ini menunjukkan gabungan pemodelan beranalisis dan PSO dapat memudahkan kaedah jangkaan stokastik dalam pembolehubah mesin serta menjadikan proses reka bentuk dan pengoptimuman reka bentuk mesin yang lebih cekap.

# **ANALYTICAL MODELLING AND EFFICIENCY OPTIMISATION OF PERMANENT MAGNET SYNCHRONOUS MACHINE USING PARTICLE SWARM OPTIMISATION**

## **ABSTRACT**

Machine design has always been a comprehensive process with inter-dependant variables that are subjected to many factors such as non-linear relationship between parameters, material properties, design limitations and application-dependant requirements. While analytical modelling has been continuously developed to predict as closely as possible to resemble the finite element analysis (FEA) and real-time machine operation, but analytical modelling as well as FEA are unable to pin-point specific machine variables required to be optimised for a particular design. Furthermore, stochastically choosing machine variables is not efficient in machine optimisation as there are complicated non-linear relationships between machine parameters in PMSM. Therefore, this research focuses on the usage of subdomain modelling for analytical prediction of magnetic field and other attributes to optimise a three-phase, 12slot/8pole surface mounted PMSM with external rotor topology, by varying selected machine variables - magnet pole arc, magnet thickness, air-gap width and slot opening individually. Subsequently, an intelligent computational algorithm - Particle Swarm Optimization (PSO) was later applied to all the machine variables simultaneously to find the optimal solution for a compromised optimal machine performance. The improved machine performance are based on the chosen performance indexes – efficiency and THDv. The results obtained from the analytical prediction and particle swarm PSO were compared with FEA for verification and was found to be in good agreement. From PSO study, the four machine design variables has been simultaneously optimised and successfully produced parameters for a performance-optimised machine. The research results has also demonstrated that by simplifying traditional stochastic methods in the targeted machine variables, a combination of analytical modelling and PSO allows a more efficient machine design and optimisation process.

# CHAPTER ONE

## INTRODUCTION

### 1.1 Background

Electrical machines have ineluctably integrated into our daily lives. From fundamental energy conversion in power generation industry, right to the miniature motorized high speed fan in a hair-dryer, electrical machines have become an indispensable component in the modern day industries and daily routines. At the same time, with rising awareness on conservation and preservation of the environment, the importance of a greener approach to the existing electric machines applications has been given much attention to. Electrical machines driven systems (EMDS) account for 43-46% of the global energy consumption, and produce 6040 Mt carbon dioxide emissions (IEA, 2011). By making the existing electrical machines work more efficiently, there will be huge economic and environmental impact. An improved electrical machine saves about 4% to 5% energy consumption. If these machines are linked to an equally-optimised electromechanical application, they will save another 15% to 20% on the energy consumption, in which leads to an effective enhancement on the energy efficiency of 20% to 30%. This ultimately reduces global electricity demand by 11% (IEA, 2011). With this reason, the global demand for electrical machines with higher efficiency has seen increasing growth since year 1995. The sales of these electrical machines are further stimulated by the enforcement of Minimum Energy Performance Standards (MEPS) in many developing countries, allowing benchmarking and comparison of electrical machines and EMDS performance standards (IEA, 2015). Thus, the designers of electrical machines have continuously sought methods to improve the existing machine designs and technology to deliver machines with better performance in terms of torque and efficiency profiles, in the face of fast-growing high-efficiency demand.

## **1.2 Permanent Magnet Synchronous Machines Development**

Permanent magnet synchronous machines (PMSM) are one of the few that offers higher efficiency compared to other available electrical machine technologies, albeit not widely distributed in the market compared to its counterparts. Due to its high power density, low torque ripple and low acoustics noise feature, PMSM is widely used and in high-demand for renewable and green energy conversion systems, such as wind turbines as well as the automotive industry. With the emerging of electric vehicles (EV) and hybrid electric vehicles (HEV), PMSM with better performance indexes has been prioritised and rigorously being developed to enhance their automotive applications. There have been many machine design techniques which were experimented to develop more efficient PMSMs, as presented in the literature. These techniques include skewing, auxiliary tooth, dummy sots and PM shape modifications (Jahns and Soong, 1996).

All these efforts were meant to minimise torque pulsation and improving machine performance, which are some of the common problems faced by a PMSM. Nonetheless, designers may come across the need for various design trade-offs in performance aspects such as magnetic and electrical traits when coming to producing electrical machines catered for high-performance applications.

Fortunately, with advanced and sophisticated technology development, finite element analysis (FEA) allows high accuracy and versatility in the modern machine designing processes. By using commercially available FE software such as Cobham Vector Field Opera 2D, an electrical machine's performance can be simulated under various conditions and environments such as static analysis and rotating machine analysis. These softwares allow conceptual designs to be tested, hence eliminating the traditional need of fabricating and testing the prototypes, and eventually reducing preliminary design costs and timescales. By defining the analysis domains into elementary regions known as finite elements, FEA is able to capture accurate, detailed and individualised aspects of many machine operational

properties such as electromagnetic characteristics and behaviour, air gap flux density, cogging torque and induced back-electromotive force (back-EMF).

Over the decades, FEA has progressed with advanced computer processing capabilities, hence allows FEA to be an essential integral in the modern machine design processes. But FEA only serves as a performance estimation tool for the electrical machine under specific configurations. Further experiences in dealing with real-time electrical machines operational conditions are required to adjust correction factors in FEA to allow a more accurate simulated performance for a satisfactory final design. On the other hand, FEA takes a substantially long computational time to generate simulation results. Furthermore, FEA is subjected to computational capabilities of the processor used. Likewise, one would need to sacrifice finer discretion of geometry in finite element to reduce computational time, which directly affects the level of accuracy.

Analytical modelling has been developed to serve as an alternative in machine design process to predict and estimate machine performance. Analytical modelling is continuously adapting to more machine related parameters and behaviours into consideration to improve the accuracy of solution in comparison to the FEA. While the introduction of various improved analytical modelling is helpful in machine design processes, modifications have to be done with consideration of other machine aspects such as machine design limitations, fabrication tolerances and material properties, hence becoming tediously long, resulting in a not optimal design as expected. Further elaboration on analytical modelling is discussed in the next chapter.

The implementation of evolutionary computation allows a more comprehensive solution to multi-dimensional engineering design problem, such as machine designing which encompasses many interrelating design variables. Particle Swarm Optimisation (PSO) is one of such computational methods where an optimal solution to a non-linear function is sought in a defined real number search space. Inspired by biological organisms' social behaviourism and some animal species working as a whole to locate the most desirable location of an area

for living (Kennedy and Eberhart, 1995), the basic PSO algorithm allows the particles to search the space by adjusting the trajectories in a multi-dimensional space. Predefined in an objective function, these particles moves towards to the best solution that they have independently found, and would eventually flock or converge towards the best solution that has been found by other particles in the search space. As to other available computational methods, PSO algorithm offers easier and simpler search mechanism, consisting comprehensive mechanism which allows particles to move at a predefined acceleration towards personal best and global best. With this reason, PSO is an excellent tool for designers to utilise in searching for the optimal multi-variables for the best performance achievable in an electrical machine. This leads to a more efficient and time-saving initial design stage.

### **1.3 Problem Statement**

Machine design is a comprehensive process with inter-dependant parameters, which are subjected to several factors such as material properties, machine design limitations and other application-dependant requirements. Therefore, it is difficult to pin-point specific machine variables to improve certain machine performance indexes such as torque profile and efficiency. While FEA allows an accurate prediction with flexible individualised settings, FEA software still rely on the computer processing capabilities to generate results within a considerable amount of time. Furthermore, accuracy depends on more refined geometry discretion in finite element, but consumes computational time. Analytical modelling was first developed to overcome the FEA's shortcomings, but still takes considerably long repetitive stochastic cycles of designing process to get to relatively better machine variables accounting other performance indexes of a machine. In this thesis, after determining the machine variables adjustments that improves a machine's performance, the utilisation of advanced computational methods such as PSO allows a faster computation of optimised variables for the required improved machine performance indexes.