FEM ANALYSIS FOR A NOVEL CONFIGURATION OF BRUSHLESS DC MOTOR WITHOUT PERMANENT MAGNET

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Abstract—This paper describes the design and analysis of a novel configuration for Brushless DC (BLDC) motor. This new structure does not use a permanent magnet in the rotor which highlights this family of BLDC motors in comparison with conventional BLDC motors. The proposed configuration consists of two magnetically dependent stator and rotor sets, in which each stator set includes nine salient poles with windings wrapped around them, and the rotor comprises of six salient poles. The magnetic field passes through a guide to the rotor then the stator and finally completes its path via the motor housing. Finite Element (FE) analysis has been carried out to confirm the accuracy of the predicted flux-linkage characteristics, which play a key role in the design process. Furthermore, the abbreviation of the evaluation method based on 3-D field solution is introduced. It provides not only confirmations of the investigation results but also exact illustration for magnetic field distribution for this complex configuration. A prototype BLDC motor is built and its test results validated the design methodology. As a consequence, a design procedure for such a BLDC motor based on new configuration is described and the simulation results are compared with measured values. On the other hand, designing a new structure of BLDC motor is proposed and FE analysis is carried out to confirm the predicted characteristics.

1. INTRODUCTION

Recently, brushless DC motors have been widely used in large-scale industry applications such as automotive, aerospace, home appliances

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and many industrial equipment and instrumentation for various applications [1–3]. Specially, the small size motors with external rotors are widely used in visual equipment such as audio equipment like tape recorders and digital audio tapes (DAT), computer disc drives (HDD and DVD) and copiers [3–5]. The construction of modern BLCD motors is very similar to the ac motor, known as the permanent magnet synchronous motor. BLDC motors come in single-phase [6], 2-phase and three-phase configurations [7]. The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery or around stator salient poles. The rotor is made of permanent magnets and can vary from two to eight pole pairs with alternate north (N) and south (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As technology advances, rare earth alloy magnets are gaining popularity. In order to make a BLDC motor rotate, the stator windings should be energized in a sequence. It is essential to know the rotor position in order to understanding as to which winding must be energized [2, 4]. The magnetic flux generated by the current in the stator winding can increase or decrease the flux density in the stator depending on the rotor position, leading to decrease or increase in inductance due to the saturation of the stator. By applying positive and negative voltage pulses consecutively and measuring the difference in inductance, it can be indicated which magnetic polarity the phase winding is facing [8]. As electromagnetic forces result from the interaction between the rotor and the stator through the magnetic field in the air-gap space in between, an accurate prediction of the instantaneous magnetic fields is essential. When designing electrical motors, both the analytical and numerical methods, e.g., finite-element methods (FEM), are used frequently. Even as FEM is well suited for failure analysis and design validation purposes, analytical methods are useful as efficient tools for quick evaluation of the motor performance with given settings of design parameters. Thus, development of effective analytical approaches for BLDC motor design syntheses continues to attract great attention from researchers, e.g., [9]. The synthesized procedure to achieve the flux density distribution for special motor with the help of numerical methods has been widely used [10, 11]. For instance, it can be used to estimate the back electromotive force (EMF) and the inductance of the stator windings [12], the frequency spectra of the magnetic induced forces which signify the magnetically induced vibration sources [13], the running torque, and some other aspects of the permanent magnet (PM) motor performances [14–16].
This paper briefly reviews the fundamentals behind the motor and also the different types of BLDC motors with different geometries and then presents a new configuration for BLDC motor, which does not use a permanent magnet in the rotor. Parametric FEM study is carried out for field analysis of proposed structure of the BLDC motor. As a confirmation of the suggested configuration, 3-D field solution is presented. Test data from the prototype is used to validate the findings of the simulation analyses and practically demonstrate the attributes of the topology.

2. NOVEL STRUCTURE OF BLDC MOTOR

As a novelty of this paper, substitution of assistant field by permanent magnet in the rotor is proposed. As shown in Figure 1, the proposed novel motor consists of two magnetically dependent stator and rotor sets (Side A and Side B), in which each stator set includes nine salient poles with windings wrapped around them and the rotor which comprises of six salient poles. Every stator and rotor pole arcs are $30\degree$. It is worth mentioning that, the number of stator poles and their configuration is completely different than that of the switched reluctance motor. The two layers are exactly symmetrical with respect to a plane perpendicular to the middle of the motor shaft. This is a three phase motor, therefore, three coil windings from one layer is connected in series with the other three coil windings in the other layer. A cut view and 3-D view of the motor are shown in Figure 1(a) and Figure 1(b) respectively. There is a stationary reel, which has the field coils wrapped around it and is placed between the two-stator sets. This reel has a rotating cylindrical core, which guides the magnetic field. The magnetic flux produced by the coils travels through the guide and shaft to the rotor and then to the stator poles and finally

![Figure 1.](image-url)
Figure 2. (a) Stator lamination and (b) rotor lamination.

closes itself through the motor housing.

Therefore, one set of rotor poles is magnetically north and the other set magnetically south. In this motor, the magnetic field has been induced to the rotor without using any brushes. In Figure 1(b) are two stator and rotor sections placed on both sides of the field coil assembly which has the rotor shaft as its main core and two front/end caps plus the motor housing. A set of photo interrupters are also placed in the back of the motor for rotor position detection. One of the most widely used methods for analysis of any types of motors is the finite element technique [17]. Figure 2 shows the shape of the stator and the rotor laminations.

Since the suggested configuration is to some extent similar to the Switched Reluctance (SR) motors, quantitative comparisons between the proposed motor and the SR motor can be explained as follow:

1. Regarding the number of rotor poles for SR motors, when the poles of one phase come into full alignment, the poles of another phase are just starting to overlap and hence are available to seamlessly take over torque production. Even though, for the suggested motor, when one phase come into full alignment, 10° overlap for the poles of another phase is occurred.

2. Typical three-phase SR motors combinations for stator and rotor poles are 6/4, 8/6, 12/8, 18/12, etc. structures. Although for the proposed motor, the numbers of stator and rotor poles are 9/6.

3. For the SR motor, torque is produced by the tendency of its moveable part to move to a position where the inductance of the excited winding is maximized. But, in the presented structure, the torque is produced based on both the above feature for SR motors and the fundamental principle of magnetism which is used as basic operation of conventional BLDC motors. For the proposed motor, substitution of assistant field by permanent magnet in the rotor is
carried out. When a current is passed through field coil, one set of rotor poles is magnetically north and the other set magnetically south. In addition to, when a current is passed through stator poles windings, it generates a magnetic field with N-S polarity on two sides of stator poles. As a consequence, by considering the influence of the opposite and similar poles on the stator and rotor, sufficient torque to move the rotor to a desired position can be achieved.

4. Due to proposed structure, two phases can be excited simultaneously. It provides higher power density in comparison with similar SR motors in which only one phase can be excited.

5. The magnetization pattern of the individual phases together with the $T-i-\theta$ characteristics of the salient poles motors dictate the amount of torque ripple during operation. Regarding to the designed configuration due to extension of overlap region, the torque ripple for the proposed motor is reduced in comparison with conventional SR motors.

3. NUMERICAL ANALYSIS OF MAGNETIC FIELD FOR BLDC MOTOR

To predict BLDC motor behavior for each novel configuration, analysis of magnetic flux is an essential part of design procedure. So flux waveforms in all parts of the machine must be calculated. Due to FEM is well known method for field solution and design validation of motors; it is used as efficient tools for accurate evaluation of the motor performance in the proposed configuration.

3.1. Preliminaries of Flux Density Distribution

As mentioned before, the design of the motor becomes complicated due to complex geometry and material saturation. The reluctance variation of the motor has an important role on the performance; hence an accurate knowledge of the flux distribution inside the motor for different excitation currents and rotor positions is essential for the prediction of motor performance. So in this section, field analysis background for the proposed BLDC is presented. Since there is no free current in the rotor region [18]:

$$\nabla \times H = 0$$  \quad (1)

So,

$$\nabla \times B = \mu_0 \nabla \times M$$  \quad (2)
The magnetic vector potential is defined as:

$$B = \nabla \times A$$

Regarding to new configuration geometry, the magnetic vector potential $A$ has only $A_z$ that is independent to $Z$. In nonconducting regions, the magnetic vector potential is assumed to have Coulomb gauge dependence and satisfies the Poisson equation as follows:

$$\nabla^2 A^I = 0 \ , \text{ Air Gap Region}$$
$$\nabla^2 A^{II} = -\mu_0 \nabla \times M \ , \text{ Rotor Region}$$

where $\mu_0$ is the free space permeability. Here, $M$ is the complex Fourier coefficient of $n$th-order magnetization components. It is written as follows:

$$M = \sum_{n=-\infty}^{\infty} \{ M_{rn} e^{-jnp\theta} i_r + M_{\theta n} e^{-jnp\theta} i_\theta \}$$

where $M_{rn}$ and $M_{\theta n}$ are the normal and tangential component of the magnetization and $np$ is the spatial wave number of the $n$th order harmonic. Solutions take the $A_n = \text{Re}\{A_n(r)e^{-jnp\theta}\}$ and are related to the component of flux density $B$ by:

$$B_{rn} = \frac{1}{r} \frac{\partial}{\partial \theta} A_z, \quad B_{\theta n} = -\frac{\partial}{\partial r} A_z$$

Due to complex magnetic circuit geometry and nonlinear properties of the magnetic materials for the proposed BLDC motor, using of the numerical techniques such as FEM for field solution according to mentioned equations is suggested.

3.2. FIELD Solution by Finite Element Method

The finite-element technique can be obtained the magnetic vector potential values throughout the motors. These vector potential values can be processed to achieve the field distribution, torque and flux leakage. For 2-D analysis of proposed motor, only one side of the motor which is symmetric to the field coil is considered. Normal boundary conditions are applied to the outer and inner borders of the motor and a magnet producing the same magnetic field density is considered to act as the field coil. It is worth mentioning that the other options for the field coils could have been using small coil windings on the rotor poles. The field analysis is carried out with the help of Magnet CAD package [19], which is based on the variational energy minimization technique to solve the magnetic vector potential. The
partial differential equation for the magnetic vector potential is given by [18],

\[-\frac{\partial}{\partial x} \left( \gamma \frac{\partial A}{\partial x} \right) - \frac{\partial}{\partial y} \left( \gamma \frac{\partial A}{\partial y} \right) = J(x, y) \]  

(7)

where, \( A \) is the magnetic vector potential. In the variational method (Ritz) the solution tool is obtained by minimizing the following function:

\[ F(A) = \frac{1}{2} \iint_{\Omega} \left[ \gamma \left( \frac{\partial A}{\partial x} \right)^2 + \gamma \left( \frac{\partial A}{\partial y} \right)^2 \right] d\Omega - \iint_{\Omega} J A d\Omega \]  

(8)

where \( \Omega \) is the problem region of integration. In the finite element (FE) analysis second order triangular elements have been used. It is mentioned that dense meshes are assigned to places where the variation of fields are significant.

For prediction of BLDC Motor dynamics, first the stator pole flux waveform is obtained. Then flux waveforms in all parts of the machine can be calculated. But, for calculation of the stator pole flux and current, voltage equation and static flux-linkage characteristic are used. Based on the energy conversion, co-energy is the integral of the flux-linkage versus current and torque is calculated from derivative of co-energy versus rotor angle. Based on flux calculation, flux linkage \((\lambda)\), magnetic energy or co-energy \((w_f \text{ or } w_f)\) and torque \((T)\) can be computed as follow:

\[ \lambda = \int_l A \cdot dl \]  

(9)

\[ w_f'(\theta, i) = \int_0^i \lambda(\theta, i) di \bigg|_{\theta=\text{const}} \]  

(10)

\[ T(\theta, i) = \frac{\partial w_f'(\theta, i)}{\partial \theta} \bigg|_{i=\text{const}} \]  

(11)

The following assumptions are made in determining the magnetic field distribution inside the motor:

1. The outer periphery of the rotor stamping can be treated as a zero magnetic vector potential line as the magnetic field outside the rotor stamping negligible
2. Magnetic materials of the stator and rotor stampings are isotropic and the magnetization curve is single valued
3. End effects are neglected,
4. Magnetic field distribution inside the motor is constant along the axial direction of the motor.
4. SIMULATION RESULTS

The BLDC motor 2-D FEM model consists of 4000 elements and 14000 meshes. So, a FE analysis has been used to build and solve nonlinear magnetic models of the proposed BLDC motor. One side of the motor cross section is shown in Figure 3. As seen from Figure 3, this motor has nine stator poles as well as six rotor poles, which will be engaged in the torque production mechanism.

![Figure 3. One side of the motor cross section.](image1)

![Figure 4. Plots of magnetic field density and magnetic flux.](image2)

(a) Aligned case (b) Non-aligned case

![Figure 5. Plots of magnetic field density and magnetic flux.](image3)
The plots of magnetic field density and magnetic flux for only field coil considered to be turned on and having 0.25 A are shown in Figure 4. In order to be able to analyze the motor in two dimensions, the normal field boundary conditions are used over the inner and outer borders of the motor. Figures 5(a) and 5(b) show the magnetic flux and the magnetic field density for aligned and nonaligned cases for a field current of 0.25 A and the stator winding current of 3 A. The plot of static torque versus rotor positions developed by the hybrid brushless DC motor is shown in Figure 6. The Torque versus angle characteristics of the motor are obtained by using the FE method in which giving a constant current in two phases of the motor occur in an appropriate switching cycle. There is a discussion on the static torque vs. position for BLDC motor in [19] which models the effects of skewing in BLDC motor on its performance. It is worth mentioning here that, the stator and rotor cores are made of a non-oriented silicon steel lamination. The magnetization curve is taken from the manufacturer’s data sheet for M-27 steel. In Figure 6 zero degrees is considered as an unaligned case. Due to the motor being new in its class, a new drive circuit having independent bidirectional control for each motor phase arises.

4.1. Methodology Evaluation for Flux Density Distribution

Based on recent research [20], 3-D magnetic field distribution in BLDC motor can be calculated as a verification method for above simulation results. As mentioned in the conclusion of [20], field expressions allow us to study the magnetic field created by alternate magnet structures. Thus it is developed for our purposes.

In this section, the abbreviation of the evaluation method based on presented technique in [20] is introduced. It provides not only confirmations of the investigation results but also exact illustration for magnetic field distribution for this complex configuration.
Furthermore, these structures are generally used in many applications like magnetic sensors, permanent magnet motors or magnetic couplings. So, their design and their optimization can be simply realized with such a procedure as the presented expressions have a very low computational cost. Additionally, such a three dimensional technique is a superior choice to a classical FEM [21–28].

4.1.1. Elementary Magnetic Field Calculation

Figure 7 illustrates the fundamental element of investigated geometry (that it’s teethes of stator) and the corresponding parameters. Inner radius of the teeth is \( r_1 \); outer radius of the teeth is \( r_2 \); its height is \( h = z_2 - z_1 \) and its angular width is \( \theta_2 - \theta_1 \). Calculations are obtained by using the Coulombian model. Accordingly, it must be considered the magnetic pole surface densities situated on the inner and outer faces of the teeth and the magnetic pole volume density positioned in the stator teeth. The fundamental magnetic field \( dH(r, \theta, z) \) can be written as follows:

\[
dH(r, \theta, z) = \frac{\sigma^*}{\mu_0} \left( \nabla G(r, r_1) r_1 + \frac{\nabla G(r, r_1)}{r_i} r_i dr_i - \nabla G(r, r_2) r_2 \right) d\theta_i dz_i
\]

where \( G(r, r_j) \) is the Green’s function expressed by

\[
G(r, r_j) = \frac{1}{4\pi \sqrt{r^2 + r_j^2 - 2rr_j \cos(\theta - \theta_i) + (z - z_i)^2}}
\]

where \( \sigma^* \) related to the fictitious magnetic pole density.

Figure 7. Fundamental element of the investigated motor poles.
4.1.2. Three-dimensional Expressions of the Magnetic Field Components

The three magnetic field components [22–24, 29–30] can be derived by computing the projection of the magnetic field $H(r, \theta, z)$ along the three axes $u_r, u_\theta$ and $u_z$. The magnetic components $H_r(r, \theta, z)$, $H_\theta(r, \theta, z)$ and $H_z(r, \theta, z)$ can be calculated. It is noted that the azimuthal component $H_\theta(r, \theta, z)$ is fully analytical whereas the radial and axial components use elliptic integrals:

$$H_r(r, \theta, z) = \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} (-1)^{(i+j+k-1)} \left( s_{i,j,k}^z + V_{i,j,k}^r \right)$$

$$H_\theta(r, \theta, z) = \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} (-1)^{(i+j+k-1)} \left( s_{i,j,k}^z + V_{i,j,k}^\theta \right)$$

$$H_z(r, \theta, z) = \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} (-1)^{(i+j+k-1)} s_{i,j,k}^z + \sum_{i=1}^{2} \sum_{j=1}^{2} (-1)^{(i+j)} V_{i,j}^z$$

where $s_{i,j,k}$, $V_{i,j,k}$, $N_{i,j}$ are introduced in [20].

By applying Equations (12)–(16) to our proposed structure, 3-D magnetic field distribution was calculated. The obtained results are presented in Table 1.

The results obtained by the 3-D method are compared with the results based on FEM and indicates an excellent conformity which is shown in Table 2.

Table 1. Results of 3-D magnetic field for the proposed BLDC.

<table>
<thead>
<tr>
<th>Magnetic field</th>
<th>$B_x(\text{max})$</th>
<th>$B_y(\text{max})$</th>
<th>$B_z(\text{max})$</th>
<th>$B_{xyz}(\text{max})$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned</td>
<td>0.612</td>
<td>0.414</td>
<td>0.082</td>
<td>0.743</td>
</tr>
<tr>
<td>Un-Aligned</td>
<td>0.392</td>
<td>0.263</td>
<td>0.069</td>
<td>0.476</td>
</tr>
</tbody>
</table>

Table 2. Comparison of FEM and 3-D field solution for the proposed BLDC.

<table>
<thead>
<tr>
<th></th>
<th>FEM $B_t(\text{max})$ [T]</th>
<th>3-D $B_{xyz}(\text{max})$ [T]</th>
<th>Tolerance %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned</td>
<td>0.710</td>
<td>0.743</td>
<td>4.4%</td>
</tr>
<tr>
<td>Un-Aligned</td>
<td>0.469</td>
<td>0.476</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
This approach is a good alternative to survey a conventional FEM such as above mentioned FEM simulation, because the calculation of the magnetic field is done without any simplifying assumption.

Figure 8. Algorithm of design parameters for new configuration of BLDC motor based on 3-D field solution verification.
5. ALGORITHM

In this paper, new configuration of BLDC motor is presented. It provides not only good characteristics for the BLDC motor in design process but also appropriate cost for the motor. For this reason, FEM simulation for magnetic field analysis regarding to specification of BLDC motor is carried out. Even more important than FEM simulation, the 3-D field analysis is offered as methodology evaluation. Then, torque calculation according to Equations (9)–(11) is done for different angles. Comparison of calculated magnetic field and torque by their requested values respectively illustrates the conformity of design parameters stage. In this level of motor design, if the obtained values are verified, construction of motor by optimized characteristics will be possible. These stages are presented in the algorithm as shown in Figure 8.

6. EXPERIMENTAL RESULTS

Use of assistant field replaced with permanent magnet in the rotor is a new idea of this work which is confirmed by FE simulation results and 3-D field solution methodology evaluation. Therefore, the motor has been fabricated and tested for performance and functionality in the laboratory. Figure 9 illustrates the novel BLDC motor fabricated in the laboratory. Flux density measurement in the teeth of the motor is carried out by GAUSSMETER BROCKHOUSE 460. Results of this measurement are shown in Table 3. Measuring results are in good agreement with those obtained by the theoretical approach based on FEM simulation in Section 4.

The static torque of the motor was obtained by blocking the motor at a different angle. The average static torque for a rated current of 3 A was measured to be about 46 N·cm over the stator pole arc (0 to 300). It suddenly went to zero at the start of stator to rotor complete

![Figure 9. The actual BLDC motor.](image-url)
Table 3. Measuring results of GAUSSMETER BROCKHOUSE 460.

<table>
<thead>
<tr>
<th>Magnetic field</th>
<th>$B_x(\text{max})$</th>
<th>$B_y(\text{max})$</th>
<th>$B_z(\text{max})$</th>
<th>$B_{xyz}(\text{max})$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned</td>
<td>0.609989</td>
<td>0.412389</td>
<td>0.081897</td>
<td>0.741783</td>
</tr>
<tr>
<td>Un-Aligned</td>
<td>0.389972</td>
<td>0.268993</td>
<td>0.068599</td>
<td>0.479688</td>
</tr>
</tbody>
</table>

Figure 10. The motor torque characteristics.

overlap. It was observed that the static torque shows lower value than computed which is expected, since, the silicon sheet steel material used to build the motor is not quite what is used for the numerical analysis. Using a motor generator assembly, the dynamic torque for the motor versus the speed has been measured by loading the motor. The torque-speed characteristics of the motor for two different field currents are shown in Figure 10(a). The power curve fitting has been used for the data points. Figure 10(b) shows the plot of the motor torque versus the current under different loads for the motor.

The static torque versus the rotor position is also obtained by using a torque meter which generally agrees with the one found numerically.

As shown in Figure 10(a), the torque-speed characteristics of the motor behave like a series of DC motors and switched reluctance motor. Moreover, as seen from the Figure 10(b), the torque is proportional to the square of the motor current which resembles the switched reluctance motor. These discussions approve the proper operation of novel structure for BLDC motor.
7. CONCLUSION

In this paper a novel BLDC motor was designed and fabricated in the laboratory. Novelty of this work results from using assistant field replaced with permanent magnet in the rotor which highlights this family of BLDC motors in comparison with conventional BLDC motors. The motor was numerically analyzed, and some of its parameters experimentally measured and tested. There are two main objectives of this paper namely, introduction of a new motor configuration without a permanent magnet and presentation a 3-D field solution as methodology evaluation for FE analysis. The result of FE analysis is in close agreement with the experimental ones. The discrepancy is due to utilizing different (but close) magnetization curve in the numerical analysis and also using a two dimensional analysis instead of a three dimensional one. As a final point, an algorithm of design parameters for new configuration of BLDC motor based on 3-D field solution verification was presented. The torque-speed and torque-current characteristics obtained from experimental tests approve the proper operation of novel proposed structure for BLDC motor.

REFERENCES

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