

# **Improvement of Tubular Permanent Magnet Machine Performance Using Dual-Segment Halbach Array**

Minh-Trung Duong<sup>1,2</sup>, Yon-Do Chun<sup>1,2</sup>, Pil-Wan Han<sup>2</sup>, Byong-Gun Park<sup>1,2</sup>, Deok-je Bang<sup>2</sup>,  
Jin-Kyu Lee<sup>1,2</sup>, Eun-Jun Rhee<sup>3</sup>

<sup>1</sup>*University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon, Duong.MT@keri.re.kr*

<sup>2</sup>*Korea Electrotechnology Research Institute, 12 Bulmosan-ro, Seongsan-gu, Changwon-si, Gyeongsangnam-do*

<sup>3</sup>*Hyundai Rotem Company, 37 Cheoldobangmulgwan-ro, Bugok-dong, Uiwang-si, Gyeonggi-do*

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## **Summary**

In this paper, modification of dual-Halbach permanent magnet (PM) array is investigated to improve performance of tubular linear machine, in terms of flux density and output power are considered. Instead of a classical Halbach array with only radial and axial PMs, proposed model is involves insertion of mid-magnets, which have magnetized angles shifted from the reference magnetized angles of axial and radial PMs. This structure leads to elimination of flux leakage and concentration of flux linkage in middle of the coil; therefore, the performance of the machine is increased.

*Keywords: electromagnetic, tubular machine, Halbach array, power density.*

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## **1 Introduction**

Tubular linear machines are commonly applied in many industrial applications, such as cryocoolers, linear compressors, or refrigerators [1] – [3]. Recent research activities for energy harvesting in vehicle suspension systems [4] or using ocean wave energy [5] have proposed the new trend for the tubular machines. From a design viewpoint, at a particular volume, the increase of the output power is very difficult. L. Zou *et al.* [6] provide the original design, which is composed of one magnet layer using a Halbach arrangement instead of only axial magnets or radial magnets array. In the following step, by using the same Halbach array structure, X. Tang *et al.* [7] modified the original model with a double layer of permanent magnet; this method eliminates the flux leakage, while flux density in the middle of the coil is concentrated. This leads to an eightfold improvement of the output power and a 3.8 times improvement of the power density compared to those values of the original design.

Another technique was studied by Y. Shen, in which mid-magnets of which the magnetization angle is shifted from the reference angle of axial and radial magnets are inserted [8]. There are two possible structures, including odd-segment or even-segment, and these structures define the number of magnet segments over a pole pitch as an odd or even number. The FEM and analytical results for a 12-slot/ 10-pole PM brushless machine illustrate that the 3-segment Halbach array exhibits significantly higher fundamental airgap flux density than of the magnet cylinder having a traditional Halbach array with two segments. Under the same theory, W. Zhao designed a linear generator for energy harvesting from body motion [9]

using an even-segment Halbach array. The eight-segment dual Halbach array is employed in the optimized generator because its magnetic flux density is greater than that of the four-segment array.

In this paper, a larger model assembled with a vehicle suspension system was designed based on the proposed segment-magnet dual Halbach array. The analysis results show that under the same operating conditions, the generator with the cylinder segment magnet yields higher output power than that of the generator with original Halbach array structure.

## 2 Tubular Machine with Classical Halbach Array

This section deals with the design specification of the tubular machine using classical Halbach array based on the actual dimensions of a commercial shock absorber in an SUV-Korando car. Analyses using FEM are validated by corresponding experiments.

### 2.1 Design Specifications

Fig. 1 shows the cross-section of the half model and its geometry over one pole pitch, as was presented in [10]. The overlapping length of the magnet array and coil windings is about 200mm but, fortunately, this value is adjustable by  $\pm 40$ mm. That is also the condition for the outer diameter, which can be flexibly chosen at values between 80mm and 160mm, while the inner diameter has to be at least 40mm, the same as the diameter of the damping part or the mechanical part [10].

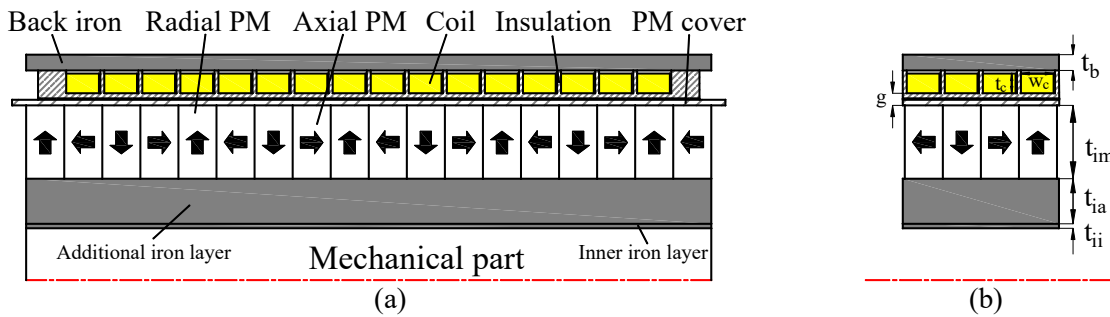


Figure 1: (a) – Cross-section of the half model; (b) – One pole pitch

Due to the relative position between the coils and the excited flux density, and with the desire to simplify the drive system, an external circuit is designed with two phases, in which phase 1 is in series connection with coil 1 and coil 3, phase 2 is in series connection with coil 2 and coil 4. It is mandatory to exactly set up the winding directions to achieve maximum power [6], [10]. The relative position between the coils and excited flux, and the external circuit, are shown in the Fig. 2.

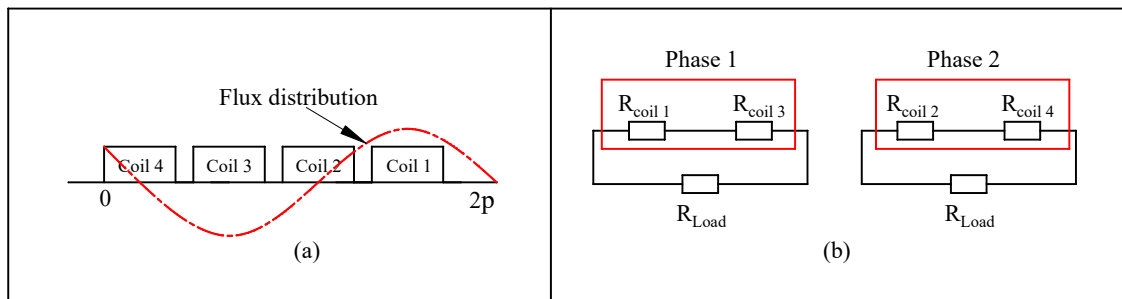


Figure 2: (a) – Coils & excited flux density; (b) – External circuit

According to [6], [10] and [11], the maximum output power occurs at the maximum vibrating speed  $v_{max}$  when the load resistance  $R_L$  equals the sum of the coil resistance  $R_c$ ; this is termed full load condition:

$$P_{\max} = V_e I_0 = B_r^2 v_z^2 \sigma V_{\text{coil}} \quad (1)$$

where  $V_{\text{coil}}$  is the coil volume.

Eq. (1) shows that output power is proportional to the square of the radial flux density, square of the vibrating speed and the volumes of the coil. The relationship among the peak to peak stroke, the vibrating speed, and the vibrating frequency is calculated as follows:

$$\text{Stroke}_{\text{peak-to-peak}} = \frac{v_{\max}}{\omega} = \frac{v_{\text{rms}} \sqrt{2}}{\pi f} \quad (2)$$

In addition, the instantaneous voltage of one coil centered at equilibrium position  $z_0$  in the regenerative shock absorber is presented as a function of time, position, magnetic flux density, geometrical parameter, suspension velocity and frequency. For the  $0^\circ$  coil or for coil 1, which has maximum magnetic flux density, if the vibration amplitude is small, the voltage is calculated by:

$$V_{0^\circ} = B_0 L \left| \frac{j\omega}{\omega_n^2 - \omega^2 + 2j\zeta\omega_n\omega} e_{\text{in}} \right| \sin \omega t \quad (3)$$

and a  $90^\circ$  coil or coil 3 will have a double frequency wave:

$$V_{90^\circ} = B_0 L \frac{\pi v_{\max}^2}{2H\omega} \sin 2\omega t \quad (4)$$

The additional iron layer is inserted to reduce the inner diameter of the PMs; this layer is composed of stainless steel, while the back iron is made of an electromagnetic material. Both radial PMs and axial PMs are made of DDP-40SH, which has relative flux density is  $B_r=1.26\text{T}$  at  $20^\circ\text{C}$  and relative permeability of  $\mu_r=1.05$ . Windings are wound around and supported by a bobbin with a total number of turns per slot of 180.

Detailed specifications of the tubular machine are briefly summarized in Table 1.

Table1: Design specifications of the tubular machine with classical Halbach array

Item	Value
Length, L (mm)	243
Outer diameter, D (mm)	160
PM thickness, $t_{\text{im}}$ (mm)	26.0
Radial PM width, $w_{\text{rm}}$ (mm)	13.5
Axial PM width, $w_{\text{am}}$ (mm)	13.5
Pole pitch, $\tau_p$ (mm)	27.0
Coil window thickness, $t_c$ (mm)	8.0
Coil window width, $w_c$ (mm)	12.1
Electrical air gap, g (mm)	4.3
Inner iron thickness, $t_{\text{ii}}$ (mm)	1.6
Added iron thickness, $t_{\text{ia}}$ (mm)	16.0
Back iron thickness, $t_b$ (mm)	5.6
Wire diameter, $w_r$ (mm)	0.6
Number of winding/ slot, turns	180
Number of poles, $N_p$	8
Number of slots, $N_s$	16
Back iron material	S20C
PMs material	NdFeB – N40SH; $B_r=1.26\text{T}$ (at $20^\circ\text{C}$ ); $\mu_r=1.05$

## 2.2 Experimental Verification of Analysis

According to [6], when a mid-size car is moving with 60mph of speed on a road of class C, vibrating frequency on the shock absorber is estimated to be approximately 0.25m/s. Under these conditions, the peak to peak stroke length and vibrating frequency are about 11.25mm and 10Hz, respectively. These conditions of the stroke length, vibrating speed, and linear frequency are considered as a standard for the models studied in this paper. When applying the standard conditions, the maximum and average power can be theoretically calculated at 76.09W and 37.8W, respectively.

To prepare for experimental verification, a prototype of a single layer coreless model was fabricated and installed, as in the illustrations provided in Fig. 3 and Fig. 4.

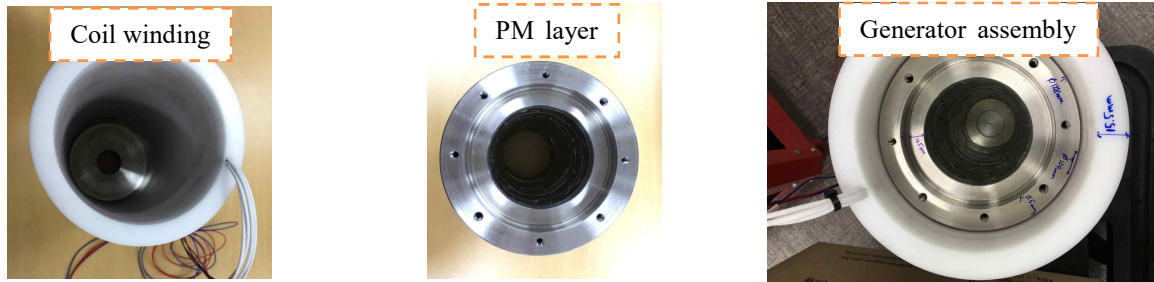


Figure 3: Prototype

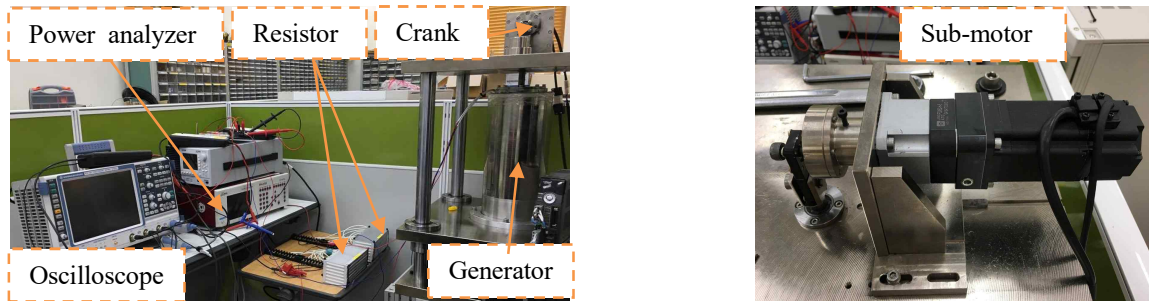


Figure 4: Experimental installment

Unfortunately, if the linear frequency of the generator is 10Hz, the required rotating speed of the sub-motor is 3000rpm, which exceeds the limitation of this motor; therefore, measurements were performed at lower vibrating speeds.

With the assumption that the peak to peak stroke length is fixed at 11.25mm, Fig. 5 presents the back EMF waveforms achieved for the load resistance when vibrating speed is 0.125m/s, which equals 50% of the standard. It can be clearly seen in the Fig. 5(b) that the frequency of load 2 is double that of load 1, which phenomenon can be predicted Eqs. (3) and (4).

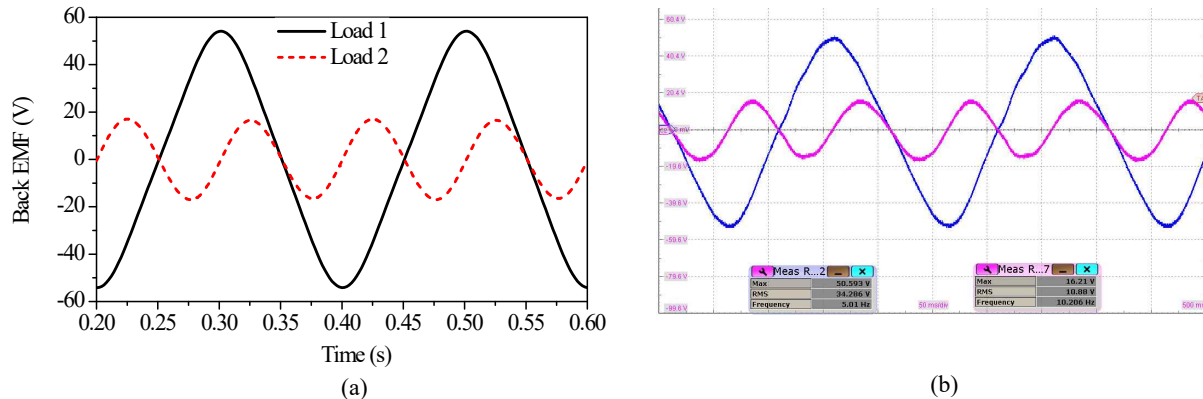


Figure 5: Back EMF of the load resistors under 0.125m/s of vibrating speed obtained from (a) – FEM analysis; (b) – Experiment

Fig. 6 illustrates the power variation according to various vibrating speeds under the full load condition. While the maximum output voltage is well-matched between the analyses and the experiments, with an average deviation of only 4.8%, the results of the average output power are not much satisfactory, at around 13.5%. It should be noted that although the resistance in one phase under full load condition is measured at nearly  $39.3\Omega$ , but in the experimental setup, only  $39\Omega$  of the load resistance can be connected.

Another noticeable phenomenon is the linear relationship between the output power and the square of the vibrating speed, according to Eq. (1). For instance, when the generator is operating at  $0.075\text{m/s}$ , about  $2.78\text{W}$  of average power can be obtained. The average power under  $0.15\text{m/s}$  of vibrating speed can be predicted according to the following:

$$P_{0.15\text{m/s}} = P_{0.075\text{m/s}} \times \left(\frac{0.15}{0.075}\right)^2 = 2.78 \times \left(\frac{0.15}{0.075}\right)^2 \approx 11.12(\text{W})$$

The measured result at  $0.15\text{m/s}$  of vibrating speed for average power is approximately  $11.46\text{W}$ , which is nearly the same as the expectation.

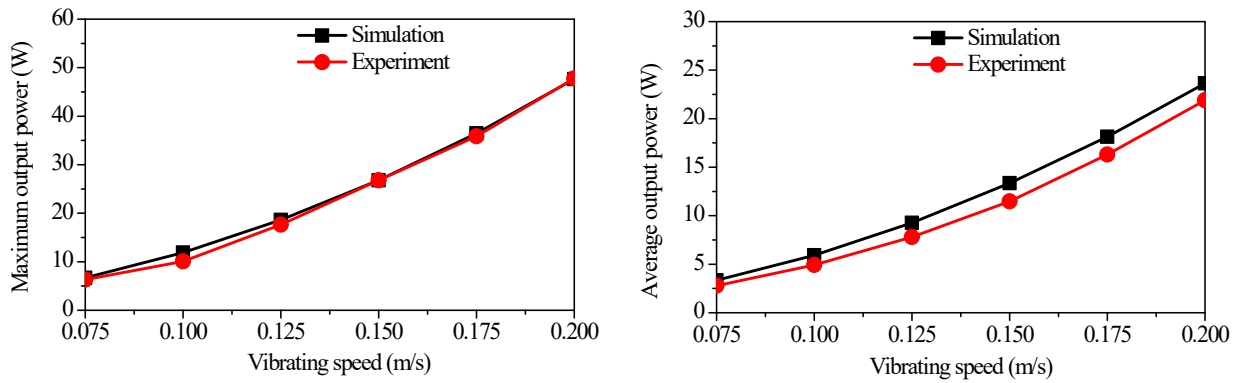


Figure 6: Power variation according to various vibrating speeds under full load condition

Fig. 7 illustrates the power variation according to various load resistances when the vibrating speed is  $0.125\text{m/s}$  and the peak to peak stroke length is  $11.25\text{mm}$ . Both the analysis and the experiment results present similar trends, with an average deviation of about 13.4%. When the load resistance equals the sum of the coil resistance, the average output power is at its maximum.

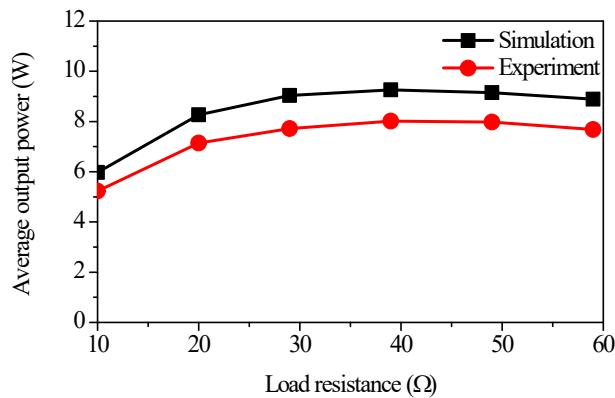


Figure 7: Average power variation according to various load resistances

### 3 Tubular Machine with Novel Halbach Array

In this section, a novel Halbach array is applied to the same tubular generator with the desire to improve the output power. Based on the results in [8], instead of applying only axial and radial PMs over one pole pitch in a classical Halbach array, a number of mid-magnets with different magnetized angles are inserted. There

are two applicable approaches, including even-segment, with an even number of magnets over one pole pitch, and odd-segment, with an odd number of magnets over one pole pitch.

From the pole pitch value, there are 4 magnet segments in the even-segment case and 5 magnet segments in the odd-segment case. Design specifications with the number of magnets, the sizes, and the magnetized direction are shown in Fig. 8 and Table 2.

For a fair comparison, the other dimensions such as length and diameter of the generator, the number of turns per slot, and the materials are the same for the 3 models.

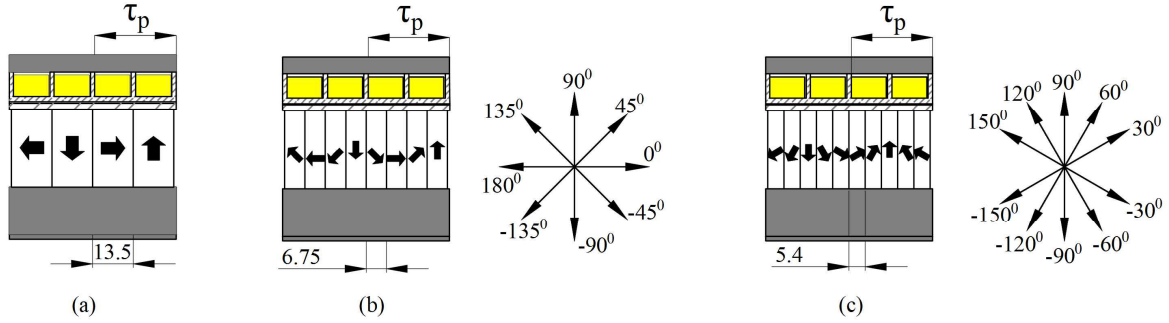


Figure 8: (a) – Classical Halbach array; (b) – 4-segment Halbach array; (c) – 5-segment Halbach array

Table 2: Specifications of the magnet segments over one pole pitch

Items	Classical Halbach array	4-segment	5-segment
Pole pitch, $\tau_p$ (mm)	27		
Number of segments/ pole pitch	2	4	5
Width of each segment (mm)	13.5	6.75	5.4
Magnetized angle of mid-magnet	---	$45^\circ$	$30^\circ$

Fig. 10 shows the flux distribution on the 3 different models under a no-load condition, 0.25m/s of vibrating speed, 11.25mm of peak to peak stroke length and 10Hz of linear speed.

According to Eq. (1), the output power is proportional to the radial flux density in the middle of the coil. In the cases of 4-segment and 5-segment magnet, the radial flux density increased by 6.8% and 5.2%, respectively; therefore, the output power can be expected to increase by around 15%.

Fig. 11 presents a comparison of the three models in terms of the radial flux density in the middle of the coil and the output power. The other characteristics are summarized in Table 3.

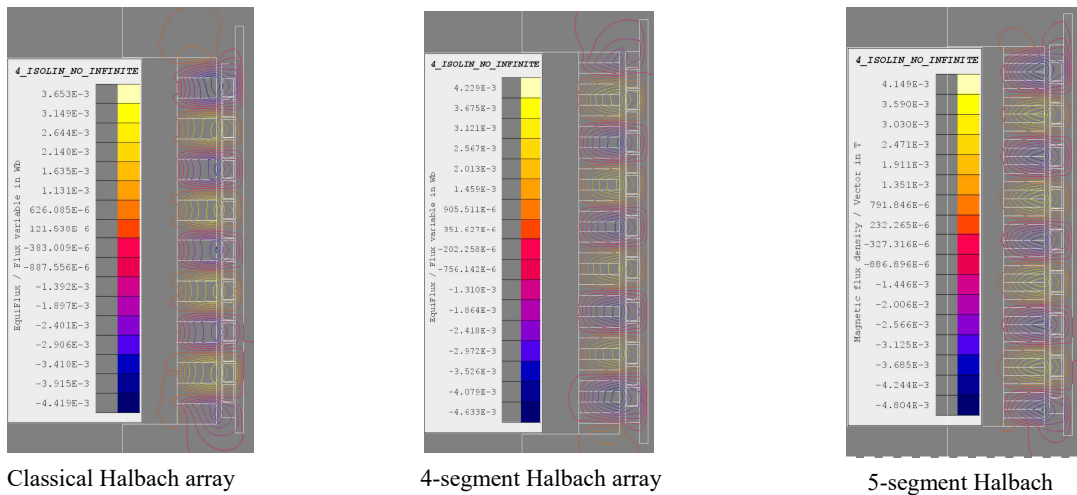


Figure 9: Flux distributions of the three different models under no-load condition

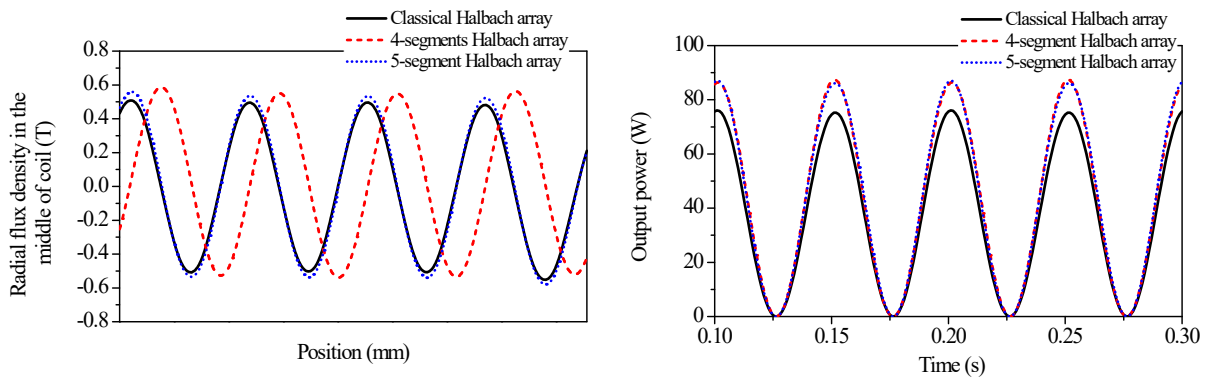


Figure 10: Comparison of three models in terms of radial flux density in the middle of coil and output power

Table 3: Comparison of three models

Items		Classical Halbach array	4-segment	5-segment
Vibrating speed, $v$ (m/s)		0.25		
Stroke length (mm)		11.25		
Linear frequency, $f$ (Hz)		10		
Radial flux density (T)	Maximum	0.55	0.59	0.58
	RMS	0.36	0.39	0.39
Maximum induced voltage (V)	Phase 1	54.10	57.98	57.86
	Phase 2	17.05	18.53	19.12
Output power (W)	Maximum	76.09	87.10	87.38
	Average	37.78	43.53	43.47

## 4 Conclusion

In this paper, a tubular permanent magnet machine composed of a novel magnet arrangement is proposed and compared with the conventional model in terms of radial flux density in the middle of coil and output power. A prototype of the tubular machine composed of the classical Halbach array was fabricated and validated with the FEM analyzed results, which show an average deviation of 13.5% in term of the output power.

Different from device using the classical Halbach array, the proposed model involves the insertion of mid-magnets, that have a magnetized direction that is shifted from that of the original axial and radial PMs. Based on FEM analyses, in the cases of 4-segment and 5-segment Halbach arrays, RMS values of the radial flux density increased by nearly 6.8%, which led to an increase of the average output power of 13.2%.

In further study, optimization of the relative dimensions and of the magnetized angle between the magnet segments will be performed.

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## Authors



### Minh-Trung Duong

He received his B.S. degrees in the Electrical Engineering Department at Hanoi University of Science and Technology in 2014. Currently, he is studying as a Ph.D. student in the integrative program at the Korea Electrotechnology Research Institute, which belongs to the Power and Energy Conversion Engineering Department, University of Science and Technology. His research interests include design and analysis of rotating machines and tubular generators, energy harvesting in vehicle suspension systems.



### Yon-Do Chun

He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from Hanyang University in 1996, 1998, and 2001, respectively. From 2001 to 2003, he held a fellowship at the Japan Society for the Promotion of Science (JSPS), and he was with the Department of Electrical Engineering at Waseda University as a visiting scholar. From 2004 to 2012, he worked at the Korea Electrotechnology Research Institute (KERI). He is currently a chief researcher, Principal Researcher, and technical leader at the Electric Motor Research Center, KERI.



### Pil-Wan Han

He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Hanyang University in 1998, 2000, and 2013, respectively. From 2000 to 2005, he worked at LG Electronics. Since 2005, he has worked at the Korea Electrotechnology Research Institute (KERI). He is currently a senior researcher at the Electric Motor Research Center, KERI.



### **Byoung-Gun Park**

He received his B.S. in Electrical Engineering from Myongji University, Yongin, Korea, in 2005, and his M.S. and Ph.D. in Electrical Engineering from Hanyang University, Seoul, Korea, in 2007 and 2011, respectively. Since 2011, he has been with the Korea Electrotechnology Research Institute (KERI), Changwon, Korea, where he is currently a Senior Researcher in the Electric Motor Research Center.



### **Deok-je Bang**

He received his B.Sc. and M.Sc. degrees in mechanical engineering from Pukyong National University, Busan, South Korea in 1996 and 1998, respectively. He received his Ph.D. degree in electrical engineering from the Delft University of Technology in The Netherlands in 2010. From 1998 to 2006, he worked in the research area of electrical machines and automatic transportation systems. In 2011, he was a principal researcher and a team leader in the Wind Turbine Research Division at Hyundai Heavy Industries. Since 2012, he has been working as a team leader with the Large Wind Generator System Research Team at the Electric Motor Research Center, Korea Electrotechnology Research Institute in South Korea. His research interests include direct-drive generators for wind and ocean energy conversion systems.



### **Jin-Kyu Lee**

He received his B.S. degree in Control & Instrumentation Engineering Department from Changwon National University in 2016. Currently, he is studying as an M.S. student at the Korea Electrotechnology Research Institute Campus, which belongs to the Power and Energy Conversion Engineering Department, University of Science and Technology. His research interests include motor control and the energy harvesting in vehicle suspension systems.



### **Eun-Jun Rhee**

He received his B.S. degree from Kyungnam University in 1994 and his M.S. and Ph.D. degrees in Mechanical Engineering from Pusan National University in 1998 and 2003, respectively. Since 2003, he has been working at Hyundai-Rotem and is currently a Principal Researcher and technical leader of Mechanical Research Team.

His research interests include suspension systems for tanks and combat vehicles, energy harvesting vehicle shock absorbers, semi-active and active suspensions, smart fluids(ER fluids, MR fluids) and their application device and control.