Design and Optimization of Neodymium Free Spoke Type Motor with Segmented Wing Shape PM

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***Abstract*—This paper proposes a new design of SPOKE type permanent magnet brush-less direct current (BLDC) motor of neodymium permanent magnet (Nd-PM) free. In this study a method to maximize the torque density has been developed using ferrite permanent magnet (Fe-PM) instead of Nd-PM. This was optimized using proposed analytical calculation method for improving torque density. Also this was verified by using the finite element analysis (FEA).**

***Index Terms*— SPOKE-type BLDC Motor, Nd-free Motor, Optimization Methods, FEA, Permanent Magnet (Ferrite).**

I. Introduction

In the field of motors, a very important step is to achieve high air-gap flux density. Normally, the air-gap flux density of the motor is approximately 0.7T – 1.0T using neodymium permanent magnet (Nd-PM) and 0.3T – 0.4T using ferrite permanent magnet (Fe-PM). The residual flux density of the Fe-PM lies between 0.4T – 0.46T and air-gap flux density is approximately 0.3T – 0.4T.

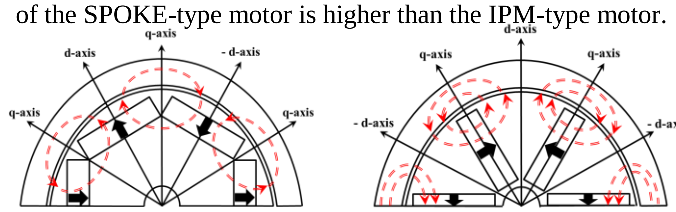
This paper proposes a design method for maximizing air-gap flux density using Fe-PM. As the production cost of Nd-PM is very high and the Fe-PM is competitively very cheaper than Nd-PM. The Halbach magnetized permanent magnet (PM) arrays offer many attractive features which can be effectively used for the design of rotary electrical machines [1]. One important characteristics of Halbach array is that they can cancel the flux in one side of the array and strengthen the flux on the other side of it [2]. So we applied the concept of Halbach magnetization using Fe-PM in the form of the combination of SPOKE-type and additional push type in order to get high output and to minimize the manufacturing cost.

The results of predictions from the analysis are compared with corresponding finite element analysis (FEA).

II. Magnet Characteristics Of Spoke-type Motor

An interior permanent magnet (IPM)-type brush-less direct current (BLDC) motor has high torque characteristic because it simultaneously uses the reluctance torque and magnetic torque [3]. The SPOKE-type BLDC motor has more additional advantages. It has a higher torque than the IPM-type BLDC motor as the magnetic resistance of PM is decreased by half of the magnet as compared with IPM-type BLDC motor [4]. The main flux path for IPM-type and SPOKE-type motors used by PM's are shown in Fig. 1

In Fig. 1(a), the main flux of the IPM-type BLDC motor has a path that passes through two magnets. However, in Fig. 1(b), the main flux of the SPOKE-type motor uses much more flux than the IPM-type BLDC motor as the flux has a path that passes through just one magnet. Consequently, the flux density of the SPOKE-type motor is higher than the IPM-type motor.



(a) IPM-type BLDC motor (b) Spoke-type BLDC motor

Fig. 1. Magnet flux characteristic by the permanent magnet

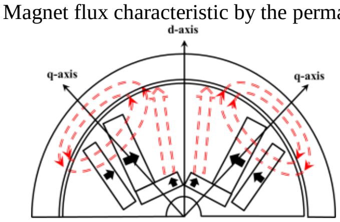


Fig. 2. Magnet flux characteristic of proposed spoke-type permanent magnet

In the proposed model pushing assistant magnet and a sub assistant magnets (Fe-PM) are inserted. The pushing magnet is inserted at the bottom of the main magnet in order to increase the length of the main magnet and the sub assistant magnet is inserted at the side of the main magnet in order to support the main magnet of the rotor. Therefore, the output characteristic of the air-gap flux density is maximized. The main flux path of the SPOKE-type BLDC motor, which includes the proposed magnet type, is shown in Fig. 2.

III. Design of Proposed Spoke-Type BLDC Motor

Our goal is to compare the simulation results of a 6-poles, 9-slots, 400 [W] IPM-type BLDC motor of Nd-PM with the newly proposed wing shaped SPOKE-type BLDC motor of Fe-PM. The output characteristics were different for Nd-PM and Fe-PM of the initial model. In order to improve the output characteristics, the proposed extra magnet and sub magnet was inserted into the inner side of the rotor. The improved model has output characteristics similar to initial motor. The flux density increases when the magneto-motive force (MMF) is increased, based on the length of the PM. It can be written as

$$F = H \cdot dl. \tag{1}$$

$$B = F / LI. \tag{2}$$

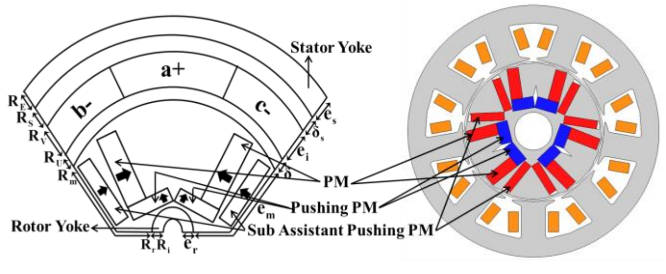
where F, H, l, L, and I are MMF, magnetic field intensity, magnet thickness, conductor length, and current respectively.

The average output torque is 1.29 Nm for initial IPM-type motor of Nd-PM and 1.27 Nm for the proposed SPOKE-type motor of Fe-PM. Therefore, the proposed motor gives the quite similar average output torque in comparison with the initial IPM-type motor of Nd-PM. This proves that the Nd-PM can be replaced by the Fe-PM. The B_g curve and average output torque is shown in Fig. 4.

IV. Analytical Solution of the Proposed Model

A. Solution of Flux density distribution

The analyzed SPOKE-type BLDC motor has 6-poles, 9-slots. The analysis was performed in 2-D, in a polar co-ordinate system by knowing the radius R_i and the dimensions e_r, e_m, δ_s, e_i, δ and e_s. The radius are determined as $R_r = R_i + e_r$ and similarly for others [5].



(a) Analytical Model (b) Wing shaped Spoke

Fig. 3. Geometry of the Analytical Model of the proposed Model.

The field distribution has been studied using cylindrical coordinates. The analytical model of rotor magnetic pole is shown in Fig. 3. The problem domain is divided into two regions: Region 1 is the air gap region and Region 2 is the magnet region. The Governing Laplacian and quasi-poissonion equations in the cylindrical co-ordinates are used to calculate the equation of radial and tangential flux density of the proposed model which is given below [6],

$$B_R = K \times \left[1 - \frac{R_r^{\,np+1}}{R_m}\right] \cdot \left[\frac{r^{np-1}}{R_s} \cdot \frac{R_m^{\,np+1}}{R_s} + \frac{R_m^{\,np+1}}{r}\right] \times \cos(np\theta) \qquad (3)$$

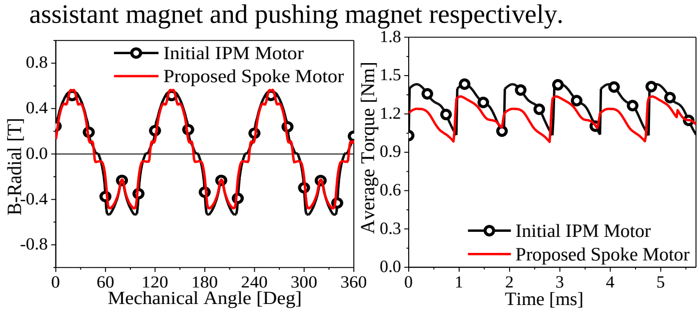
$$B_\theta = K \times \left[1 - \frac{R_r^{\,np+1}}{R_m}\right] \cdot \left[\frac{r^{np-1}}{R_s} \cdot \frac{R_m^{\,np+1}}{R_s} - \frac{R_m^{\,np+1}}{r}\right] \times \sin(np\theta) \qquad (4)$$

Here,

$$D_o = 2\left\{(1-\mu_r)\frac{R_r^{\,2np}}{R_m}\left[(1-\mu_r)+(1+\mu_r)\frac{R_m^{\,2np}}{R_s}\right] - (1+\mu_r)\left[(1+\mu_r)+(1-\mu_r)\frac{R_m^{\,2n.p}}{R_s}\right]\right\}$$

$$R_m = \frac{2l_m w_m + 2l_s w_s + 2l_r w_r}{w_m + w_s + w_r/4} \quad \text{and} \quad K = -\sum_{n=1,3,5\ldots}^{\infty} \frac{4B_r}{D_o} \cdot \frac{np}{1+p}(1+\mu_r) \qquad (5)$$

where p is the pole pair number, μr is the relative recoil permeability of the magnet, θ is the relative position of the stator with respect to the rotor, R_r is the internal radius of the magnet, R_m is the volume of the magnet, R_s is the stator outer bore radius, R_i is the stator inner bore radius, r is the mean air gap radius where the flux density has to be calculated. l_m, l_s, l_r, w_m, w_s and w_r is the length and width of main magnet, sub assistant magnet and pushing magnet respectively.



(a) Air-gap flux density (b) Average output torque

Fig. 4. Comparison of initial model and optimized SPOKE-type model

B. Solution of Back Electromotive Force

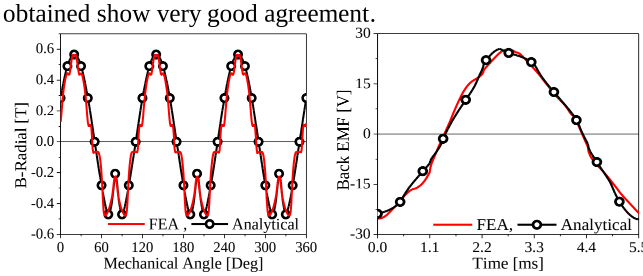
The Back Electromotive Force (BEMF) of the analytical model of permanent magnet BLDC motor has been calculated from the no-load flux density distribution with the knowledge of armature winding distribution which is given below.

$$E_A(t) = Nl_s R\omega \sum_{n=1,3,5\ldots}^{\infty} k_{dn} \left\{ \lambda_0 B_{rn} 2\sin\left(np\frac{\zeta_c}{2}\right) + \sum_{m=1}^{N_\lambda} (B_{rn}\lambda_{am} - B_{\theta n}\lambda_{bm}) \frac{\sin\left[(np+mQ_s)\frac{\zeta_c}{2}\right]np}{np+mQ_s} A_m + \sum_{m=1}^{N_\lambda} (B_{rn}\lambda_{am} + B_{\theta n}\lambda_{bm}) \frac{\sin\left[(np-mQ_s)\frac{\zeta_c}{2}\right]np}{np-mQ_s} A_m \right\} \times \sin[n(pt\omega - \alpha_0)] \qquad (6)$$

where α_o is equal to zero for phase *A*, 2π/3 for phase *B* and 4π/3 for phase *C*.

V. Results and Discussion

The concept of complex relative flux path due to the air-gap permeance has been adopted by considering the stator slotting effect to calculate the exact air-gap field [7]. It can be seen that the flux density and the BEMF was obtained analytically using newly calculated equations (3) and (6) respectively and numerically using FEA for R_i=5, R_r=7.5, R_m=30.8035, Rs=43, r=27.5, μ_r=1 and Br=0.45. The maximum values are B_R=0.5650 and $E_A(t)$=25.2580. The waveforms are shown in Fig. 5, which represents the accuracy of the proposed model, and the results obtained show very good agreement.



(a) Flux density. (b) Back EMF

Fig. 5. Comparison of Analytical and FEA results.

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