Torque Analysis of Permanent Magnet Hybrid Stepper Motor using Finite Element Method for Different Design Topologies

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ABSTRACT

This paper discusses about permanent magnet hybrid stepper motor magnetic circuit using finite element method for different geometric designs like uniform air-gap, non uniform air-gap, for different air-gap lengths, different tooth pitches and extra teeth on stator using PDE toolbox of Matlab at different current densities. Implementing these results in equivalent circuit model (permeance model), motor performance is analyzed for an existing motor for steady state conditions. These results suggest modifications for better performance of the PMH stepper motor like reduction of cogging torque and improvement in steady state torque with minimum THD.

Keywords: Cogging torque, FEM, Instantaneous Torque, PDE toolbox, Permeance model

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1. INTRODUCTION

Stepper motors are used in a variety of applications, including high and low propulsion technology, solar array tracking system in satellites, computer peripherals, machine tools, robotics, etc. Stepper Motors are divided into two major groups, one without permanent magnet and the other with permanent magnet. The term hybrid is derived from the fact that the motor is operated under the combined principles of permanent magnet and variable reluctance motors. The motor having the permanent magnet rotor and multiple teeth both on the stator and rotor poles, with excitation in stator poles is called the hybrid stepper motor.

Hybrid stepper motors (pmh) are highly preferred in space applications as they can provide accurate positioning in open loop system [1]. The positional accuracy of the stepper motors will be high only when its step angle is very small. Hence for space applications hybrid stepper motor is the best choice as it can offer small step angles in the range of 0.5° to 1.8°. The other classes of stepper motors such as variable reluctance stepper motor and permanent magnet stepper motor will be suitable only for applications which require large step angles.

The design of a hybrid stepper unlike that of conventional ac motors such as induction motor and synchronous motor using equivalent magnetic circuit analysis is not easy because of the complex air-gap geometry, which results in complex air-gap permeance variation [2]. Because of this, analysis using electromagnetic computation is a complex task and these results in the dependency of FEM technique for design and analysis.

Since hybrid stepper motor has a large number of teeth on the stator and rotor surface and a very small air gap, the magnetic saturation in the teeth becomes severe while increasing the flux density in the air-gap.
In addition both radial and axial flux is produced because of axially magnetized permanent magnet and geometric characteristics.

This makes the analysis of hybrid stepper motor more difficult using 2D FE modeling. Three dimensional FE analyses is one of the solutions for nonlinear analysis of axially unsymmetrical hybrid stepper motor under this situation. But in order to reduce the computational time involved in the analysis a 2D equivalent of the 3D model of the motor was developed and used.

2. FEM OF HYBRID STEPPER MOTOR

Tooth layer unit (TLU) [3] is a rectangle area that has a tooth pitch width and two parallel lines behind the teeth of stator and rotor. The area is shown in Fig.1. The factors of the nonlinear material and the non-uniform distribution of magnetic field in the teeth of stator and rotor are taken full consideration in this computation model. There are two basic assumed conditions in the computation model of TLU.1. The lines AB and CD of the TLU in Fig.1 are considered as iso-potential lines. 2. The magnetic edge effect of stator pole is ignored, which is assumed that the distribution of the magnetic field for every tooth pitch width is the same.

In Fig.1, \(u_s\) and \(u_r\) are the scalar quantities of the iso-potential lines AB and CD. The magnetic potential difference \(F\) is given in (1).

\[
F = u_s - u_r \quad (1)
\]

If \(\Phi(\alpha)\) is assumed as the flux in a tooth pitch width per axial unit length of iron core and \(\alpha\) is the relative position angle between stator and rotor, then the specific magnetic conductance \(G\) of TLU is given in (2).

\[
G = \frac{\Phi(\alpha)}{F} \quad (2)
\]

Fig.1. Tooth layer unit

Apparently, \(G\) is related to the saturation extent of iron core and is changed with \(F\) and the relative position angle \(\alpha\) and it can be obtained by the numerical computation on the magnetic field of TLU shown in Fig.1 [3]. The lines AC and BD are the periodic boundary lines because the distribution of the magnetic field is considered as the same for every tooth pitch width. The magnetic field in TLU is irrational field and the magnetic equations for the field are given in the rectangular coordinates in (3).

\[
\frac{\partial}{\partial x} \left( \mu \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial \phi}{\partial y} \right) = \begin{cases} 
\varphi_{CD} = 0 \\
\varphi_{AB} = 0 \\
\varphi(x,y)_{AC} = \varphi(x + \lambda,y)_{BD} 
\end{cases} \quad (3)
\]

where \(\phi\) is the scalar quantity, \(\mu\) is the magnetic permeability and \(\lambda\) is the tooth pitch. For a certain position angle \(\alpha\) and a magnetic potential difference \(F\), the distribution of the magnetic field of TLU can be calculated by the 2D finite element analysis. The flux per axial length of TLU is given in (4).

\[
\varphi(\alpha, F) = \sum B_e \left( \int_{m} m \right)_e \quad (4)
\]
Here the nodes \( j \) and \( m \) are on the border \( AB \) as shown in Fig1. \((j\overline{m})\) is the length of unit \( e \) from node \( j \) to \( m \) and \( B_e \) is the flux density. The specific magnetic conductance \( G \) will be used in the calculation of the whole nonlinear network equations of the motor.

3. RESULTS AND ANALYSIS
   a. Design of Hybrid Stepper Motor

A practical 1.8\(^\circ\) (mechanical) PMH stepper motor is chosen for design. It has 4 poles in the stator and 2 sections in the rotor with AlNiCo \( 5 \) magnet axially magnetized. The main structure parameters of the motor are shown in Table1.

| Stator poles | Tooth per stator pole | Outside diameter of stator | Inside diameter of stator | Outside diameter of stator shell |
|--------------|-----------------------|---------------------------|---------------------------|----------------------------------|
| 04           | 8                     | 10.108 cm                 | 5.936 cm                  | 10.652 cm                        |
| Tooth number of rotor | Number of turns per phase | Section length of rotor | Outside diameter of rotor | Inside diameter of rotor |
| 50           | 46                    | 10.26 cm                  | 4.2 cm                    | 1.74 cm                          |
| No of turns per stator pole | Rated voltage | Rated current | SWG of conductor | Torque |
| 92           | 12 V                  | 1 A                       | 36                        | 1.5 Nm                            |

PDE toolbox of Matlab for FEM analysis is used to investigate mmf due to permanent magnet for different topologies which is difficult to investigate by mathematical model [4]. Different topologies considered are 1) Uniform air-gap (0.137 mm) with extra teeth on stator 2) Uniform air-gap (0.137 mm) without extra teeth on stator 3) Non-uniform air-gap (0.137 mm) with extra teeth on stator 4) Non-uniform air-gap (0.137 mm) without extra teeth on stator 5) Uniform air-gap (0.93 mm) with extra teeth on stator 6) Uniform air-gap (0.93 mm) without extra teeth on stator 7) Non-uniform air-gap (0.93 mm) with extra teeth on stator 8) Non-uniform air-gap (0.93 mm) without extra teeth on stator. The details of all the eight topologies are shown in Table 3.

All topologies are investigated with Iron (99.8\%) and Iron (99.95\%), for rare earth permanent magnets NdFeB, \( S_mC_{017} \) at current capacities of 0.5 A and 1 A. The related magnetic potential diagrams are shown from Fig. 2 to Fig. 5 for one / two iron core materials (99.8\% and 99.95\%) with NdFeB as permanent magnet. Fig. 2 shows for Uniform air-gap (0.137 mm) with extra teeth on stator without excitation. Fig. 3 shows for uniform air-gap (0.137 mm) with extra teeth on stator with excitation of 0.5 A. Fig. 4 shows for uniform air-gap (0.137 mm) without extra teeth on stator without excitation and Fig. 5 shows for uniform air-gap (0.137 mm) without extra teeth on stator with excitation of 0.5 A. Similarly for all remaining topologies, for different core materials and different permanent magnets at different current densities, magnetic potential is investigated with and without excitation. This magnetic potential is multiplied with axial length (10.26 cm) and air-gap lengths (0.137 mm, 0.93 mm) to get total mmf.

![Magnetic potential as contour and flux density as arrows of PMH motor for topology 1 without excitation for two core materials, iron (99.8%), Iron (99.9) for NdFeB permanent](image1.png)

Fig. 1. Magnetic potential as contour and flux density as arrows of PMH motor for topology 1 without excitation for two core materials, iron (99.8\%), Iron (99.9) for NdFeB permanent.
Fig. 3. Magnetic potential as contour and flux density as arrows of PMH motor for topology 1 with excitation of 0.5A for core material, iron (99.8%) for NdFeB permanent magnet.

Fig. 4. Magnetic potential as contour and flux density as arrows of PMH motor for topology 2 without excitation for two core materials, iron (99.8%), Iron (99.9%) for NdFeB permanent magnet.

Fig. 5. Magnetic potential as contour and flux density as arrows of PMH motor for topology 1 with excitation of 0.5A for core material, iron (99.8%) for NdFeB permanent magnet.
3.2. Permeance Model of Hybrid Stepper Motor

The gap permeances \(P_1 - P_5\) [5] are calculated using (5) for the tooth layer unit shown in Fig.6 [6]

\[
P_1 = \mu_0 \frac{x}{g}
\]
\[
P_2 = \mu_0 \frac{2}{\pi} \ln \left(1 + \frac{1}{2} \frac{x}{g} \right)
\]
\[
P_3 = \mu_0 \frac{1}{\pi} \ln \left(\frac{g^{+2d} - 1}{g^{+2d} + 1} \frac{x}{g} \frac{x}{g} \right)
\]
\[
P_4 = \mu_0 \frac{2}{\pi} \ln \left(\frac{g^{+2d} - 1}{g^{+2d} + 1} \frac{x}{g} \frac{x}{g} \right)
\]
\[
P_5 = \mu_0 \frac{x - 4d}{g + 2d}
\]

(5)

Here, \(x\) = equivalent length of step angle mm, \(t = 1.32\) mm, \(s = 1.42\) mm, \(d = 1.32\) mm, air-gap length, \(g = 0.137\) mm and \(0.93\) mm are considered for the analysis. Suppose that the number of teeth per stator pole is \(Z_s\), the total permeance per pole, \(P_t\) is given in (6), considering \(P_1\) to \(P_5\) are in parallel

\[
P_t = Z_s [P_1 + 2(P_2 + P_3 + P_4) + P_5] \text{ Wb/A} \tag{6}
\]

The Permeance per pole per phase is given by (7)

\[
P\alpha = P_t + \sum_{n=1}^{\infty} P_n \cos(n0) \tag{7}
\]

Since the displacement is from \(0 = 0\) to \(2\pi\) radians corresponds to one-pitch of a tooth, the electric angle \(\theta\) is related to the mechanical step angle \(\theta_m\), as in (8), where \(Z_r\) is the number of teeth of the rotor

\[
\theta_\alpha = Z_r \theta_m \tag{8}
\]

The gap permeance Fourier coefficients (?) for all topologies are evaluated using (5), (6), (7) and (8) and tabulated in Table 2.

Steady state torque and cogging torques are obtained using (9) and (10) respectively [5].

\[
T_0 = -\frac{Z_i}{2} (NI) (B_0 A_m) \frac{\rho_0}{\rho_t} \sin \theta_e \text{ Nm} \tag{9}
\]

where \(Z_i\) is rotor teeth, \(N\) is turns per coil per phase, \(I\) is per phase current in A, \(B_0\) is flux density of permanent magnet in Wb/m\(^2\), \(A_m\) is area of permanent magnet in m\(^2\), \(\rho_0\) and \(\rho_t\) are Fourier coefficients and \(\theta_e\) is electrical angle in degrees.

\[
T_{cog} = \frac{Z_e}{2} P_m P_m^2 \rho_4 \sin 4 \theta_e \text{ Nm} \tag{10}
\]

where, \(P_m\) is permanent magnet permeance in Wb/A, \(F_m\) is mmf of permanent magnet in AT and \(\rho_4\) is Fourier gap coefficient. Steady state torque and cogging torque are obtained using mmf of permanent magnet and mmf due to excitation from Table 3 for all topologies for two iron cores (99.8%, 99.95%) with

\[
\text{Title of manuscript is short and clear, implies research results (First Author)}
\]
rare earth permanent magnets NdFeB and Sm$_2$Co$_{17}$ at current capacities of 0.5 A and 1A. These results are tabulated in Table 3.

![Table 2. Fourier coefficients of gap permeance for different topologies](image)

| Topology | Fourier coefficients of gap permeance |
|----------|--------------------------------------|
|          | $\rho_{1 \times 10^{-4}}$ | $\rho_{1 \times 10^{-5}}$ | $\rho_{2 \times 10^{-5}}$ | $\rho_{3 \times 10^{-5}}$ | $\rho_{4 \times 10^{-5}}$ | $\rho_{5 \times 10^{-5}}$ |
| 1        | 4.320 | 3.222 | 2.809 | 4.276 | 3.280 | 1.915 |
| 2        | 5.375 | 3.043 | 2.464 | 5.321 | 3.681 | 1.679 |
| 3        | 1.184 | 7.665 | 5.904 | 1.172 | 8.294 | 4.024 |
| 4        | 7.093 | 3.832 | 2.952 | 7.022 | 4.636 | 2.012 |
| 5        | 1.656 | 8.950 | 6.893 | 1.640 | 1.082 | 4.699 |
| 6        | 1.506 | 8.136 | 6.526 | 1.552 | 1.025 | 4.448 |
| 7        | 4.328 | 2.338 | 1.801 | 4.070 | 2.829 | 1.227 |
| 8        | 2.164 | 1.169 | 9.005 | 2.142 | 1.414 | 6.138 |

Fig. 7 and Fig. 8 show the responses of permeances for topology 1 and 2 respectively. Fig. 9 and Fig. 10 are responses of steady state torque and cogging torque of iron core (99.8%) for topology 1 and topology 2 respectively at 0.5 A.

![Fig. 7. Permeances for topology 1](image)

![Fig. 8. Permeances for topology 2](image)
3.3. **Instantaneous Torque of Hybrid Stepper Motor**

Instantaneous torques of even harmonic and odd harmonic in Nm can be evaluated using (11), (12) respectively

\[
T_e = 2N^2 I^2 \left\{ (P_2 - 4P_4 + 3P_6) \sin \theta \\
+ (3P_6 - 8P_8 + 5P_{10}) \sin 2 \theta \\
+ (5P_{10} - 12P_{12}) \sin 3 \theta + \ldots \right\} 
\]

(11)

\[
T_o = 2N I F_m \left\{ P_1 + (-3P_3 + 5P_5) \cos 2 \theta \\
+ (-7P_7 + 9P_9) \cos 4 \theta \\
+ (-11P_{11} + 13P_{13}) \cos 8 \theta \right\} 
\]

(12)

Total torque in Nm is investigated using (13)

\[
T_t = T_e + T_o 
\]

(13)

Fig.11 and Fig.12 are the responses of $T_e$, $T_o$ and $T_t$ for topology 1 at 0.5A and for topology 2 at 0.5A respectively for iron core (99.8%).

Instantaneous torques are investigated using mmf of permanent magnet and mmf due to excitation from Table 3 for all topologies for iron (99.8%), iron(99.95%) for rare earth permanent magnets NdFeB, Sm$_2$Co$_{17}$ for current capacities of 0.5A, 1A to calculate THD and tabulated in Table 3.

MMF is found uniformly distributed in uniform small air-gap distribution. Maximum MMF is interacted between stator and rotor for uniform airgap topology. Steady state torque is varying with current density linearly for uniform air-gap topology for iron (99.8) type with Sm$_2$Co$_{17}$ permanent magnet. When air-gap is increased steady state torque is lost and more harmonic in nature. Cogging torque is low for non-uniform low air-gap without extra teeth on stator topology with iron (99.8) stator and rotor core but very low steady state torque. Cogging torque is more than steady state torque for large non uniform air-gap topology.

![Fig.9. Steady state torque and cogging torque for topology 1 at 0.5A](image)

![Fig.10. Steady state torque and cogging torque for topology 2 at 0.5A](image)
Table 3. MMF and Torque and THD of instantaneous torque for different topologies

| Topology | Stator, rotor core Iron (%) | Permanent magnet | Current density (A/m²) | MMF due to PM, $A_{PM}$ | MMF due to excitation, $A_{EXC}$ | Instantaneous torque THD % | $T_{0}$ (Nm) | $T_{cog}$ (Nm) |
|----------|-----------------------------|------------------|------------------------|----------------------|-------------------------|--------------------------|-----------|-------------|
| 1        | NdFeB                       | 170648           | 4.578                  | 23.6352              | 12.46                   | 0.1596                   | 0.0171   |             |
| Iron (99.8) | Sm$_2$Co$_17$           | 341296           | 4.578                  | 30.7940              | 15.57                   | 0.1995                   | 0.0171   |             |
| 1        | NdFeB                       | 170648           | 4.578                  | 30.7940              | 15.57                   | 0.1995                   | 0.0171   |             |
| Iron (99.95) | Sm$_2$Co$_17$           | 341296          | 4.578                  | 107.779              | 17.36                   | 0.4960                   | 0.0712   |             |
| 2        | NdFeB                       | 170648           | 4.578                  | 30.7940              | 17.36                   | 0.4960                   | 0.0712   |             |
| Iron (99.8) | Sm$_2$Co$_17$           | 341296          | 4.578                  | 30.7940              | 17.36                   | 0.4960                   | 0.0712   |             |
| 2        | NdFeB                       | 170648           | 6.159                  | 92.3820              | 17.72                   | 0.8051                   | 0.1289   |             |
### Table

| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 6.159 | 184.764 | 18.82 | 1.6100 | 0.1289 |
|--------|-----------------|-------|--------|-------|---------|-------|--------|--------|
| (99.95) | 170648 | 6.159 | 92.3820 | 18.01 | 0.8051 | 0.1289 |
| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 1.232 | 30.7940 | 6.08 | 0.0604 | 0.0580 |
| (99.8)  | 170648 | 1.232 | 15.3972 | 3.04 | 0.0320 | 0.0580 |
| 3      | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 6.159 | 184.764 | 18.82 | 1.6100 | 0.1289 |
| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 1.232 | 30.7940 | 6.08 | 0.0604 | 0.0580 |
| (99.8)  | 170648 | 1.232 | 15.3972 | 3.04 | 0.0320 | 0.0580 |
| 4      | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 1.232 | 30.7940 | 6.08 | 0.0604 | 0.0580 |
| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 6.159 | 184.764 | 18.82 | 1.6100 | 0.1289 |
| (99.95) | 170648 | 6.159 | 92.3820 | 18.01 | 0.8051 | 0.1289 |
| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 1.232 | 30.7940 | 6.08 | 0.0604 | 0.0580 |
| (99.8)  | 170648 | 1.232 | 15.3972 | 3.04 | 0.0320 | 0.0580 |
| 5      | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 6.159 | 184.764 | 18.82 | 1.6100 | 0.1289 |
| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 1.232 | 30.7940 | 6.08 | 0.0604 | 0.0580 |
| (99.8)  | 170648 | 1.232 | 15.3972 | 3.04 | 0.0320 | 0.0580 |
| 6      | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 1.232 | 30.7940 | 6.08 | 0.0604 | 0.0580 |
| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 6.159 | 184.764 | 18.82 | 1.6100 | 0.1289 |
| (99.95) | 170648 | 6.159 | 92.3820 | 18.01 | 0.8051 | 0.1289 |
| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 1.232 | 30.7940 | 6.08 | 0.0604 | 0.0580 |
| (99.8)  | 170648 | 1.232 | 15.3972 | 3.04 | 0.0320 | 0.0580 |
| 7      | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 6.159 | 184.764 | 18.82 | 1.6100 | 0.1289 |
| Iron   | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 1.232 | 30.7940 | 6.08 | 0.0604 | 0.0580 |
| (99.8)  | 170648 | 1.232 | 15.3972 | 3.04 | 0.0320 | 0.0580 |
| 8      | Sm$_2$Co$_{17}$ | NdFeB | 341296 | 6.159 | 184.764 | 18.82 | 1.6100 | 0.1289 |

### 4 CONCLUSION

Fem analysis is done for magnetic circuit analysis of PMH stepper motor using PDE toolbox of Matlab whose responces are shown in Fig.2, Fig.3, Fig.4 and Fig.5 for first two topologies. Equivalent circuit model analysis is used for gap permeance, steady state, cogging torques and instantaneous torque analysis whose responces are shown in Fig.7, Fig.8, Fig.9 and Fig.10, Fig.11, Fig.12 respectively. Similarly investigation carried for 8 topologies. Finally for getting rated steady state torque (1.5 Nm) with low THD, low uniform air-gap (0.137 mm) with extra stator teeth on stator (topology 1) with iron (99.95%) for stator and rotor cores with current density of 341296 A/m$^2$ (1 A for 36 SWG) is investigated. Cogging torque to Steady state torque ratio (4.77%) is not effected by variation of permanent magnet material for the above topology. Cogging torque can be minimized by providing extra teeth on stator.

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