A comparative analysis of four-pole brushless DC motors with different slot and winding arrangement based on THD values

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ABSTRACT

Brushless DC motors (BLDC) are widely used in variable speed drive applications. Nowadays the relationship between the number of poles, slots and winding arrangements in BLDC motors continues to be a very challenging topic. The main objective of this work was to develop and compare four-pole BLDC motors with different slot numbers (6, 12 and 15) and winding arrangements. Three-dimensional finite element analysis (FEA) was conducted to characterize the proposed designs. The Total Harmonic Distortion (THDv) which tells the amount of harmonics present in the voltage have been obtained and compared based on the different slot numbers and winding arrangement. In the study, an extensive investigation of the THDv values in four-pole BLDC motors having different slot and winding configurations has been carried out. From the simulated results it is evident that the lowest THDv and corresponding sinusoidal back emf can be obtained by implementing 15 slots within four-pole designs. The performance values have been examined comparatively by analysing the motors at the rated condition.

Keywords: BLDC; FEM; Slot, Total harmonic distortion

1. Introduction

The torque speed characteristics of conventional DC motors are linear. However, excitation is done mechanically with brush and collector assembly. This causes frequent motor failure. BLDC motors have been developed to overcome this negative situation and to provide the torque speed characteristic of DC motors. BLDC motors are electronically commutated motors [1]. BLDCs are a class of synchronous motors and consist of silicon sheets whose armature is placed one after the other, armature windings and rotor with permanent magnets. The back electromotive force (emf) formed in BLDCs is trapezoidal. Thus, this back electromotive force provides an increase in the power-to-weight ratio [1, 2].

There are two main factors that allow the development of BLDCs. The first of these is the production of high energy density magnets with the development of material technology. Another is the decrease in the cost of power electronic elements due to developments in semiconductor technology. The use of magnets with high energy density has resulted in significant reductions in costs by producing more compact machines [3,4]. Improvements in power electronics have also made it possible to design a drive circuit that increases reliability and simplicity.

BLDC motors have high efficiency, low inertia, long life, low noise, low manufacturing cost, easy speed control, and a wide torque-speed curve. Because of these properties, BLDC motors have a wide range of applications in the automotive, aerospace, ventilation systems, healthcare and home appliances sectors [5-10].

Studies on BLDC’s generally focus on magnet geometries and motor control [11,12]. Recent studies on the interaction
between the number of poles and the number of slots in electrical machines have also been conducted [13-15].

Studies on optimization of total harmonic distortion can be classified into two groups. The first one is to use control methods, and the second one is to make geometric changes in the design of the machine. In [16] high frequency harmonic components of the BLDC motors are optimized by using an RC filter which is connected to the input. With the designed filter, the THD value of the phase voltage has been reduced from 62% to 31% and the THD value of the line current has been reduced from 47% to 14.7%. In [17] the cascaded H bridge multilevel inverter with current control reduces the effects of harmonic components in the switching frequency and its multiples. In permanent magnet machines the position, the structure and the magnetization direction of the magnet affect the performance of the machine. In an internal magnet BLDC motor, four different magnet positions and the effect of magnetization direction of these magnets have been examined and 64% improvement has been realized according to the first design [18]. Similarly, THD performances have been investigated in a BLDC motor whose direction of magnetization has specified as parallel, radial and concentration. The highest harmonic distortion has been observed in radial directional motor with high number of slots [19]. The structure of the magnets can be changed by adjusting the offset value. Thus, the efficiency, the cogging torque, and the THD values can be optimized. In [20] FEA has been performed by changing offset value of BLDC motor between 5-30 mm. The THD value has been reduced 15.8% to 2.11% by using 30 mm offset value.

This study obtained the THD of the BLDC motors, which are rated at 100 W, 3000 rpm 4/6, 4/12 and 4/15 pole/slot numbers, for comparative analysis. The design details of each motor were given in previous studies [21].

### 2. Motor Designs with Different Combinations

Table 1 presents the characteristics of 4-pole motors with 3 different pole/slot combinations in consequence of analytical and optimization studies.

**Table 1. Motor parameters**

| Parameter                  | 4 pole / 6 slot | 4 pole / 12 slot | 4 pole / 15 slot |
|----------------------------|-----------------|------------------|------------------|
| Stator Outer Diameter (mm) | 90              | 30               | 30               |
| Length (mm)                | 28              | 13               | 9                |
| Stator Core Material       | M270-35A        |                  |                  |
| Rotor Outer Diameter (mm)  | 54.2            |                  |                  |
| Magnet Type                | N40UH           |                  |                  |
| Slot Clearance (mm)        | 5               | 2                | 2                |
| Slot Width (mm)            | 1              | 1.3              | 9                |
| Net Slot Area (mm$^2$)     | 233.03          | 106.53           | 72.53            |

All the physical and material properties except the slot geometries have been determined to be the same in order to fairly compare the examined motors. The slot geometries have been determined by analytical and finite element analyses to obtain optimal values according to the varying number of slots. Figure 1 provides the cross-sectional views of the BLDC motors subject to the study.

![Fig. 1. A cross-sectional view of the motors a) 4 pole/6 slot, b) 4 pole/12 slot and c) 4 pole/15 slot](image)

Table 2 shows the performance values obtained in the analyses of the designed motors under full load and no load.

**Table 2. Motor performance**

| Parameters                  | 4 pole / 6 slot | 4 pole / 12 slot | 4 pole / 15 slot |
|-----------------------------|-----------------|------------------|------------------|
| Efficiency (%)              | 85.32           | 85.16            | 85.29            |
| Output Power (W)            | 100             | 100              | 100              |
| Cogging Torque (Nm)         | 0.107           | 0.204            | 0.05             |
| Rotor Yoke Flux Density (T) | 1.65            | 1.71             | 1.74             |
| Stator Slot Fill Factor (%) | 51.0            | 51.3             | 51.6             |

Table 2 demonstrates the motor performance values. The efficiency values of the motors are about at the same level. This is due to the improvement of each different design in itself. The slot fill factor, which is an important physical limit of the motor design, is determined to be the maximum and the same for all motors. FEA has been applied to the designs in order to examine the magnetic flux distributions of the motors. The magnetic flux distributions of designed 3D models are given in Figure 2.
The winding characteristics vary for designs realized in different pole/slot combinations. The optimal winding properties for each pole/slot combination have been tried to be determined. As a result, obtained phase voltage variations of 4 pole/6 slot, 4 pole/12 slots and 4 pole/15slot designs are given in Figure 3.

3. Calculation of Total Harmonics Distortion

Harmonics are multiples of the fundamental frequency and cause distortions in the voltage and load current. The presence of harmonic components causes distortion of the fundamental wave. In this case, when the electrical machines are examined, the harmonics cause the distortion in the generator voltage [22], overheating of electromechanical equipment [23] and the operation of the motors at noisy and increased Δt temperatures [24]. Harmonics cause additional core loss in machines, resulting in excessive heating of the motor core. It is possible to discuss two types of harmonic concepts for electric machine. The first one is the time harmonic due to the source being far from the sinusoidal form, and the other is the space harmonic due to the geometry of the machine.

In BLDC machine, space harmonics depend on the air gap flux waveform. Even though the voltage wave applied to the motor is pure sine, harmonic components can be present in the magnetomotive force due to the slot structure of the motor and the distribution of the winding. Space harmonics can cause acoustic noise, vibration and core saturation. Space harmonics can be optimized by changing the winding configuration or the geometric structure of the machine [25-27].

Periodic signals can be expressed as the sum of the sine components at different frequencies. Each of these sine expressions is called Fourier components. This series is known as the Fourier series. The coefficients of the Fourier series can be found through measuring, graphical, and analytical methods [28]. In this study, analyses have been performed by using graphical method. In this method, the average value of each waveform is calculated by dividing the waveform into equally spaced vertical parts. The waveforms to be obtained in the air gap can be expressed mathematically by Fourier series as in Equation 1:

\[ V(\theta) = A_0 + \sum_{n=1}^{\infty} (A_n \cos n\theta + B_n \sin n\theta) \]  

In the equation, \( V \) is the voltage value, \( \theta \) is the space angle expressed in electrical degrees, \( n \) is the harmonic number and \( A_n \) and \( B_n \) are the Fourier coefficients. Fourier coefficients can be expressed in Equation 2 and Equation 3:

\[ A_n = \frac{2}{m} \sum_{k=1}^{m} (y_k \times \cos(n \times \theta_k)) \]  
\[ B_n = \frac{2}{m} \sum_{k=1}^{m} (y_k \times \sin(n \times \theta_k)) \]

In the equation, \( m \) represents the number of vertical divisions, \( n \) the degree of harmonic, and \( y_k \) is the flux value corresponding to each \( \theta_k \).

In the Fourier analysis, the number of vertical divisions increases the accuracy of the coefficients. However, the number of excess vertical divisions increases the number of transactions. The voltage waveform can be expressed as the sum of the fundamental and harmonic components as in Equation 4 [29]:

\[ V_s(t) = V_d(t) + \sum_{h=1}^{n} V_{sh}(t) \]  

Equation 4 represents the line voltage, the fundamental component and the value of the voltage at the harmonic
frequency. Distortions that occur in the form of voltage or current waves can be expressed in percent of THD. The distortion component of the Equation 4 is obtained by Equation 5 [22]:

\[ V_{ds}(t) = V_s(t) - V_s(t) \sum_{h=1} V_{sh}(t) \] (5)

THD in voltage,

\[ THD = 100 \times \frac{V_{ds}}{V_{cl}} \] (6)

4. Simulation Results

As mentioned in the previous section, in BLDCs, space harmonics depend on the physical structure of the motor. Space harmonics are caused by the slot structure and the non-sinusoidal distribution of the phase windings [30]. In this study, THD values of the machines with different pole/slot numbers are analysed and given in Table 3.

Table 3. THD values of motors

| Pole / Slot Combinations | THD (%) |
|--------------------------|---------|
| 4 pole/6 slot            | 22.30   |
| 4 pole/12 slot           | 18.04   |
| 4 pole/15 slot           | 3.05    |

Harmonic spectrums have been obtained by performing a Fourier analysis for the motors with different slot numbers with the help of MATLAB (License number: 40692431) software. Figure 4 presents the graphs of the analyses.

5. Conclusions

This paper has given a brief summary of THDv values of four-pole BLDC motors with different winding patterns and slot numbers to contribute to a reduction in the THDv values of BLDC motors. Performance outputs have been obtained for each pole/slot combination that is optimized to offer maximum efficiency and to be compared with a fair criterion. Simulation and comparison results between 6, 12 and 15 slot designs demonstrate that lowest THD and corresponding sinusoidal back emf can be obtained by applying 15 slots within four-pole designs in the study, as shown in Table 3. Although they are arranged to offer approximately the same efficiency values in the study, designs with high THD values can present significant problems such as acoustic noise, vibration, saturation risk of core and increased winding Δt temperatures. Therefore, although the nameplates of these motors with different combinations are similar in terms of efficiency, THD values have a significant impact on the motor’s operating performance and should be reduced as much as possible in design stage. Authors aim to examine the Δt temperatures of each design for future research.

Figure 4. Harmonics spectrum of motors in phase voltage a) 4pole/6slot, b) 4pole/12slot, c) 4pole/15slot

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