Back-EMF design of PM Motor using PCB winding by Space Harmonic Analysis Methods

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Abstract — This paper presents a method to design the waveform of back electromotive force (back-EMF) of permanent magnet (PM) motor using printed circuit board (PCB) windings. At first, the flux density distribution resulting from PM is determined based on the space harmonic analysis method in the winding region. Then the required back-EMF can be obtained by adjusting winding distribution. It can be done by modifying the shape, width and distance between patterns of PCB windings. The validity of the proposed method is verified by finite element analysis results, and finally will be compared with experimental ones.

I. INTRODUCTION

In the design of permanent magnet (PM) motors, the shape and amplitude of back-EMF are important factors influencing on motor's performance [1], [2]. Particularly, the unwanted harmonic components included in back-EMF generate torque ripples and losses in the motor [3]. In conventional PM motors, the waveform of back-EMF is determined by the magnetization of PM and tooth shape of stator [4]. However, in this case, it is not possible to design the shape of back-EMF considering the magnetization distribution of PM by adjusting each turns of windings.

This paper presents a method to design the shape of back-EMF of PM motor using printed circuit board (PCB) winding. Based on the space harmonic analysis method, when the magnetization distribution of PM is given, the magnetic field in the winding region is determined by solving a governing equation having magnetic scalar potential as field variable. Once the flux density distribution in the winding region is calculated, the required back-EMF can be obtained by adjusting winding distribution. It can be done by modification of shape, width, and distance between patterns of PCB windings. The validity of the proposed method is verified by finite element analysis results, and finally will be compared with experimental ones. Fig. 1 shows the procedure to design back-EMF shape of PM motors using PCB windings.

II. PRINCIPLE OF THE METHOD

A. Governing equation

In order to obtain magnetic field distribution produced by PM, the stator and rotor core are assumed to have infinite permeability. When current is absent in solution region, magnetic field intensity, $\vec{H}$ can be represented using magnetic scalar potential, φ.

$$\vec{H} = -\vec{\nabla}\varphi \cdot \qquad (1)$$

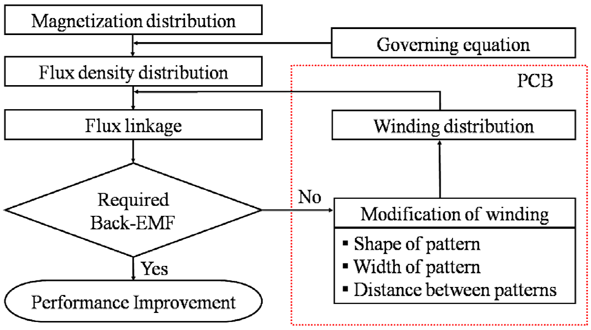

Fig. 1. Procedure to Design back-EMF waveform

For the PM type slotless radial motor, the magnetic scalar potential distribution is governed by Laplace and quasi-Poisson equation in polar coordinates as follows [1].

$$\frac{1}{r}\frac{\partial \varphi_a}{\partial r} + \frac{\partial^2 \varphi_a}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 \varphi_a}{\partial^2 \theta^2} = 0 . \qquad \text{in the air gap (2)}$$

$$\frac{1}{r}\frac{\partial \varphi_m}{\partial r} + \frac{\partial^2 \varphi_m}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 \varphi_m}{\partial^2 \theta^2} = \frac{\vec{\nabla} \cdot \vec{M}}{\mu_r} . \text{ in the magnet (3)}$$

where μ_r is the magnet relative permeability, $\vec{M}$ is magnet magnetization and the subscripts a and m denote the air and magnet regions respectively. With analysis or experimental results on the magnetization distribution, the radial and tangential magnetization components can be described by Fourier series. This permits arbitrary periodic magnetization of PM, thereby making it possible to design the shape of back-EMF considering magnetization by modifying winding distribution. By applying the customary boundary conditions to (2) and (3), the flux density distribution in each region can be obtained .

B. Winding distribution

With the information on the flux density distribution in the winding region, PCB patterns can be designed to have appropriate winding distribution and resulting required flux linkage waveform. Unlike the conventional winding layouts such as lap, wave, concentric and distributed winding, the PCB winding can be adjusted by modifying the shape, width, and interval of each pattern as shown in Fig.2. Finally, the winding distribution can be described by following Fourier series.

$$N(\theta) = \sum_{n=-\infty}^{\infty} N_k e^{jn\theta} . \qquad (4)$$

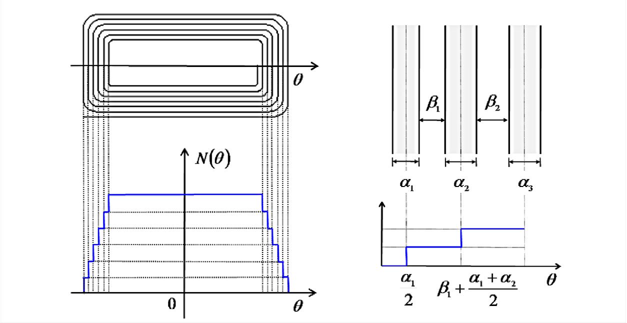

Fig. 2. Coil winding and winding distribution

C. *Back-EMF*

From the magnetization and winding distribution, the flux linkage in a coil is given as

$$\lambda_{coil} = L_{st} \int_{-\pi/2}^{\pi/2} N(\theta)\cdot B(\theta+\alpha) R d\theta . \qquad (5)$$

where L_{st}, α are axial length and rotation angle of a rotor, respectively. The associated back-EMF is the derivative e of the flux linkage as follows.

$$e_{coil} = \frac{d\lambda}{dt} = \frac{d\theta}{dt}\frac{d\lambda}{d\theta} = \omega_e \frac{d\lambda}{d\theta} . \qquad (6)$$

For the highly saturated ferromagnetic materials, B-H curve of the core is considered to scale down the amplitude of the flux density.

III. COMPARISON WITH FEM RESULT

To verify the validity of the proposed method, it is applied to the slotless PM motor as shown in Fig. 3 and compared the results with finite element analysis. With the radial magnetization of PM, the winding has two different lay outs. One coil has the same interval between each pattern (case I) and the other one has narrow interval toward the inside of the coil (case II) as shown in Fig. 4. The back-EMF waveform for each case by space harmonic method has a good agreement with the results by finite element analysis. This shows the proposed method can be applied to PM motor design for accurately predicting motor performance as well as for adjusting the shape of back-EMF. Finally, experimental results will be compared with the proposed method with further analyses.

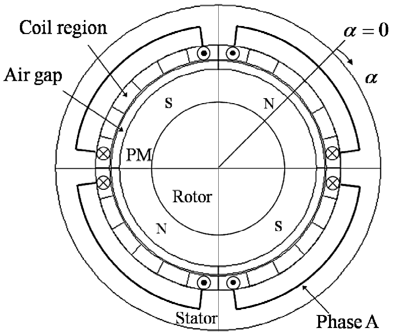

Fig. 3. Basic model (4 pole slotless motor)

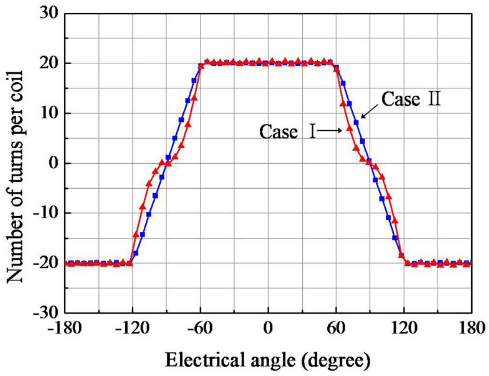

Fig. 4. Winding distribution in slotless motor

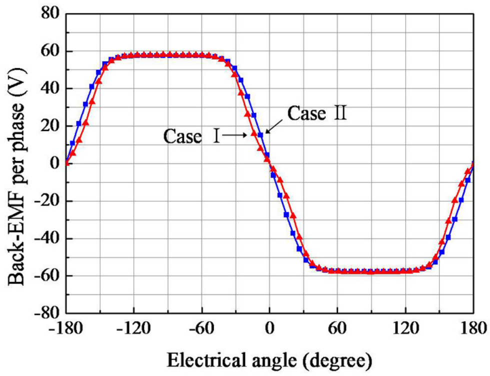

Fig. 5. Back-EMF waveform by space harmonics method

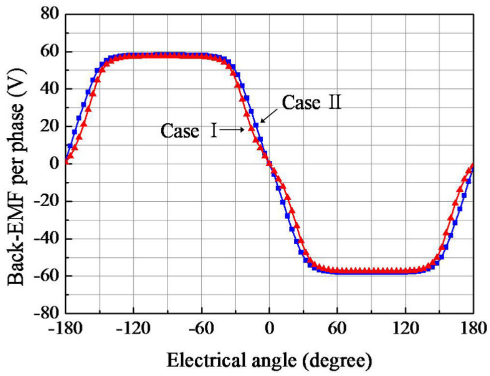

Fig. 6. Back-EMF waveform by FEM analysis

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