UNIVERSITI PUTRA MALAYSIA

DESIGN AND ANALYSIS OF A SINGLE AND DOUBLE STATOR OF SINGLE-PHASE SLOT-LESS PERMANENT MAGNET GENERATOR

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By

NORAFIZA BINTI MASRUNI

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

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Dedication

TO MY BELOVED PARENTS, MY SISTERS, MY BROTHERS, MY FIANCÉ, AND MY FRIENDS.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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SEPTEMBER 2009

Chairman: Norhisam Misron, PhD

Faculty: Engineering

Permanent magnet (PM) generator has been an object of numerous research studies with different structures and geometries proposed for different applications. Generator is a machine that is used to convert mechanical energy into electrical energy. Due to the availability and decreasing cost of high energy PM material, PM generator is more attractive than other types of power generator. For agriculture application, the existing generator that is available in the market does not meet the size and power capability requirements.

The proposed PM generator operates in a single-phase, slot-less type, and the flux direction in the air gap is radial. The PM generator was developed for agriculture application especially for high speed performance between 3000 revolution per minute (rpm) to 8000 rpm. The prime mover for this PM generator is a petrol engine with capability of 1.3 horse power (hp). The external force from the engine will make the generator rotates with high speed. The electrical power produced energizes an

electric motor suitable for pruner application. Thus, in this research, the design and analysis of the PM generator is studied. The PM generator is aimed to produce an output voltage of 130 V with the overall diameter size of 104 mm.

At the early stage, a single-phase slot-less PM generator is designed with a single stator and the PM is placed in the v-shape pattern to provide the required flux. Based on the flux distribution in the PM generator, it shows that about half of the upper flux goes to the air gap and travel in the stator while the other bottom half goes to the shaft. This means that half of the bottom flux is wasted at the shaft. According to this characteristic, a double stator slot-less PM generator is proposed with a circular pattern PM with air gap between the inner and outer stator to improve the performance of the generator. Based on this design, all the generated flux is used to generate the voltage.

In order to understand the conditions where the PM generator shows potential advantages, various parameters are varied such as number of pole and radius of the rotor. Generally, the technique used to examine the performance of the PM generator is permeance analysis method (PAM) and finite element method (FEM). The theoretical analysis is verified by comparing the predicted and measured output power, resistance, and inductance on a prototype of the PM generator. Based on the results, the highest output power could be achieved by single stator slot-less PM generator with diameter of 104 mm at speed of 3000 rpm is equal to 110 W when it has 6-pole with rotor radius of 36 mm. On the other hand, the double stator slot-less PM generator could produce 200 W at speed of 3000 rpm when it has 8-pole and rotor height of 22 mm.

Abstrak thesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

REKABENTUK DAN ANALISIS SATU DAN DUA STATOR BAGI PENJANA KUASA MAGNET KEKAL SATU FASA TANPA CELAH

Oleh

NORAFIZA BINTI MASRUNI

SEPTEMBER 2009

Pengerusi: **Norhisam Misron, PhD**

Fakulti: **Kejuruteraan**

Penjana kuasa magnet kekal telah menjadi satu objek untuk beberapa kajian dengan beberapa struktur and geometri telah dicadangkan untuk pelbagai aplikasi. Penjana kuasa adalah mesin yang digunakan untuk mengubah tenaga mekanikal kepada tenaga elektrikal. Atas sebab kewujudan dan pengurangan kos magnet kekal berkuasa tinggi, penjana kuasa magnet kekal menjadi pilihan yang sangat menarik berbanding penjana kuasa jenis lain. Untuk aplikasi pertanian, penjana kuasa sedia ada di pasaran tidak menepati saiz dan keupayaan tenaga yang diperlukan.

Penjana kuasa magnet kekal yang direka beroperasi dalam satu fasa, jenis tanpa celah, dan arah aruhan dalam celah angin berbentuk radial. Penjana kuasa magnet kekal ini dibangunkan untuk kegunaan pertanian terutamanya untuk aplikasi pada halaju tinggi antara 3000 rpm sehingga 8000 rpm. Penggerak utama bagi penjana kuasa magnet kekal ini ialah enjin petrol dengan keupayaan 1.3 hp. Daya luaran daripada enjin akan membolehkan penjana kuasa ini berputar dengan kelajuan yang tinggi. Kuasa elektrik yang dihasilkan sesuai untuk membekalkan kuasa kepada motor elektrik dalam aplikasi pruner. Justeru, dalam kajian ini, rekabentuk dan

analisis penjana kuasa magnet kekal dijalankan. Penjana kuasa magnet kekal disasarkan supaya ia dapat mengeluarkan keluaran voltan sekitar 130 V dengan diameter keseluruhan 104 mm.

Pada peringkat awal, penjana kuasa magnet kekal tanpa slot satu fasa direkabentuk dengan menggunakan stator tunggal dan magnet kekal diletakkan dalam keadaan berbentuk-v untuk membekalkan fluks yang diperlukan. Berdasarkan penyebaran aruhan dalam penjana kuasa magnet kekal, didapati bahawa separuh daripada fluks teratas pergi ke jarak udara dan bergerak ke dalam stator manakala separuh fluks di bawah tertumpu ke shaf. Ini bermaksud separuh daripada aruhan pada angker telah dibazirkan pada shaf. Berdasarkan ciri-ciri ini, penjana kuasa magnet kekal dwi-stator tanpa celah dicadangkan bersama magnet kekal bercorak gegelung pada celah udara di antara dalaman dan luaran stator untuk memperbaiki prestasi penjana kuasa ini. Berdasarkan rekabentuk ini, semua aruhan digunakan untuk menghasilkan voltan.

Untuk mengenalpasti keadaan di mana penjana kuasa magnet kekal berpotensi menunjukkan kelebihannya, pelbagai parameter dipelbagaikan seperti bilangan kutub dan jejari rotor. Secara amnya, teknik yang digunakan untuk mengkaji prestasi penjana kuasa magnet kekal adalah kaedah analisis permeance (PAM) dan kaedah bahagian tercapai (FEM). Kajian teori disahkan dengan membandingkan nilai yang dijangka dan nilai yang diukur bagi kuasa keluaran, rintangan, dan galangan prototaip penjana kuasa magnet kekal. Berdasarkan keputusan yang diperolehi, kuasa keluaran yang paling tinggi yang boleh dicapai oleh satu stator bagi penjana kuasa magnet kekal tanpa celah dengan diameter bersamaan 104 mm pada halaju 3000 rpm ialah 110 W apabila ia mempunyai 6-kutub dengan jejari rotor bersamaan 36 mm. Manakala, penjana kuasa magnet kekal tanpa celah dengan dua stator boleh meghasilkan 200 W apabila ia mempunyai 8-kutub dan ketinggian rotor ialah 22 mm.

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The author understands that the intellectual property of this research belongs to Dr. Eng. Norhisam Misron and Universiti Putra Malaysia. Both of them have rights at any aspect of design and finding throughout this research.

I certify that a Thesis Examination Committee has met on September, 14 2009 to conduct the final examination of Norafiza binti Masruni on her thesis entitled "Design and analysis of a single and double stator of single-phase slot-less permanent magnet generator" 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 Master of Science.

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

NORAFIZA BINTI MASRUNI

Date: 10 February 2010

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LIST OF ABBREVIATIONS

DC	Direct current
AC	Alternating current
rpm	Revolution per minute
f	Frequency (Hz)
n	Speed (rpm)
p	Number of pole
N	Number of turns for coil winding
PM	Permanent magnet
PAM	Permeance Analysis Method
FEM	Finite Element Method
N	North pole
S	South pole
2D	Two-dimensional
3D	Three-dimensional
$\Re$	Reluctance (H^{-1})
P	Permeance (H)
l	*Length (m)*
μ	Permeability (H/m)
A	Area (m^2)
g	Air gap (m)
r_r	Radius rotor (m)
θ	Angle (°)
V_{emf}	Induced voltage (V)
ϕ	Magnetic flux (Wb)
E_G	Generator rms voltage (V)
E_a	Armature voltage (V)
L_c	Coil inductance (H)
I_a	Armature current (A)
P_l	Losses power (W)

R_c	Coil resistance (Ω)
ε_h	Hyteresis coefficient
ε_e	Eddy current coefficient
B	Magnetic flux density (T)
NdFeB	neodymium-iron-boron
B_r	Remanence flux density (T)
H_c	Coercive force (kA/m)
H_k	Magnetic field intensity of the PM at operating point (A/m)
A_m	Area of PM (m^2)
w_m	Width magnet (m)
l_m	Length magnet (m)
h_m	Height magnet (m)
R_L	Load resistance (Ω)
R_a	Armature resistance (Ω)
V_o	Output voltage (V)
X_s	Synchronous reactance (Ω)
ρ	Coil resistivity (Ω/m)
w_c	Width coil (m)
l_c	Length coil (m)
h_c	Height coil (m)
d_c	Diameter of coil (m)
ϕ_l	Flux linkage (Wb-turns)
r_{ri}	Inner radius of rotor (m)
r_{ro}	Outer radius of rotor(m)
σ	Distance of PM from the surface of the shaft (m)
δ	Distance of PM from the surface of the rotor (m)
P_{ts}	Total permeance for single stator (H)
P_{td}	Total permeance for double stator (H)
θ_c	Angle of coil area (rad)
g_o	Air gap between outer stator and rotor (m)

g_i	Air gap between inner stator and rotor in (m)
r_i	Outer radius of the inner stator in (m)
r_o	Outer radius of the rotor in (m)
h_{co}	High of outer coil in (m)
h_{ci}	High of inner coil (m)
V_s	Source Voltage (V)
C	Capacitor (F)

CHAPTER 1

INTRODUCTION

Electrical energy is formed by a combination of prime mover and generator. Prime mover will provide external force which is mechanical energy to rotate the generator's shaft. Typical types of prime movers are steam turbines, gas turbines, wind turbines, hydraulic turbines, diesel engines, and internal combustion engines [1]. A generator can also be driven by human strength [2].

Basically, there are three main groups of electric generators which are synchronous, induction, and parametric generator [1]. Synchronous generator is the commonly used type that is compatible with renewable energy resources. A PM generator is one of a synchronous generator and it can be divided into two types which are slot type and slot-less type. The direction of the flux in the PM machines could be either radial or axial according to the flux direction in the air gap [3].

PM generators are found in many applications in wind power generation [4, 5, 6], hydroelectric power generation and solar dynamic power generation [7]. Other applications of power generation are in the aerospace [8], mine areas and vehicle applications [9, 10, 11, 12].

The use of PM in construction of electrical machines brings much benefit such as the construction work is easy and maintenance required is low since field winding is eliminated. Furthermore, no electrical energy is absorbed by the field excitation system, thus there is no excitation loss which means substantial increase in the efficiency [13].

The PM can be surface mounted or exterior and interior or embedded in the generator [14, 15]. The surface-mounted PM machine has magnets at the air gap surface and is liable to damage at high speeds or even in the assembly and fabrication process [4]. The rotor structure for an interior PM rotor will tend to have a smooth rotor design. Thus, windage losses will be equal to or lower than those of conventional induction machines [4].

In a PM machine, cogging torque is produce due to the interaction between the rotor magnets and the slots and teeth of the stator [16]. The cogging torque could be reduced due to the effect of machine symmetry that deals with supplementary slots method and asymmetrical distribution of the magnet on the rotor [17]. Combination methods of magnet shifting, optimizing the magnet arc, changing slot opening width, and manipulation of design parameters such as pole number combination and effect of slot almost eliminates the cogging torque [16, 18, 19]. However, the slot-less PM machine has proven could eliminate rotational cogging torque due to permanent magnet positioning, core loss reduction and eventually increase its efficiency, and has a linear current versus torque relation [20, 21].

It is expected that the iron loss of the slot-less PM synchronous machine can be greatly decreased compared to the slot type because there are no teeth in the area where the magnetic flux density is high [22]. The sum of conductor eddy current loss and core loss in a slot-less design is at a lower level than found in a slot type design [7]. Furthermore, a slot-less stator design effectively reduce the weight of the generator compared to slot type design.

A portable PM generator is essential for a new mechanical cutter system for an oil palm application since the existing mechanical cutter system faced certain limitation in terms of its capability for a higher oil palm tree [23]. This is because a longer pole will cause bending to the pole which results to an ineffective transmitting motion to the cutting head [23]. Therefore, the new mechanical cutter system that used an electric motor requires a PM generator as its power supply.

The major contribution in this study is to design and analyze a single stator and double stator of a single-phase slot-less PM generator by using permeance analysis method (PAM) and finite element method (FEM). In order to determine the capability and characteristic of the PM generator, the effect of various parameters are taking into account. The dimension of PM generator parameter such as size of permanent magnet, size of the rotor, and number of poles will be varied to obtain optimized dimension to produce the highest possible power.

1.1 Problem Statement

Recent researches using electric motor as a part of an oil palm mechanical cutter system requires a power supply to activate the motor [23]. According to this application, a portable generator is needed since the use of rechargeable battery is not practical due to its power and cycle life limitation [2]. The drawback of using battery could be solved by using a generator. However the available generators in the market are heavy and bulky which is not suitable for such application. The new mechanical cutter system is better than old mechanical cutter system since it could solve the problem results from the bending of pole for a higher oil palm tree while maintain the power capability.

The generator that is appropriate for this application must be small in size and light weight since the users have to carry the generator along with the whole mechanical cutter system. As a result, a portable generator that specially designed for the mechanical cutter system is proposed that fulfill the requirement in terms of its size, weight, and its power capability. The size of the generator is depends to the size of prime mover used for mechanical cutter system. The generator weight must less than 2 kg and capable to supply 130 V to a pure resistive load.

PM generator is proposed instead of other type of generator since it has high efficiency, compact, and has high power density. Furthermore, the PM generator has a very simple magnetic structure which is amenable for low cost manufacturing. Beside that, it requires low maintenance because it has internal magnetic source. A slot-less type PM generator is selected due to the fact that it eliminates the rotational cogging torque as well as core losses which usually exist in the stator teeth of a slot type PM generator. Moreover, a slot-less stator design reduces the weight of the PM generator.

A single-phase PM generator is chosen in order to reduce the power electronics component used to control and convert the energy produced by the PM generator. As a result, the cost for the mechanical cutter system could be reduced. The PM generator also simple in design since PM is used to supply the magnetic flux. So the brushes and the commutator that exist in dc machine are not required [24].