International Journal of Engineering & Technology, 7 (4.39) (2018) 513-517

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Characteristic Analysis of High-Speed PMSG According to Winding Distribution

Kyung-Hun Shin [1], Ick-Jae Yoon [2], Junghyo Nah [3], Jang-Young Choi [4*]

[1]*Department of Electrical Engineering, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon 34134, South Korea*
**Corresponding author E-mail: choi_jy@cnu.ac.kr*

Abstract

Background/Objectives: In this study, we investigate the distribution of windings with optimum performance from the performance analysis according to the winding distribution of a high-speed permanent magnet synchronous generator (PMSG).
Methods/Statistical analysis: Electromagnetic parameters of the high-speed PMSG are derived using the finite element analysis. The relationship between the winding coefficient and the electromagnetic parameter is defined, and the change in the parameters, according to the winding distribution, is confirmed. The generating characteristics analysis is performed using the equivalent circuit method (ECM), and the efficiency characteristics are analyzed from the ECM and the loss analysis.
Findings: This paper presents the influence of winding distribution on the electromagnetic performance of high-speed PMSGs. The factors affecting the performance of the PMSG are back electromotive force (EMF), inductance, and resistance. As regards low-speed PMSGs, back EMF and resistance generally have a large effect on performance. However, as regards a high-speed PMSG, the reactance increases as the operating frequency increases. Therefore, inductance, as well as back EMF and resistance, are the main factors affecting performance. We propose a method to select the optimal winding distribution based on the investigation of the influence of the winding distribution on the electromagnetic performance using the ECM considering loss characteristics.
Improvements/Applications: Based on the analysis results, it is possible to use winding distribution as a design point in both the initial and optimum designs of the high-speed PMSG.

Keywords: *High-speed PMSG, electromagnetic performance, winding distribution, equivalent circuit method, generating characteristic.*

1. Introduction

Nowadays, the demand for alternative sources of energy, owing to environmental pollution and energy depletion, is increasing, and research on high-speed permanent magnet synchronous generators (PMSGs) with high efficiency and power density is actively underway[1]. Therefore, efficient and stable utilization of alternative energy is an important issue. Owing to the development of rare-earth permanent magnet manufacturing technology with high energy density and the development of robust structure, high-speed PMSGs are gaining considerable amount of attention from many researchers and institutions worldwide [2,3]. In addition, high-speed PMSGs have favorable application prospects such as in household appliances, aircraft engines, micro-gasturbines, flywheel applications, among others [4]. As mentioned above, performance optimization of PMSGs, which can be widely used in many applications as well as research, is one of the main issues encountered during the design stage.
Many studies have been actively conducted on the design and performance optimization of PMSGs [5–7]. S.-M. Jang et al. have optimized the performance of the PMSG using ferrite PMs to optimize performance (minimize cogging torque) [5]. H. Zhang et al. presented a study on the effects of stator geometry on electromagnetic performance and losses. [6]. S.-H. Lee et al. carried out performance optimization, such as cogging torque and back electromotive force (EMF) total harmonic distortion(THD), according to the thickness of the PM, PM ratio, and the chamfering of the stator shoe as design parameters [7]. There are no studies comparing electromagnetic characteristics and generating characteristics by windings distribution. This distribution directly affects the synchronous generator circuit constant such as back EMF, resistance, and inductance. This paper presents the influence of winding distribution on the electromagnetic performance of high-speed PMSGs. The factors affecting the performance of the PMSG are back EMF, inductance, and resistance. As regards low-speed PMSGs, back EMF and resistance generally have a considerable effect on performance. However, as regards a high-speed PMSG, the reactance increases as the operating frequency increases. Therefore, inductance as well as back EMF and resistance are the main factors affecting performance. In this paper, we study the distribution of windings of high-speed PMSGs with optimum output performance.

2. Electromagnetic Performance of High-Speed PMSG

Figure 1 illustrates the designed stator and rotor of the high-speed PMSG. The high-speed PMSG has a 36-slot stator with a three-phase distribution winding, a rotor consisting of a full PM, and a sleeve to prevent scattering of the PM. It produces a better air-gap flux density distribution and, hence, a more sinusoidal output-voltage waveform. Moreover, material (SCM 440) with high strength is used for the shaft coupling part owing to the stiffness of its shaft.

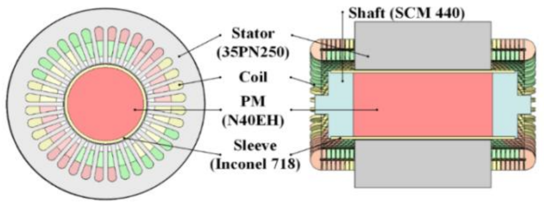


Figure 1: Structure of high-speed PMSG

2.1. Electromagnetic Parameters by Winding Distribution

In electric machinery, the winding distribution can be divided into distribution and concentrated winding. The distributed winding method is mainly used in high-speed PMSGs for sinusoidal flux distribution. The distributed winding method can be divided into full and short pitch winding. Each winding method has advantages and disadvantages. However, there are no published papers on high-speed PMSG that comprehensively analyze the correlation between winding distribution and electromagnetic performance.
Distributed short pitch winding has an advantage in which the harmonic reduction rate is very large as the magnitude of the harmonic decreases by the product of the distribution and short pitch coefficient. However, the distributed short pitch winding also causes a reduction in the magneto-motive force (MMF) owing to the stator coil. This is called the winding coefficient and is expressed as follows [8]

$$k_w = k_d \cdot k_p \tag{1}$$

Where k_d is the distribution coefficient and represents the ratio of the magnitude of the distributed winding MMF to the concentrated winding MMF, k_p is the pith coefficient and represents the ratio of the magnitude of the short pitch winding MMF to the full pitch winding.
In this paper, we analyze the performance of the generator according to the electromagnetic parameter changes based on the short pitch coefficient of the PMSG with distributed winding. This is shown in figure 2. The skew coefficient, owing to the skew of the stator or the rotor, is not considered.

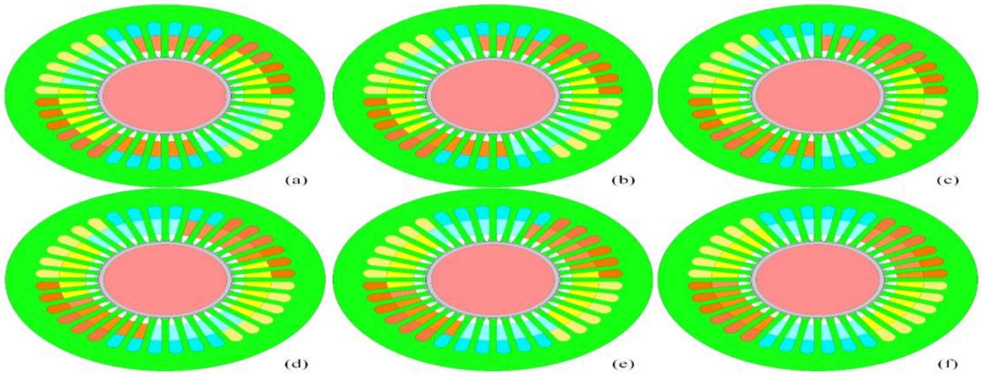


Figure 2: Structure of high-speed PMSG according to winding distribution:(a) coil pitch 13, (b) coil pitch 14, (c) coil pitch 15, (d) coil pitch 16, (e) coil pitch 17, (f) coil pitch 18

2.1.1. Resistance

The resistance can be generally divided into the slot resistance, in which the conductor is effectively distributed, and the end winding resistance, which connects the conductor and the conductor. The phase resistance is expressed as (2) [9].

$$R_{p\square} = \rho_c \frac{L_c}{A_c} \tag{2}$$

Where L_c is the length of the conductor, A_c is the area of the conductor, and ρ_c is the resistivity of the conductor.
For conductive materials, the resistivity is a function of temperature and is expressed as (3).

$$\rho_c = \rho_0 \left\{1 + \alpha\left(T - T_0\right)\right\}\frac{L_c}{A_c} \tag{3}$$

Where ρ_0 is the resistivity at the temperature of T_0, likewise ρ_c is the resistivity at the temperature of T and □ is the temperature coefficient of resistivity.
The length of the conductor is calculated from the z-axis length of the stator and the length of the end as shown in figure 3. The length of the end is calculated from the average radius (r_{coil}) from the center of the generator to the coil and r_{coil_end} from the coil pitch. From this, the length of the conductor is expressed as (4).

$$L_c = 2L_{stk} + 2r_{coil\_end} \times \pi \tag{4}$$

The area of the conductor is obtained from the area of the wire and the number of strands. The number of strands of the wire is calculated from the slot area, the number of conductors, and the area of the wire used for fabrication. The total length of the conductor is represented by the sum of the lamination length of the stator and the end turn. The equivalent winding diagram for converting the conductor length of the end turn is shown in figure 3.

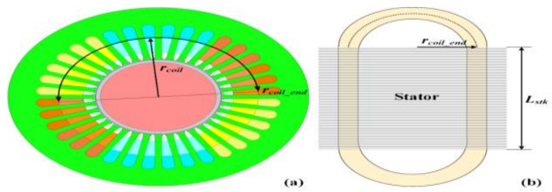


Figure 3: Stator resistance calculation model

2.1.2. Back-EMF

The no-load (EMF) in one phase of the stator winding by PM flux of the PM rotor is expressed as (5) [10].

$$E_{p\square} = \pi\sqrt{2}fN_{p\square}\varphi_f\, k_w \tag{5}$$

Where N_{ph} is the number of the stator turns per phase, and k_w is the stator winding coefficient.
The back EMF, generated from the magnetic flux varying with time, is an important parameter indicating the generation voltage and the output characteristic in the high-speed PMSG. As shown in (5), not only the rotational speed of the rotor and the number of turns of the conductor but also the winding factor are important factors in determining the magnitude of the back EMF.

2.1.3. Inductance

Synchronous inductance, in a synchronous machine, is calculated by the sum of self and mutual inductance. Self-inductance can be divided into air-gap and leakage inductance.
Here, the air-gap inductance can be expressed as (6); a main parameter constituting magnetic inductance and mutual inductance [10].

$$L_g = \frac{\pi}{4}\frac{\mu_0 N_{p\square}^2 D_g L_{stk}}{p^2 g} k_w \quad (6)$$

Where μ_0 is the permeability of vacuum, D_g is the diameter of the air-gap, L_{stk} is the z-axis length of the stator, p is the number of poles, and g is the length of the air gap.

2.2. Loss Analysis According to Winding Distribution

Generally, the heat source of an electric machine is an electric loss. This loss can be largely classified into copper and iron loss. The copper loss is attributed to the current, flowing through the coil and resistance. Iron loss can be divided into hysteresis loss and eddy current loss, attributed to the hysteresis characteristic of the material itself and induced voltage, respectively. It can also be classified into rotor loss owing to non-sinusoidal distribution of flux density, and bearing friction and windage loss as mechanical losses.
It is critical to predict the loss and design of the electric machine because loss in the electric machine is an important factor in determining the operating condition or efficiency of the machine. In particular, iron loss is a source of heat loss generated from an iron core used in an AC power machine. It is an important factor in efficiency as well as in designing an AC power machine. The loss of the rotor is a major cause of rotor heat generation in electric machine operating at high speeds, and this is very important for the prediction of the rotor loss because it is very difficult to cool or dissipate the rotor.
In this paper, the finite element analysis is used to calculate the iron loss and the rotor offspring according to the winding distribution and load resistance. To calculate the efficiency according to the load resistances, the loss analysis results according to load resistances were obtained by using the curve-fitting method. The stator copper loss can be estimated from the stator resistance and the current flowing through the stator. This is accomplished by using the equivalent circuit method (ECM) in the next chapter, according to the load resistance. The efficiency of the generator was predicted by reflecting the results of the copper loss according to the output current and load resistance.

2.3. Generating Characteristic Analysis

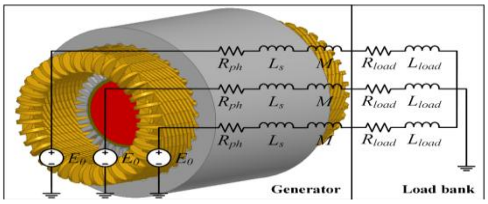


Figure 4: Equivalent circuit of high-speed PMSG

Figure4 shows the equivalent circuit of a high-speed PMSG. In the figure 4, $E_0(=K_e \cdot \omega)$ is the back-EMF at operating speed, R_{ph} is the armature resistance, L_s is self inductance, $M$is mutual inductance, V_t is the terminal load voltage, I_{ph} is the phase current, and ω is the angular velocity, respectively.
For the case when the generator works at an arbitrary operating speed and power factor is constant, output voltage and current can be extended as follows

$$V_t = E_{p\square}\sqrt{\frac{R_{load}^2 + X_{load}^2}{(R_{p\square}+R_{load})^2 + (X_s + X_{load})^2}} \quad (7)$$

$$I_{p\square} = \frac{E_0}{\sqrt{(R_{p\square}+R_{load})^2 + (X_a + X_{load})^2}} \quad (8)$$

Where $X_{load}(=\omega \cdot L_{load})$ is the reactance component of the load and $X_s(=\omega \cdot (L_s+M))$is the synchronous reactance.
For the case when X_{load} in (9) and (10) set 0, namely, if the load assumes only resistance load, they can be rewritten as follows

$$V_t = E_{p\square}\sqrt{\frac{R_{load}^2}{(R_{p\square}+R_{load})^2 + (X_s)^2}} \quad (9)$$

$$I_{p\square} = \frac{E_{p\square}}{\sqrt{(R_{p\square}+R_{load})^2 + X_s^2}} \quad (10)$$

Therefore, output power can be expressed as follows

$$P_{out} = 3 \cdot V_{t,rms} \cdot I_{p\square,rms} \quad (11)$$

From the viewpoint of electromagnetic efficiency, input power can be expressed as the sum of output power and loss. Therefore, it can be expressed as (11).

$$P_{in} = 3 \cdot V_{t,rms} \cdot I_{p\square,rms} + P_{copper} + P_{core} + P_{rotor} + P_{mec\square}. \quad (12)$$

Where P_{copper} is the stator copper loss, P_{core} is the stator iron loss, P_{rotor} is the rotor loss, and P_{mech} is the mechanical and stray loss.

3. Results and Discussion

3.1. Electric Circuit Parameters

Table 1 describes the predicted electrical parameters of high-speed PMSG. As mentioned in previous sections, resistance, back EMF, and inductance are affected by the winding factor. Moreover, as shown in figure 5, back EMF characteristics are analyzed in proportion to the speed. The electrical parameters reported in table 1 are employed for the prediction of generating characteristic analysis such as output power, terminal voltage, phase current, and efficiency leveraging ECMs.

Table 1.Analysis of electromagnetic performance according to coil distribution

	Coil pitch 13	Coil pitch 14	Coil pitch 15	Coil pitch 16	Coil pitch 17	Coil pitch 18
Back-EMF (@15krpm)	340.61	353.3	363.35	370.66	375.1	376.92
Inductance [uH]	160.69	179.3	197.52	214.98	230	243.2
Resistance [mOhm]	8.7	9.3	9.8	10.2	10.8	11.6

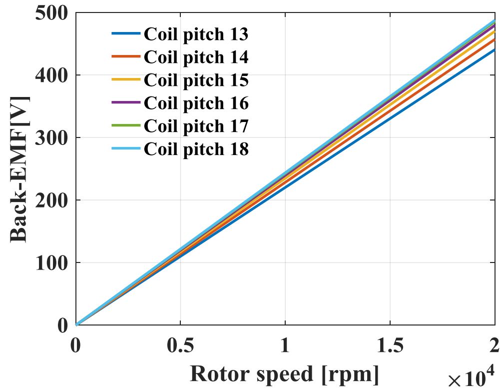


Figure 5: Back-EMF according to rotor speed

3.2. Generating Characteristics

Figures 6 and 7 illustrate the load characteristic in rating speed condition and the speed characteristic of rating resistance load condition of targeted analysis model, respectively. Generating performances obtained using back EMF constant, phase resistance, and synchronous inductance.

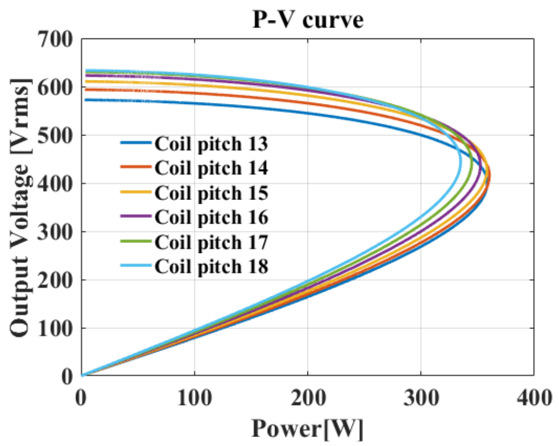


Figure 6: Power-voltage curve according to coil pitch

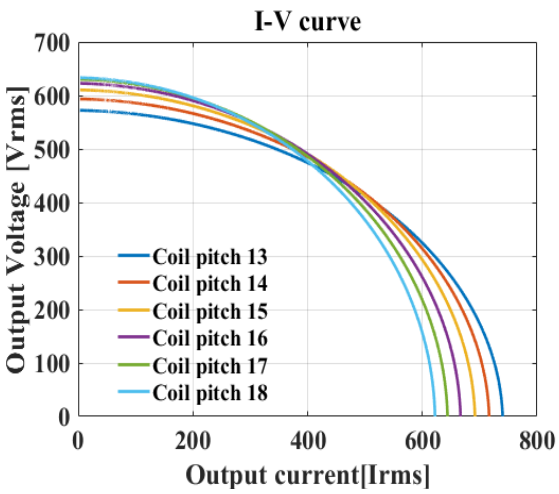


Figure 7: Current-voltage curve according to coil pitch

The electromagnetic loss analysis can be obtained as shown in figure 8 –figure 10. For each load resistance, the finite element analysis was performed at the rated speed to derive the loss value. The curve-fitting method was used to predict the loss at all load resistances. The nominal current is predicted using the ECM. The stator copper loss is calculated from the calculated resistance value.

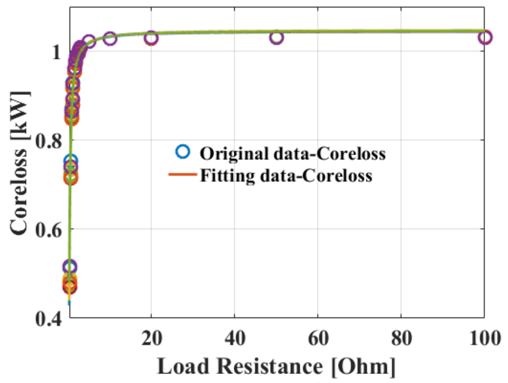


Figure 8: Core loss

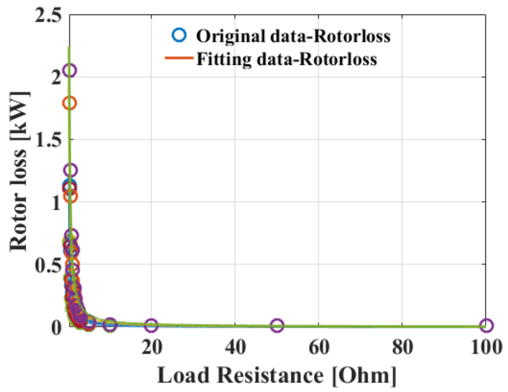


Figure 9: Rotor loss

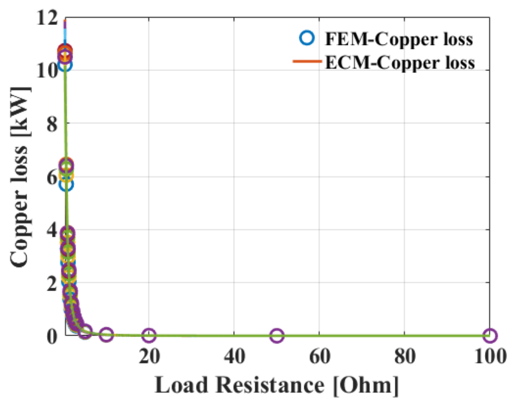
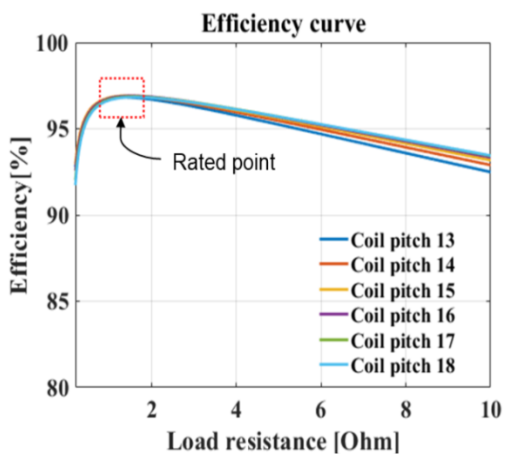


Figure 10: Copper loss

As shown in figure 11, efficiency is calculated from the loss and generating characteristics analysis result. Based upon these results, the optimal model is obtained when the coil pitch is 14–16.



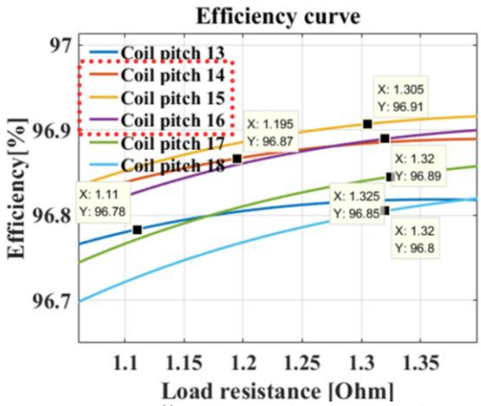


Figure 11: Efficiency according to coil pitch

4. Conclusion

This study presents the electromagnetic parameters and electromagnetic performance of a high-speed PMSG according to the winding distribution. The relationship between the electromagnetic parameters and the winding factor, according to the distribution of windings, of the stator, was analyzed. These results were analyzed by generating characteristic analysis using the ECM. Based upon the results, the high-speed PMSG has a large voltage drop component owing to the inductance. This is compared to the conventional PMSG and was observed to have a great influence on the performance characteristics. In addition, it is possible to select the winding distribution with optimal efficiency by performing loss analysis according to each winding distribution. The proposed analysis results demonstrate that the design of the high-speed PMSG is an important factor in determining its performance.

Acknowledgment

This research was supported by both a grant from National R&D Project “Development of Wave Energy Converters Applicable to Breakwater and Connected Micro-Grid with Energy Storage System” funded by Ministry of Oceans and Fisheries, Korea(PMS3780) and NRF(National Research Foundation of Korea) Grant funded by Korean Government(NRF-2017H1A2A1042264-Global Ph.D. Fellowship Program).

References

[1] Uehara, A., Pratap, A., Goya, T., Senjyu, T., Yona, A., Urasaki, N., & Funabashi, T. (2011). A coordinated control method to smooth wind power fluctuations of a PMSG-based WECS. IEEE Transactions on energy conversion, 26(2), 550-558.
[2] Hong, D. K., Joo, D., Woo, B. C., Jeong, Y. H., & Koo, D. H. (2013). Investigations on a super high speed motor-generator for microturbine applications using amorphous core. IEEE Transactions on Magnetics, 49(7), 4072-4075.
[3] Li, W., Zhang, X., Cheng, S., & Cao, J. (2013). Thermal optimization for a HSPMG used for distributed generation systems. IEEE Transactions on Industrial Electronics, 60(2), 474-482.
[4] Rahman, M. A., Chiba, A., & Fukao, T. (2004, June). Super high speed electrical machines-summary. In Power Engineering Society General Meeting, 2004. IEEE (pp. 1272-1275). IEEE.
[5] Binder, A., Schneider, T., & Klohr, M. (2006). Fixation of buried and surface-mounted magnets in high-speed permanent-magnet synchronous machines. IEEE Transactions on Industry Applications, 42(4), 1031-1037.
[6] Zhou, F., Shen, J., Fei, W., & Lin, R. (2006). Study of retaining sleeve and conductive shield and their influence on rotor loss in high-speed PM BLDC motors. IEEE transactions on magnetics, 42(10), 3398-3400.
[7] Chan, T. F., Lai, L. L., & Yan, L. T. (2004). Performance of a three-phase AC generator with inset NdFeB permanent-magnet rotor. IEEE transactions on energy conversion, 19(1), 88-94.
[8] Krishnan, R. (2017). Permanent magnet synchronous and brushless DC motor drives. CRC press.
[9] Hanselman, D. C. (2012). Brushless motors: magnetic design, performance, and control of brushless dc and permanent magnet synchronous motors. E-Man Press LLC.
[10] Gieras, J. F. (2002). Permanent magnet motor technology: design and applications. CRC press.