Novel Dual-Excitation Permanent Magnet Vernier Machine

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Abstract - **A novel Dual-Excitation Permanent Magnet Vernier Machine; DEPMVM, which has the feature of high torque at low speed, is presented. This machine has two stators both inside and outside of a ring shaped rotor, and its coils are wound around the yokes. These special structures are adopted as a result of detailed investigations of the machines which make use of the so-called 'magnetic gearing effect.' A prototype machine of the DEPMVM is designed and fabricated, and its experimental results indicate the promising nature of the machine.**

I. INTRODUCTION

A Permanent Magnet Vernier Machine; PMVM has the feature of high torque at low speed, and is thus suitable for direct drive applications [1], [4]. The high torque at low speed feature is based on the so-called 'magnetic gearing effect,' which is also made use of in many types of stepper motors and various types of machines such as the ones in [2] and [3]. This research aims to pursue the high torque at low speed feature of the PMVM for the middle to high power applications. Regarding this type of machine, there are several typical forms for each of the stator, the windings and the rotor, and most of the machines are considered as combinations of these forms. In this paper, firstly a discussion concerning those typical forms is set forth, which reveals some key factors for obtaining desirable properties. Then a novel type of the PMVM, named the Dual-Excitation Permanent Magnet Vernier Machine is proposed, taking account of all those key factors. Basic experimental results of a prototype machine are presented thereafter.

II. OVERVIEW OF THE PMVM

Fig. 1 shows the half cross sectional view of a typical configuration of the 3-phase PMVM. Its structure is quite similar to the ordinary permanent magnet machines, except that the stator has uniformly pitched teeth on its surface toward the airgap, and that the number of the rotor poles is quite large.

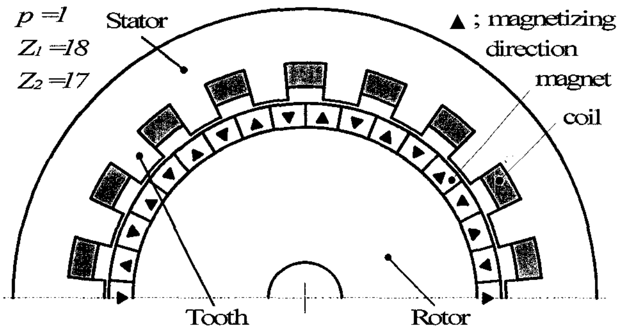
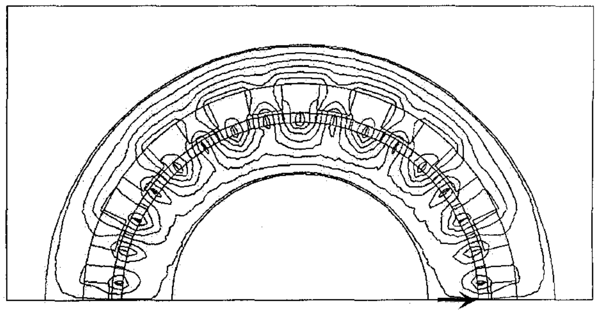
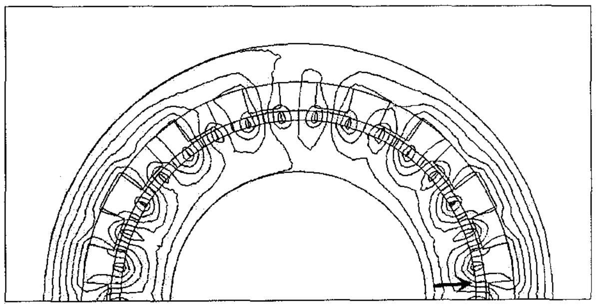


Fig. 1 Typical configuration of the PMVM



(a) Rotor position of 0



(b) Rotor position of $\pi/(2Z_1)$

Fig. 2 Change of the permanent magnet flux distribution with rotor position

With the PMVM there exists a fundamental rule, which characterizes this machine, as requiring

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$$Z_2 = Z_1 \pm p \qquad (1)$$

where p, Z_1, and Z_2 are the numbers of winding pole-pairs, stator teeth, and rotor pole-pairs, respectively. Due to this rule, a unique phenomenon appears as to be explained with Fig. 2. This figure shows the difference of the flux distribution with the rotor position in a PMVM. The parameters of the machine are p=1, Z_1=18, and Z_2=17. The flux is due only to the permanent magnet, and between the two figures (a) and (b) there is a slight difference of the rotor positions, which corresponds to a quarter of the stator tooth pitch. It is noted that the number of the pole-pairs of the flux distribution equals to the value of p, which is one in this case. Thus, a steady torque is yielded by synchronizing the coil mmf to the flux rotation. It is also observable that the flux distribution changes 90 electrical degrees with the indicated difference of the rotor position. That is, a small movement of the rotor makes a large change of the flux, which results in a high torque. This phenomenon based on the rule, (1), can be denoted as the 'magnetic gearing effect.'

It can be also mentioned that the cogging torque and the torque ripple become substantially low so as to be negligible in this type of machine.

Let some of the basic equations of the PMVM be shown here for the later references. The flux linkage of one phase coil due to the permanent magnet, λ, can be expressed as [4]

$$\lambda = k_w N \Phi \cos Z_2 \theta \qquad (2)$$

where k_w is the winding factor, N is the number of turns of one phase coil, Φ is the amplitude of the flux linking a full pitch coil, and θ is the mechanical angle of the rotor. Then the amplitude of a phase back-emf E becomes

$$E = \omega_m Z_2 k_w N \Phi \qquad (3)$$

where $\theta = \omega_m t$, and ω_m is the mechanical angular velocity. When the sinusoidal coil current flows so that the current vector is in phase with the back-emf, the torque is expressed as [4]

$$T = \frac{3}{\sqrt{2}} Z_2 k_w N I \Phi \qquad (4)$$

where I is the effective value of the coil current.

III. Motivations Toward The DEPMVM

Although there are several variations for the PMVM, most of them can be considered as combinations of typical configurations for each of the stator, the windings, and the rotor. For each of them, a study for obtaining desirable properties can be addressed as follows.

A. Stator

For the stator, two typical configurations exist as shown in Fig. 3. Figure (a) shows the split-pole type[3] and figure (b) shows the open-slot type[1], [4]. The former is found in most of the small power stepper motors, in which the large number of teeth is necessary for the high-resolution position control. In the case of a large machine, however, this structure has problems in that the slots between the teeth become large "dead" spaces, and that the copper density in a slot must be lower because of the difficulty in winding coils due to the narrow open slot. On the other hand, there is no such "dead" spaces in the latter because its slots are utilized as the locations for the coils, and the coils can apparently be wound more densely. Hence, the open-slot type is more suitable for the higher power machines.

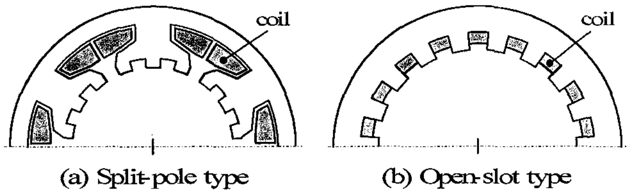


Fig. 3 Two types of the stator configurations

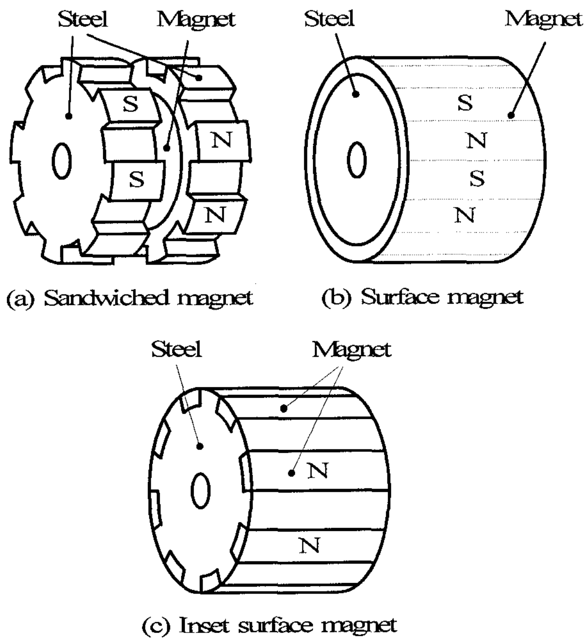


Fig. 4 Three types of the rotor structures

B. Windings

When the number of winding poles is increased with a certain size of the PMVM, Φ in (3) is reduced roughly to the half corresponding to the reduction of the coil pitch, while the other parameters stay almost the same, and consequently the torque decreases. Hence the number of winding poles should be selected to be as small as possible.

C. Rotor

For the rotor, there are three typical types; the axially sandwiched magnet type which is common in the hybrid stepper motors, the surface magnet type[1], [3], [4], and the inset surface magnet type[2], as shown in Fig. 4. Although there are considerable differences with the torque production among them, the most critical issue here is their effects on the coil inductance. Since the number of winding poles should be small for obtaining a high torque, the coil inductance tends to be quite large. With the axially sandwiched magnet type and the inset surface magnet type, the inductance can reach 2 or 3 p.u., which is too high from the view point of the power factor and current control. The reason of this large inductance is that the iron part of the rotor is directly facing the airgap. On the contrary, the surface magnet type gives more reasonable inductance because of the large virtual airgap.

D. Machine shape

In addition to the above issues, a large rotor diameter is advantageous, for the number of the rotor poles can be easily increased.

From the above discussion, several key factors for realizing the desirable properties can be enumerated. Table 1 is the summary of these factors, along with the merits, the problems, and the solutions. With an open slot stator, there is a need for a tight coil fixation, while a lower number of the winding poles has an inherent problem of long coil-ends. Meanwhile, if the rotor diameter is large, the inside of the rotor becomes a large vacancy. Unifying all the solutions to these problems, the Dual-Excitation Permanent Magnet Vernier Machine; DEPMVM can now be presented, the structure of which is shown in Fig. 5. As the name suggests, there exist two stators both inside and outside of the rotor, for a large rotor diameter and a good use of space. Another feature of the DEPMVM is the adoption of the 'drum windings,' in which the coils are wound around the yokes. This solves the problems of the coil fixation with the open-slots and the long coil-ends with small number of winding poles at the same time, while its major performance becomes the same to the conventional windings.

TABLE 1
KEY FACTORS FOR THE DESIRABLE PROPERTIES

Key factors	Merits	Problems	Solutions
Open-slot	Effective use of space	Need of coil fixation	'Drum winding'
2 winding poles	Torque increase	Long coil-ends	
Surface magnet	Low inductance	---	---
Large rotor diameter	Torque increase	Large vacancy inside	Dual-excitation

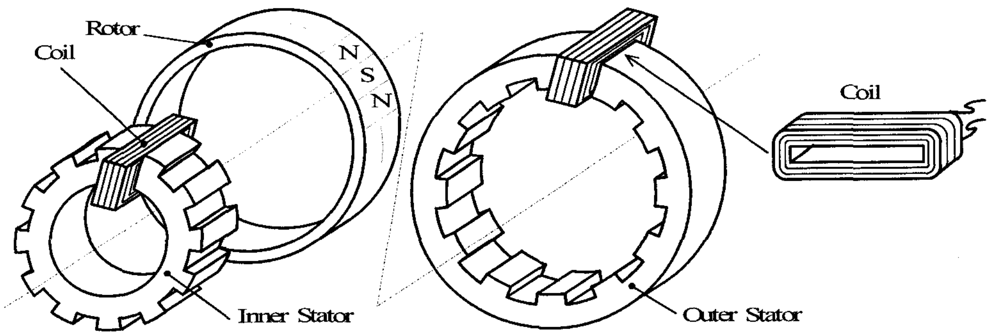
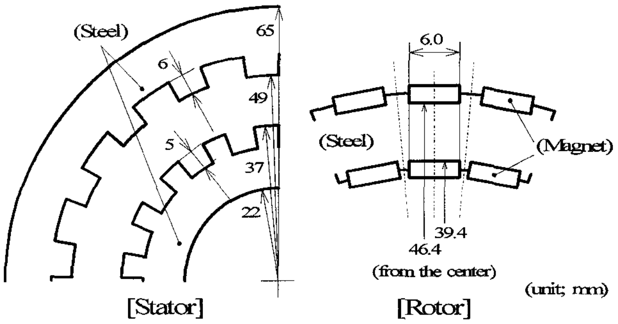


Fig. 5 Concept of the Dual-Excitation Permanent magnet Vernier machine

IV. DESIGN AND ANALYSIS OF A PROTOTYPE MACHINE



- Specifications
Z_1=18, Z_2=17, p=1, Slots/pole/phase/stator; 3
Numbers of coil turns; 26(outer), 18(inner) /slot
Rated current; 4.4A, Rated speed; 300r/min
Rated power; 530W, Rated torque; 16.9Nm
Permanent magnet; NdFeB (Br=1.23T, Hc=-8.9e5)
thickness; 2.0m
Steel lamination stack length; 60mm

Fig. 6 Dimensions and specs of the prototype DEPMVM

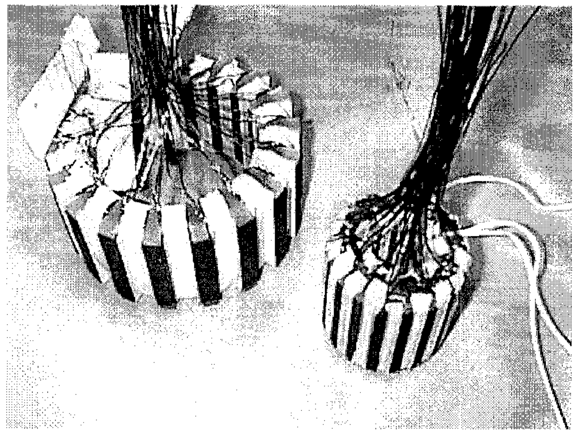
A prototype 3-phase DEPMVM has been constructed, whose major dimensions and specifications are shown in Fig. 6. The outer and the inner airgaps are set to fairly large values of 0.6mm and 0.4mm respectively, for the easiness of fabrication, although the smaller airgaps are desirable and feasible. The box-shaped permanent magnets are used for the rotor poles, for which the sizes are all the same. Fig. 7 (a) exhibits the outer and the inner stators with wound coils, and (b) shows the rotor. The assembly of the prototype is as shown in Fig. 8. For the output side shaft a conventional ball bearing is used, while a ring shaped slip bearing is used for the other side.

Design of the machine is aided by magnetostatic FEM analyses by using Maxwell 2D Field Simulator Ver. 6.5.04 (Ansoft Co.). The major items to be evaluated are as follows:

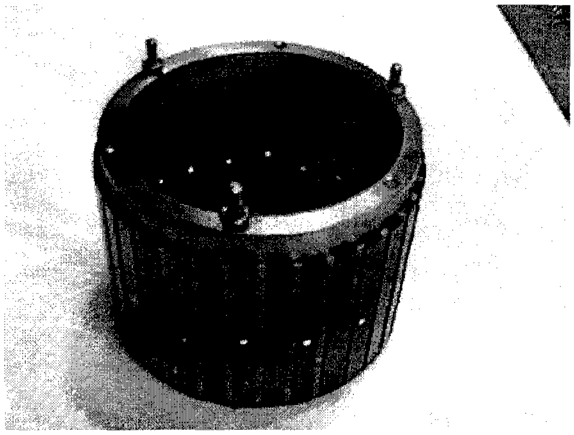
1) The back-emf calculated from (3), with the flux linking the coil obtained from the analysis when the coil current is zero.
2) The torque determined by (4), with the flux used in 1).
3) The coil inductance obtained from the flux linkage when 50% coil current flows and the magnets are removed.

The above evaluations are effective only when the flux density of the iron part is lower than the saturation level. Therefore, it is also confirmed by analysis that the flux density of the iron parts does not exceed 1.6T with 150% coil current operation.

Table 2 shows the acquired values from the analyses. Those values are to be compared with the experimental ones in the next section.



(a) Outer(left) and inner(right) stators with coils



(b) Rotor

Fig. 7 Pictures of the stators and the rotor

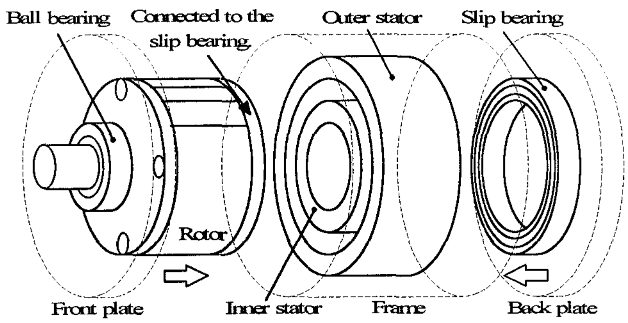


Fig. 8 Assembly of the prototype machine

TABLE 2
ANALYTICAL VALUES WITH THE PROTOTYPE DEPMVM

Back-emf	Rated torque	Inductance
39.9Vrms/phase	16.9Nm	15.0mH/phase

V. Experimental Results

The resistance and the inductance of the machine are indicated in Table 3. It can be noted that the measured values agree quite well with the design values.

TABLE 3
Resistance And Inductance Of A Phase Coil

	Resistance	Inductance
Measured	1.39Ω	16.6mH
Designed	1.33Ω	15.0mH

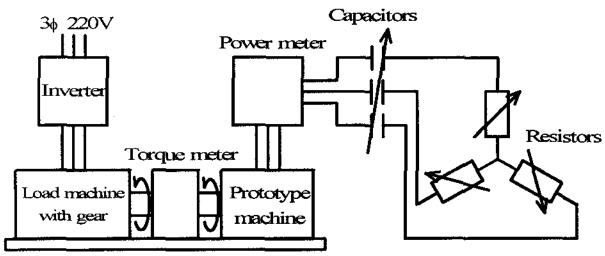
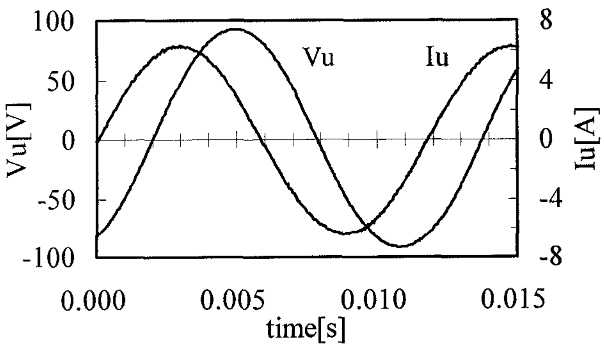


Fig. 9 Schematic of the experimental setup

Fig. 9 shows the schematic of the test equipment. The prototype machine is coupled with a load machine via a torque meter, and tested as a generator. In actual use, however, the machine is to be driven by an inverter, and in that case the current vector is controlled to be in phase with the back-emf vector to obtain the maximum torque. To realize this condition, capacitors are inserted in series between the machine terminals and a balanced, Y-connected resistor load. The phase of the current is controlled so as to achieve the above condition by adjusting the value of the capacitance.



Vu; U phase voltage, Iu; U phase current
Rotor speed : 300r/min

Fig. 10 Voltage and current waveform at the rated operation

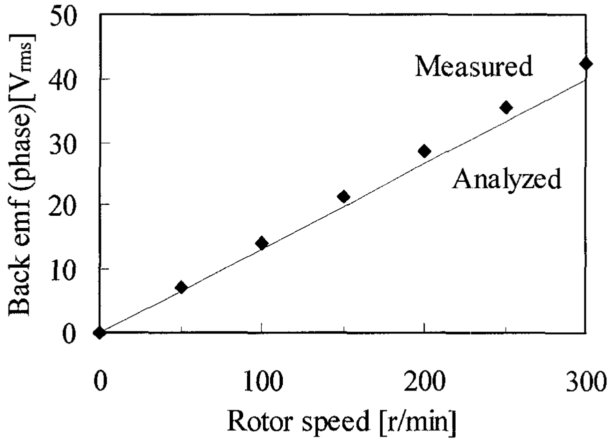
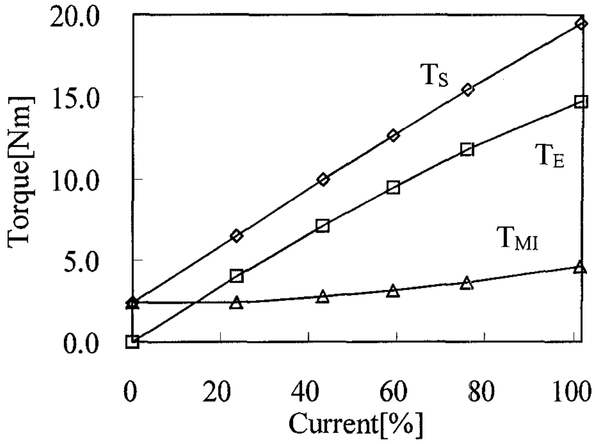


Fig. 11 Back-emf v.s. rotor speed



Rotor speed : 300 r/min.
Fig. 12 Measured torques v.s. current

Fig. 10 shows the terminal voltage and the coil current waveforms in the rated speed rotation. As can be seen, the waveforms are almost perfectly sinusoidal, which is desirable for smooth torque production.

Fig. 11 shows the measured and analyzed values of the back-emf. Two values agree fairly well, and the linear variation of the back-emf with the speed is confirmed. The THD of the waveform is 0.62%.

Fig. 12 indicates the torque to current characteristics at the rated speed. Each curve in the figure is obtained as follows:

-Shaft torque T_S ; The torque required to drive the machine
-Effective torque T_E ; $3(R+R_a)I^2/\omega_m$
-Mechanical & iron loss torque T_{MI} ; $T_S - T_E$

Here, R is the load resistance, R_a is the coil resistance, and I

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is the coil current. All are the phase values. The effective torque at the rated current is 14.8Nm, which is about 12% lower than the designed rating, 16.9Nm. This discrepancy is mainly because of the iron loss, which is not taken into account in the analysis. It is noted that the mechanical loss and the iron loss are significant, the sum of which reaches 4.7Nm during rated operation. From the fact that the T_{M1} at the no-load condition is 2.4Nm, it can be understood that the torque due to the iron loss at the rated operation is at least (4.7-2.4=) 2.3Nm. Even this least possible value is more than twice as high as the expected value. Further investigation is needed to clarify the cause of this discrepancy. On the other hand the large mechanical loss comes from the slip bearing which has a large friction. Therefore, the mechanical loss can be reduced substantially by adopting a lower friction bearing.

Table 4 summarizes the cogging torque at 1 r/min rotation, and the torque ripple at 10 r/min rotation with the short-circuited machine terminals. The cogging torque is almost negligible. The amplitude of the torque ripple is about 0.3Nm, and the frequency of it is corresponding to the mechanical rotation. That is, the torque ripple is caused by the eccentricity of the positions or shapes of the parts, and not because of the harmonics of the coil mmf. Hence, it is confirmed that both the cogging torque and the torque ripple become quite low in this machine.

TABLE 4

COGGING TORQUE AND TORQUE RIPPLE

Cogging torque	Torque Ripple (10r/min)	
	Amplitude	Frequency
Not observed.	0.3Nm	10r/min

VI. CONCLUSIONS

The major achievements shown in this paper are as follows:

1) A novel Dual-Excitation Permanent Magnet Vernier Machine has been proposed as a result of the discussion with the desirable properties of the PMVM.
2) A prototype machine has been designed and fabricated.
3) Tests of the prototype machine have been implemented. Consequently, it is confirmed that the DEPMVM can realize the high-torque at low-speed feature, and the actual performance of the machine agrees well with the analysis, although there remains a need for careful investigations of the iron loss.

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