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IV. New Energy and Distributed Power System

Optimal Design of Spoke Type BLDC Motor Considering Irreversible Demagnetization of Permanent Magnet

Gyu-Hong Kang[1], Jin Hur[2], Ha-Gyeong Sung[2] and Jung-Pyo Hong[1]
[1]Dept. of Electric Eng., Changwon National University
[2] Precision Machinery Center, Korea Electronic Technology Institute (KETI)
E-mail: ipmsm@korea.com or jinhur@keti.re.kr, Website: http://www.hipem.com

***Abstract*-This paper presents a design strategy of spoke type BLDC motors considering an irreversible demagnetization of a permanent magnet (PM). So, the irreversible demagnetization characteristic of the motor is analyzed by rotor structure. The instantaneous currents in either starting or lock rotor condition, which are calculated from the current dynamic analysis, applied to the analysis of irreversible demagnetization field by FEM. In irreversible demagnetization analysis by FEM, the variation of residual flux density in PM is analyzed using the non-linearity of magnetic core on B-H plan. The analysis results are compared to several rotor structures and used for optimize the rotor structure.**

I. INTRODUCTION

PM motors has been interested as a good choice for many applications. There is a continuing need for new motors with reduced size and higher performance [1]. A spoke type BLDC motor is of to have a rotor structure of interior type PM with higher saliency ratios. It means the magnetic flux generated by PMs arrangement of spoke type is highly concentrated in air gap and the higher reluctance torque is generated. The reluctance torque induces torque ripple and vibration in the motor and surrounding structures. However, it could be contributed on the effective torque by current control in inverter fed system [2], [3]. Therefore, the PM arrangement and driving control circuit have to be considered together in the design stage of spoke type motor.

In PM motor, the instantaneous current in the starting or locked rotor condition could cause the tremendous external demagnetizing field for PMs. It is occurring the irreversible demagnetization and is reducing the residual flux density of PM. So, it is cause the deterioration of the performance of PM type BLDC motor. Therefore, the irreversible demagnetizing characteristics of PM must be considered for designing the rotor structure of BLDC motor.

The main object of this paper is to design high performance spoke type BLDC motor considering the irreversible demagnetization of PMs through a transient analysis including driving circuit. So, in this paper, we compared irreversible demagnetization characteristics of the spoke type BLDC motor with an interior type PM motor (IPM) and surface mounted PM motor (SPM) and confirmed the spoke type motor has a great advantage over SPM and other IPM toward trend of high torque and small size. From the results, the design parameters such as PM positions and structure etc. due to irreversible demagnetizing effects are investigated and applied on the design of the spoke type BLDC motor.

II. ANALYSIS

A. *Current Dynamic Analysis*

In spoke type PM motor, the reluctance torque strongly influences the torque characteristics. In addition, the reluctance torque by difference of *d-q* axis inductances is induced torque ripple and vibration of machine having two times of period of electromagnetic torque [1], [5]. However, it could be contributed on the effective torque by control of current phase in inverter fed system. So, the driving circuit considering conduction and freewheeling period must be considered to exactly analyze the characteristics and determine the optimal current phase for high performance.

This paper develops a dynamic analysis method for obtaining optimal current phase. This method coupled magnetic field by FEM with electric circuit considering controlled current phase angle in voltage source inverter. The spatial distribution of circuit parameters such as the back EMF, self and mutual inductances are calculated using the developed method, and then there are applied to electric circuit analysis for the instantaneous current and torque controlled by current phase with advanced angle [4].

Fig. 1 shows analysis process of instantaneous torque and Fig. 2 shows the current flow in conduction and freewheeling period at six-switched converter.

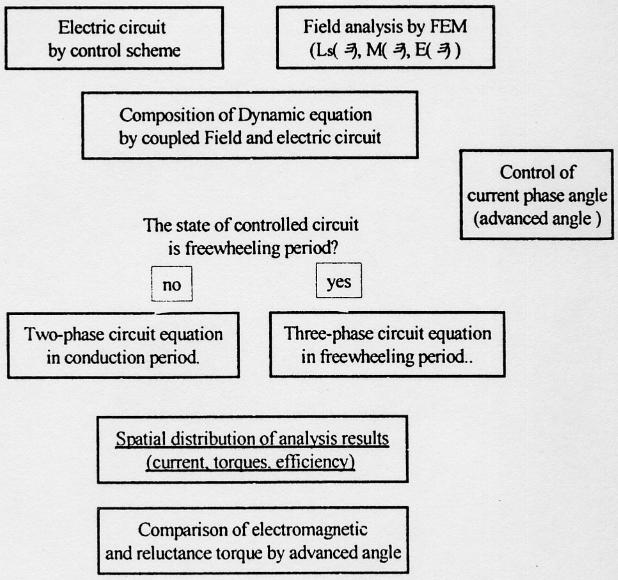


Fig. 1. Schematic diagram for Dynamic analysis process by coupled field and electric circuit.

In conduction period, two phases out of three phases are energized as shown by the solid line in Fig. 1(a). The voltage equation for computation of instantaneous current in conduction period is given by

$$V_a - V_b = R(i_a - i_b) + \frac{d}{dt} p(L_a(\theta) - M(\theta))\, i_a + e_a - \frac{d}{dt}(L_b(\theta) - M(\theta))\, i_b - e_b \quad (1)$$

$$\frac{di_a}{dt} = \frac{1}{(L_a(\theta) + L_b(\theta) - 2M(\theta))}(V_a - V_b - e_a - e_b - 2Ri_a) \quad (2)$$

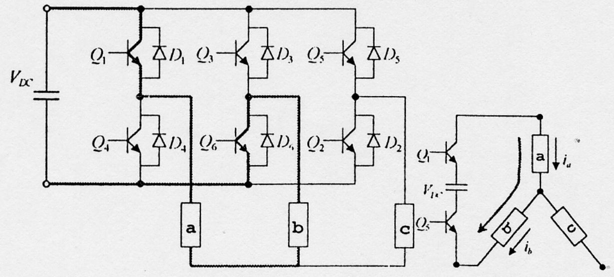
However, when the phase commutates from C to B, A-B phases are conducted immediately after switching off the A-C phases and C phase current is freewheeling through diode D_2. The current freewheeling in commutation period is generated by inductance of the motor. So, the voltage equation should be reconstructed to three phases considering freewheeling current as follows:

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \end{bmatrix} = -\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \dfrac{R}{L_a(\theta) - M(\theta)} \\ \dfrac{R}{L_b(\theta) - M(\theta)} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \end{bmatrix} + \begin{bmatrix} \frac{1}{3} & 0 \\ 0 & \frac{1}{3} \end{bmatrix}\begin{bmatrix} \dfrac{R}{L_a(\theta) - M(\theta)} \\ \dfrac{R}{L_b(\theta) - M(\theta)} \end{bmatrix}\begin{bmatrix} 2V_{ac} - V_{bc} - 2e_a + e_b + e_c \\ 2V_{bc} - V_{ac} + e_a - 2e_b + e_c \end{bmatrix} \quad (3)$$

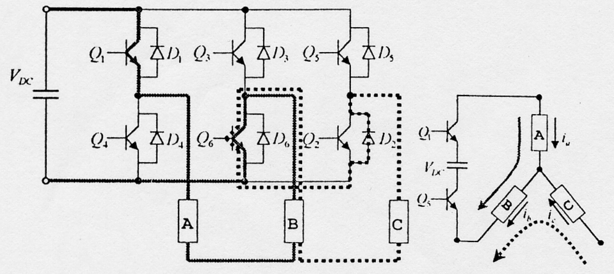
B. *Method of Irreversible Demagnetization Analysis*

The instantaneous peak current in starting or transient state is calculated from current dynamics analyses and the calculated instantaneous current is applied to irreversible demagnetizing FE analysis for external magnetic field computation. Fig. 3 shows the demagnetization curve of the ferrite type permanent magnet on B-H plane. When operating point p_1 moves to p_2 due to the external demagnetizing field, the residual flux density, B_r, is decreased to B_r`, and the irreversible demagnetization is occurred [7].

Fig. 4 presents the process of irreversible demagnetization analysis of BLDC motor. As the magnetic flux density in each element of the permanent magnet region is less than the knee point by the external demagnetizing field, the residual flux density of the element renews in analysis process.



(a) Current flow in conduction period



(b) Current flow in freewheeling period

Fig. 2. Current flow in conduction and freewheeling period of BLDCM

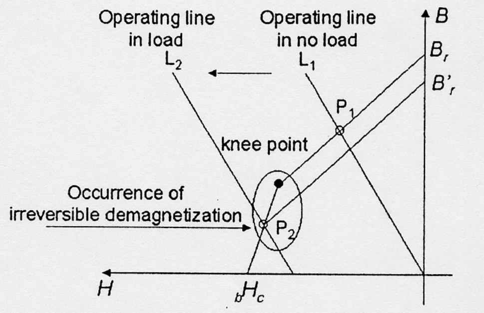


Fig. 3. Demagnetization curve of the ferrite type PM on B-H plane

III. Results and Discussion

From the irreversible demagnetization analysis, the results of residual flux density variation in PM are compared to several type rotor structures. Fig. 5 shows the variation of residual flux density comparison of each rotor structure in PM by (-) *d*-axis instantaneous peak current. In case of spoke type rotor, PM is demagnetized entirely by external field on the other hand the SPM type rotor occurred partial irreversible demagnetization. Moreover, IPM type rotor is hardly demagnetized so the regional irreversible demagnetization rate according to rotor structure is different.

Fig. 6 shows the back EMF distribution between initial condition that the PMs are fully magnetized and demagnetized condition that is induced external field on (-) *d* axis. The air gap flux of spoke type BLDC motor is concentrated so the back EMF is largest in three type rotor on the other hand it has weak external demagnetizing effect. The IPM type BLDC motor have robust demagnetizing field but back EMF is less then the other type rotor.

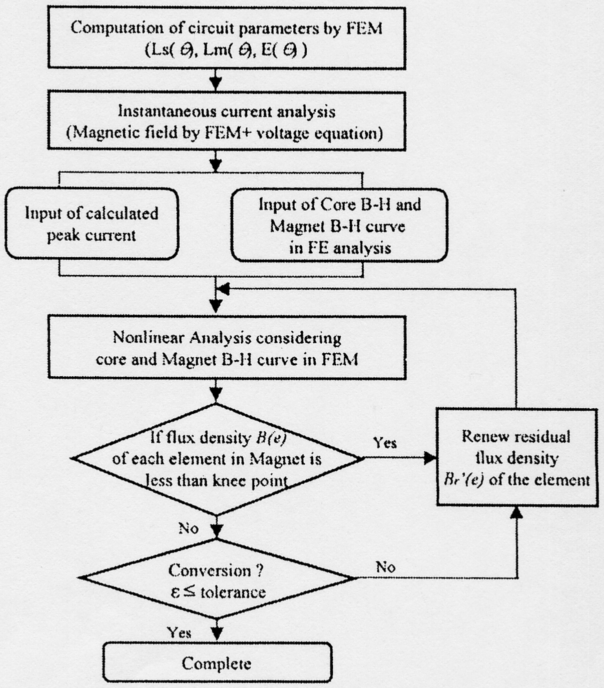
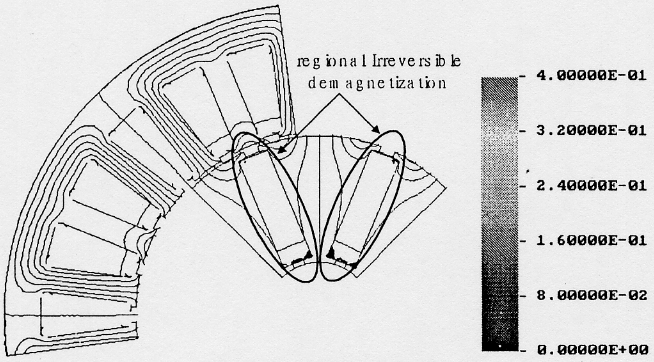
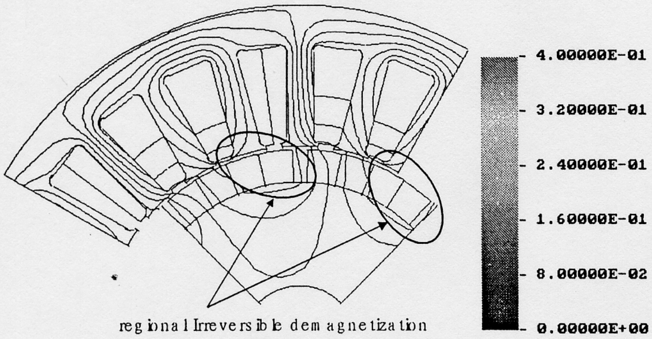


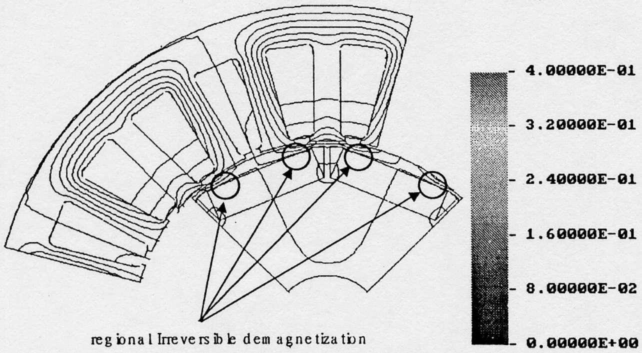
Fig. 4. Irreversible demagnetization analysis process of PM type BLDC motor



(a) Spoke type BLDC motor

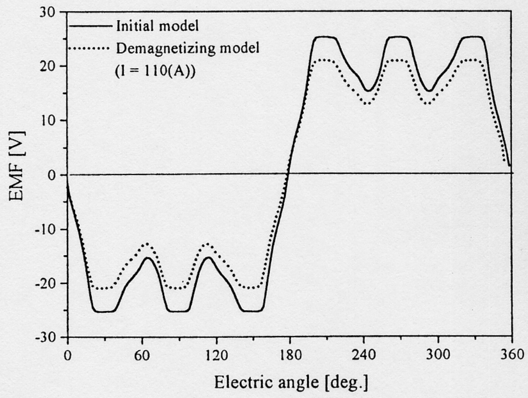


(b) SPM type BLDC motor

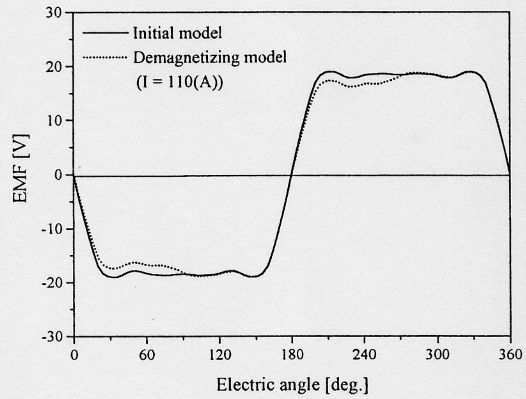


(c) IPM type BLDC motor

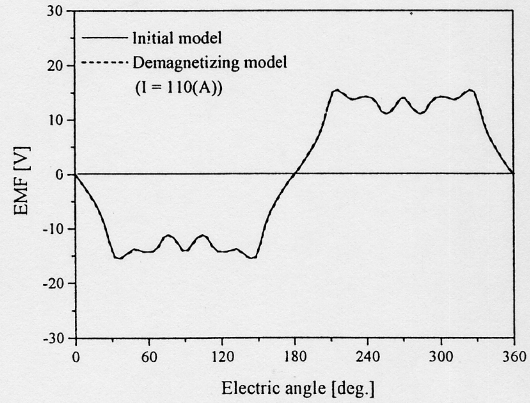
Fig 5. Comparison of residual flux density



(a) Spoke type BLDC motor



(b) SPM type BLDC motor



(c) IPM type BLDC motor

Fig6. Back EMF characteristics of initial versus demagnetizing model.

Therefore, the design of PM type BLDC motor should be considered to air gap flux density and irreversible demagnetization effect by rotor structure.

IV. DESIGN OF SPOKE TYPE BLDC MOTOR

A. Consideration of design parameters

In the spoke type BLDC motor, PMs are arranged to both side of rotor pole face, so it is lead to concentrate the magnetic flux generated by PMs in air gap. Therefore, for the higher performance of spoke type BLDC motor, we should fully investigate the distribution characteristics of magnetic flux according to the design parameters.

In this paper, the pole number and PM height versus arc length of pole face is chosen to design parameters under the condition having a constant rotor dimension as shown in Fig. 7. Fig.8 shows air gap flux density distribution according to the pole numbers From the effect of flux concentration, the magnetic flux density in the air gap increases with pole number until 0.5[T] in spite of the residual flux density of 0.39[T]. The characteristic of magnetic flux density due to

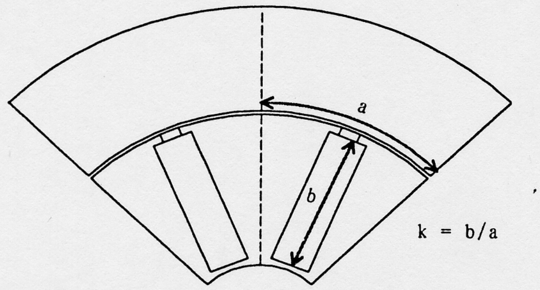


Fig. 7. Design parameter by PM height versus arc length of pole face (k)

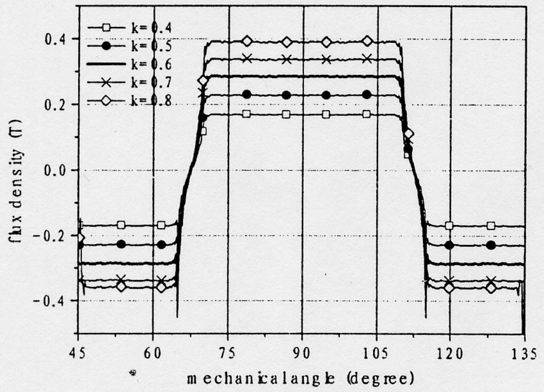


Fig. 8. Air gap flux density by k

pole shape ratio (k), which is PM height versus arc length of pole face, is shown in Fig. 8. As shown in Fig.8, the magnetic flux density have a large variation according to the pole shape ratio, so it is very important design parameter for high performance design of spoke type BLDC motor.

B. Consideration of design parameters

The design results are presented to Table I compared with design result of SPM type BLDC motor. As shown in Table I, the rotor diameter of spoke type BLDC motor is less than SPM type BLDC motor and rotor volume is reduced about 25(%) under constant power condition. Moreover, the magnet volume is reduced about 19(%) in comparison with SPM type BLDC motor. Also, the energy density of spoke type PM motor is higher then the SPM type BLDC motor.

From the results, the design of spoke type BLDC motor has to consider the irreversible demagnetization characteristics of PM because the concentration of the magnetic flux.

TABLE I. DESIGN RESULTS BY EQUIVALENT MAGNETIC CIRCUITS

Items	SPM type BLDC	Spoke type BLDC
Output power [W]/RPM	300 / 3000	300 / 3000
Pole #/ Slot #/ Turn #	8 / 24 / 64	8 / 24 / 64
Teeth width (mm)/ Slot depth (mm)	**1.94 / 8.2**	**2.3 / 8.7**
Stack length / Rotor diameter (mm)	61.1 / 61.1	55.5 / 55. 5
Magnetization Length of PM (mm)	2.9	2.9
Width of PM (mm)	18.7	16.7
Total volume of PM (Cm^3)	**26.5**	**21.5**
Rotor volume (Cm^3)	**179.15**	**134.27**

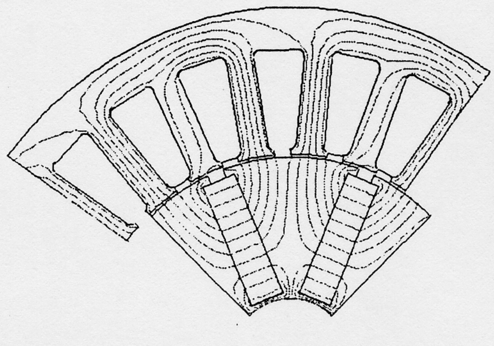


Fig. 9. Equip-potential distribution by FEM

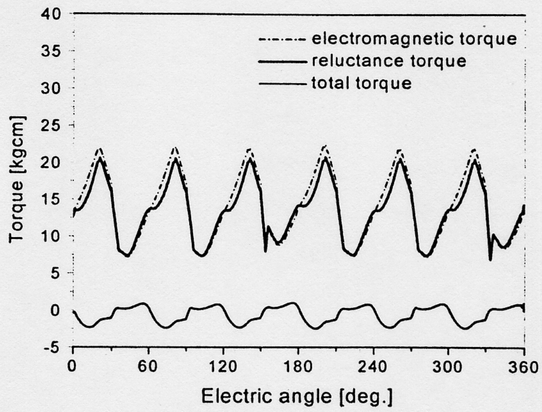


Fig. 10. Commutation torques distribution

V. CONCLUSION

In this paper, the design of spoke type BLDC motor considering the irreversible demagnetization of PM has been performed for higher motor performance. So, the irreversible demagnetization characteristics analysis is performed on three type of BLDC motor. From the analysis results, we confirmed that spoke type motor has a great advantage over SPM and other IPM toward high torque and small size, and the design process of the motor have to consider the irreversible demagnetization characteristics.

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