UNIVERSITI PUTRA MALAYSIA

DESIGN AND IMPLEMENTATION OF DOUBLE ROTOR SWITCHED RELUCTANCE MOTOR USING MAGNETIC CIRCUIT ANALYSIS

CHOCKALINGAM ARAVIND VAITHILINGAM

FK 2013 117

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By

CHOCKALINGAM ARAVIND VAITHILINGAM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2013

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DEDICATIONS

To my parents,

Mr.Tenkasi Vaithilingam Chockalingam

and

Mrs.Gomathy Chockalingam

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

DESIGN AND IMPLEMENTATION OF DOUBLE ROTOR SWITCHED RELUCTANCE MOTOR USING MAGNETIC CIRCUIT ANALYSIS

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CHOCKALINGAM ARAVIND VAITHILINGAM

March 2013

Chair: Norhisam Bin Misron, PhD

Faculty: Engineering

With its high robustness nature and simplicity in design, the switched reluctance machines are finding its way for most of the modern day applications. The torque generating capability of such machines highly depends on the energy density available in the air-gap. The energy density in the air-gap depends on the flux traverse as the rotor moves from its full non-overlap position to the overlap position towards the excited stator pole. One way to improve the air-gap energy density is through the reduction of the air-gap length and the other through the extension of flux-linking the stator and rotor pole surface (typically known as pole-arcs). The reduction of the air-gap length is limited to a minimal value due to the mechanical oscillations that develop as the machine picks up the speed. Also the pole-arc value has to be designed appropriately in order to avoid the uneven pull due to the sequential excitations of the phases. This eventually introduces high torque ripples and vibrations inside the machine.

To address this issue a dual air-gap structure through a double rotor structure is proposed in this investigation. Initially the concept of the flux tube technique based on the integration techniques used in this analysis is introduced with respect to generic dual air-gap structure. In this method the energy density of a small strip in the uniform magnetic path of the structure is computed and then integrated over the whole surface, making the computation results more accurate. Unlike the conventional flux tube techniques where estimation of flux values are used in this analytical method the results are more accurate. The algorithm to derive the magnetic characteristics of the machine is presented. A quantitative analysis is performed on the various possible pole-arc values to derive the best possible combinations to be used in the design of the double rotor structure. It is found from the analysis that with the outer rotor pole arc at 35°, the inner rotor pole arc valve at 45°, the stator inner surface pole arc at 30° and the outer surface pole arc at 50° the machine exhibit lesser Total Harmonic Distortion (THD)of 13.45%. Numerical evaluation of the results from the above analysis is performed using Finite Element Analysis (FEA) tool. The maximum torque in case of the numerical FEA is about 1.755 N-m whereas by the analytical method is about 1.652 N-m. The percentage error is due to the flux shape assumption in the analytical computations. The average torque for analytical is 0.947 N-m and through numerical is 0.953 N-m. The percentage error in the computation is about 6.35%. Analysis of the design of the dual rotor structure reveals particular aspects of difficulties to assemble. A support structure for both the stator and the rotor are developed. The fabricated machine is then tested to evaluate the analytical and the simulation results. In the full overlap L_a the error through FEA computations is about 12.90% due to the setting of the design parameter and about 8.13% error for the analytical due to practical limitation. In the full non-overlap condition Lu the error percentage is very small and is negligible.

The time taken for the FEA simulation of one point is about 2 min 30 sec and the calculation of the iterations for one position is about 10 min. Numerical comparative evaluations of the proposed machine with its conventional structure for the same volume and same mmf value is also performed through FEA. The maximum torque generated by the selected Double rotor switched reluctance machine is about 1.755 N-m with the THD value of 13.45%. The maximum torque generated by the conventional switched reluctance machine is about 1.272 N-m with THD value of 67.13%. This analysis is performed using the finite element tool. Motor Constant Square Density (G) is used as the comparative evaluation parameter and it is found that the proposed machine exhibit 65% increase in torque value compared to that of the conventional machine.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doctor Falsafah

REKABENTUK DAN PELAKSANAAN DUAL PEMUTAR UNTUK MOTOR ENGGANAN BERSUIS DENGAN MENGGUNAKAN ANALISISLITAR MAGNET

Oleh

CHOCKALINGAM ARAVIND VAITHILINGAM

Mac 2013

Pengerusi: Norhisam Bin Misron, PhD

Fakulti: Kejuruteraan

Dengan sifat keteguhan yang tinggi dan kesederhanaan dalam reka bentuk, mesin keengganan mencari jalan bagi kebanyakan aplikasi moden. Keupayaan menjana tork mesin sangat bergantung kepada kepadatan tenaga yang ada di jurang udara. Ketumpatan tenaga di jurang udara bergantung kepada fluks traverse bergerak dari kedudukan bukan bertindih sepenuhnya dengan kedudukan bertindih ke arah tiang pemegun teruja. Salah satu cara untuk meningkatkan ketumpatan tenaga jurang udara ialah melalui pengurangan panjang jurang udara dan yang lain melalui pemberian fluks yang menghubungkan pemegun dan pemutar permukaan tiang (biasanya dikenali sebagai tiang-lengkok). Pengurangan panjang jurang udara adalah terhad kepada nilai minimum disebabkan oleh ayunan mekanikal yang membangunkan mesin memungut kelajuan. Juga nilai tiang-arka perlu direka untuk mengelakkan tarikan tidak sekata kerana pengujaan urutan fasa. Ini akhirnya memperkenalkan riak tork yang tinggi dan getaran di dalam mesin.

Untuk menangani isu ini struktur dwi-jurang udara melalui struktur dua pemutar adalah dicadangkan dalam penyiasatan ini. Pada mulanya konsep teknik tiub fluks berdasarkan teknik integrasi yang digunakan dalam analisis ini diperkenalkan berkenaan dengan generik dua struktur udara jurang. Dalam kaedah ini, ketumpatan tenaga jalur kecil di jalan magnet seragam struktur dikira dan kemudian dikamirkan ke atas seluruh permukaan, menjadikan proses pengiraan yang lebih tepat. Berbeza dengan teknik tiub fluks yang konvensional di mana anggaran nilai fluks yang digunakan dalam analisis kaedah ini mempunyai keputusan yang lebih tepat. Algoritma untuk mendapatkan ciri-ciri magnet mesin dibentangkan. Analisis kuantitatif dilakukan ke atas pelbagai kemungkinan nilai tiang-arka untuk mendapatkan kombinasi terbaik mungkin untuk digunakan dalam reka bentuk struktur pemutar berganda. Daripada analisis dengan luar arka kutub pemutar pada 35°, pemutar tiang injap arka dalaman pada 45°, pemegun dalaman arka tiang permukaan pada 30° dan luar arka tiang permukaan dari 50° pameran mesin kurang Jumlah Penyelewengan Harmonik (THD) kurang daripada 13.45 %.

Penilaian berangka hasil dari analisis di atas dilakukan dengan menggunakan Analisis Unsur Terhingga (FEA). Tork maksimum dalam kes FEA berangka adalah kira-kira 1.755 Nm manakala dengan kaedah analisis adalah kira-kira 1.652 Nm. Kesilapan peratus adalah disebabkan oleh andaian bentuk fluks dalam pengiraan analisis. Tork purata bagi analisis adalah 0.947 Nm dan melalui angka adalah 0.953 Nm. Kesilapan dalam pengiraan peratusan adalah kira-kira 6.35%. Analisis reka bentuk struktur pemutar dual mendedahkan aspek-aspek tertentu kesukaran untuk berhimpun. Satu struktur sokongan untuk kedua-dua pemegun dan pemutar dibangunkan. Mesin direka kemudiannya diuji untuk menilai analisis dan keputusan simulasi. Dalam pertindihan penuh L_a kesilapan melalui pengiraan FEA adalah kira-kira 12.90 % disebabkan penetapan parameter reka bentuk dan kira-kira 8.13 % kesesatan kerana analisis batasan praktikal. Dalam keadaan penuh bukan bertindih L_u peratusan kesilapan adalah sangat kecil dan boleh diabaikan. Masa yang diambil untuk simulasi FEA satu titik adalah kira-kira 2 min 30 saat dan pengiraan lelaran untuk satu kedudukan adalah kira-kira 10 minit. Penilaian angka perbandingan mesin yang dicadangkan dengan struktur konvensional bagi jumlah yang sama dan nilai mmf yang sama juga dilakukan melalui FEA. Tork maksimum yang dihasilkan oleh pemutar Double yang dipilih dihidupkan mesin keengganan adalah kira-kira 1.755 Nm dengan nilai THD daripada 13.45 %. Tork maksimum yang dihasilkan oleh mesin konvensional keengganan adalah kira-kira 1.272 Nm dengan nilai THD daripada 67.13 %. Analisis ini dilakukan dengan menggunakan Analisis Unsur Terhingga. Ketumpatan Motor Kuasa Dua (G) digunakan sebagai perbandingan parameter penilaian dan didapati bahawa mesin yang dicadangkan 65 % peningkatan dalam nilai tork berbanding dengan yang mesin konvensional.

ACKNOWLEDGEMENTS

My hearty thankfulness to all my friends and family who are behind the determination and will in this journey of knowledge seeking. My hearty regards to my supervisor for moulding me towards the culture of high impact research and horning my skills for the community as a whole. My kind words of gratitude for the supervisory committee for their splendid encouragement and helping to shape the research to what it is now. My kind acknowledgements for my colleague in the electrical machines laboratory, to my students for their constant and encouraging support. To my pillars of support my sister, little niece, my best partner and my adorable kind for their patience and love accommodating their support on me throughout the years.

I certify that a Thesis Examination Committee has met on (**insert the date of viva voce**) to conduct the final examination of (**Chockalingam Aravind Vaithilingam**) on his (or her) thesis entitled "**Design and Development of Double Rotor Switched Reluctance Motor using Magnetic Circuit Analysis**" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the (**Doctoral in Philosophy**).

Members of the Thesis Examination Committee were as follows:

Name of Chairperson, Ph.D.
Title (e.g. Professor/Associate Professor/Ir)
Name of Faculty
Universiti Putra Malaysia
(Chairperson)

Name of Examiner 1, Ph.D.
Title (e.g. Professor/Associate Professor/Ir)
Name of Faculty
Universiti Putra Malaysia
(Internal Examiner)

Name of Examiner 2, Ph.D.
Title (e.g. Professor/Associate Professor/Ir)
Name of Faculty
Universiti Putra Malaysia
(Internal Examiner)

Name of External Examiner, Ph.D.
Title (e.g. Professor/Associate Professor/Ir) – Omit if not relevant
Name of Department and/or Faculty
Name of Organisation (University/Institute)
Country
(External Examiner)

SEOW HENG FONG, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of **Doctor of Philosophy**. The members of the Supervisory Committee were as follows:

Norhisam Misron, PhD
Associate Professor
Name of Faculty
Universiti Putra Malaysia
(Chairperson)

Ishak Aris, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohammad Hamiruce Marhaban, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Senan Mahmod Abdullah, PhD
Associate Professor
Faculty of Engineering
Univeristy of Mosul Iraq
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently,submitted for any other degree at Universiti Putra Malaysia or at any other institution.

CHOCKALINGAM ARAVIND VAITHILINGAM

Date: 09 January 2013

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LIST OF ABBREVIATIONS

FEM	Finite Element Method	
SRM	Switched Reluctance Motor	
CSRM	Cylindrical Switched Reluctance Motor	
DRSRM	Double Rotor Switched Reluctance Motor	
THD	Total Harmonic Distortion	
DC	Direct Current	
AC	Alternating Current	
BLDC	Brushless DC Motor	
q	Number of Phases	[-]
N	Number of Turns	[-]
$k_{fringing}$	Fringing Constant	[-]
k_b	Motor Slope Constant	[-]
k_L	Inductance Ratio	[-]
k_t	Torque Constant	[-]
k_m	Motor Constant	[-]
N_s	Number of Stator Poles	[-]
N_r	Number of Rotor Poles	[-]
lg	Length of Air gap	[mm]
R_s	Resistance	[ohms]
L_s	Inductance of the Motor	[H]

mmf	Magneto motive force	[Ampere-turn]
i	Injected Current	[Amperes]
μ_0	Permeability of air	[-]
μ_r	Relative Permeability	[-]
P	Permeance	[Webers/Ampere-turn]
I_z	Current per Conductor	[Amp]
W_{sp}	Stator Pole Width	[mm]
H_{sp}	Stator Pole Height	[mm]
H_{sut}	Height of the Stator Upper Teeth	[mm]
H_{slt}	Height of the Stator Lower Teeth	[mm]
α_{cu}	Temperature Co-efficient of Copper	[-]
α	Outer Rotor Displacement Angle	[deg]
ρ_{cu}	Electrical Resistivity of Copper	[mm/S]
β_s	Stator Pole Arc Angle	[deg]
β_r	Rotor Pole Arc Angle	[deg]
β_{os}	Stator Outer Teeth Pole-arc	[deg]
β_{is}	Stator Inner Teeth Pole-arc	[deg]
β_{or}	Outer Rotor Pole Arc Angle	[deg]
β_{ir}	Inner Rotor Pole Arc Angle	[deg]
ϕ_1	Magnetic Flux linkage in air-gap 1	[deg]
ϕ_2	Magnetic Flux linkage in air-gap 2	[deg]
τ_s	Stator Pole Pitch	[deg]
τ_r	Rotor Pole Pitch	[deg]
θ_r	Rotor Angle	[deg]

θ_{on}	Turn ON Angle	[deg]
θ_{off}	Turn OFF Angle	[deg]
ω_m	Mechanical Rotational Speed	[rpm]
ϵ	Stroke Angle	[deg]
ψ	Flux Linkages	[Weber-turns]
R_{lg}	Reluctance of the Air gap	[Ampere/Vs]
R_{ory}	Reluctance of the Outer Rotor Yoke	[Ampere/Vs]
R_{orp}	Reluctance of the Outer Rotor Pole	[Ampere/Vs]
R_{usp}	Reluctance of the Upper Stator Pole	[Ampere/Vs]
R_{csp}	Reluctance of the Center Stator Pole	[Ampere/Vs]
R_{lsp}	Reluctance of the Lower Stator Pole	[Ampere/Vs]
R_{irp}	Reluctance of the Inner Rotor Pole	[Ampere/Vs]
R_{iry}	Reluctance of the Inner Rotor Yoke	[Ampere/Vs]
A_{or}	Area of the Outer Rotor Pole	[mm^2]
A_s	Area of the Stator Pole	[mm^2]
A_{ir}	Area of the Inner Rotor Pole	[mm^2]
A_{orc}	Area of Outer Rotor Core	[mm^2]
D_{or}	Diameter of the Outer Rotor Pole	[mm]
D_{os}	Diameter of the Outer Stator Surface	[mm]
D_{ir}	Diameter of the Inner Rotor Pole	[mm]
D_{sh}	Diameter of the Shaft	[mm]
E_b	Back emf	[volt]
F_t	Tangential Force	[N]
F_a	Axial Force	[N]
$lg2$	Inner Air gap Length	[mm]
$lg1$	Outer Air gap Length	[mm]

H_{or}	Height of the Outer Rotor Pole	[mm]
H_{ir}	Height of the Inner Rotor Pole	[mm]
i_p	Peak Current	[Amperes]
J_z	Current Density	[Ampere/mm^2]
P_p	Number of Pole-pairs	[-]
L_{stk}	Stack Length	[mm]
L_p	Mid-point Inductance	[mH]
L_u	Completely Non-overlap Inductance	[mH]
L_a	Completely Overlap Inductance	[mH]
l_{orc}	Length of the Outer Rotor Core	[mm]
l_{irc}	Length of the Inner Rotor Core	[mm]
T_f	Fundamental Torque	[N-m]
T_e	Average Electromagnetic Torque	[Nm]
T_{ripple}	Torque Ripple	[N-m]
T_{max}	Maximum Torque	[N-m]
T_{avg}	Average Torque	[N-m]
T_{min}	Minimum Torque	[N-m]
T_{x-axis}	Torque About x-axis	[N-m]
V_{dc}	Applied Voltage	[volts]
W_{co}	Co-energy	[watt-sec]
W_f	Field Energy	[watt-sec]
W_{mech}	Mechanical Power losses	[hp]
W_{Fe}	Iron Losses	[w]
V	Volume of the Machine	[mm^3]

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Switched Reluctance Machines (SRM) are already in the market for more than two decades finding its place in replacing the induction machines which is the workhorse in various applications. The advancements and the rapid progress in electronic control and their integration in drive technologies, SRM are fast becoming a commercial alternative for modern low power applications. With the available choice of converter circuits and micro-controllers, the design engineers today can optimize the design of such machines for specific applications. To maximize the torque generating capability, the machine is operated close to saturation developing a highly non-linear relationship between the output torque to the input current and the rotor position [?]. Though this type of machines are gaining more recognition in market due to its rugged construction, low manufacturing cost, fault tolerant capability and high efficiency they are highly influenced by the generation of torque ripple and noise due to the non-linear characteristics. Majority of the research work and publications in the literature propose the use of advanced control algorithm to address the common issues. The variations in the machine design is attempted by few [?, ?, ?]. The investigation on the design variations on the mechanical structure as in the documented works are very little. The research documented in this thesis major in the area of design of electrical machines through magnetic circuit analysis. It is rooted with a new design concept, in the reluctance machine by introducing dual air-gap through the double rotor structure. The concept, is realized with an increase of the flux linkage area by division of the single cylindrical air-gap of the motor to a dual air-gap through double rotor structure, named hereby Double Rotor Switched Reluctance Motor (DRSRM)[?]. Specifically, this study is dedicated to the analysis of the dual magnetic circuit concept, the development of analytical model and to evaluate the performance of through numerical and measurement results. The interest for the introduction of the double rotor concept emerged through the similar structure introduced for the brush-less machines for torque density improvements [?, ?]. This double rotor concept may address as a potential solution applied to the reluctance machine and therefore the present study is aimed to provide a step forward for the introduction of this concept to the manufacturers of low power reluctance machine applications. Therefore, this thesis introduce the double rotor structure design based on the concept of air-gap length reduction. In this research a structural topology selection approach to the magnetic fields of the double rotor machine is investigated, that could identify the geometry of the machine. Based on the above concept the objectives and methodology of the study are defined. An outline of the thesis concludes this introductory chapter.

1.2 Problem Statement

The simple structure and absence of windings or magnets on the rotor, reluctance machines are more suitable for variable speed applications [?]. The torque generating capability is highly influenced by the flux linkage in the air-gap. In order to increase the flux linkage area the double rotor structure that introduces the division of air-gap surface as two rotor-stator interactions is proposed. The new structure proposed based on the dual magnetic circuit is expected to exhibit better torque generating capability.

1.3 Objectives

In terms of knowledge creation, the project involves research into design of a novel double rotor switched reluctance motor. In order to achieve this, the research work is divided into the following specific research objectives:

1. **to propose a dual air-gap structure machine and to analyse its magnetic characteristics through a new flux tube method**

2. **to propose the step by step design of the machine involving the design constraints and to derive the best possible combinations that develop low total harmonic distortion.**

3. **to evaluate the analytical results with that of the numerical results.**

4. **to fabricate the machine and to study the performance of the machine.**

5. **to compare the proposed structure with dual air-gap with that of the conventional cylindrical single air-gap for the same volume using the FEA tool.**

1.4 Scope of Study

In this research, focus is given to introduce the concept of dual air-gap through double-rotor structure. The dual rotor as is investigated in the present research introduces two magnetic air-gap cylindrical surfaces replacing the single magnetic air-gap cylindrical surface. This increases the flux linkage area for larger energy conversion without the addition of core material. However the design is constrained with the choice of pole-arcs as it determines the torque generating capability in this type of machines.

The limitations on the machine structure evolve this type of machines for low power applications at large. The increase in size and volume of such machine is expected to be competitive for drive applications. Mathematical analysis is made on the various pole-arcs and the constraints in the design are proposed. This serves as a guidance in the design of such machines in future. Due to the manufacturing limitations, the analysis is performed for interval of 5°. However the use of optimal tool would narrow the value of the pole-arcs more accurate, once again the fabrication would be highly intricate. With the derived constraints the machine is analysed for the magnetic characteristics through the proposed flux tube methods. The torque, inductance, flux linkages characteristics of the proposed machine is derived from this analysis.

Finite Element Method (FEM) analysis software tool is used for capturing the magnetic characteristics such as flux flow, magnetic density and torque characteristics to validate the above analytical method used in the design. This is also used to study the effects of variation of the machine parameters including the height and width of the poles and pole teeth. The tool is also used to built the conventional machine for validation of the proposed machine torque characteristics. The effect of eddy current and magnetostiction is not considered as the results evolve from static conditions. In most previous researches, the torque density comparisons are discussed without considering the volume and power of the motor. In this work, the motor constant square density is used as a quality factor to evaluate the proposed structure. Motor constant square density is used as evaluation parameter as it includes the torque, the volume and the power rating of the machine.

1.5 Contribution of the Thesis

1. The magnetic circuit analysis approach using flux tube methods is introduced. The procedure outlined herewith is simple and is one of the major developments in this dissertation. The formulations of this approach is used in the design and development of the double rotor structure. This method is used for development of the novel double rotor reluctance motor.

2. None of the previous research attempt for the symmetrical double rotor strategy about the common axis in reluctance machines due to the mechanical design constrains. This work could pave way for further research in the multi-rotor design and also the design aspects can be extended to the design of other electrical machines. This covers a the design procedure of a 6/4 (6 stator and 4 rotor poles) double rotor switched reluctance motor from the first principles of electro-magnetics including the limitations to be taken care in the design.

3. Lastly the evaluations of the double rotor motor is presented through experimental results with that of the design results

1.6 Outline of the Thesis

The thesis consists of five chapters in which each chapter presents the flow of the research study involved. This thesis is devoted to the design and development of double rotor switched reluctance machine through magnetic circuit analysis. The outline of the thesis is as follows:

Chapter One gives a brief introduction of the research background of this study. The research requirements are stated as the problem statement to define the key research aspects used. The objective and aim of the study are listed to set the focus of the research. Subsequently, the scope of the research work is highlighted.

Chapter Two presents working principles and application of the demonstration machine. The background research work in terms of the reluctance machine design is comprehensively documented.

Chapter Three presents the methodology that includes the design of the double rotor reluctance machine through magnetic circuit analysis, the analytical computation using flux tube methods to derive the best parameters of the machine, the finite element to evaluate the analytical results, the selection of the best model based on the selected pole arc combinations. The prototype development and fabrication process, the measurement set-up used in this investigations is explained towards end of the chapter

Chapter Four presents the results and discussions on the computations of the analytical approach using flux tube methods, the numerical analysis using FEA tool and that of the experimental results.

Chapter Five concludes the thesis dissertation in term of the design process and the analysis result of DRSRM. Also, this chapter includes a few recommendations that can be implemented in this research field in the future.

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