

Design and Analysis of a Novel Two Phase Doubly Salient Permanent Magnet Machine

Zhou Zhiqing*, Chi Yongbin

School of Mechanical and Automotive Engineering, South China University of Technology
Guangzhou, China 510640

*Corresponding author, e-mail: ssimpson@163.com

Abstract

A novel two-phase doubly salient permanent magnet machine (FMDSM) with new winding configuration is proposed in this paper. This machine is identical to the existing doubly salient permanent magnet machine (DSPM) with respect to the mechanical structure, whereas the winding configuration is totally different from that in the latter. The structure and operation principle of FMDSM is analyzed, and power and sizing equations are derived analytically, which provides the designer with initial calculation to determine the motor frame. Allowing for the new winding configuration utilized, the magnetic features of FMDSM are investigated by using the FEA. The results show that this new machine is suitable to the application of DC square wave, and the output torque produced is smoother due to no cumbersome commutating torque ripples compared with the existing DSPM. Further, the prototype is fabricated to validate the above analysis.

Keywords: DSPM (doubly salient permanent magnet machine), permanent magnet (PM) machine, design of electric machine, analysis of electric machine

Copyright © 2014 Institute of Advanced Engineering and Science. All rights reserved.

1. Introduction

The doubly salient permanent magnet motor with the embedded permanent magnet in stator iron (DSPM) has gained wide attentions and deep studies in the past due to the advantage of the wide speed range, simple and robust mechanical configuration, and good heat radiation [1]-[10]. The past study mainly referred to the DSPM with concentrated winding around the salient pole in stator iron. The concentrated winding has some advantages such as simple and short end winding, but there is the small flux linkage change which makes the material and space utilization poor [6].

While mainly applying for the small-medium size power, it is essentially necessary that make the motor simpler and lower cost. In literature [13], a single-phase doubly salient permanent magnet machine with 4/6 pole was proposed, which makes the DSPM simpler clearly compared with the existing 3-phase DSPM; Another single-phase doubly salient permanent magnet machine (SDSPM) with the same 4/6 pole topologies had been presented in literature [14]. The full-pitch winding configuration was utilized to further make the motor structure simpler, notwithstanding the cost of the longer end-winding. Meanwhile, the advantage of less loss for that type of motor was also revealed. It is evident that SDSPM exhibits the capability of higher utilization of space due to the bipolar flux linkage and more permanent magnet accommodated.

However, there exist some drawbacks for the motor mentioned in these literatures, such as the zero-torque zone, the significant torque ripples and starting difficulty, which limit its applications when motoring. In other sides, the switching loss of the driving circuit for this type of motor will also be increased due to the more numbers of rotor pole than stator pole.

In this paper, a novel two-phase doubly salient permanent magnet machine (FMDSM) is proposed. The key feature is that its full-pitch winding turns spans three or more stator salient poles. There is only one-phase turn accommodated in one stator slot. In order to explain the operational principles, the two-phase 12/8 pole FMDSM is used as an example, which is similar to the well-known three-phase 12/8 poles DSPM with respect to the mechanical structure [8]. Its structure and operation principle are analyzed, and power and sizing equation is derived analytically. Further, the magnetic characteristics is investigated and validated by experiment.

2. Prototype Machine and Its Operation Principle

2.1. Prototype Machine

Figure 1a shows the cross section of the proposed FMDSPM. This new machine is the same as the existing DSPM with 12/8 pole with respect to the structure topology, i.e. salient pole stator and rotor iron core, and the rotor without any exciting source [9], whereas the winding configuration is totally different from that in the latter. For the proposed FMDSPM, the new winding configuration is utilized, as shown in Figure 1b. The two-phase winding turns are accommodated in eight of twelve stator slots and each of eight stator slots just holding one-phase winding turns. One phase winding is constituted by four winding turns distributing at a certain interval circumferentially. Thereby, only two phase windings are formed for the proposed FMDSPM. Further, since the remaining four stator slots hold nothing, more permanent magnets can be mounted through extending permanent magnet into that stator slots as shown in Figure 1a. Thus, higher power density can be accomplished.

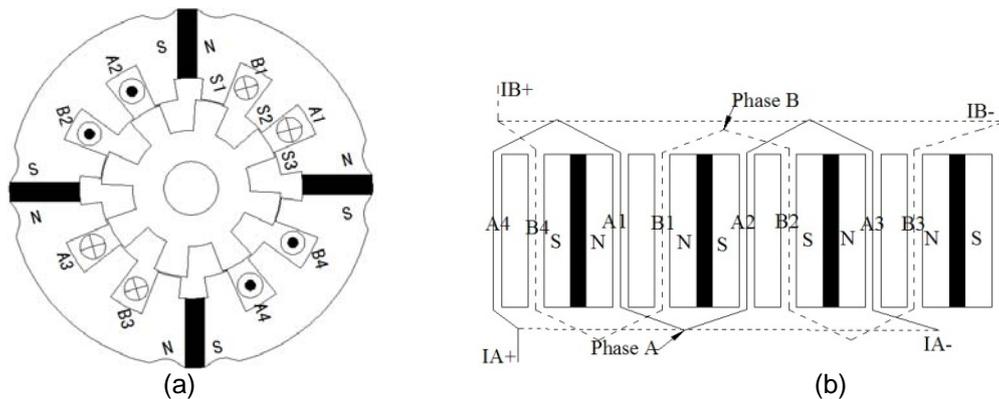


Figure 1. Machine prototype and its armature windings configuration (a) Machine prototype. (b) Two phase-windings configuration.

2.2. Operation Principle

The operation principle of the existing DSPM is depicted in literature [1]-[3]. Two of three phase windings are energized simultaneously at any times and in sequence. Hence eight stator salient poles keep excited at any times in order to produce the anticlockwise torque on the rotor teeth [1].

In contrast to the well known case, the single-phase armature winding in the FMDSPM is excited to generate output torque. Figure 2 shows the developed linear model of single-polar stator section to explain the operation principle of the proposed FMDSPM. In Figure 2, the S1, S2 and S3 are denoted as the stator pole, and R1, R2 and R3 denoted as the rotor pole. The solid-line arrows are indicated as the rotor moving left, and the dotted-line arrows indicated as the flow direction of PM flux.

In Figure 2a, the phase-B winding is energized with positive current, and the PM flux goes through S1 and air-gap into R1, the R1 would be aligned with the S1. In Figure 2b, both phase-B and phase-A winding is respectively excited with negative and positive current. At this moment, the PM flux would be flowed through the S2 and air-gap into the R2 and torque is produced in order to make the rotor move left to the position as shown in Figure 2c. From Figure 2c, the phase-A winding begins to be energized with the negative current to make the PM flux flow through the S3 and air-gap into the S3, and move the rotor left to the position as shown in Figure 2a. Thus, an electric period is completed.

Intuitively, conducting sequence of armature phase winding is totally different from that in DSPM [1]. Clearly, the mutual inductance between phase windings can be negligible, and smoother output torque can be obtained expectedly.

As a result of the arguments expressed above, a set of idealized sequence curves for the proposed FMDSPM can be derived as shown in Figure 3, where $i_A, i_B, \psi_{pmA}, \psi_{pmB}, L_A, L_B$

and T_r are respectively denoted as the phase-A and -B winding current, the flux linking phase-A and -B windings, the inductance of phase-A and -B winding, the total reluctance torque. The flux linkages have bipolar, which makes the power density of proposed FMDSPM higher compared with the existing DSPM. From Figure 3 it can easily found that the reluctance torque for this new machine is of zero value throughout the whole period due to the periodic change of the reluctance like the existing DSPM.

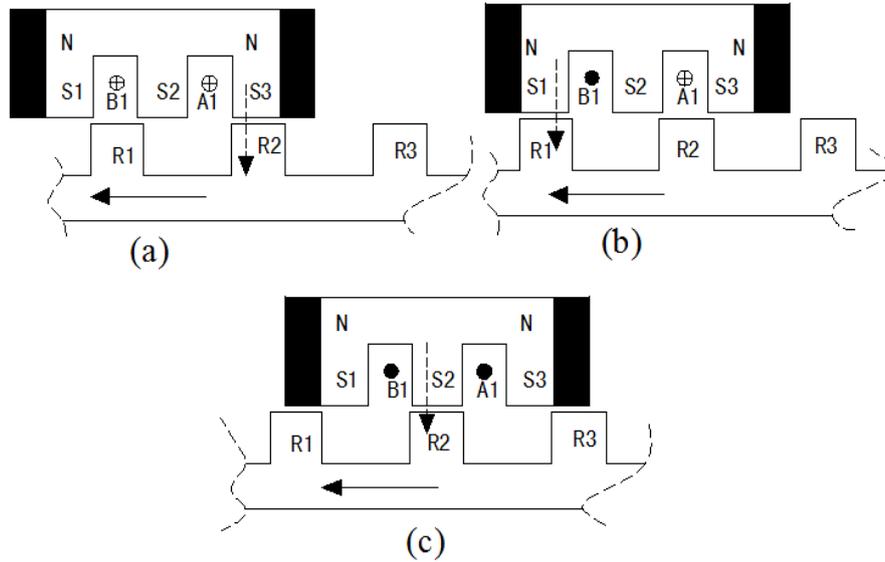


Figure 2. Developed linear model of FMDSPM. (a) Phase-A winding carry positive current. (b) Phase A and phase B carry negative and positive current respectively. (c) Phase-B winding carry negative current

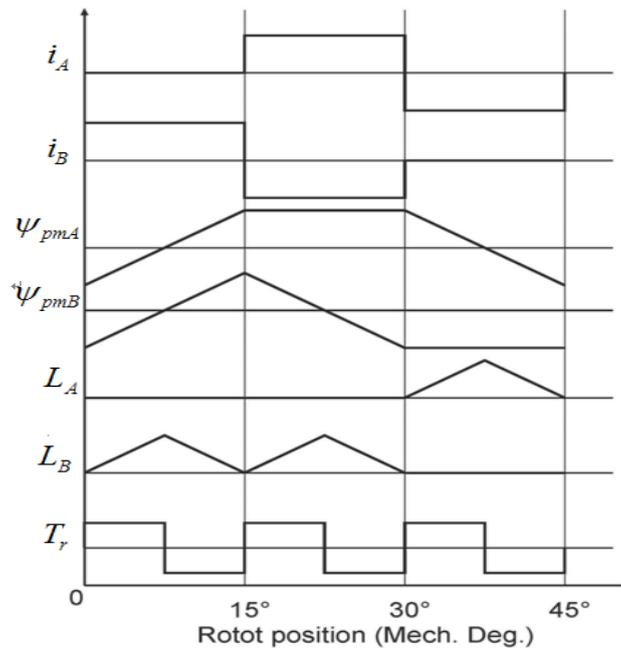


Figure 3. Idealizing waveform of FMDSPM for illustrating its operation principle

3. Power and Sizing Equations

In general, if the stator leakage inductance is neglected, the output power equation could be derived from the relationship of inductance, flux linkage, current and the end voltage in per-phase winding [1]-[3]. From the preceding analysis section of operation principle, the approach to produce the torque is the same for both the proposed FMDSPM and well known DSPM except that the armature winding is excited with different way. Besides, the flux linkage of phase winding turns for the proposed machine is bipolar. The leakage flux is negligible as stator pole is unaligned with the rotor pole, then the rotational voltage induced in the armature winding due to the flux produced by PM can be expressed as

$$e = N d\psi_{pm}/dt = N n_r d\psi_{pm}/d\theta = N n_r 2\psi_a / (\theta_{rp}/3) \quad (1)$$

Where, ψ_a is the maximum flux linkage at aligned position; $\theta_{rp} = 2\pi/N_r$ is the rotor pole pitch, therein, N_r is the rotor pole numbers, for the FMDSPM with 12/8 pole, displacement Angular radian in one stroke is nearly equal to $\theta_{rp}/3$. n_r is the rotor Angle speed in mechanical radian/s. N is the number of per phase winding turns. Wherein

$$\psi_a = k_d \alpha_s \ell_{ps} \tau_s B_\delta = k_d \alpha_s \ell_{sl} (\pi D_g / N_s) B_\delta \quad (2)$$

Substituting eq. (2) into eq. (1) yields:

$$e = N n_r (6\pi k_d \alpha_s \ell_{sl} D_g B_\delta) / (\theta_{rp} N_s) \quad (3)$$

Where, α_s is the stator pole arc factor; $n_r = 2\pi\omega_r/60$, ω_r is the speed of rotor in rpm; k_d is the flux leakage factor. Generally, the range of k_d can be presented as 0.9~0.93. ℓ_{sl} is the stack length; D_g is the stator inner diameter; B_δ is the air-gap flux density; N_s are the stator pole numbers.

From the idealized waveform in Figure 3, the input power into the motor can be expressed as

$$P_o = (m/T) \int_0^T e i d\theta = (3/T) e_{pk} i_p \Delta T \quad (4)$$

Where, $T \square \theta_{rp}/n_r$, $T \square \theta_{rp}/n_r$, $\Delta T \square \theta_{rp}/(3n_r)$, m is the numbers of machine phase, e_{pk} is the peak value of back-EMF, i_p is the magnitude of phase current. Further, Combining eq. (3) and eq. (4), the input power equation takes on the following form

$$P_o = \frac{3}{T} N m n_r \frac{6\pi k_d \alpha_s \ell_{sl} D_g B_\delta}{\theta_{rp} N_s} i_m \Delta T = N m n_r \frac{3k_d N_r \alpha_s \ell_{sl} D_g B_\delta}{N_s} i_m \quad (5)$$

To indicate the effect of the current waveform, the definition of a current waveform factor k_i is defined as below

$$k_i = i_m / i_{rms} = \left((1/T) \int_0^T (i(t)/i_m)^2 dt \right)^{-1/2} \quad (6)$$

Where, i_{rms} is the RMS phase current which is related to the stator electrical loading A_s , and it is expressed as the below

$$A_s = Cm Ni_{rms} / (\pi D_g) \quad (7)$$

Where, m is the number of phases of each stator; the factor C is the number of phases conducting at any time, for well know DSPM, $C = 2$, for the proposed FMDSPM, $C = 1$ or 2 ; Usually, The range of A_s is selected to be 10~30A/mm [3].

Combining eq. (5), eq. (6) and eq. (7), the power equation developed is expressed as the following form

$$P_o = \pi \frac{N_r}{N_s} \alpha_s k_d k_i A_s B_\delta n_r D_{hg}^2 \ell_{sl} \eta = \frac{\pi^2}{30} \frac{N_r}{N_s} \alpha_s k_d k_i A_s B_\delta \omega_r D_g^2 \ell_{sl} \eta \quad (8)$$

Where, η is efficiency of the proposed FMDSPM. From eq. (6), $k_i = 1$ may be determined when two phase windings are conducting during the entire period.

Using eq.(7) to correspond to the rated power output, and keeping the stack length as a multiple or submultiples of stator inner diameter, then the following is obtained:

$$\ell_{sl} = k_\ell \cdot D_{hg} \quad (9)$$

Where, k_ℓ is the aspect ratio coefficient, and should be chosen based upon the nature of the application and space constraints.

Combining eq. (8) and eq. (9) results in the D_g^3 sizing equation:

$$P_o = \left(\pi^2 / 30 \right) (N_r / N_s) \alpha_s k_\ell k_d k_i A_s B_\delta \omega_r \eta D_g^3 \quad (10)$$

From eq. (10), D_g is evaluated if the rated speed, B_δ , k_d , k_i , and k_ℓ are known, and further the ℓ_{sl} can be calculated from eq. (9).

As long as the main parameters is derived, the other structural dimensions, i.e. stator outer surface diameter, the depth of the stator and rotor yoke, and the height of stator and rotor pole can be determined with the similar method for SR machine.

Table 1. Designed Data of FMDSPM, As Well As DSPM

| PARAMETER | FMDSPM | DSPM |
|---------------------------------------|----------------------|----------------|
| Power (Kw) | 1.8 | 1.8 |
| Stator outer size (mm) | 160 (Outer diameter) | 160x160 |
| Stator inner diameter. (mm) | 80 | 80 |
| Stator core length (mm) | 80 | 80 |
| Stator pole number. | 12 | 12 |
| Rotor pole number | 8 | 8 |
| Stator pole arc. (Mech. Deg.) | 20 | 20 |
| Rotor pole arc. (Mech. Deg.) | 15 | 15 |
| Stator slot deep.(mm) | 19 | 19 |
| Phase number | 2 | 3 |
| The turns number of per phase.(turns) | 100 | 100 |
| Magnetic remanence. (T) | 1.08 | 1.08 |
| Magnet permanent size. (LxWxH) [mm] | 4x(80x12x32) | 4x (80x12x32) |



Figure 4. Prototype for the proposed FMDSPM

For a specific motor, it can be seen from eq. (7) that the product of N and i_{rms} is a constant, and the number of turns per phase N can be calculated when the electric load, current and bore diameter is given. Hence, the conductor size is chosen such that the available winding space will be filled; further, the resulting current density is calculated and checked against the maximum permissible value. The PM volume and size could be determined through the method given in [4].

The design data of the proposed FMDSPM using the sizing equation introduced above are shown in table 1, and would be verified from the back-EMF and torque. Figure 4 exhibits the prototype of FMDSPM motors.

4. Analysis and Verification

4.1. Analysis

Through using the FEM, the flux distribution plot of FMDSPM is illustrated in Figure 5, where the plots are shown under no-load condition and load condition with the current of $-7A$ respectively. Due to the symmetry, only half of whole machine is exhibited. It could be easily seen that more fluxes go through the stator salient pole S1 into the rotor pole. At this moment, the normal air-gap flux-density waveform is displayed in Figure 6, with the no-load (figure 5a) and load conditions (figure 5b). It is clearly evident that, the electric flux has little effects on the air-gap flux distribution, which is mainly determined by the PM flux.

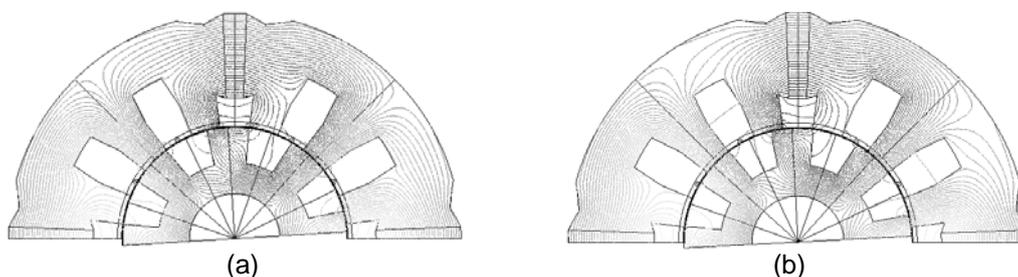


Figure 5. Flux distribution plots for FMDSPM under the no-load and load conditions at the position of 3° . (a) No-load condition. (b) Load condition of $-7A$.

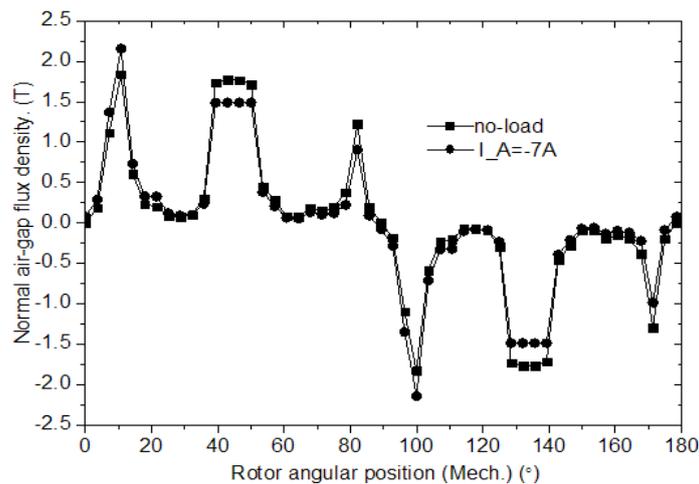


Figure 6. Flux distribution waveform at a position of 3°

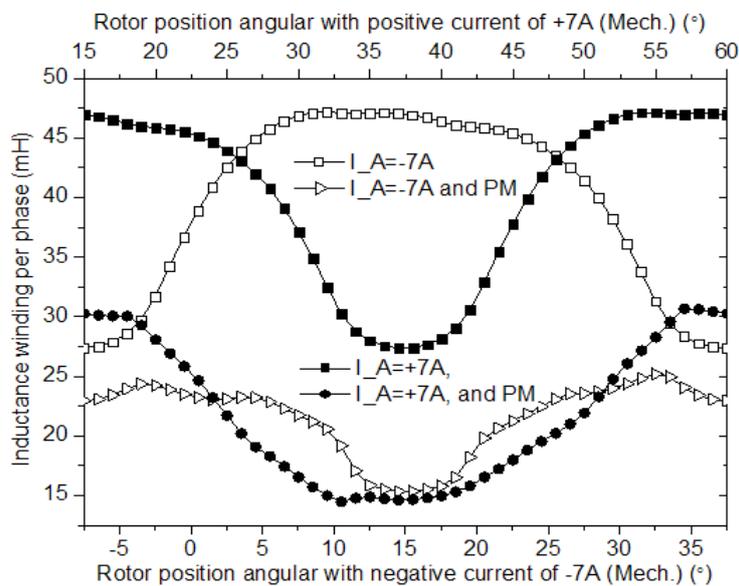


Figure 7. Inductance of the phase winding excited with negative and positive current under the no-load and load conditions.

The inductance characteristic plays important pole in the course of design and control development. For FMDSPM, the cross coupling between armature and PM flux has to be taken into consideration when calculating the inductance. As the magnetic saturation arising, the inductance would depend on not only the position, but the amplitude of armature current. Thus, the total flux including armature and PM flux can be expressed below and the inductance L can be further derived as follow

$$\psi_a = \psi_{pm} + Li \Rightarrow L = (\psi_a - \psi_{pm}) / i \tag{11}$$

Hence, by using the FEA [12], the inductance can be calculated precisely and revealed

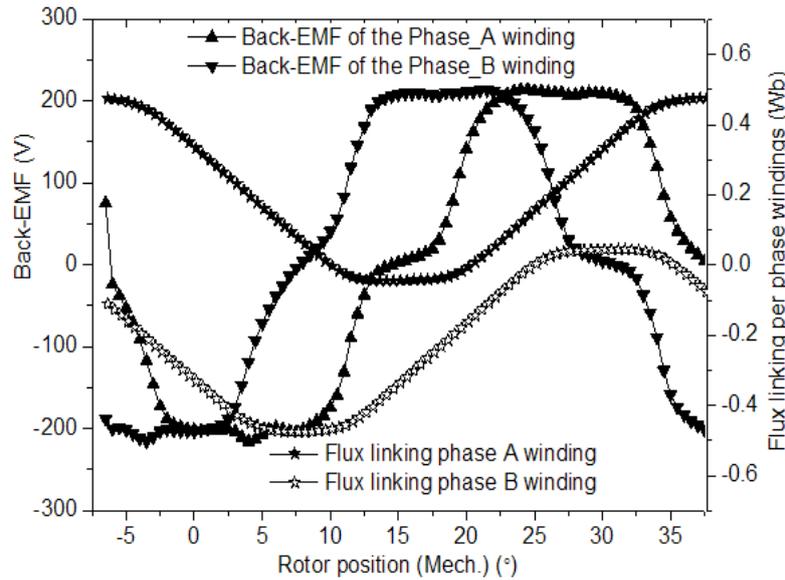


Figure 8. Flux and back-EMF waveforms.

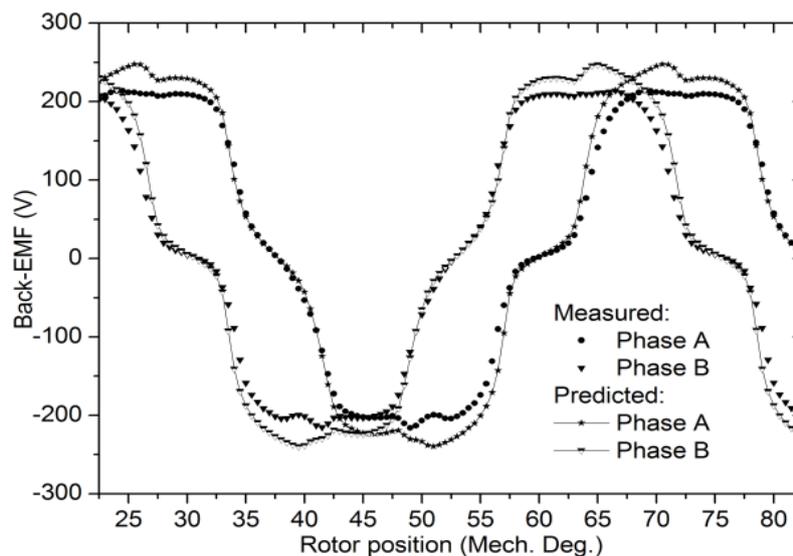


Figure 9. Measured back-EMF waveform at 1000 rpm for the FMDSPM

in Figure 7, where the " $I_A = \pm 7A$ " means that there only exists armature flux without PM flux. The " $I_A = \pm 7A$ and PM" means that there exist both armature and PM flux. Different from the existing DSPM, the \pm current in the per-phase winding for the FMDSPM would aid the flux. Backward the operation principle, it could be known that, when the immediate stator pole S2 is excited, two phase windings are energized simultaneously. Moreover, for the magnetic-circuit structure around single phase winding is in asymmetry, the inductance changes in the different way under the exciting conditions of positive and negative currents, as shown in Figure 7.

The flux linking per-phase winding can be obtained through the FEM. Its waveform is displayed in Figure 8. The flux varies linearly with the rotor position. Hence, it can be concluded that this new machine is more suitable to the application of DC square wave. With the armature flux negligible, the back-EMF can be approximately given by eq. (1) and shown in Figure 8. The back-EMF waveform has a trapezoidal wave shape, which is in line with the flux waveform.

4.2. Results and Discussion

The prototype machine has been fabricated to test its back-EMF and static torque. The back-EMF can be obtained with the rotor operating at 1000 rpm driven by controlled DC machine. The results are shown in Figure 9 and are clearly in good agreement with the calculated shown in Figure 8. However, the differences arise mainly due to the manufacturing errors and the error of energy stored in PM. Further, it could be found that the shapes of stator or rotor poles have significant effect on the back-EMF, the study of which is progressing and its results would be provided in later paper. From Figure 9, it can also be seen that the waveform of back-EMF have the shape of rectangular. Hence, it is proved that this new machine is more suitable to the application of DC square wave.

The static torque can be measured through the rotor locked and the results are displayed in Figure 10. Apparently the measured and calculated results are in closed accordance with each other. Hence, this model is verified effectively.

For comparison, the model of the existing 12/8 pole DSPM is established too, and its main parameters are listed in Table 1. For all of stator slots filled with windings, the stator core looks more like the square shape in order that the identical permanent magnet can be hold. With the method of FEA, the calculated torque is shown in Figure 10. In the region of -3° ~ 12° degree, its average torque is clearly of lower value compared with the proposed FMDSPM. Besides, the significant torque pulsation can be seen. To cancel this torque pulsation, the control strategy of regulating the switching angular has to be adopted [5]. Even so, it is nearly impossible for the commutating torque ripples from the mutual inductance between adjacent phase windings to eliminate.

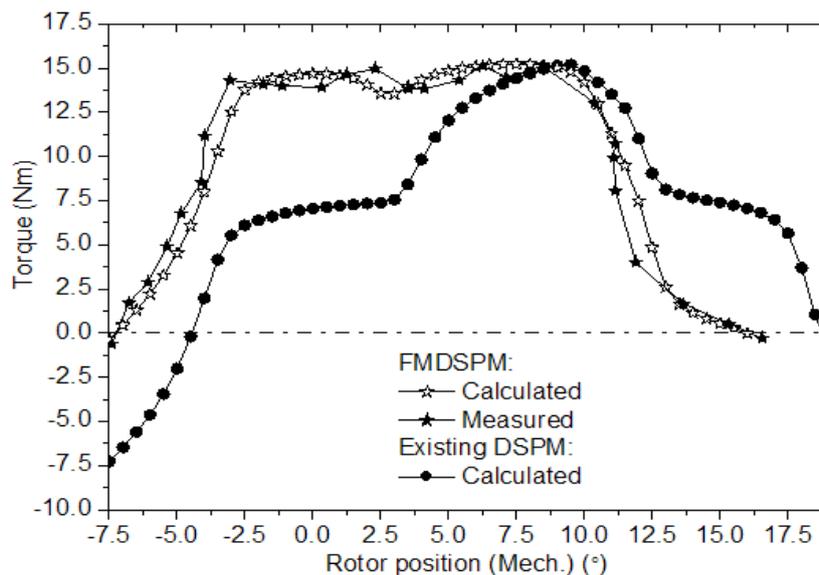


Figure 10. Torque waveform of the FMDSPM as well as DSPM

To investigate the characteristics of output torque, the steady analysis has been performed with the equal amplitude of both input voltage and current for both machines, and the results are shown in Figure 11. It is exhibited that the proposed FMDSPM has the capability of smoother output torque comparing to the existing DSPM. For the DSPM, there are two spots where prominently commutating torque ripples arises, whereas only one spot with commutating torque ripple for the proposed FMDSPM. Hence, smoother output torque can be produced by the FMDSPM. Moreover, there is no zero torque zone for the FMDSPM, although only two-phase armature windings are formed. Therefore, the starting is no problem.

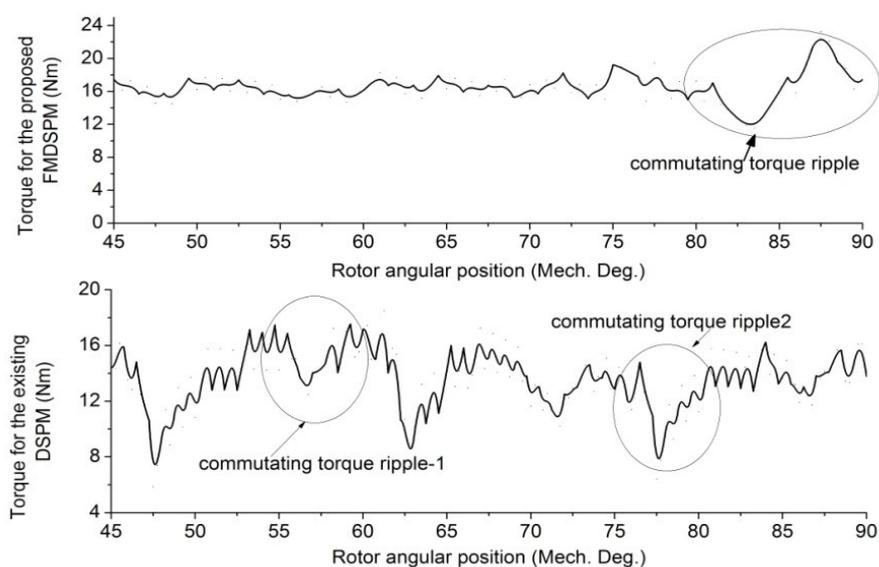


Figure 11. Steady torque waveform for both proposed FMDSPM and existing DSPM

5. Conclusion

In this paper, a novel two-phase doubly salient permanent magnet machine (FMDSPM) with new winding configuration is proposed. Its power and sizing equation is derived analytically, which provides the designer with a practical way to make an initial calculation of motor frame. Thus, a 12/8 pole two-phase FMDSPM is designed and taken as the example. With the FEA, its magnetic feature is investigated, and validated by experiment.

It is evident that this new machine is more suitable to the application of DC square wave. Due to the drawback of commutating torque ripples, conducting angular of switch device have to be regulated in order to obtain smoother output torque. Due to only one spot where commutating torque arises during one electric cycle, the smoother torque ripple can prominently be produced by the FMDSPM. Also, for only two phase winding formed, less switching devices would be required to make this new machine operate in the expected way and further the control system would become simpler compared with the existing three-phase DSPM. Again, more permanent magnets can be accommodated so that higher power density can be achieved.

Obviously the performance of this new machine is influenced markedly by the stator/rotor core geometry and permanent magnet, and can be improved through the method depicted in literature [11], [12], which is the future work, and provided in another paper.

It can be expected that this new machine would be utilized for variety of industrial applications where smooth output torque and low cost are required.

Acknowledgements

Zhou Zhiqing thanks the HEP-EDRIVING CO., LTD for the financial and testing support

References

- [1] Liao Y, Liang F, Lipo TA. A Novel Permanent Magnet Motor With Doubly Salient Structure. *IEEE Trans on TIA*. 1995; 31(5): 1069-1078.
- [2] Ming Cheng, KT Chau, CC Chan. Static Characteristics of a New Doubly Salient Permanent Magnet Motor. *IEEE Trans on energy conversion*. 2001; 16(1): 20-25.
- [3] Ming Cheng, KT Chau, CC Chan. Design and Analysis of a New Doubly Salient Permanent Magnet Motor. *IEEE Transactions on Magnetics*. 2001; 37(4): 3012-3020.
- [4] KT Chau, Ming Cheng, CC Chan. Performance Analysis of 8/6-pole Doubly Salient Permanent Magnet Motor. *Electric machines and power systems*. 1999; 27: 1055-1067.

-
- [5] Ming Cheng, KT Chau, CC Chan, Qiang Sun. Control And Operation of a New 8/6-pole Doubly Salient Permanent Magnet Motor Drive. *IEEE Trans on Indus App.* 2003; 39(5): 1363-1371.
 - [6] J Zhang, M Cheng, Z Chen. Investigation of a New Stator Interior Permanent Magnet Machine. *IET Electric power applications.* 2008; 2(2): 77-87.
 - [7] Ming Chen, KT Chau, CC Chan, E Zhou, X Huang. Nonlinear Varying-Network Magnetic Circuit Analysis for Doubly Salient Permanent-Magnet Motors. *IEEE Trans on Magnetics.* 2000; 36(1): 339-349.
 - [8] Lin Mingyao, Cheng Ming, Zhou E. Design and Analysis of a New 12/8-pole Doubly Salient Permanent-Magnet Motor. *Journal of Southeast University.* 2002; 32(6): 944-949. (In Chinese)
 - [9] KT Chau, JZ Jiang, Yong Wang. A Novel Stator Doubly Fed Doubly Salient Permanent Magnet Brushless Machine. *IEEE Trans on Magnetics.* 2003; 39(5): 3001-3003.
 - [10] Sarlioglu B, Yifan Z, Liao TA. A Novel Doubly Salient Single Phase Permanent Magnet Generator. *IEEE Trans on IAS.* 1994; 29(1): 9-15.
 - [11] Zahra Malekjamshidi, Mohammad Jafari, Kourosh Mahmoodi. Operation of a Fuzzy Controlled Half-Bridge DC-Converter as a welding current-source. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2012; 10(1): 17-24.
 - [12] Reza Ilka, S Asghar Gholamian. Optimum design of a five-phase PMSM FOR underwater vehicles by use of PSO. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2012; 10(5): 925-932.
 - [13] Bian Dunxin, Zhan Qionghua. A Novel Single Phase Doubly Salient Permanent Magnet Motor. IEEE International Conference, on PEDS'99. 1999: 725-730.
 - [14] Cheng Ming, Chau KT, Sun Qiang Zhou E. Inductance Measurement of Doubly Salient Permanent Magnet Motors. *Electrical machines and systems.* 2001; 2: 842-845.