Magnet Field Analysis Model to Halbach PM Slotless Linear Generator for Wave Energy Conversion

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Magnetic field analysis model of Halbach PM Arrays is presented based on analytical method and equivalent-magnetizing-current (EMC) in this paper. To reduce the total harmonic distortion (THD) of EMF waveform, a Halbach PM Arrays slotless tubular linear generator for wave energy conversion is proposed and analyzed. Moreover, the generator is assessed by the magnetic field analysis model and finite-element methods (FEM), and constructional details of the generator are proposed for suitable air-gap flux density. The influence of the main design parameters for the slotless generator is investigated, and is compared with those of R-magnetized structure. The analysis results obtained by the model and FEM method confirm the exactness of the proposed generator.

Index Terms — **Halbach PM Arrays, equivalent-magnetizing-current (EMC), linear generator, wave energy conversion**

I. INTRODUCTION

As the exploitation of sea wave energy deepens, many new types of linear generators for direct-drive energy convertor have aroused wide attention and discussions [1]. Compared traditional slotted linear generator, a PM slotless tubular linear generator can easily meet demands such as enough air-gap flux density, low cogging force, flexible structure and light weight.

In this paper, an analysis model for the magnetic field by EMC method and analytical method is compared with FEM, and a PM slotless tubular linear generator with Halbach PM Arrays is proposed and analyzed based on the model. Lastly, based on the same configurations of the stator, using the analysis model proposed above and FEM, the amplitude of electromotive force (EMF) of the generator and THD of EMF wave form with different PM parameter are obtain.

II. MAGNETIC FIELD ANALYSIS

The tubular slotless-generator has a symmetric structure along the *z*-axis, so half section is selected as the analysis region. Fig.1 shows the analysis model of the motor for the magnetic field by EMC method. The source of PM is expressed in the form of Fourier series.

Assuming that the windings current is zero, PM is the only source to produce the magnetic field. Some assumptions are adopted to simplify the analysis, such as all regions are extended infinitely in the direction $\pm Z$ and the permeability of back iron is infinite. The permeability of the back iron and iron yoke are infinite.

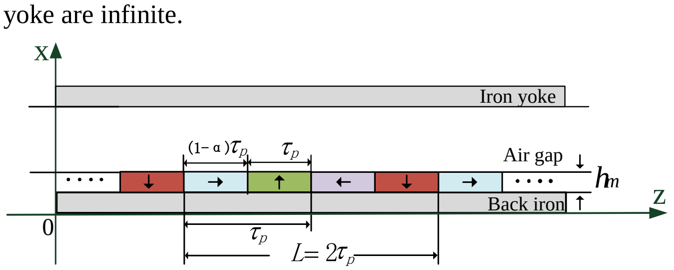

Fig.1. Analysis model

The calculation expression of magnetizing angle of magnet in Halbach PM arrays is as follows:

$$\theta_M = \left(-\theta'_{m(i+1)}\right) - \left(-\theta'_{m(i)}\right) = 180^\circ / M \tag{1}$$

Where θ_M is angle difference of the adjacent two permanent magnets, M is the permanent magnet numbers of per pole, $\theta'_{m(i)}$ and $\theta'_{m(i+1)}$ are the ith and $(i+1)$th magnetizing angles respectively (n is integer). In the condition of $M=2$, α_p=0.5 the value of θ_M is 90°, as is shown in Fig. 1, where τ_p is pole pitch, α_p is the ratio of the X-direction length of the Z-direction magnetized PM to a pole pitch τ_p.

In Fig.1, the magnetization vector general formula of Halbach magnet array is expressed as follows:

$$\tilde{M} = \sum_{n=-\infty}^{\infty} \left[\tilde{M}_{xn} e^{-jK_n Z} i_x + \tilde{M}_{zn} e^{-jK_n Z} i_z \right] \tag{2}$$

Where $\tilde{M}_{xn}$ and $\tilde{M}_{zn}$ are magnetization vector Fourier coefficients of radial component and axial component , K_n is the angular frequency of the n-order harmonic component, and it is expressed as follow:

$$K_n = \frac{2n\pi}{L} \tag{3}$$

The magnetization vector general formula of PM array is expressed based on Fourier series definition as follows:

$$\tilde{M}_{xn} = \frac{1}{h_m} \int_0^{h_m} M_x e^{jk_n x} dx \tag{4}$$

$$\tilde{M}_{zn} = \frac{1}{L} \int_0^{L} M_z e^{jk_n z} dz \tag{5}$$

Then, magnetization vector Fourier coefficients $\tilde{M}_{xn}$ and $\tilde{M}_{zn}$ can be derived as follows:

$$\tilde{M}_{xn} = \begin{cases} \sqrt{2} \cdot M_0 / \pi |n| & n = \pm(8m+1) \text{ or } n = \pm(8m+3) \\ -\sqrt{2} \cdot M_0 / \pi |n| & n = \pm(8m+5) \text{ or } n = \pm(8m+7) \\ 0 & n: \text{ even} \end{cases} \tag{6}$$

$$\tilde{M}_{zn} = j^n \tilde{M}_{xn} \tag{7}$$

When L is 51.2 mm, h_m is 4 mm, and NdFeB magnet is adopted in the linear generator, the retentiveness B_r is 1.3 T, then M_0 is 0.325×10^6 A/m.

$$\begin{cases} \tilde{B}_{xn} = \left(-\dfrac{j\mu_0 k_n}{2r_n}\tilde{M}_{zn} + \dfrac{\mu_0}{2}\tilde{M}_{xn}\right)\cdot\left(1-e^{-r_n h_m}\right)\cdot e^{r_n x} \\ \tilde{B}_{zn} = \left(-\dfrac{j\mu_0 r_n}{2k_n}\tilde{M}_{xn} - \dfrac{\mu_0}{2}\tilde{M}_{zn}\right)\cdot\left(1-e^{-r_n h_m}\right)\cdot e^{r_n x} \end{cases} \quad x \leqslant 0 \tag{8}$$

$$\begin{cases} \tilde{B}_{xn} = \left(-\dfrac{j\mu_0 k_n}{2r_n}\tilde{M}_{zn} + \dfrac{\mu_0}{2}\tilde{M}_{xn}\right)\cdot\left(1-e^{-r_n h_m}\right)\cdot e^{-r_n (x-h_m)} \\ \tilde{B}_{zn} = \left(\dfrac{j\mu_0 r_n}{2k_n}\tilde{M}_{xn} - \dfrac{\mu_0}{2}\tilde{M}_{zn}\right)\cdot\left(1-e^{-r_n h_m}\right)\cdot e^{-r_n (x-h_m)} \end{cases} \quad x \geqslant h_m \tag{9}$$

Where $r_n = |k_n|$, correspondingly, the harmonic content of flux density along x and z directions are derived from (6), (7), (8) and (9).

III. Generator Topology

A tubular slotless-generator is designed for wave energy generation, as shown in Fig.1. It consists of a stator with iron yoke, slotless topology and pie windings, and a translator of generator made of steel, where Halbach PM arrays rings are mounted on it.

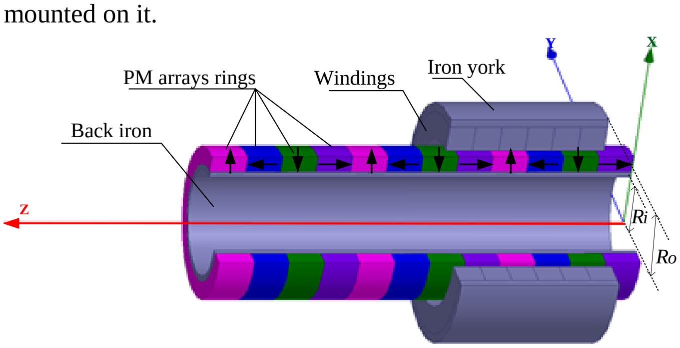

Fig.2.3-D Model of generator with *T*-structure PM arrays rings

In the comparison analysis, the main parameters of the slotless-generator are identical as shown in Table I. The dynamic characteristics analysis is here restricted to no-load case with a constant speed of 0.4 m/s. In order to evaluate the influence of one parameter on performance, the other parameters are kept identical.

TABLE I
Parameters of the Generator

Symbol	Item	Value
L_S	Stator thickness	90 mm
R_o	Stator outside radius	66.5 mm
R_i	Translator inside radius	30 mm
τ_p	PM Pole pitch	25.6 mm
Hm	PM thickness	4 mm

IV. Performance Analysis

The air-gap flux density of the slotless-structure is lower than that of slotted-structure [2-3]. Fig.3 shows EMF of the generator with Halbach PM arrays and R- magnetized.

Based on the analysis model above and FEM, the amplitude of electromotive force (EMF) and THD of EMF wave form with different α and detent force with different *k* are obtain, as are shown in Fig.4 and Fig.5, where α= h_m / L, *hm* and L are the permanent magnet thickness and length respectively.

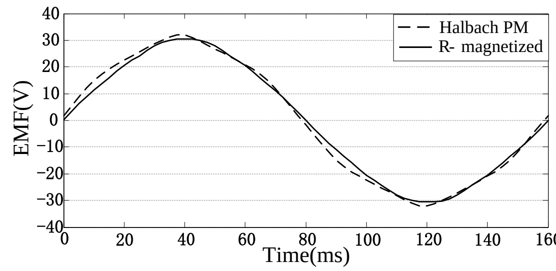

Fig.3. EMF with claw-structure and *T*-structure PM arrays

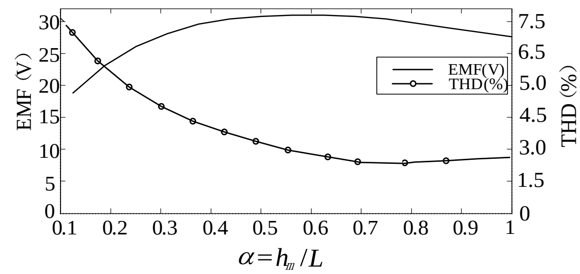

Fig.4. EMF and THD of EMF wave form with different α

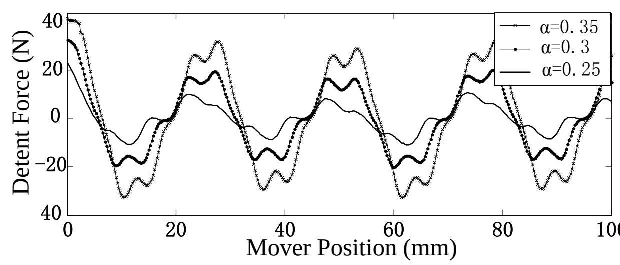

Fig.5. Detent force with different K

V. Conclusion

The performance of the Halbach PM Arrays slotless linear generator is assessed by magnetic field analysis model and FEM. Then, the influence of the main design parameters are compared with those of R-magnetized structure and Halbach PM Arrays structure. The constructional optimization details are significant to meet better performance for linear generator in energy conversion system.

References

[1]M.A. Mueller, "Electrical generators for direct drive wave energy converters", *IEE Generation, Transmission and Distribution*, vol. 149, pp.446-456, 2002.

[2] N. Bianchi, S. Bolognani, D. D. Corte, and F. Tonel, "Tubular linear permanent magnet motors: An overall comparison," *IEEE Trans. Ind. Appl.*, vol. 39, no. 2, pp. 466–475, Mar. 2003.

[3] Sung Whan Youn, Jong Jin Lee, Hee Sung Yoon, and Chang Seop Koh, "A New Cogging-Free Permanent-Magnet Linear Motor" *IEEE Trans. on Magn.*, Vol. 44, NO. 7, JULY 2008.