Faculty of Electrical Engineering

MODELLING AND ANALYSIS OF NEW DOUBLE STATOR SLOTTED ROTOR PERMANENT MAGNET MACHINE

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DECLARATION

I declare that this thesis entitled "Modelling and Analysis of New Double Stator Slotted Rotor Permanent Magnet Machine" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ……

Name : Suhairi Rizuan bin Che Ahmad

Date : ……

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

Signature : ……

Supervisor Name : Assoc Prof. Dr. Raja Nor Firdaus Kashfi bin Raja Othman

Date : ……

DEDICATION

To my beloved wife and children's,

Fatma Mulyani Binti Alluwi (wife)

Fatma Nur Iman,

Muhammad Luqman Nasrullah

Fatma Nur Adni

My beloved parents,

Che Ahmad Bin Senik, Zainab Binti Said, Alluwi Bin Ahmad, and Ruhani Binti Zakaria

My beloved siblings,

Suraya, Sukma, Suhaila, Suhardi, Suhairul, Sukiman, Suaini, Shukri, Shafini and Farrahanim

Lastly, my colleagues and friends.

ABSTRACT

Over the past few years, the usage and demand of permanent magnet machine were very high due to its high power density and high efficiency. There are many stator topologies used in designing permanent magnet machine such as double stator topology. The main constraint of the double stator topology is to maintain its mechanical air gap between the inner and outer stator. A significantly large air gap was noted because the rotor was made from non-ferromagnetic material that led to uneven flux distribution. The second issue refers to the complex design of the double stators that shared similar magnetic and mechanical structures. They required more computational time in designing the double stators. Most researchers have looked into the design of electrical machine for either motor or generator. However, a few of them has investigated the motor-generator mode configurations. This thesis discussed the modelling and analysis of a new double stator slotted rotor permanent magnet machine (DSSR-PMM). A new slotted rotor from ferromagnetic material was used for the double stators in order to maximise the flux produced by the permanent magnet and coil by reducing flux leakage. The implementation of slotted rotor optimised the magnetic flux and evenly distributed the air gap of the inner and outer stator. The Permeance Analysis Method (PAM) for modelling the sizing equation of DSSR-PMM reduced computational time. The PAM formulated the sizing equation to calculate the magnetic flux of air gaps in the inner and outer stator. The performance of the DSSR-PMM under motor-generator mode was analysed in three main condition systems i.e. motoring mode, generating mode and motor-generator modes. In the motoring or generating mode configurations, both inner and outer stator served as the motor or generator or vice-versa. In this research, the numerical design used finite element method (FEM) to validate PAM. The FEM was also used to analyse the characteristics of flux linkage, back EMF, and inductance. For further validation, a prototype of DSSR-PMM was fabricated and tested with various loading conditions to derive the electromagnetic torque, the output power, and the efficiency for the proposed structure. The results from FEM and measurement were verified and they appeared to be in good agreement. The highest efficiency and torque had been achieved by using motoring mode of 94 % and 16.2 Nm respectively. The generating mode showed consistent efficiency value with maximum power and efficiency of 1000 W and 75% respectively. As for the motor-generator mode, the DSSR-PMM showed simultaneous performance as the motor and the generator depended on primary and secondary modes. In motor-generator mode displayed similarity in graph pattern for torque, efficiency, input, and mechanical power. For benchmarking purpose, the proposed DSSR-PMM exhibited 19% higher percentage of power density, when compared to the previous double stator structure. It was discovered that the flux linkage and back EMF was increased by 50% and 46% when the double stator slotted rotor structure implemented in comparison to the single stator topology with the same design structure. The output torque was increased as the structure has two air gaps in the inner and outer stators which was advantageous to the DSSR-PMM in motoring mode. The efficiency of DSSR-PMM in generating mode was maintained as the speed of generator was increased. As for advantage the DSSR-PMM can operate in wider operating speeds and loads. The details on individual losses, a use of optimum power driver circuit and the fabrication cost of DSSR-PMM need to consider for future research. This thesis offers guidelines for designing and analysing DSSR-PM machine.

ABSTRAK

Sejak beberapa tahun yang lepas, penggunaan dan permintaan terhadap mesin magnet kekal sangat tinggi kerana ketumpatan kuasa dan kecekapan yang tinggi. Pelbagai topologi pemegun yang digunakan untuk merekabentuk mesin magnet kekal seperti topologi dua pemegun. Kekangan utama topologi dua pemegun adalah untuk mengekalkan jurang udara mekanikalnya antara pemegun dalaman dan luaran. Terdapat jurang udara yang besar disebabkan oleh pemutar yang diperbuat daripada bahan bukan ferromagnet membawa kepada pengagihan fluks yang tidak sekata. Isu kedua adalah reka bentuknya yang rumit kerana mempunyai dua pemegun dan berkongsi struktur mekanikal dan magnetik yang sama. Ini memerlukan masa yang lebih untuk proses pengkomputeran dan rekabentuk. Kebanyakan penyelidik menjalankan penyelidikan untuk rekabentuk motor atau penjana. Walau bagaimanapun, segelintir daripada mereka yang terlibat rekabentuk unuk mod motor-penjana. Tesis ini membincangkan pemodelan dan analisis mesin magnet kekal berlubang alur dua pemegun (DSSR-PMM) yang baru. Pemutar berlubang alur yang baru menggunakan bahan ferromagnetik untuk memaksimumkan fluks yang dihasilkan oleh magnet kekal dan gegelung dengan mengurangkan fluks yang bocor. Pemutar alur berlubang juga membolehkan fluks magnet dioptimumkan dan diagihkan secara sama rata di antara jurang udara dalaman dan luaran pemegun. Kaedah Analisis Telapan (PAM) telah digunakan untuk pemodelan persamaan ukuran DSSR-PMM untuk mengurangkan masa pengiraan. PAM merumuskan persamaan ukuran untuk mengira fluks magnet dalam jurang udara pemegun dalaman dan luaran. Prestasi DSSR-PMM di bawah mod motor-penjana dianalisis dalam tiga keadaan iaitu mod pemotoran, mod penjanaan dan mod motor-penjana. Dalam konfigurasi ini, kedua-dua pemegun dalaman dan luaran bertindak sebagai motor atau penjana atau sebaliknya. Dalam kajian ini, rekabentuk berangka menggunakan kaedah unsur terhingga (FEM) untuk mengesahkan PAM. FEM juga digunakan untuk menganalisis ciri-ciri fluks, EMF dan kearuhan. Untuk pengesahan lanjut, prototaip DSSR-PMM telah direka dan diuji dengan pelbagai nilai beban untuk mendapatkan daya kilas elektromagnetik, kuasa keluaran dan kecekapan untuk struktur yang dicadangkan. Keputusan FEM dan pengukuran telah disahkan dan didapati bersesuaian. Daya kilas dan kecekapan tertinggi dicapai oleh mod motor iaitu 16.2 Nm 94%. Untuk mod penjana menunjukkan nilai kecekapan yang konsisten dengan kuasa maksimum dan kecekapan adalah 1000 W dan 75%. Bagi mod motor-penjana pula, DSSR-PMM menunjukkan prestasi serentak sebagai motor dan penjana bergantung kepada mod yang dirujuk samada primer atau sekunder. Dalam mod motor-penjana ini menunjukkan corak kesamaan untuk daya kilas, kecekapan, kuasa masukan dan mekanikal. Sebagai penanda aras, DSSR-PMM yang dicadangkan mempunyai ketumpatan kuasa 19% lebih tinggi berbanding struktur dua pemegun sebelumnya. Fluks dan EMF meningkat 50% dan 46% apabila perbandingan diantara struktur dua pemegun dengan struktur satu pemegun dibuat. Daya kilas keluaran meningkat kerana mempunyai dua jurang udara dalam dan luar yang memberi manfaat kepada DSSR-PMM dalam mod motor. Kecekapan DSSR-PMM dalam mod penjanaan konsisten walaupun kelajuan penjana meningkat dan memberi kelebihan kepada DSSR-PMM untuk beroperasi pelbaga kelajuan dan beban. Kehilangan kuasa, penggunaan litar pemacu kuasa optimum dan kos pembuatan DSSR-PMM perlu dipertimbangkan untuk penyelidikan masa depan. Tesis ini menyediakan garis panduan untuk reka bentuk dan analisis mesin DSSR-PM.

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a_g	-	Air gap area
g	-	Air gap
A_m	-	Area of permanent magnet, [m^2]
A_{coil}	-	Area of copper, [m^2]
A_{slot}	-	Area of coil between the slot, [m^2]
ABS	-	Acrylonitrile butadiene styrene
AC	-	Alternative current
I_a	-	Armature current, [A]
R_a	-	Armature resistance, [Ω]
T_{avg}	-	Average torque, [Nm]
Θ	-	Angle of stator teeth, [°]
Back EMF	-	Back electromotive force
BLDC	-	Brushless DC
k_e	-	Back EMF constant
V_{emf}	-	Back EMF voltage, [V]
V_b	-	Back EMF of the motor, [V]
c	-	Capacitance, [uF]
CPF	-	Coil packing factor
CFM-TS-FEM	-	Circuit-field-motion coupled time stepping finite element

		method
CNC	-	Computer numerical machine
H_c	-	Coercive force
I	-	Current, [A]
P_{copper}	-	Copper losses, [W]
P_{coreloss}	-	Core losses, [W]
W	-	Co-energy of DSSR-PMM
DC	-	Direct current
DOE	-	Design of experiment
DPMSM/G	-	Double side permanent magnet synchronous motor/generator
DSP	-	Data signal processor
DS-AFPMG	-	Double stator axial flux pm generator
DS-BLDC	-	Double- stator brushless dc permanent magnet machine
DSCR-PMM	-	Double-stator cup-shape rotor pm machine
DS-ECVT	-	Double-stator double-rotor brushless electrical continuously variable transmission
DS-HESG	-	Dual-stator hybrid excited synchronous wind generator
DS-PMBL	-	Double-stator permanent magnet brushless motor
DS-PMBLDC	-	Double-stator permanent magnet brushless dc motor
DS-PMG	-	Double stator permanent magnet generator
DS-PMMGG	-	Double-stator magnetic geared machine
DS-PMSG	-	Dual stator five phase permanent magnet synchronous generator
DS-PMSM	-	Double- stator permanent magnet synchronous motor