

Halbach Array Permanent Magnet Tubular Linear Generator for Direct-Driver Wave Energy Conversion

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Abstract—H array tubular linear permanent magnet generator (TLPMG) is proposed to extract wave energy. The magnetic field is analyzed by numerical calculation, and verify by finite element analysis. From Fourier decomposition method, the H array has a well sinusoidal curve than quasi-H. Finally, a prototype is manufactured and validate by an experiment.

I. THE STRUCTURE OF GENERATOR

Linear generator [1-3] is always used to extract wave energy due to its simple structure and high efficiency. The structure of H array generator is shown in Fig. 1. It consists of 8 H array permanent magnets (PMs), stator, coils and back-iron. The PMs and back-iron is connected with buoy and moves with the wave, thus, the current is induced according to the Faraday laws.

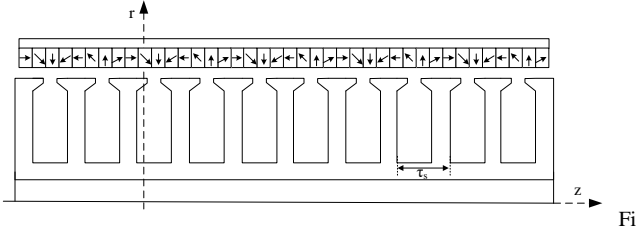


Fig. 1. The structure of the wave generator

II. OPEN-CIRCUIT FLUX DENSITY DISTRIBUTION

The numerical calculation is an important method for permanent magnet motor design [4]. In order to establish an analytical solution for magnetic field distribution in an H magnetized tubular permanent magnet generator, the following assumptions are made.

- 1) The axial length of the generator is infinite.
- 2) The back iron is infinitely permeable.
- 3) Neglecting slotting effects, if present, can be taken into account by introducing a Carter coefficient.
- 4) Assuming the permanent magnet magnetized is uniform and no demagnetization.

Consequently, the magnetic field analysis is considered two regions, that is airspace/winding region *I* and permanent magnet region *II* as shown in Fig. 2.

The governing field equations in terms of the vector magnetic potential A_θ are:

$$\begin{cases} \frac{\partial^2 A_{1\theta}}{\partial r^2} + \frac{1}{r} \frac{\partial^2 A_{1\theta}}{\partial^2 r} - \frac{1}{r^2} \frac{\partial A_{1\theta}}{\partial \theta^2} + \frac{\partial^2 A_{1\theta}}{\partial z^2} = 0 \\ \frac{\partial^2 A_{11\theta}}{\partial r^2} + \frac{1}{r} \frac{\partial A_{11\theta}}{\partial r} - \frac{1}{r^2} \frac{\partial A_{11\theta}}{\partial \theta^2} + \frac{\partial^2 A_{11\theta}}{\partial z^2} = -\mu_0 \frac{\partial M}{\partial z} \end{cases} \quad (1)$$

In the cylindrical coordinate system, the magnetization M is given by

$$M = M_r \vec{e}_r + M_z \vec{e}_z \quad (2)$$

where M_r and M_z is the components of M in the r and z axis, respectively. Fig.2 shows the eight array H magnetization and the distribution of M_r and M_z . Where B_r is remanence, α is the angle between the z axis and magnetized orientations. M is a periodic function which period is $2\tau_p$ and the τ_p is the pole pitch, which can be expanded into a Fourier series having the forms

$$M_r = \sum_{n=1}^{\infty} M_{rn} \sin(m_n z) \quad (3)$$

$$M_z = \sum_{n=1}^{\infty} M_{zn} \cos(m_n z) \quad (4)$$

$$m_n = \frac{n\pi}{\tau_p} \quad (5)$$

$$M_{rn} = \frac{4B_r}{n\pi\mu_0} \sin\left(\frac{n\pi}{2}\right) \sin\left(m_n \frac{\tau_{mr}}{2}\right) + \frac{8B_r \sin \alpha}{n\pi\mu_0} \sin\left(m_n \frac{\tau_{rz}}{2}\right) \times \sin(n\pi) \left(\frac{\tau_p + \tau_{mz} - \tau_{mr}}{2}\right) \quad (6)$$

$$M_{zn} = \frac{4B_r}{n\pi\mu_0} \sin\left(m_n \frac{\tau_{mz}}{2}\right) + \frac{8B_r \cos \alpha}{n\pi\mu_0} \sin\left(m_n \frac{\tau_{rz}}{2}\right) \sin\left(\frac{n\pi}{2}\right) \times \sin\left(m_n \left(\frac{\tau_p + \tau_{mr} - \tau_{mz}}{4}\right)\right) \quad (7)$$

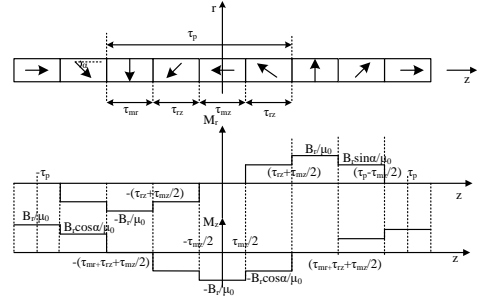


Fig. 2. Distribution of M_r and M_z .

Thus, the equation (1) can be simplified as

$$\begin{cases} \frac{\partial^2 A_{1\theta}}{\partial r^2} + \frac{1}{r} \frac{\partial^2 A_{1\theta}}{\partial^2 r} - \frac{1}{r^2} \frac{\partial A_{1\theta}}{\partial \theta^2} + \frac{\partial^2 A_{1\theta}}{\partial z^2} = 0 \\ \frac{\partial^2 A_{11\theta}}{\partial r^2} + \frac{1}{r} \frac{\partial A_{11\theta}}{\partial r} - \frac{1}{r^2} \frac{\partial A_{11\theta}}{\partial \theta^2} + \frac{\partial^2 A_{11\theta}}{\partial z^2} = \sum_{n=1}^{\infty} P_n \cos\left(\frac{n\pi}{\tau_p} z\right) \end{cases} \quad (8)$$

where

$$P_n = -\frac{4B_r}{\tau_p} \sin\left(\frac{n\pi}{2}\right) \sin\left(m_n \frac{\tau_{mr}}{2}\right) + \frac{8B_r \sin \alpha}{\tau_p} \times \sin\left(m_n \frac{\tau_{rz}}{2}\right) \times \sin\left[(n\pi) \left(\frac{\tau_p + \tau_{mz} - \tau_{mr}}{2}\right)\right] \quad (9)$$

If the permeability of the back-iron is assuming to be infinite, and only two regions are considered. The field regions are shown in Fig. 3. The boundary conditions to be satisfied by

(7) are

$$\begin{aligned} B_{zI}|_{r=R_0} &= 0; & H_{zII}|_{r=R_s} &= 0 \\ B_{rI}|_{r=R_m} &= B_{rII}|_{r=R_m}; & H_{rI}|_{r=R_m} &= H_{rII}|_{r=R_m} \end{aligned} \quad (10)$$

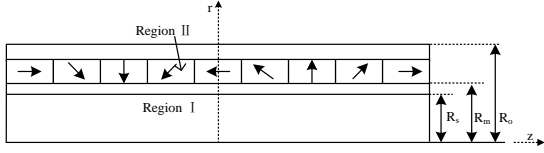


Fig. 3 Field region

According to the boundary conditions and solved the equation (8), the flux density components can be obtain as following

$$B_{Ir}(r, z) = \sum_{n=1}^{\infty} [a_{In} I_1(m_n r) + b_{In} K_1(m_n r)] \sin(m_n z) \quad (11)$$

$$B_{Iz}(r, z) = \sum_{n=1}^{\infty} [a_{In} I_0(m_n r) + b_{In} K_0(m_n r)] \cos(m_n z) \quad (12)$$

$$\begin{aligned} B_{IIr}(r, z) &= \sum_{n=1}^{\infty} \{ [F_{An}(m_n r) + a_{IIIn}] I_1(m_n r) \\ &+ [-F_{Bn}(m_n r) + b_{IIIn}] K_1(m_n r) \} \sin(m_n z) \end{aligned} \quad (13)$$

$$\begin{aligned} B_{IIz}(r, z) &= \sum_{n=1}^{\infty} \{ [F_{An}(m_n r) + a_{IIIn}] I_0(m_n r) \\ &+ [-F_{Bn}(m_n r) + b_{IIIn}] K_0(m_n r) \} \cos(m_n z) \end{aligned} \quad (14)$$

where $I_0(m_n r)$, $I_1(m_n r)$ are modified Bessel functions of the first kind, and $K_0(m_n r)$, $K_1(m_n r)$ are modified Bessel functions of the second kind, of order 0 and 1.

III. COMPARISON WITH FINITE ELEMENT ANALYSIS

The finite element analysis is employed to validate the effectiveness of the method. The magnets are sintered NdFeB, for which has high magnetized, high-energy and high coercive force and it's $B_{rem}=1.2T$ and $\mu_r=1.05$, and the material for back-iron and stator are D23. A prototype is manufactured to illustrate the analysis and is shown in Fig. 4.



Fig. 4 Manufactured prototype

In order to calculate conveniently, we assume the different permanent magnet is the same length. Fig. 5 and Fig. 6 show the comparison with B_r and B_z for numerically calculated and FEA, it clearly see that the analytical solutions agree extremely well with the finite element analysis.

Comparison with B_r for 8 H array and quasi-H is shown in Fig. 7. As one can see that the H array has a well sinusoidal curve than quasi-H. From Fourier decomposition method, the THD for 8 H array and quasi-H are 15.57% and 37.45% respectively. That is to say, it has a low cogging force and a high efficiency. The EMF for no-load at 0.4m/s is shown in Fig.8.

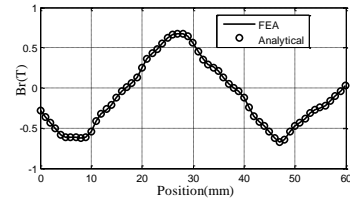


Fig. 5 Comparison with B_r for FEA and analytical

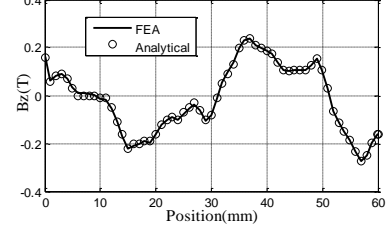


Fig. 6 Comparison with B_z for FEA and analytical

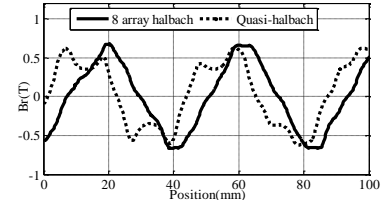


Fig. 7 Comparison with B_r for 8 H array and quasi-H

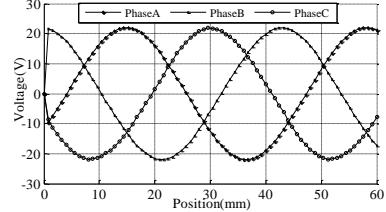


Fig. 8 EMF for no-load at constant speed

IV. CONCLUSIONS

In this paper, an H permanent magnet with 8 arrays has been proposed to extract wave energy. Through numerically calculated and FEA, this structure has good performance such as sinusoidal magnetic field, symmetric three phase electromotive force. Finally, a prototype is manufactured and validate by an experiment.

REFERENCES

- [1] Rao K S R, Sunderan T, Adiris M R, et al. Performance and design optimization of two model based wave energy permanent magnet linear generators[J]. Renewable Energy, 2017, 101:196-203.
- [2] C.Boström, M. leijon. 'Operation analysis of a wave energy converter under different load conditions', IET Renew. Gener., 2011, Vol. 5, Iss. 3, pp. 245-250.
- [3] Liu C, Yu H T, Hu M, et al. Research on a permanent magnet tubular linear generator for direct drive wave energy conversion[J]. Iet Renewable Power Generation, 2014, 8(3):281-288.
- [4] Jiabin Wang, David Howe. 'Tubular Modular Permanent-Magnet Machines Equipped With Quasi-H Magnetized Magnets—Part I: Magnetic Field Distribution, EMF, and Thrust Force', IEEE TRANSACTIONS ON MAGNETICS, SEPTEMBER 2005VOL. 41, NO. 9, pp.2470-2478.