

# Design of a Vernier Machine with Permanent Magnet on both sides of Rotor and Stator

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**Abstract**— This paper propose a new type of vernier machine with permanent magnets (PMs) on both sides of rotor and stator. The rotor is of the flux concentrating structure and the stator has also PMs between the flux modulation poles (FMPs). Comparing the other types of the vernier machine, the proposed model has a huge increase in the induced voltage and developed torque for the same size. This shows the possibility of the new suggested machine to the direct-driven applications such as wind-power generators and in-wheel motors.

**Index Terms** — direct drive, flux modulation, gearing effect, vernier machine

## I. INTRODUCTION

In industrial applications such as wind power generators and in-wheel motors, electrical machines have been used with a mechanical gear to generate a big power at the relatively low speed. However, the mechanical gear causes several problems such as noise, vibration and low efficiency. In order to overcome these drawbacks, direct-driven electrical machines have been proposed using high-grade PMs and vernier machines are also considered as a good candidate for their magnetic gearing effects [1].

The vernier machines are divided into two categories according to the existence of PM, vernier reluctance machines and permanent magnet vernier (PMV) machines [2]. And, the PMV machines are classified into two types according to the flux modulation method for the gearing effect in the air gap region. One is called as the pole splitting permanent magnet vernier (PSPMV) machine which has flux modulation poles (FMPs) on the stator and PMs on the surface of the rotor [3]. The other is vernier hybrid (VH) machines. In this machine, the PMs mounting on the surface of the stator teeth modulates the flux from the stator coils and the rotor has only teeth [4].

In this paper, a new type of PMV machine is proposed to pursue high power at low speed. It has flux concentrating structure on the rotor and has PMs between the FMPs on the stator. The main magnetic flux from the PMs on the rotor and stator has same direction. Comparing the basic PMV machine, which has PM on the surface of the rotor, the proposed model has a huge increase in the induced voltage and developed torque. With the variation of the ratio of tooth between the stator and rotor, characteristics of the machines are investigated including the induced voltage, average torque and its ripple as well. The analysis results shows the possibility of the new suggested machine to the direct-driven applications and allows ferrite PM machines to achieve power densities approaching those of PM machines using rare earth magnets.

## II. PERMANENT MAGNET MACHINE

### A. Structure of PMV machines

For comparison, two PMV machines which have the flux concentrating structure on the rotor are shown in Fig. 1. All other things except the existence of the PMs between the FMPs on the stator are same. The stator has three-phase concentrated windings for rotating magnetic field of 2 poles and each stator tooth is split into 7 FMPs. According to the theory of magnetic gearing effect, the number of pole pairs of the rotor PMs can be determined as 20 by

$$p_r = N_s - p_s \quad (1)$$

Where  $p_r$  is the number of pole pairs of the rotor PMs,  $N_s$  is the number of the FMPs, and  $p_s$  is the number of pole pairs due to the stator windings. Consequently, these PMV models have high to low speed ratio of 20 as follows;

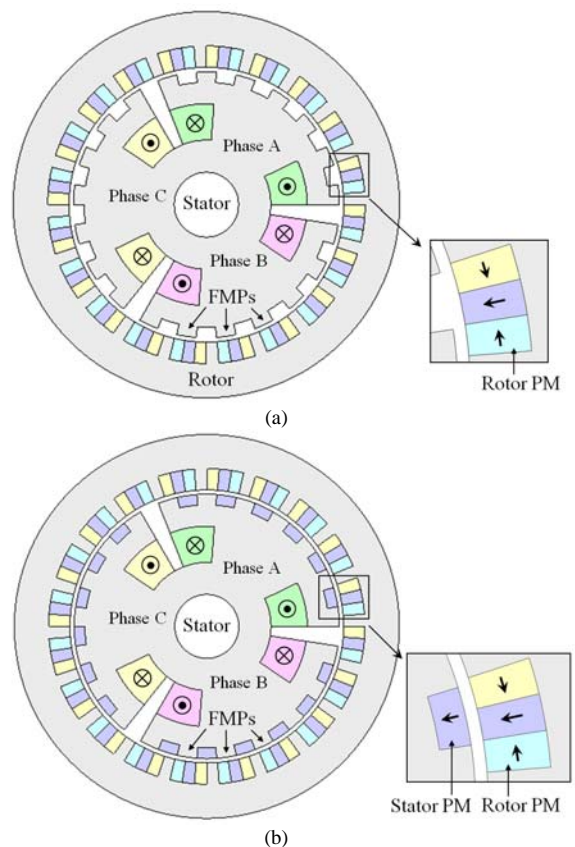


Fig. 1. Structure of the PMV machine (a) model I (b) model II

$$G_r = \frac{\omega_s}{\omega_r} = \frac{N_s - p_s}{p_s} \quad (2)$$

Where  $\omega_s$  and  $\omega_r$  are the rotating speeds of the magnetic field of the stator and the rotor, respectively.

### B. Comparison of performances

Table I shows the analysis results of the induced voltages and torques for the two PMV models and a basic PSPMV model, which has the FMPs on the stator and PMs mounting on the surface of the rotor. Each model has the same grade of NdFeB magnet having residual flux density of 1.2 T and also operates in the same speed, 150 rpm. By comparing with PSPMV model and PMV model I, the flux concentrating structure on the rotor improves the characteristics of the fundamental of the induced voltage, and average torque. However, this structure also increases the total harmonic distortion (THD) of the induced voltage, cogging torque and torque ripple as well. However, by inserting PMs between the FMPs on the stator, the PMV model II decrease the THD of the induced voltage and torque ripple while the induced voltage and torque are increased. Although the PMV model II generates a higher cogging torque of 1.17Nm than the PMV model I, the torque ripple caused in the PMV model II is decreased by 46% comparing with the PMV model I. In addition, the THD of the induced voltage is also decreased in the PMV model II comparing with PMV model I.

### C. Design of the PMV model II

In the PMV model II, the width of the FMPs influences the flux modulation in the air gap as well as the reluctance torque caused by interacting with the teeth on the rotor. In addition, the width of the FMPs determines the width of the stator PM. Thus, the width of the FMPs is selected as design variable. In order to adjust the width of the FMPs, the width ratio is defined as proportion of the FMPs width to the width of the rotor teeth. When the width of the rotor is fixed as value of 5mm and the width ratio is increased from 0.6 to 1.8, the fundamental of the induced voltage tend to be increased up to 82 V and the THD of it is can be decreased to 5% as shown in Fig.2. In the case of the torque characteristic, the average torque has the highest value when the width ratio is 1.5. This is similar trend with the fundamental of the induced voltage. On the contrary, the torque ripple has the minimum value when the width value is about 1.3. The further research shall be done with the optimum design of the PMV model II considering the other design parameters such as the thickness of the FMPs, width of teeth on the rotor and magnetization pattern of the rotor PM.

TABLE I  
PERFORMANCE COMPARISON OF THE PSPMV AND PMV MODELS

		PSPMV model	PMV model I	PMV model II
Induced voltage	Fundamental [V]	22.73	53.73	79.01
	THD [%]	2.49	5.50	3.65
Generated torque	Average [N.m]	30.67	60.91	88.31
	Torque ripple [%]	-	25.96	15.35
	Cogging [N.m]	0.01	0.20	1.17

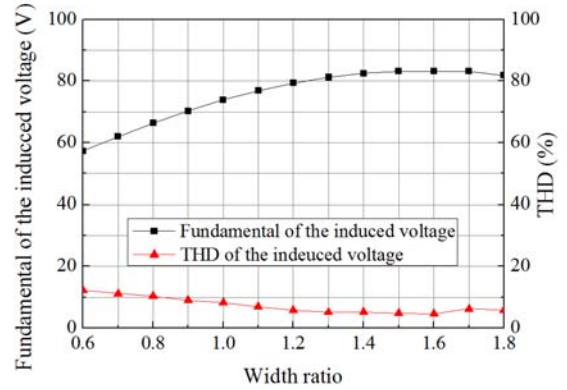


Fig. 2. Comparison of the induced voltage in a phase (@150rpm)

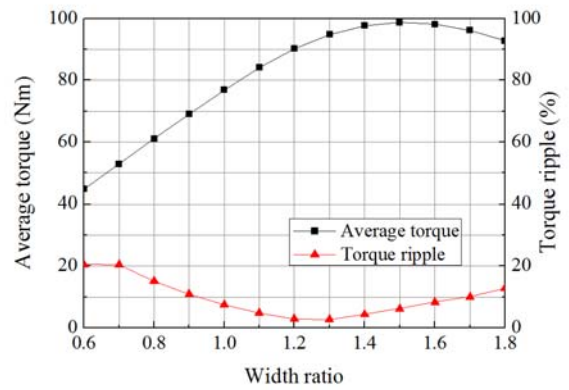


Fig. 3. Comparison of the torque waveforms for the PMV models and PSPMV model

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