Design and analysis of a novel topology for slotless brushless DC (BLDC) motors with enhanced torque and efficiency

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Abstract

A novel high-torque slotless brushless DC (BLDC) motor is proposed. The proposed topology has a unique concentrated winding structure and accordingly the motor design is effectively modified with its dual-rotor structure. The rotor structure of the proposed motor may be modified itself and form three different topologies. First, the basic structures of the new slotless BLDC motor and its operation principle are described. Then, design methodology of the proposed motor is explained. Initial analysis of the motor is subsequently conducted using 2D finite element (FE) simulations. Next, design parameters of the proposed motor are further optimized using Salp algorithm. The proposed topologies are compared with the conventional single and dual-rotor structures. Finally, experimental prototype is built for verification. The simulation and experimental results exhibit that the proposed slotless BLDC motor has high torque and efficiency in comparison with the conventional structures and may be a good candidate for small-sized BLDC motors. Moreover, the results show that the proposed BLDC motor has nearly ideal back-EMF which makes sensorless methods more efficient for the proposed motor.

1 | INTRODUCTION

Brushless DC (BLDC) motors have attracted research attentions because of its various advantages. They are widely used in the range of low-to-medium power applications like various drills. Slotless BLDC motors, in which the stator core has no teeth for windings, can be effectively used in small-size and high-speed applications like medical instruments. Cogging torque in slotless BLDC motors is almost zero hence the vibration and noise can be extremely reduced. Slotless structures make it possible to use large magnets and then torque density may be enhanced. The heat from winding in a slotless BLDC motor can be further transferred hence cooling is easier in comparison with the slotted BLDC motors [1,2].

As mentioned, cogging torque is eliminated in slotless BLDC motors hence the production of the smooth torque, which is required in many applications, can be facilitated. However, the torque density is low in comparison to the slotted BLDC motors due to large air gap. The motor permanent magnet (PM) arrangement can thus be modified to enhance the torque density. For large air gap slotless BLDC motor designs, for example coreless ones, Halbach magnetization can be used to make the magnetic field strong and uniform [3]. The Halbach configuration is also found to have superior power density for slotless BLDC motor design with magnetic core in the stator [4]. Multi-face design of slotless motor, in which the motor collects the magnetic flux linkage on three face of the rotor, is another attempt in order to increase the torque density [5].

Slotless PM motors like any other slotless motors, for example slotless hysteresis motors [6], have some inherent characteristics which makes it suitable for high-speed and low-volume applications like robotics industries [7]. Pfister and Perriard [8], in which different ways of modelling and optimization to design a very high-speed PM motor are considered, have initially used slotless structure before any optimization. The optimized slotless PM motor has reached the speed of 200 kr/m. In high-speed slotless motors, the switching frequency is high and it can thus result in high iron losses [9]. To reduce the iron losses and then increase efficiency, thin lamination should be used in slotless BLDC motors. For example, in a converter-fed BLDC motor switching at 10 kHz, the losses are reduced by 50% using 0.1 mm lamination instead of 0.3 mm [10]. In addition, as the position is required to be precisely detected for
high-speed slotless BLDC motors, self-sensing techniques may be used in motor design [11] or its drive [12].

In the literature studies, there are some analytical methods for modelling and optimization of the slotless BLDC motors all of which have considered the conventional topology of the slotless BLDC motors and there is no vast variety of magnetic structures in slotless BLDC motors [13,14]. Indeed, most of the researches have been conducted to redesign and optimize the winding configuration of the slotless BLDC motors. That is because slotless windings have a large variety of structures with complicated geometries. Some of them like toroidal, concentrated and distributed overlap windings can be modelled as a 2-dimensional (2D) problem [15]. However, some other slotless winding like skewed winding shapes, for example Faulhaber, rhombic and diamond winding, cannot be simplified as a 2D problem [16,17]. This would also increase manufacturing cost of the slotless windings. Slotless BLDC motors may utilize flexible printed circuit board (PCB) that in optimized form can increase the power density by 23% compared to the skewed and rhombic windings which is made of round wire [18].

The slotless winding topology may also be improved using non-constant wire width and shortened end-windings [19]. Reconfiguring of the slotless winding from series to parallel or from star to delta may increase torque-speed limitations [20]. However, dynamic winding reconfiguration may result in torque jolts if the winding inductance is low [21]. Eventually, considering all topologies dual or double-sided machines had has many benefits both in slotless or slotted machines [22,23]. Herein, a new configuration of slotless BLDC motor is introduced. Section 2 describes the proposed motor and its working principles. In Section 3, modelling of winding configuration is presented for the proposed motor. Next, initial FEM analysis is carried out considering different PM structure in the rotor side. As a result, the proposed motor can be divided into three topologies with some changes in the rotor PM design. Section 4 provides design procedure for the proposed motor topologies. In the last step of the procedure, an optimization using SSA algorithm is also considered to reduce the magnet size as small as possible. Section 5 provides the comparison results at the beginning. As the proposed motor has inherently a dual-rotor structure and this is unavoidable, the proposed motor topologies are compared with both single and dual-rotor structures of the conventional one. The third topology of the proposed motor exhibits the best performance. Next, experimental results are presented. Considering low torque production in the slotless motors, the proposed motor produces more torque and its efficiency is high. In addition, the winding structure of the proposed motor has less complexity in comparison with the other motor designs.

2 | DESCRIPTION OF THE PROPOSED TOPOLOGY

2.1 | Basic structure

The proposed slotless BLDC motor is illustrated in Figure 1. The proposed design has two (inner and outer) rotors and the stator is located between them. The outer and inner rotors contain PM materials direction of which can be radial with back-iron, as shown in Figure 1(a), or can be orthoradial without back-iron, as in Figure 1(b). There may be different pole number for the proposed structure and four-pole configuration is selected here. The stator is laminated and is in the form of a cylindrical shell with some bolt holes. The phase winding includes four concentrated coils which are located around the stator shell with appropriate coil directions and mechanical shifts. The working principle is explained in the subsequent section in detail.

2.2 | Principle of operation

The arrangement of the phase windings in the proposed slotless BLDC motor is so that the magnetic flux can be produced in the inner and outer side of the stator. Figure 2

![Figure 1](image-url) Illustration of the proposed slotless BLDC motor (a) with rotor back-iron and (b) without rotor back-iron
illustrates the magnetic flux paths in three different excitation modes. In Figure 2, flux paths of the proposed slotless BLDC motor with rotor back-irons, see Figure 1(a), is illustrated. The proposed BLDC motor without back-irons, see Figure 2(b), will have similar magnetic flux paths in both sides but passing through PMs because there is no rotor back-iron in this structure. The interactions of the stator magnetic fluxes with PM fluxes in the inner and outer air gaps produce torque.

The space between PMs in the structure with radial magnetization has no PM or magnetic materials and should have a distance equal or more than air gap length to avoid flux leakages between adjacent PMs. However, in the structure with ortheradial magnetization, there should be magnetic material between PMs in the rotor. Moreover, the space between PMs in the proposed BLDC motor can be filled with additional PMs with radial magnetization like Halbach arrangement. Considering these modifications, the structure having no back-iron seems to have better performance. The complexity of this design for the proposed motor may be slightly high but it may be more beneficial. The cogging torque in slotless BLDC motors is almost zero and the mentioned modifications in the proposed design will have no effect on the cogging torque. The analysis of the proposed motor and calculation are presented in the subsequent section.

3 MODELLING AND INITIAL ANALYSIS USING FEM

Despite of slotted BLDC motors, single tooth equivalence cannot be used in the analysis of slotless designs. In addition, because of no cogging torque, fractional pitch constructions may not necessarily used. Slotless BLDC motors typically have concentrated full pitch coils and for the proposed construction, one coil per pole per phase is selected. To analysis the proposed structure, the motor is supposed to be constructed of two parts, as illustrated in Figure 3. In this division, the coil sides of different phases on the stator are electrically isolated but they have the same current in each part. Also, each coil region is equally divided into two regions. Now, full pitch coils having two coil sides per magnet pole can be considered for each part.

In each pole pitch, \(\tau_p\), there are six coil sides with spread angle of \(\gamma_s/2\). To describe the flux linking each coil, it is assumed that the coil turns are uniformly distributed in the coil regions. Therefore, the number of linked turns can be considered as a function of angular position.

The number of coil turns behaves like a trapezoidal function in terms of angular position and can be represented as a Fourier series for each part as follows:

\[
n(\theta) = \sum_{k=-\infty}^{\infty} \frac{N_p}{4\pi} \sin\left(\frac{k\pi}{2}\right) \text{sinc}\left(\frac{k\pi R}{2\tau_p}\right) e^{j\theta} \tag{1}
\]

where \(N_p\) is the total number of the phase turn. If radial depth of the coil region is not high, as in the proposed BLDC motor, the radial magnet field will slightly vary with radius passing through each coil region. Therefore, the flux linkage of the phase for the proposed slotless BLDC motor can be expressed as

\[
\lambda_p(\varphi) = \int_{\pi(\text{elec.})} 2Ln(\theta)\left[R_{cB_g}(\theta, \varphi) + R_{cB_g}(\theta, \varphi)\right] \tag{2}
\]

where \(\varphi\) is the offset angle between magnet and coil centre. This angle for the phase (A) is shown in Figure 3 and depends to the relative angular position of the PMs with the phase.
winding. $L$ is stack length, $R_{ci}$ and $R_{co}$ are mean radiuses of the coil region, as depicted in Figure 3. $B_{gi}(\theta, \varphi)$ and $B_{go}(\theta, \varphi)$ are air gap flux densities in the inner and outer parts of the proposed BLDC motor, respectively. These magnetic flux densities can be written as Fourier series and both are dictated by the shape of PMs and way of excitation in the inner and outer sides of the stator. Three different PM topologies are considered for the proposed slotless motor that will be explained in detail later. Finally, the corresponding back-EMF can be calculated using the following formula

$$e_p = \frac{d}{dt}A_p(\varphi) = \omega_c \frac{d}{d\theta}A_p(\varphi) \quad (3)$$

where $\omega_c$ is the electrical angular speed. The motor torque production can be calculated using the back-EMF and the current feeding the motor. However, to obtain a precise evaluation of the motor FE calculations are also considered.

As explained in Section 2.2, the proposed slotless BLDC motor uses the same structure in both of the inner and outer rotor sides. Three different topologies are considered in the rotor structure. In the first topology, the PM magnetization is radial and back iron is required. In the second topology, orthoradial magnetized PMs are used and there is no need to back iron. However, non-magnetic material should be used to mechanically support the PMs. In the third topology, orthoradial magnetized PMs, as in the second topology, are used together with radial magnetized PMs which are inserted between them like Halbach structure. These proposed structures are typically built and examined using FEM. The main features including PM and iron materials, motor outer radius, motor active length and air gap length are fixed for each topology and then it is tried to obtain torque capability with the same supply. Figure 4 shows the magnetic flux lines for three different topologies. In first topology, narrow magnets with wide back iron is needed but in the next two topologies wide magnets are used with no back iron.

To get insight into magnetic behaviour of the three topologies, the normal and tangential components of the magnetic flux density in the air gap are extracted and illustrated in Figure 5. In the first design, there is a smooth normal component of the
magnetic flux density in the air gap but in the next two designs, a focused normal component can be seen. In the proposed slotless BLDC motor, two phases are conducting each time and normal components of its magnetic flux density in the air gap are focused in some angular positions (see flux lines of Figure 2). Therefore, from torque production point of view, it may be advantageous to use orthoradial PMs which produce focused magnetic flux density, as in Figure 5(b) and 5(c).

The contraction between the stator and rotor magnetic fluxes produces the torque. According to the previous explanation, it seems that this contraction in the second and third topology with orthoradial PMs might be high. This is verified using FEM and shown in Figure 6. During simulation, excitation of two phases remains unchanged for half cycle. As shown, torque of the third topology is the highest. Back-EMF production of the proposed slotless BLDC motor

**Figure 4** Flux lines for (a) the first, (b) second and (c) third topology of the proposed slotless BLDC motor ($B_{\text{max}} = 1.5$ T)
with different rotor topologies are also illustrated in Figure 7. Fixing the rotor speed at 10,000 r/min, the RMS values of the back-EMF for all of the topologies are approximately the same and are about 5 V. As shown, the first topology has a flat back-EMF with low amplitude, whereas the other topologies have nearly sinusoidal back-EMF with high

**FIGURE 5** Normal and tangential components of magnetic flux density in the inner and outer air gap of (a) the first, (b) second and third topologies.
amplitude. If angular length of the orthoradial PMs decreases, a flat back-EMF can be obtained. However, the torque production capability of the motor will be accordingly decreased. Additional examination is provided in subsequent section.

4 | DESIGN FEATURES AND OPTIMIZATION USING SALP ALGORITHM

To precisely design and analysis of the proposed slotless BLDC motor, it is necessary to derive the motor output in terms of the design parameters. As explained in the previous section, the proposed motor can be divided into two inner and outer parts. The total electric loading can be expressed as follows

\[ ae = \frac{3N_p I(D_o + D_i)}{2\pi D_o D_i} \]  

(4)

where \( D_o \) and \( D_i \) (\( D_o / i = 2R_{\text{co}(i)} \)) stand for the inner and outer air gap diameters. Let us assume \( B_o \) and \( B_i \) as the average value of magnetic flux density in the inner and outer air gaps. The total magnetic flux of one pole can then be written as follows

\[ \Phi_i = \frac{\pi}{4} L(B_o D_o + B_i D_i) \]  

(5)

FIGURE 6 Torque productions for different topologies of the proposed slotless BLDC motor

FIGURE 7 Illustration of the back-EMF at two different rotor speeds for (a) the first, (b) second and (c) third topologies of the proposed motor
Despite of slotted motors, flux density limitation in teeth is no longer an issue. Therefore, peak value of the flux density may be increased beyond maximum 1.6 T. According to the flux density distribution in the air gaps, the average value of it can be written as follows

\[ B = B_{pk} \frac{1 + \kappa}{1 + 2\kappa} \]  

(6)

where \( B_{pk} \) is peak value and \( \kappa \) is shape coefficient of the flux density distribution. In most cases, the flux density distribution is nearly a trapezoidal function and then \( \kappa \) indicates the ratio of rise/fall angle to the flat area angle. In case of sinusoidal distribution, the coefficient is about 1.33. Now, the total flux can be written in terms of peak values as follows

\[ \Phi_t = \frac{\pi}{4} L \left( \frac{B_{pk,i}(1 + \kappa_i)D_i}{1 + 2\kappa_i} + \frac{B_{pk,o}(1 + \kappa_o)D_o}{1 + 2\kappa_o} \right) \]  

(7)

the indexes i and o refer to the variables of inner and outer parts. In the proposed BLDC motor, the flux distribution in the inner and outer air gaps is approximately the same, thus \( \kappa = \kappa_i = \kappa_o \).

To simplify, it is assumed that the mentioned total flux all belongs to the fundamental harmonic. Induced back-EMF per phase may precisely calculated using (3) but considering this simplification, we can write the back-EMF as follows

\[ e_p = \frac{15\sqrt{2}}{2} \frac{\pi^2}{\pi^2} \left( \sin \frac{\pi s}{2} \right) N_i L \left( \frac{B_{pk}(1 + \kappa)}{1 + 2\kappa} \right)(D_i + D_o)n_m \]  

(8)

where \( \gamma_c \) is the winding spread on the stator in electrical degree and \( n_m \) stands for mechanical speed of the rotor. In (8), peak value of the flux density in the inner and outer air gaps is the same, that is \( B_{pk} = B_{pk,i} = B_{pk,o} \). In BLDC motors, each time two phases are conducting and thus converting electromagnetic power. Using (8) and (6), and also substituting current from (4), the maximum available power in the air gaps can be obtained as follows

\[ P = \left( 10\sqrt{2} \pi^2 \right) \left( \sin \frac{\pi s}{2} \right) (L_D D_o)(ac)(B)n_m \]  

(9)

Based on (9), the winding spread angle should be as small as possible so that for a perfect concentric winding the term \( \left( \sin \frac{\pi s}{2} \right) \) will be maximum. However, to avoid large air gaps, the winding turns should be distributed on the stator. Moreover, the phase windings start to overlap for \( \gamma_c > \pi/3 \). Therefore, it seems that \( \gamma_c = \pi/3 \) in electrical radians is satisfactory.

Design procedure of the proposed slotless BLDC motor are summarized in Figure 8. In the first step, average magnetic flux density is defined based on nominal power, rated speed and lamination thickness. In the second step, electrical loading is estimated according to the power and size range of the motor. Cooling limitation is also considered in this step. As explained in the previous paragraph, the winding spread angle should be close to \( \pi/3 \) in electrical radians and this is defined in step 3. In the next step, the product of motor length, inner and outer diameters can be calculated using (9). Taking the motor nominal voltage and power into account, the phase current can be calculated in step 5.

In the proposed BLDC motor, half of the total magnetic flux in the inner and outer air gaps is passing through the stator. Considering a maximum flux density in the stator will give us an equation as follows

\[ \frac{32\pi D_i D_o (ac) A_w}{3I f_c \gamma_c} = \pi \xi_e (D_o + D_i)^2 ((\pi/16)\xi_e (D_o + D_i) - D_i) \]

\[ -((\pi/2)\xi_e (D_o^2 - D_i^2)(D_o + D_i) + (D_o^2 - D_i^2)(D_o + 3D_i) \]

(10)

in which \( A_w \) is the conductor area, \( f_c \) is fill factor in the winding region and \( \xi_e \) is the ratio of average flux density in the air gap to maximum allowable flux density in the stator.

In BLDC motors like some other motor types, there is an empirically relation between the motor length and pole pitch. For the proposed BLDC motor, considering average diameter and mechanical limitations, this relation can be written as follows

\[ 8L / \pi (D_o + D_i) \leq 2 \]  

(11)

The designs with large diameter might bring some advantages and in the proposed motor, end windings is not a big concern. In step 6, considering step 4 and also (10)–(11), the main dimensions are calculated. In the next step, number of turns is obtained using (4). The stator width can be obtained using maximum flux density limitation as follows

\[ \omega_s = \frac{\pi \xi_e}{8 \gamma_i} (D_o - D_i) \]  

(12)

This is calculated in step 8. If the first topology is the case, the inner and outer back-irons must be additionally calculated. Considering saturation, the following equation are used in step 9 for calculating the inner and outer back iron width

\[ \omega_{b0} = \frac{\pi \xi_e}{8 \gamma_i} D_o \quad \omega_{bi} = \frac{\pi \xi_e}{8 \gamma_i} D_i \]  

(13)

Air gap length can be estimated by mechanical requirements for nominal power as well as air gap flux density. In step 10, the air gap length is estimated and will be corrected during the final step. For the proposed design procedure, the
magnet dimensions including the width and angle of the inner and outer magnets are calculated and optimized in the final step. Figure 9 shows the magnet dimension and orientation for different topologies. In this step, SSA optimization algorithm is simply used to get the best values for the magnet dimensions, that is $a_{\text{no}}$, $a_{\text{mi}}$, $w_{\text{mo}}$, and $w_{\text{mi}}$ [24]. This is separately carried out for different topologies. The first objective is to minimize the volume of magnets as follows:

$$f(a_{\text{mi}}, a_{\text{no}}, w_{\text{mi}}, w_{\text{no}}) = w_{\text{mi}}^2 a_{\text{mi}} + w_{\text{no}}^2 a_{\text{no}} + 2(\delta_1 w_{\text{mi}} a_{\text{mi}} + \delta_2 w_{\text{no}} a_{\text{no}})$$

where $\delta_1$ and $\delta_2$ are constant and relate to the main parameters in the design procedure. The second goal in the optimization is that the mean value of flux density must be kept constant. Therefore, the second objective function is the air gap flux density that is calculated using FEM analysis coupled with the algorithm program. In the optimizing process using SSA, magnet's widths and angles for each topology are the input arrays and the air gap flux density together with volume of magnets form the objective functions. The results of the design and optimization are provided in subsequent section.

In summary, in two previous sections the proposed slotless BLDC motor with its different rotor PM topology is presented and preliminary evaluated. It is necessary to mention that the other different topologies of the PM in the proposed motor is just an option and they are not regarded as a new structure. In the subsequent section, the proposed motor with its different options is compared with the conventional slotless BLDC motor. To make the comparison more reasonable, the proposed motor is compared with both single-rotor and double-rotor conventional motors.

5 | COMPARISON RESULTS AND EXPERIMENTAL VERIFICATION

Herein, three different topologies have been introduced for the proposed slotless BLDC motor and were technically explained in the previous sections. These topologies exhibit high torque capability. In this section, the third topology of the proposed motor is on the focus because it demonstrates the highest torque. The other topologies are also considered.

To precisely examine the torque performance of the proposed slotless BLDC motor, it is configured using the design procedure in the previous section and compared with conventional slotless BLDC motors. To make it more reasonable, the comparisons are carried out for both slotless BLDC motors considering some fixed dimensions. The conventional slotless BLDC motor, which is introduced in the study by Seo et al. [1], has chosen for comparison as a single-rotor BLDC motor. To obtain high torque, hexagonal windings were used in the conventional motor. There are some other optimized structures of the conventional slotless BLDC motor in the literature as well but the torque capability has not considerably changed. Therefore, the mentioned conventional single-rotor BLDC motor is considered here for comparison. In addition,
as the proposed slotless BLDC motor is unavoidably in a double-rotor form, the comparison is continued with a conventional double-rotor slotless BLDC motor. Therefore, double-rotor structure is also designed for the conventional slotless BLDC motor. As in the third topology of the proposed motor, Halbach array is also used in the double-rotor structure of the conventional motor to make the comparisons more reasonable. Figure 10 shows this conventional double-rotor motor along with the proposed (third design) motor. The main dimensions and active materials for both motors is the same. For the conventional motor, all coil sides of the phases are situated in one side of the stator but in the proposed motor, coil sides of any phase are located in both side of the stator. Table 1 summarizes the design specifications for both conventional and proposed motor topologies. It should also be mentioned that the number of turns for each design and accordingly the phase nominal current and the coil radius can be slightly changed based on the supply voltage and this will not affect torque production capability of the motors.

The produced electromagnetic torque in terms of input current for both single- and double-rotor conventional motors along with the proposed motor with its different topologies are shown in Figure 11. As shown, all three topologies of the proposed motor exhibit high torque in comparison with the

**FIGURE 10** Schematic of the proposed (left) and conventional (right) double-rotor slotless BLDC motor

**TABLE 1** Design specification of the slotless BLDC motors

| Parameter                  | Conventional design | Proposed design |
|----------------------------|---------------------|-----------------|
|                            |                     | First topology  | Second topology | Third topology |
| Rated power (W)            | 15                  | 18              | 18              | 20             |
| Rated voltage (V)          | 12                  | 12              | 12              | 12             |
| Motor outer radius (mm)    | 10.5                | 10.5            | 10.5            | 10.5           |
| Motor axial length (mm)    | 26                  | 26              | 26              | 26             |
| Air gap length (mm)        | 0.3                 | 0.3             | 0.3             | 0.3            |
| Remanence of PMs (T)       | 1.26                | 1.26            | 1.26            | 1.26           |
| External radius of stator (mm) | 10.5      | 6.6             | 6.9             | 7.5            |
| Internal radius of stator (mm) | 7.5               | 4               | 5               | 5              |
| External radius of PMs (mm)| 5.2                 | 3.9 (inner PMs) | 3.9 (inner PMs)| 3.9 (inner PMs)|
|                            |                     | 10.5 (outer PMs)| 8.2 (outer PMs)| 10.5 (outer PMs)|
| Internal radius of PMs (mm)| 1.6                 | 2 (inner PMs)  | 2.5 (inner PMs)| 2 (inner PMs)  |
|                            |                     | 8.6 (outer PMs)| 7.5 (outer PMs)| 8              |
| PM orientation             | 100% radial         | 45% radial      | 100% radial     | 100% orhoradial|
|                            | 55% orhoradial      |                 |                 |                |
| Number of turns per phase  | 33                  | 34              | 34              | 36             |
| Coil radius (mm)           | 0.13                | 0.18            | 0.15            | 0.15           |
Use of double-rotor structure in the conventional slotless BLDC motor shows no advantage and the proposed motor has already the highest torque. The high torque capability of the proposed motor will be clear and advantageous when copper loss is also considered in the analysis. Accordingly, the electromagnetic torque for both conventional and proposed topologies in terms of copper losses are shown in Figure 12. As a result, the comparison exhibits high torque for the proposed motor topologies. Even though the same main dimensions and materials are considered here, comparison of torque densities based on active material volume will be more informative. The torque densities based on copper losses are shown in Figure 13. As shown, the torque density of the conventional topologies. Use of double-rotor structure in the conventional slotless BLDC motor shows no advantage and the proposed motor has already the highest torque. The high torque capability of the proposed motor will be clear and advantageous when copper loss is also considered in the analysis. Accordingly, the electromagnetic torque for both conventional and proposed topologies in terms of copper losses are shown in Figure 12. As a result, the comparison exhibits high torque for the proposed motor topologies. Even though the same main dimensions and materials are considered here, comparison of torque densities based on active material volume will be more informative. The torque densities based on copper losses are shown in Figure 13. As shown, the torque density of the
The proposed slotless BLDC motor topologies is approximately twice the torque density of conventional motor topologies. The results also exhibits that in the conventional slotless BLDC motors, the single-rotor structure with the same main dimension and active materials has more torque in comparison to the double-rotor structure.

Eventually, the proposed motor has more torque in comparison to any structure of the conventional motor. Although torque production is the main concern in the slotless motors among other characteristics, the proposed and conventional slotless motor topologies are additionally examined in terms of torque ripple. The torque ripple comparison is shown in Figure 14. For an ideal square-wave phase current, the proposed motor topologies exhibit less torque in comparison to the conventional ones. It should also be mentioned that the torque ripple can be further mitigated by using many drive strategies.

To experimentally verify the proposed slotless BLDC motor, first its mechanical design is considered. Because of its specific double rotor structure, a new mechanical design procedure is introduced and illustrated in Figure 15(a). Preparation of the stator lamination is shown in Figure 15(b) and winding arrangement on the stator is shown in Figure 15(c). The inner and outer rotors of the proposed motor are shown in Figure 15(e).
in Figure 15(d). To enhance the life time of bearing and avoid rotor eccentricity in the proposed design, the bearing width should be selected properly. The assembled form of the motor is shown in Figure 15(e). In addition, an improved DEC module with maximum 28 V input voltage is used to drive the proposed motor. The experimental setup is shown in Figure 16. To properly show the agreement between simulation and experimental results, the motor tested under high

**Figure 17** The simulated and measured waveforms of back-EMF in proposed slotless BLDC motor (0.2 V/div, 2 ms/div)

**Figure 18** The simulated and measured waveforms of phase current in proposed slotless BLDC motor (2 V/div, 1 ms/div)
6 | CONCLUSION

Brushless DC motors have many advantages and are on the focus of the many researchers. The slotted BLDC motors have been suffering from cogging torque. On the other side, slotless BLDC motors have nearly zero cogging torque. However, slotless BLDC motors exhibit low torque in comparison with the slotted ones. Slotless design may be nonetheless used in small-sized BLDC motors. Torque improvement makes the slotless BLDC motors more suitable for low power applications like some special medical instruments. A novel slotless BLDC motor that has high torque capability is discussed. The proposed motor itself has three topologies with some differences in rotor PM structure. The paper explains winding configuration and design procedure of the proposed topologies. Although the proposed motor has inherently a double rotor structure, its winding configuration is simple in comparison to the other slotless motors that mitigates the total costs. It also includes SAA algorithm for optimization. Initial simulations have been carried out to examine the proposed structures. Since the proposed motor is inherently in a dual-rotor form, a complete comparison with both single- and dual-rotor structures of conventional slotless motor are included. The experimental results are also provided for verification. The simulated and experimental results show that the proposed motor produces high torque effectively and considerably in comparison with the conventional ones.

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