DESIGN AND ANALYSIS OF SLOT TYPE EMBEDDED PERMANENT MAGNET GENERATOR

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RINGKASAN : *Sejak akhir-akhir ini, penjana elektrik dengan magnet kekal menjadi semakin terkenal dalam pelbagai aplikasi kerana kos pembuatan yang rendah, rekabentuk yang mudah, saiz yang kecil, dan ringan. Walau bagaimanapun, rekabentuk penjana elektrik yang sedia ada mempunyai sedikit ketidaksesuaian terutama pada halaju tinggi pada lokasi magnet kekal tersebut di mana ia diletakkan pada permukaan luar rotor. Ini membuatkan ketidakstabilan pada voltan keluaran penjana elektrik tersebut. Kertas kerja ini mempersembahkan rekabentuk terbaru penjana elektrik magnet kekal yang menyelesaikan masalah yang telah disebut di atas. Dalam penjana elektrik magnet kekal ini, magnet kekal ditempatkan di dalam rotor. Ini membolehkan output keluaran penjana elektrik ini lebih stabil. Kedua-dua keputusan teori dan eksperimen bagi penjana elektrik magnet kekal dibentangkan dan dibincangkan. Daripada keputusan yang diperolehi, telah terbukti bahawa rekabentuk penjana elektrik magnet kekal ini lebih sesuai digunakan untuk halaju yang tinggi berbanding rekabentuk yang sedia ada.*

ABSTRACT : Permanent Magnet Generator (PMG) is getting popular lately in many applications due to its low production cost, simple design, small size, and light weight. However, the current design of PMG suffers from dislocation of permanent magnet that located around the outer surface of the rotor especially at high speed. This may cause instability in its output voltage. This paper presents a new design of PMG which addresses the problem mentioned above. In this PMG, the permanent magnets are embedded inside the rotor. This would lead to a more stable output voltage. Both the theoretical and experimental results of the proposed PMG are presented and discussed. The result confirms that the new design of PMG is more suitable for high speed than the existing design.

KEYWORDS : Permanent Magnet Generator, rotational generator, slot type, losses, Permeance Analysis Method, rotor radius, slot number.

INTRODUCTION

Due to the availability and decreasing cost of high energy permanent magnet material, PMG (Permanent Magnet Generator) is more attractive than other types of power generator. The PMG has a very simple magnetic structure which is amenable for low cost manufacturing. The electronics component that required controlling the output voltage is less compared with the three-phase PMG and reduced the cost for the system. These PMG also has a simple design since permanent magnet is used for supplying the magnetic flux. As a result, the brushes and the commutator that exist in dc machine are not required (Hyung-Woo Lee *et al.*, 2005). The size and performance of high-speed PMG depend on the permanent magnet properties (Jonathan *et al.*, 2005). Beside that, both voltage and inductance have influence to the available power of the PMG. Thus, to gain the desired inductance, certain number of slot, pole, and other parameters must be selected properly (Tuomo Lindh *et al.*, 2007).

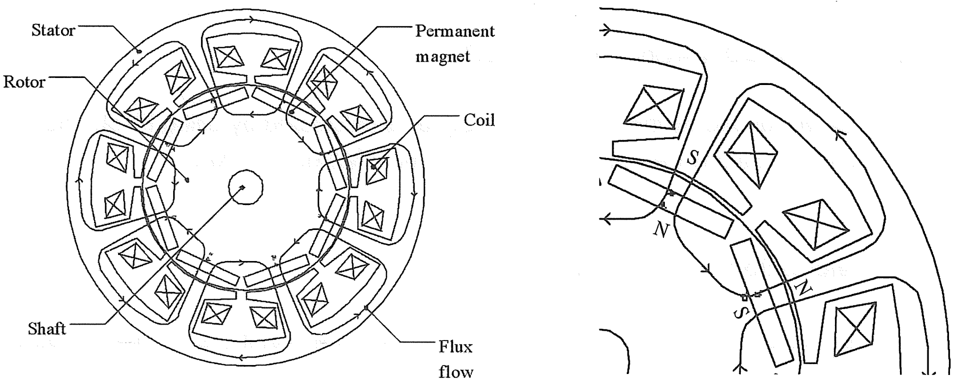
The designed PMG operates in a single-phase and the flux direction in the air gap is radial. In general, the PMG was developed for agriculture application and especially for energizing the linear motor in pruner application. A petrol engine with maximum speed of 10,000 rpm is attached to the shaft of the PMG that provides mechanical energy to it. The PMG consists of a stator, a rotor, permanent magnets, coil windings, and a shaft which are attached to the prime mover. Basically, this PMG is in a rotational generator category because it relies on a constant source of rotational mechanical energy (Arnold, 2007).

In this paper, the optimization of the PMG was achieved by using Permeance Analysis Method (PAM). The PAM uses the magnetic equivalent circuit approach that consists of building a permeance network which is representative of the studied magnetic circuit (Delforge and Lemaire, 1995). The parameters such as number of slot and radius of the rotor are varied in order to get the best performance especially in terms of the output power of the PMG.

Basically, the output power of the PMG at high speed is the main objective in this design. Therefore, the induced voltage, the effect of armature reaction, and the losses due to high super rotation are considered. This is an important issue in both the design and analysis of a generator since an iron loss in a rotational field has a large value (Lei Ma *et al.*, 2003).

BASIC STRUCTURE AND PRINCIPLE OF SLOT TYPE PMG

A PMG with an 8-slot stator carrying a concentrated coil winding, and an 8-pole rotor with radially magnetized neodymium-iron-boron (NdFeB) permanent magnet is developed. It is capable of producing 700 W as output power at 9000 rpm. The detail view of the stator and rotor structure are given in Figure 1. The stator is composed of coils and yoke for stator winding availability (Fengxiang Wang *et al.*, 2003). The rotor structure is formed by permanent magnets, rotor core, and a shaft as illustrated in Figure 1(a). The permanent magnets are embedded in the rotor since the PMG is designed for high speed application. The basic flux path of the PMG is also shown in Figure 1. As can be seen from Figure 1(b), the N pole permanent magnets drive the flux through the air gap into the stator yoke teeth. The flux then travels along the stator yoke and also along the stator core. Subsequently, the flux will return across the air gap and then enter the rotor core through the S pole permanent magnet. The rotor and stator are made from magnetic material such as soft steel (SS400). However the shaft is made from non ferromagnetic material (SUS403).



(a) Prototype of a 8-pole PMG

(b) The cross section of a PMG

Figure 1. *Basic structure of the PMG*

Figure 2 shows the electrical equivalent circuit of the generator when connected to the load. Here, E_G represents the induced voltage by the PMG. Furthermore, R_C and L_C are internal resistance of coil winding and self inductance of the generator respectively. The load consists of purely resistance, R_L with particular value of 50 Ω as the reference of the real load. The induced voltage in the PMG is based on Faraday Law as in Equation (1). It states that the induced voltage of any closed circuit is equal to the time rate of change of the magnetic flux linkage by the circuit (Chapman, 1999).

$$E_G = N\frac{d\Phi}{dt} \tag{1}$$

Hence for this PMG, the prime mover is attached to the shaft and hence will rotate the rotor and will produce rotating magnetic field in the stator. Consequently, the winding coil at the stator yoke will cut these magnetic fields. Therefore, voltage is induced in the PMG.

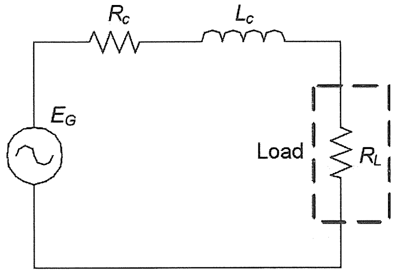


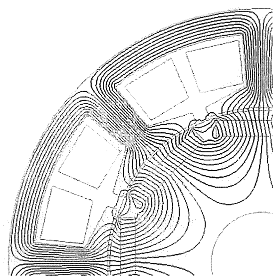
Figure 2. *General electrical equivalent circuits*

ANALYSIS OF LUMPED MAGNETIC CIRCUIT

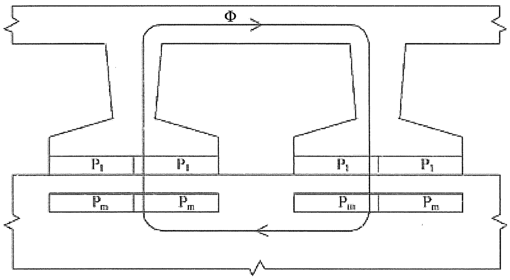
Basically, the flux, Φ induced by the permanent magnet is calculated by using PAM. The direction of flux flow is determined by using Finite Element Method (FEM).

Permeance Calculation for Inductance

The permeance consideration area and its magnetic equivalent circuit are shown in Figures 3 and 4, respectively.



(a) 2D flux direction (FEM)



(b) Simplified flux path and permeance area in rectangular model

Figure 3. *Permeance consideration*

As can be seen in Figure 3(b), there are two permeance areas which were considered; the air gap and permanent magnet. Permanent magnet is considered as air gap in order to determine the total permeance for the coil. However, to examine the flux produced by the permanent magnet, the permeance at the permanent magnet, P_m is short circuited. P_1 is the permeance area between the stator teeth and the rotor and can be calculated using Equation (2). The magnet permeance is given by Equation (3).

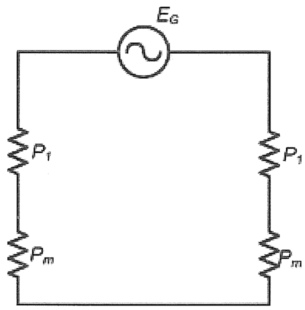


Figure 4. *Magnetic equivalent circuit*

$$P_l = \frac{\mu_o l \theta}{\ln\left[1 + \frac{g}{r_r}\right]} \tag{2}$$

$$P_m = \frac{\mu w_m l}{2h_m} \tag{3}$$

Here, μ_o is the permeability factor in air in [H/m], μ is the permeability in the material in [H/m], θ is the angle of stator teeth in [rad], l is the depth of the PMG in [m], g is the air gap between the stator teeth and the rotor in [m], r_r is the rotor radius in [m], w_m is the width of the permanent magnet slot in [m], and h_m is the height of the PM slot in [m].

Based on the magnetic equivalent circuit in Figure 4, the total permeance, P_t for one pole is calculated by using Equation (4). Focus will only be given to one pole since the other poles are identical.

$$P_{tl} = \frac{1}{2}\left[\frac{(\mu_o \mu w_m l \theta)}{(2\mu_o h_m \theta) + (\mu w_m)\left[\ln\left[+ \frac{g}{r_r}\right]\right]}\right] \tag{4}$$

The inductance, L_c and resistance, R_c of the coil winding is calculated by using Equations (5) and (6), respectively. These values are necessary in order to identify the characteristic of the PMG especially the maximum current in the circuit. Furthermore, the capability of the generator is limited by the impedance of the stator coil (Jiabin Wang *et al.*, 2005).

$$L_c = \frac{N^2}{2}\left[\frac{(\mu_o \mu w_m l\theta)}{(2\mu_o h_m \theta) + (\mu w_m)\left[1\text{n}\left[+ \frac{g}{r_r}\right]\right]}\right] \tag{5}$$

$$R_c = \frac{N^2 \rho l_c}{A} = \frac{2N^2 \rho\,(\,l + w_y + w_c\,)}{w_c h_c} \tag{6}$$

$$N = \frac{w_c}{d_c} \text{ x } \frac{h_c}{d_c} \tag{7}$$

Here, N is the number of turns, l_c is the length of coil winding in [m], A is the area of winding slot in [m^2], ρ is the density of copper [8900 kg/m^3], w_y is the width of the stator yoke in [m], d_c is the diameter of coil, w_c is the width of coil slot in [m], and h_c is the height of coil slot in [m]. Number of turns usually will fall about 60% from the total turns that it can be.

Flux calculation

As mentioned before, the permeance at the magnet is short circuited in order to determine the flux at the magnet. Therefore, the total permeance of the flux of the magnet is given by

$$P_{tf} = \frac{\mu_o l\theta}{21\text{n}\left[1 + \frac{g}{r_r}\right]} \tag{8}$$

Assuming the B-H curve of the permanent magnet and the permeance line of the PMG is shown in Figure 5, the intersection point of these two lines is an operating point of the permanent magnet for the particular permeance model. By solving the intersection of these two straight lines, the permanent magnet operating point can be determined as in Equations (9) until (11).

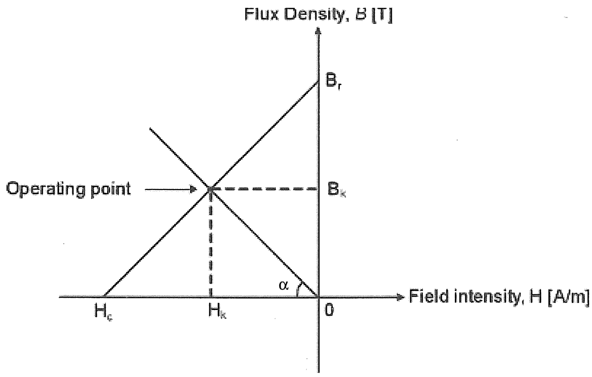


Figure 5. *B-H curve and operating point of permanent magnet*

$$\tan \alpha = \frac{P_{tf} H_c h_m}{B_r w_m l} \tag{9}$$

$$B_k = (-\tan \alpha) H_k \tag{10}$$

$$H_k = \frac{-B_r}{\left[\frac{B_r}{H_c} + \tan \alpha\right]} \tag{11}$$

Here, α is the angle of the permeance line slope, H_c is a coercive force in (kA/m), B_r is a remanent flux density in [T], B_k is a magnetic flux density of the permanent magnet at operating point in [T], and H_k is the magnetic field intensity of the permanent magnet at operating point in [A/m]. Consequently, the flux in the PMG can be calculated as in Equation (12).

$$\phi = \frac{(\mu_o B_r H_c^2 h_m \theta)}{\left[2B_r^2 w_m \ln\left[1 + \frac{g}{r_r}\right]\right] + (H_c^2 \mu_o h_m \theta)} \tag{12}$$

Generated Voltage and Current

The voltage generated, E_G by the PMG for one slot is calculated by using Equation (1). As seen in Table 1, the measured and predicted coil resistance and inductance for 8-pole PMG with rotor outer diameter of 30 mm (measured at the rated fundamental frequency of 12 Hz) are in good agreement. Maximum current when load is connected to the generator is calculated using Equation (13). According to this equation, it can be seen that the maximum current is dependent on the induced voltage as well as inductance. Thus at high speed, the current value will reach a saturation state.

$$I_c = \frac{E_G}{\sqrt{(R_c + R_l)^2 + (2\pi f L_c)^2}} \tag{13}$$

where I_c is the current carried by the coil when a pure resistive load is connected to the generator.

Table 1. Measured and predicted coil resistance and inductance (8-pole)

	Resistance [Ω]	Inductance [mH]
Measured	17.68	69.36
Predicted	15.54	75.04

Power Losses Calculation

It is required to measure the power losses occurred in the motors during the operation of the PMG in order to examine the validity of the evaluation method proposed. The machine losses which were considered include armature reaction effect, copper losses, hysteresis losses, and eddy current losses. Armature reaction field is usually only around 10% to 20% of the magnitude of the open circuit field (Zhu and David Howe, 1993). The armature reaction effect is estimated based on the inductance and current of the coil winding as shown in Equation (14) (Yuefeng Liao *et al.*, 1995).

$$E_\alpha = L_c \frac{dI_c}{d_t} \tag{14}$$

The copper losses, hysteresis losses, and eddy current losses are estimated using Equations (15) until (17), respectively (Lei Ma *et al.*, 2003). Here, f is the frequency in [Hz], ε_h is hysteresis coefficient (2.46 x 10^{-2}), ε_e is eddy current coefficient (8.55 x 10^{-3}), and α is a constant (2.03) (Jiabin Wang *et al.*, 2005).

$$P_{copper} = R_c (I_c)^2 \tag{15}$$

$$P_{hys} = \varepsilon_h (f) B^{\alpha} \tag{16}$$

$$P_{eddy} = \varepsilon_e (f)^2 B^2 \tag{17}$$

Power generated, P_G includes the effect of armature reaction and can be calculated as Equation (18). The total open circuit losses, P_{losses} is then determined as Equation (19).

$$P_G = I_c (E_G - E_{\alpha}) \tag{18}$$

$$P_{losses} = P_{copper} + P_{hys} + P_{eddy} \tag{19}$$

Output power is equals to power generated by the generator minus the losses power in the circuit. Thus, the total output power from the generator, P_{out} is calculated based on Equation (20).

$$P_{out} = P_G - P_{losses} \tag{20}$$

DESIGN AND ANALYSIS OF PMG

In the design of the PMG, several different numbers of slot and pole, inner diameter of the stator, and also outer diameters of the rotor were considered in order to examine the best structure in terms of output power. All parameters will be considered since it will affect the value of flux produced in the PMG. However, the number of slot and the number of pole are kept equal since the PMG was designed for a single phase. The outer diameter of the stator, the height of the stator teeth, and the height of the air gap between the stator teeth and the rotor were kept constant due to the space limitation. The width of the permanent magnet and the stator teeth are dependent on the number of the stator slot because as the number of stator slot increases, the size of stator teeth is decreased. Then, the suitable size of the yoke is chosen based on the size of stator teeth in order to avoid the flux becomes saturated when the area of the yoke is small.

Design of PMG Parameters

Figure 6 shows the simplified model of the PMG in rectangular shape together with the various parameters used to predict the flux in the PMG. The values of these parameters used as a prototype 8-pole PMG are shown in Table 2. Here, r_o stands for outer radius of the rotor. The total turns, N, used both in PAM and the experiment is 100 turns, that have been calculated using Equation (7). The outer diameter of the stator is kept constant at 104 mm due to the space limitation of the generator system.

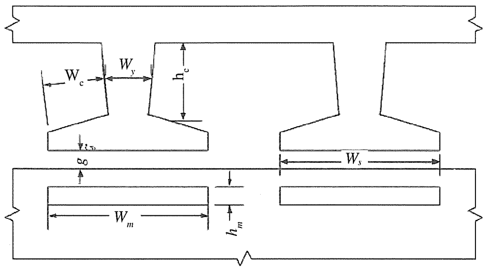


Figure 6. *Design parameters*

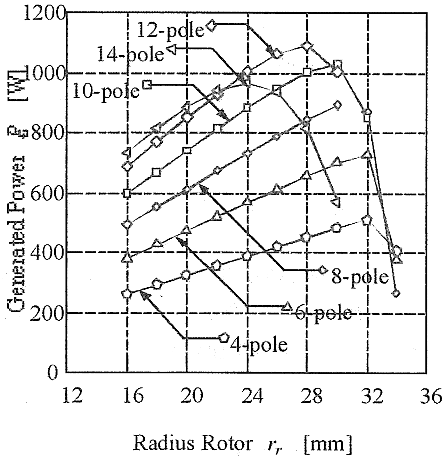
Table 2. 8-pole PMG parameters for analysis

Item	Element	Value [mm]
Stator	w_y	7.94
	g	0.5
	w_s	21.29
	l	24
Rotor	r_o	30
	h_m	3
	w_m	19
	l	24

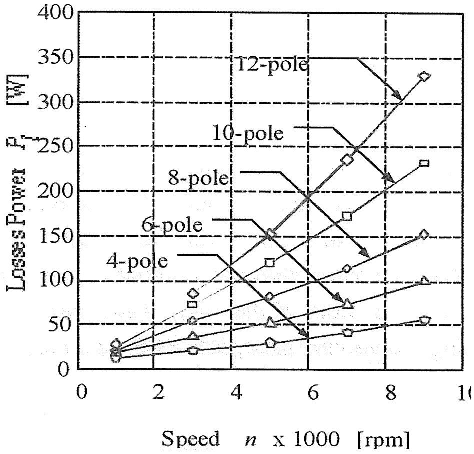
Characteristic of PMG

Figure 7(a) shows the calculated variation of the generated power of the PMG running at 9000 rpm as a function of the rotor's radius and number of pole. The power losses of the PMG as a function of speed and number of pole are shown in Figure 7(b).

By increasing the number of pole, the generated power and power losses are also increased since the total impedance in the generator is increased. Based on Figure 7(a), 12-pole PMG will generate the highest power. However, based on Figure 7(b), the power losses of 12-pole PMG is also high. As a result, the total output power would be reduced. Finally, the PMG with moderated generated power would produce high output power since its power losses is small.



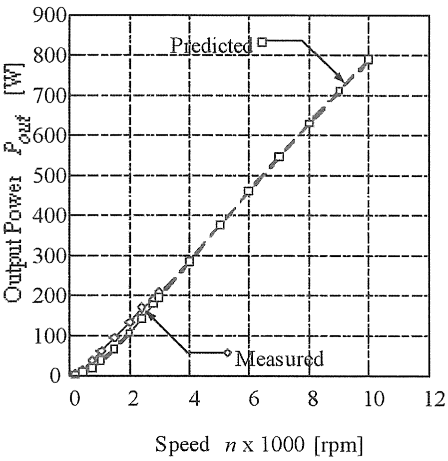
(a) Generated power (9000 rpm)



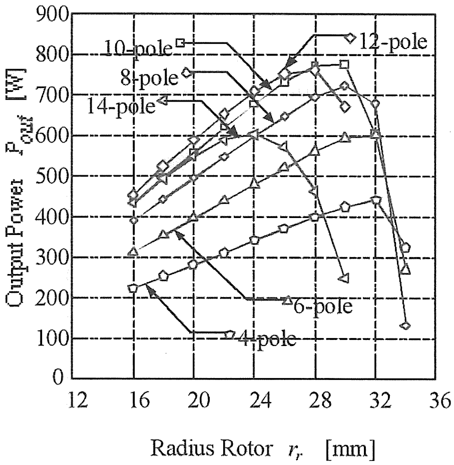
(b) Losses power (r_r = 28 mm)

Figure 7. *PMG power characteristic*

In order to validate the calculation for evaluating the performance of the PMG, the result for 8-pole PMG is compared with the measurement shown in Figure 8(a). The behavior of the PMG based on the calculation and actual measurement is absolutely similar. However, the value of the predicted output power is slightly different from the measurement method and can still be accepted.



(a) Comparison of output power (r_r = 30 mm)



(b) Output power (9000 rpm)

Figure 8. *Output power of the PMG*

Optimization of the best size for the required specification as shown in Table 3 is done by using PAM. Various values of the rotor size had been studied repeatedly and the output power had been evaluated. For the optimization of similar outer size of the PMG, the dimensioning was done iteratively via analytical approach based on some simplifying assumption. An analytical design procedure, based on the equivalent magnetic circuit approach and permanent magnet B-H curve characteristics was used to estimate the magnetic loading, which determines the stator yoke dimensions, the specifications and dimensions of the magnets. The suitable PMG rotor outer diameter, number of pole, width of stator yoke, width of the permanent magnet as well as width of the rotor teeth that could fulfil the specification required are calculated using the verified analytical method based on Equation (12) in order to get high value of flux.

Table 3. PMG specification

Specification	Value [unit]
Output power	700 W
Output voltage	200 V
PMG size	104 mm
PMG depth	24 mm

Figure 8(b) shows the calculated variation of the output power of the PMG running at 9000 rpm as a function of the rotor's radius and number of poles. The maximum output power of the PMG is different for each number of poles. Furthermore, each pole would reach maximum output power at different size of rotor. This proved that the size of the rotor and the number of the pole would affect the performance of the PMG. Based on Figure 8(b), the maximum output power is achieved when the rotor radius is of 30 mm for 10 poles. The maximum output power that can be obtained based on this optimized model using PAM method is 775 W. The main parameters of the PMG based on the optimization results are given in Table 4.

Table 4. Optimization parameter (10-pole)

Item	Element	Value [mm]
Stator	w_y	6.11
	g	0.5
	w_s	16.5
	l	24
Rotor	r_o	30
	h_m	3
	w_m	14.85
	l	24

CONCLUSION

In this paper, the analytical method to predict the performance of the PMG is presented by using PAM. The result shows that the number of pole and the size of the rotor influences the output of the PMG. As a result, the best structure of the PMG is achieved when the number of slot and pole is 10 and the radius of the rotor is equals to 30 mm. It has been shown that the maximum output power achieved using this structure is about 750 W. The future of the PMG is very bright as the cost of permanent magnet materials has decreased markedly.

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