UNIVERSITI PUTRA MALAYSIA

A DUAL IRON-RING DOUBLE-STATOR PERMANENT MAGNET INTEGRATED WITH A MAGNETIC GEAR FOR LOW SPEED POWER GENERATOR

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By

MUSTAFA SHEHU SALIHU

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

April 2018

DEDICATION

To my parents

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

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Chairman : Professor Norhisam Bin Misron, PhD
Faculty : Engineering

Magnetic gears and magnetic geared permanent magnet (PM) machines have recently been emerging as a new class of future electromechanical machines which can address problems of low-speed power generators. A magnetic geared generator integrates a magnetic gear with a low torque, high-speed PM generator to produce a compact low-speed, high torque machine with the advantages of a direct drive PM machine and magnetic gear. Although, previous low-speed PM generators designed with high number of poles and magnetic geared generators both eliminate the use of a mechanical gear, their power density capacity is low to generate sufficient electrical power for low-speed applications. The proposed magnetic geared generator with high power density due to the dual-iron ring is specifically aimed to address problems of low-power density in low-speed power generators. A magnetically coupled configuration structure is implemented in the generator design with dual-iron rings and three layers of mutual PMs. This configuration enables the three PMs achieve total flux-linkage in both outer and inner machines, therefore increasing the number of air gaps and power density. The proposed machine operates simultaneously as a magnetic gear and electrical power generator. A two dimensional finite element method (2D FEM) is used to study and predict the performance characteristics of the magnetic geared generator. A prototype of the magnetic geared generator is fabricated and experimentally evaluated, for performance parameters such as transmission torque, electrical power-speed characteristics and efficiency. In addition, the proposed magnetic-geared generator is compared with previous magnetic-geared generators and the effectiveness is verified by using power density evaluation. It is found from the measured results that the magnetic geared PM generator with an active stack length of 30 mm, size of 150 mm and active volumetric density of 393 cm^3 achieved maximum DC power and AC power of ≈ 250 W and ≈ 360 W, respectively. The maximum torque achieved on DC load and AC load are ≈ 12 Nm and ≈ 11 Nm respectively, with an

efficiency of ≈ 55% at prime speed of 250 rpm on DC load and ≈ 52% at prime speed of 250 rpm on AC load, with a power factor of 0.99 respectively. The magnetic geared PM generator demonstrates overload protection by slipping at prime speed in excess of 500 rpm. In addition, the magnetic geared PM generator was found to achieve a measured maximum active power density of ≈ 917 kW/m^3. The calculated and measured results are in good agreement to verify the validity of the proposed magnetic geared generator design. The proposed magnetic-geared generator has a higher power density than the previous magnetic-geared generators. Also, the maximum electrical power of the proposed magnetic-geared generator is sufficient for low-speed applications. The power due to the dual-iron rings is greater than the early magnetic-geared generators.

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

MAGNET KEKAL PEMEGUN KEMBAR GELANG-BESI DUAAN BERSEPADUKAN GEAR MAGNETIK UNTUK PENJANA KUASA BERKELAJUAN RENDAH

Oleh

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Gear magnet dan mesin magnet kekal bergear magnet telah baru-baru ini muncul sebagai kelas baru mesin elektromekanik masa depan yang boleh menangani masalah gear mekanikal dan mesin bergear mekanikal. Penjana bergear magnet bersepadukan gear magnet dengan kilas rendah, penjana PM berkelajuan tinggi untuk menghasilkan mesin kilas berkelajuan tinggi yang padat, dengan kelebihan mesin PM pemacu langsung dan gear magnet. Walaupun, penjana PM berkelajuan rendah sebelumnya direka dengan bilangan kutub yang tinggi dan penjana bergear magnet, kedua-duanya menghapuskan penggunaan gear mekanik, kapasiti ketumpatan kuasa mereka adalahterlalu rendah untuk menghasilkan kuasa elektrik yang mencukupi untuk aplikasi berkelajuan rendah. Penjana bergear magnet yang dicadangkan dengan ketumpatan kuasa yang tinggi disebabkan oleh gelang-besi duaan ini khususnya bertujuan untuk menangani masalah kepadatan berkuasa rendah pada penjana kuasa berkelajuan rendah.Struktur tatarajah yang digabungkan secara magnetik dilaksanakan dalam reka bentuk penjana dengan gelang-besi duaan dan tiga lapisan PM bersama. Tatarajah ini membolehkan tiga PM mencapai total hubungan fluks dalam mesin luar dan dalaman, oleh itu meningkatkan jumlah jurang udara dan ketumpatan kuasa. Mesin yang dicadangkan ini beroperasi secara serentak sebagai alat magnetik dan penjana kuasa elektrik. Kaedah elemen terhingga dua dimensi (2D FEM) digunakan untuk mengkaji dan meramal ciri-ciri prestasi penjana bergear magnet. Prototaip penjanabergear magnet telah direka dan dinilai secara ujikaji, bagi parameter prestasi seperti kilas penghantaran, ciri-ciri kuasa dan kecekapan kuasa elektrik.Tambahan pula, penjana bergear magnet yang dicadangkan telah dibandingkan dengan penjana bergear magnet yang sedia ada sebelumnya dan keberkesanannya telah disahkan dengan menggunakan penilaian ketumpatan kuasa. Adalah didapati dari hasil yang diukur bahawa penjana PM bergear magnet dengan panjang tindanan aktif 30 mm, saiz 150 mm dan ketumpatan volumetrik aktif 393 cm3

telah masing-masing mencapai kuasa DC maksimum dan kuasa AC $\approx$ 250 W dan $\approx$ 360 W. Kilas maksima yang telah dicapai pada beban DC dan beban AC masing-masing adalah $\approx$ 12 Nm dan $\approx$ 11 Nm, dengan kecekapan $\approx$ 55% pada kelajuan prima 250 rpm pada beban DC dan $\approx$ 52% pada kelajuan prima 250 rpm pada beban AC, dengan faktor kuasa 0.99 masing-masing.Penjana PM bergear magnet menunjukkan perlindungan beban lebih dengan tergelincir pada kelajuan utama melebihi 500 rpm. Adalah juga didapati bahawa penjana PM bergear magnet telah mencapai ketumpatan kuasa maksimum yang diukur sebanyak $\approx$ 917 kW / m3. Hasil yang dikira dan diukur adalah dalam sekaitan yang baik untuk mengesahkan kesahan reka bentuk penjana bergear magnet yang dicadangkan. Penjana bergear magnet yang dicadangkan mempunyai ketumpatan kuasa yang lebih tinggi daripada penjana bergear magnet sebelumnya. Juga, kuasa elektrik maksima penjana bergear magnet yang dicadangkan adalah mencukupi untuk aplikasi berkelajuan rendah. Kuasa disebabkan oleh gelang-besi duaan adalah lebih besar daripada penjana bergear magnet yang awal.

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This thesis was submitted to the Senate of the 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:

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- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

2-D	Two Dimensional	
3-D	Three Dimensional	
AC	Alternating Current	
ALT	Average Length of One Coil Turn	[mm]
AWG	American Wire Gauge	
CMG	Coaxial Magnetic Gear	
CSFM-TS-	Circuit-Field-Motion Coupled Time-Stepping Axisymmetric Finite	
DC	Direct Current	
DOF	Degree of freedom	
DSMGM	Double-Stator Magnetic Geared Machine	
EMF	Electromotive Force	[V]
FEM	Finite Element Method	
FMDD	Flux Modulated Direct Drive	
FFT	Fast Fourier Transform	
GCD	Greatest Common Multiple	
LCM	Lowest Common Multiple	
MGDSPMG	Magnetic Geared Double-Stator Permanent Magnet Generator	
MG	Magnetic Gear	
MGM	Magnetic Geared Machine	
MGPM	Magnetic Geared Permanent Magnet	
MGPMM	Magnetic Geared Permanent Magnet Machine	
MIPMG	Motor Integrated Permanent Magnet Gear	
mmf	Magnetomotive Force	
NdFeB	Neodymium-Iron-Boron	
PC	Permeance Coefficient	
PF	Power Factor	
PM	Permanent Magnet	
rms	Root mean Square	
SmCo	Samarium Cobalt	
TPLM	Tubular Linear Permanent Magnet Machine	

LIST OF SYMBOLS

α_{ph}	Electrical Angle Between Two Slots	[deg]
A_{cu}	Cross-Sectional Area of Copper	[mm^2]
A_g	Airgap Flux Density	[T]
A_M	Cross-Sectional Area of a Magnet Pole	[mm^2]
b_{si}	Inner Stator Tooth Width	[mm]
B_r	Remanence	[T]
b_{so}	Outer Stator Tooth Width	[mm]
d_r	Distribution Ratio Factor	
d_{so}	Outer Stator Lip Thickness	[mm]
d_{si}	Inner Stator Lip Thickness	[mm]
f	Frequency	[Hz]
f_c	Cogging Torque Factor	
f_{LKG}	Leakage Coefficient	
g	Effective Airgap Length	[mm]
G_r	Gear Ratio	
h_{si}	Inner Stator Tooth Height	[mm]
h_{so}	Outer Stator Tooth Width	[mm]
H_c	Magnetic Field Intensity	[At/m]
H_M	External Magnetization Field	[At/m]
I_{DC}	Current of DC Source	[A]
I_{phase}	Current Per Phase	[A]
I_{rms}	Root Mean Square Current	[A]
k_{slope}	Torque-Speed Constant	
l_M	Magnet Thickness	[mm]
m_1	Number of Phases	
n_s	Number of Pole Pieces	
N_{phase}	Number of Phases	
N_s	Number of Stator Slots	
P_{AC}	Power of AC Source	[W]
P_{cu}	Copper Loss	[W]

P_{DC}	Power of DC Source	[W]
$P_{density}$	Active Power Density	[W/cm^3]
P_{Fe}	Iron Loss	[W]
P_{mech}	Mechanical Power	[W]
P_{rms}	Root Mean Square Power	[W]
q_1	Number of Slots Per Pole Per Phase	
R_{phase}	Resistance Per Phase	[Ω]
R_c	Resistance Per Coil	[Ω]
$S_{apparent}$	Apparent power	[W]
S_{wi}	Inner Stator Slot Opening Width	[mm]
S_{wo}	Outer Stator Slot Opening Width	[mm]
T_{avg}	Average Torque	[Nm]
T_{field}	Field Torque	[Nm]
T_{prime}	Prime Torque	[Nm]
T_{max}	Maximum Transmission Torque	[Nm]
T_r	Transmission Torque Ratio	
V_A	Active Volume	[mm^3]
V_{DC}	Voltage of DC Source	[V]
V_{rms}	Root Mean Square Voltage	[V]
W_{bii}	Inner Stator Back Iron Width	[mm]
W_{bsi}	Inner Stator Slot Base Width	[mm]
W_{bio}	Outer Stator Back Iron Width	[mm]
W_{bso}	Outer Stator Slot Base Width	[mm]
W_{sto}	Outer Stator Slot Top Width	[mm]
W_{sti}	Inner Stator Slot Top Width	[mm]
Z_{planet}	Number of Planet Gear Teeth	
Z_{ring}	Number of Ring Gear Teeth	
Z_{sun}	Number of Sun Gear Teeth	
θ_{air}	Air Slot Angle	[deg]
θ_{iron}	Pole Piece Angle	[deg]
η	Efficiency	
μ_{rec}	Relative Recoil Permeability	

μ_0	Permeability of Free Space	μ_0
ω_{field}	Rotational Speed of Field Rotor	ω_{field}
ω_{planet}	Rotational Speed of Planet Gear	ω_{planet}
ω_{prime}	Rotational Speed of Prime Rotor	ω_{prime}
ω_{planet}	Rotational Speed of Planet Gear	
ω_{prime}	Rotational Speed of Prime Rotor	
ω_{ring}	Rotational Speed of Ring Gear	
ω_{sun}	Rotational Speed of Sun Gear	

CHAPTER 1

INTRODUCTION

1.1 Background

In the last 10 years, research and development in magnetic gear technology have led to the advancement of a new class of electrical machines called magnetic geared machines. The operating principle of a magnetic gear is similar to a mechanical gear as torque is transferred from the low speed shaft to the high speed shaft with permanent magnets. A magnetic geared machine is an electrical machine which is obtained from a conventional permanent magnet (PM) machine integrated with a magnetic gear (MG). Some studies have reported that the magnetic geared machine can achieve a high torque density as a magnetic geared motor or high power density as a magnetic geared generator [Frandsen et al., 2015; Zhang, Liu, and Chen, 2016; Johnson, Gardner, and Toliyat, 2017]. Also, the resultant magnetic geared machine can be used as generators for low-speed power generation applications [Oshiumi, Niguchi, and Hirata, 2014; Johnson, Gardner, and Toliyat, 2017]. A study by Niu, Chau, and Yu (2009) found that permanent magnet (PM) machines with a double-stator topology achieved greater performance characteristics than conventional single-stator permanent magnet machines. The research on magnetic geared double-stator PM machines has steadily increased recently in the last 10 years, although very few studies have been conducted on this class of MG machines. This could be as a result of the machine's complex structure which comprises of several parts. Jian and Chau (2010) proposed a double-stator MG PM machine with its structure composed of two PM rotors and a single rotating modulating iron ring rotor. The magnetic geared machine was designed to operate in a motor/generator power-splitting mode for applications in electric vehicles (EVs). Although this magnetic-geared machine has high-transmission torque, the power density is low. This is because the two PM rotors rotate at different speeds which cause the inner and outer machines to be unbalanced; therefore the MG machine cannot operate as a generator in full mode. To solve this problem, Niu, Ho, and Fu (2013) presented an improved modified design by removing the modulating pole piece rotor and retaining two PM rotors. Non-magnetic ferrite poles were equally inserted between each pair of PMs to achieve a power-split electromechanical device (motor/generator). However, the proposed MG machine cannot operate fully as a generator as a result the power density is low. Liu, Chau, and Zhang (2012) proposed a double-stator MG PM machine design which consisted of a single PM rotor for low-speed, high torque applications. The MG machine has a high torque density as a motor but it cannot function as a generator because there is no field PM to excite the coil windings in the outer and inner stators to produce electrical power. Wang et al. (2015) published in a study two double-stator magnetic flux-modulated mnemonic machine designs that combined magnetic gearing principle and the concept of flux-mnemonic. The first machine design presented was a dual-layer PM magnetic flux-modulated mnemonic machine (MFMM) with PMs mounted on both the outer stator and rotor, while the second machine design proposed was a single layer PM magnetic flux-modulated mnemonic machine with all PMs fixed only on the outer stator. Although the two proposed magnetic-geared machines have high-transmission torque density, the excitation power density is low. This is because the field PMs which could excite the coil windings to produce electrical power is mounted on the tips of the stator teeth and this blocks the magnetic flux from the coils. Although previous studies conducted on MG double-stator PM machines have contributed significantly to the present knowledge about this class of magnetic geared machines, it can be reasonably assumed that there are wide areas of research on magnetic geared double-stator PM machines as in the documented works are very little, therefore requiring further investigation.

This research work presents a dual iron-ring magnetic geared double-stator PM generator with high power density which is essentially important for low-speed power generators. The proposed magnetic geared generator may address the problems associated with low-speed power generation in Malaysia particularly for applications such as low-speed wind power generation. This is very useful for applications where high power density is required for low-speed power generation. For this reason, the present study is aimed to introduce this concept to the industry such as manufacturers of low-speed power generators. Therefore this research work proposes a dual-iron ring structure design based on the concept of magnetic geared machines. In this research work, the structure of the magnetic-geared generator with dual-iron rings is investigated that will identify the geometry of the machine. Consequently, the objectives and methodology of the research work are defined. This introductory chapter concludes with an outline of the thesis.

1.2 Problem Statement

Mechanical geared electrical machines are suitable for low-speed applications, mostly when operated as generators. But the problems and reliability of mechanical gears limit the power and speed performance of mechanical geared electrical machines. To solve this problem for low-speed applications, the mechanical gear is removed and a direct drive permanent magnet (PM) generator is designed with high number of poles in order to generate electrical power at low-speed. Although it eliminates the use of a mechanical gear and is desirable for this application, the machine must have high-power density to generate sufficient electrical power for low-speed applications. With the introduction of magnetic gears, research and development has progressed rapidly in the last 10 years with the introduction of magnetic geared machines. A magnetic geared generator integrates a magnetic gear with a low torque, high speed power generator which results to a compact low speed, high torque machine with the advantages of a direct drive PM machine and mechanical geared machine.

Previous magnetic geared generators have a high transmission torque density. However, the power due to the magnetic gear is low because with few numbers of air gaps, the field excitation from the permanent magnets is not sufficient to excite the coil windings in the stator and generate electrical power. This also reduces the power density for low-speed power generators. In order to address this problem, a double-stator magnetic geared generator with a dual-iron ring structure is proposed with a high-power density. The new proposed structure with a dual-iron ring, integrates a magnetic gear with a double-stator PM machine. This increases the number of air gaps and field excitation from the permanent magnets with better power density generating capability for low-speed power generators in Malaysia.

1.3 Aim and Objectives

The main aim of this research work is to develop a new structure of magnetic geared double-stator permanent magnet generator for low-speed power generation applications. A low-speed magnetic geared generator with high power density due to dual-iron ring is proposed. To achieve this concept, the research work is divided into the following specific research objectives as follows:

1. To propose a new structure of magnetic geared double-stator permanent magnet generator with dual-iron ring.
2. To design a magnetic geared double-stator permanent magnet generator with high power density due to the dual-iron ring for low-speed power generation applications in Malaysia.
3. To simulate and analyze the magnetic geared machine's magnetic circuit using finite element analysis method.
4. To fabricate and experimentally test the performance characteristics of a prototype magnetic geared double-stator permanent magnet generator.

1.4 Scope of study

In this research, the aim is to introduce the concept of magnetic gearing by integrating with a double-stator permanent magnet generator through a triple-rotor structure. The triple-rotor magnetic gear concept studied in this research introduces six magnetic air-gaps with radial and tangential components. Also dual -iron rings are used to produce flux path and modulate the space harmonics in the air-gap between the field permanent magnets and prime mover permanent magnets. This increases the magnetic flux area for torque transmission between the inner and outer rotors. However the machine design is constrained with the selection of both inner and outer stator structure and magnet pole-arcs as they determine the cogging torque and transmission torque of the generator. Although it has a complex mechanical structure, the expected increase of the proposed machine's power density is expected to be suitable for low-speed power generator applications.

Parametric analysis is used to study various magnet pole-arcs and stator structure to determine the optimal design. Performance characteristics that include; cogging torque, transmission torque, electrical power, voltage, current and speed characteristics are obtained from this analysis. A two dimensional finite element method (2D FEM) analysis software tool is used to study its magnetic characteristics such as flux flow, flux density, harmonic spectrum, torque characteristics and efficiency. The effects of variation of the machine parameters including the stators slot width, tooth angle, tooth thickness and magnet pole-arc are also studied to find their effects on the machine's performance. Three dimensional finite analysis (3-D FEM) is not considered in this research as it requires a lot of calculation time, computation power and more powerful computers. Also in most previous research, 2-D FEM is mostly used because models can be evaluated quickly by simulation and its accuracy is 10% less than 3-D FEM.

In this research work a prototype will be fabricated and tested to validate the simulation results. The power characteristics will be used as a quality factor to evaluate the proposed machine. The power characteristics evaluation parameters include the torque, speed, electrical power, active volume and power rating of the machine. Finally, detailed thermal analysis and analytical modeling of the machine is beyond the scope of this research because thermal constraints need to be specified and the thermal property of materials is a complex problem that involves a lot of variables. Also is quite complicated to conduct analytical computation because of the machine's complex structure with six air gaps.

1.5 Contribution of the Thesis

1. The proposed magnetic-geared generator has originalities in its structure, particularly the placement of dual-iron rings in the air gaps between the prime and field permanent magnets. The introduction of two modulating iron rings for both outer and inner air gaps is one key contribution to the design of the proposed machine. By integrating a magnetic gear designed with two modulating iron rings and three independent permanent magnet rotors, a higher power density low-speed power generator is achieved.
2. In the previous research a single rotor for the PMs is used while in another study two PM rotors are utilized in the structure. The structure of the proposed magnetic geared double-stator PM generator is designed with three permanent magnet rotors and two iron rings to increase the flux density in the air gaps between the prime PMs and field PMs in order to achieve higher power density.
3. The proposed magnetic-geared generator has greater power density and the effectiveness is verified by comparison with previous magnetic-geared generators.

1.6 Outline of the Thesis

This thesis research work comprises of five chapters in which the process of the study is presented in each chapter. The thesis is focused on the development of a novel magnetic geared double-stator permanent magnet generator through finite element analysis and fabrication of a prototype. The thesis is organized as follows:

Chapter One presents a brief introduction of the research background to this study which includes the key problems to be addressed, the problem statement, aims and objectives of the study, scope and limitations.

Chapter Two reviews the history of magnetic gears and magnetic geared machines, discusses the previous published works and variation in design of proposed structures. The basic operating principles of magnetic gearing are described and numerous structures of magnetic geared machines are studied. The contributions and limitations of previous works are discussed and compared including the most recent state in development of magnetic geared permanent magnet (PM) machines.

Chapter Three describes the methodology and design of the magnetic geared double-stator PM generator through finite element analysis, the parametric design approach to derive the best parameters for optimal design and the finite element analysis to predict its performance characteristics. The development of the prototype, process of fabrication, manufacturing considerations, construction and mechanical assembly are explained. The experimental setup and measurement procedure for evaluating performance characteristics including validation with the calculated results are also reported.

Chapter Four presents the findings and results achieved, while discussions and evaluation of the magnetic geared PM generator's performance characteristics are presented. Also validation of the proposed magnetic geared PM generator design by comparison of measured with predicted results is reported.

Chapter Five concludes the research work from the design process to the performance analysis results. The contributions achieved in this study are summarized; recommendations and possible future work in this research area are identified.

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