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A FEM Analysis of BLDC Ceiling Fan with Different Slot-Pole Combinations

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BLDC motors have recently made significant advancements in the automation industry. Due to their high efficiency and power density, they are widely used in everyday applications such as fans, electric bikes, rail transit, and automobiles. The slot-pole structure is a key factor influencing motor design. This research explores various slot-pole combinations to enhance performance.

For ceiling fan applications, a balanced and highly efficient stator with concentrated winding has been designed based on different slot-pole configurations. Two commonly used combinations—18-slot/16-pole and 12-slot/14-pole—were analyzed. However, these configurations result in high cogging torque and a low winding factor, reducing the efficiency of BLDC ceiling fans.

To overcome these issues, a 24-slot/22-pole combination is proposed. This design improves torque production, power efficiency, and magnetic flux density while reducing cogging torque and increasing cogging frequency. The effectiveness of this structure is evaluated using the finite element method (FEM) in Ansys Electronics Desktop software.

Keywords: Brushless DC (BLDC) Motor; Ansys Maxwell Rmxprt; Ceiling Fans; slot-to-pole combination and Finite Element Analysis.

Introduction:

In the late 1960s, P.H. Trickey and T.G. Wilson invented and designed the brushless DC (BLDC) motor. However, due to the unavailability of permanent magnets, this concept became a reality only in the 1980s when Power Tec Industrial Corporation confirmed their availability [1]. The BLDC motor consists of a stator, rotor, and an inverter circuit that drives the motor. It is considered one of the most efficient types of electric motors due to its high power density, high-speed capabilities, durability, and simple design [2]. These features make BLDC motors widely used in applications such as rolling and automotive industries [3], electric vehicles [4][5][6], ceiling fans [7], washing machines [8], air conditioners [9], gliders, drones [10], CNC machines [11], robotics [12], and marine applications [13].

BLDC motors come in two main types: inner and outer rotor designs. Motors with a higher number of magnetic poles produce greater torque, which is why an outer rotor BLDC motor is preferred for such applications [14][15]. In contrast, inner rotor BLDC motors are used for high-speed applications. They have fewer magnetic poles, allowing higher rotational speeds but limiting torque production [16].

To achieve optimal performance, a suitable drive control topology is essential. It helps minimize speed fluctuations and ensures torque stability. Various control methods have been explored for BLDC motors, including PID control [17][18], fuzzy logic control [19], artificial neural networks (ANN) [20][21], and other advanced techniques.

Ansys Maxwell has been widely used to design, verify, and validate different motor types. For instance, induction motors [22], brushed DC motors [23], and three-phase induction motors [24] have been designed using this software. Similarly, Ansys Maxwell has been applied to develop AC synchronous motors [25], permanent magnet synchronous motors (PMSM) [26], synchronous reluctance motors (SRM) [27], and brushless DC (BLDC) motors [28][27].

Research studies [2][5], [27][29] indicate that altering the number of poles and stator slots in a BLDC motor affects power output and load-handling capacity. A comparative analysis of three different slot-pole combinations—12-slot/10-pole, 18-slot/20-pole, and 9-slot/8-pole—has been conducted. Findings suggest that the 18-slot/20-pole combination delivers the highest torque at low speeds, making it suitable for agro-electric vehicle (EV) applications [30]. Additionally, a comparison of 12, 18, 24, and 30-slot stators with 4-pole rotors indicates that the 30-slot stator provides the lowest cogging torque and best performance [30]. Another study [31] found that a 24-slot/16-pole BLDC motor is more efficient than a 36-slot/18-pole motor. Researchers in [29] compared three different slot configurations (6, 12, and 15) with 4-pole rotors and concluded that the 15-slot stator offers lower total harmonic distortion (THD) and a more sinusoidal back-EMF waveform than the 6-slot and 12-slot motors.

While existing research focuses on high-torque EV applications, it does not provide sufficient insights for designing BLDC motors for ceiling fans. This study aims to address that gap by optimizing BLDC motor design specifically for ceiling fan applications.

The literature suggests that a higher slot number results in better torque production, lower THD, and a more sinusoidal back-EMF. This research investigates three different slot-pole combinations—12/14, 18/16, and 24/22—using the finite element method (FEM) in the Ansys Maxwell RMxprt environment. These combinations are analyzed based on key design parameters, back-EMF characteristics, and cogging torque performance.

Problem Statement:

BLDC motors are gaining popularity due to their high-power density and simplicity. However, improper motor design can lead to low power efficiency and high cogging torque. In the fan industry, two conventional slot-pole combinations—12-slot/14-pole and 18-

slot/16-pole—are commonly used [7]. These combinations exhibit high cogging torque and lower power density, resulting in reduced efficiency and shorter lifespan.

Research Objectives:

The main objective of this research is to highlight the inefficiencies of the commonly used 12-slot/14-pole and 18-slot/16-pole BLDC ceiling fan configurations. These two combinations are analyzed in terms of power density, cogging torque, back-EMF, and winding factor. A comparison is made with the proposed 24-slot/22-pole combination, which offers higher cogging frequency and lower cogging torque. Additionally, the proposed design improves power density and provides a more sinusoidal back-EMF. Finite element analysis (FEM) is conducted using Ansys Maxwell RMxprt to validate the findings.

Research Methodology:

The design of a BLDC motor depends on various factors, including the slot-pole combination, stator winding patterns, the number of turns, magnetic field density, and air gap. This research focuses specifically on the impact of slot-pole combinations. Figure 1 illustrates the research methodology.

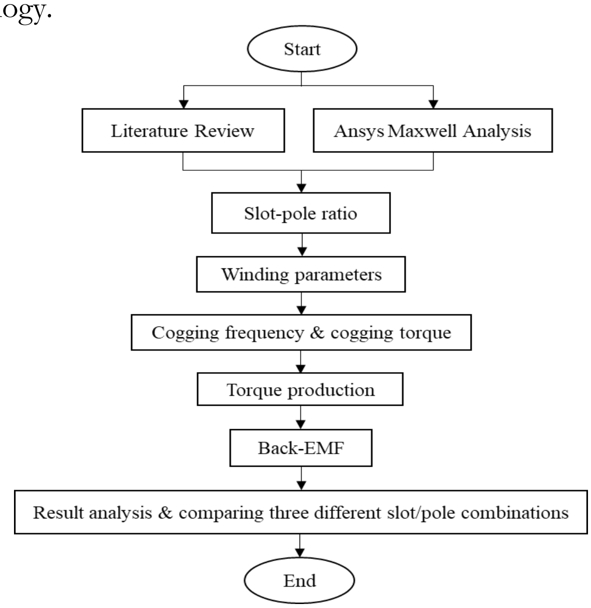


Figure 1. Methodology flow diagram

Currently, the ceiling fan industry primarily uses two slot-pole combinations: 12-slot/14-pole and 18-slot/16-pole [7]. However, these configurations result in lower torque production, reduced winding factors, lower winding periodicity factors, and high cogging torque, which negatively impact motor efficiency.

This research proposes a 24-slot/22-pole combination, which enhances torque production, winding periodicity factor, winding efficiency, and cogging frequency. The 12/14, 18/16, and 24/22 slot-pole configurations, designed in Ansys Maxwell RMxprt, are shown in Figure 2

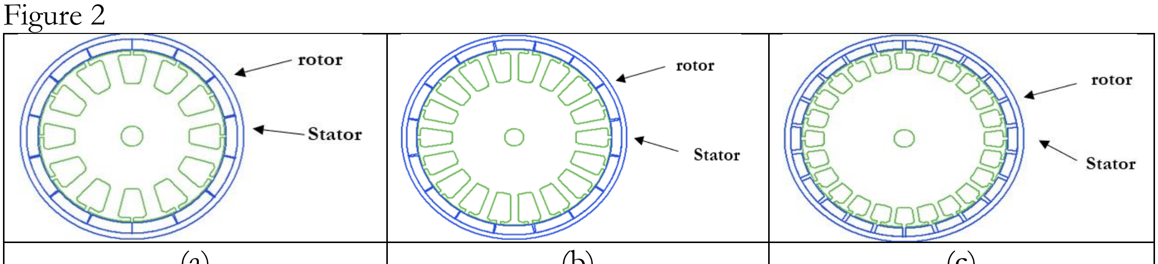


Figure 2. Ansys designed a BLDC motor with (a) 12-slot, 14-pole, (b) 18-slot, 16-pole, (c) 24-slot, 22-pole combinations.

Table 1 presents the design parameters for the 12-slot/14-pole, 18-slot/16-pole, and 24-slot/22-pole BLDC motors. The maximum observed number of turns per slot is 300. A small air gap of 1 mm is chosen to achieve higher torque production with lower input power [32].

Table 1. Design parameters of different slot-pole BLDC motors

Parameters	slot-pole combinations		
	12/14	18/16	24/22
Stator diameter (mm)	132.5	158	158
Steel type	M19_24G		
Number of winding layers	2		
Stacking factor	0.95		
Number of turns	300	300	300
Rotor position	outer rotor		
Rotor inner diameter (mm)	135	159	159
Rotor outer diameter (mm)	160	185	185
Length of magnets (mm)	25		
Magnet type	XG196/96		
Control mode	DC		

Slot-Pole Ratio:

The slot-pole ratio, denoted as 'q,' is a key factor in BLDC motor design. Mathematically, it is defined by Equation (1):

$$q = \frac{N_s}{N_{ph}.N_p} \qquad (1)$$

Where N_s = number of slots

N_{ph}= number of phases

N_p = number of poles

This ratio influences torque, electromagnetic performance, and overall efficiency. A higher ratio results in greater torque production, while a lower ratio reduces torque because multiple rotor poles interact with a single stator slot.

Winding Periodicity:

The winding periodicity factor (z) represents the repetition of winding patterns in the stator. A higher value improves magnetic balance and reduces cogging torque. Mathematically, it is defined by Equation (2).

$$z = \frac{N_s}{gcd(N_s, N_{ph}.N_p)} \qquad (2)$$

Where, gcd = greatest common divisor,

Cogging Frequency:

Cogging frequency is a key factor in determining the generated cogging torque. A higher cogging frequency results in lower cogging torque. Mathematically, it is defined by Equation (3).

$$f_{cog} = LCM(N_s, N_p) \qquad (3)$$

Where LCM denotes the least common multiple.

Ansys Maxwell Analysis:

Using Ansys Maxwell, the winding factor, cogging torque, generated torque, and back electromotive force (BEMF) have been analyzed.

Winding Factor:

The winding factor (kw) measures the efficiency of stator windings in generating magnetic flux and back-EMF. Mathematically, it is defined by Equation (4).

$$k_w = k_{mn}.k_{en} \qquad (4)$$

Where, k_w = winding factor,
k_{mn}= magnetic winding factor, &
k_{en}= electrical winding factor

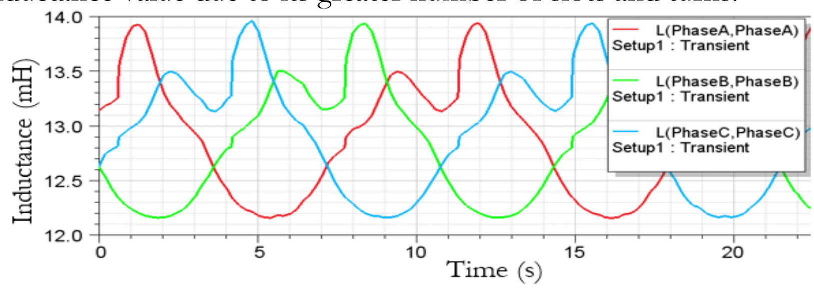
Cogging torque periodicity

Using the finite element method (FEM), cogging torque and back-EMF analysis are performed. The study is conducted under different load conditions to evaluate cogging torque. The periodicity of cogging torque is determined by varying the rotor angle over a single-slot pitch [30]. Mathematically, it is defined by Equation (X).

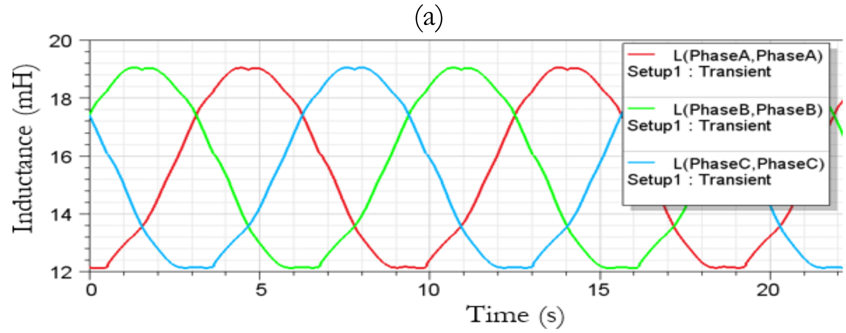
$$P_{cog} = \frac{360}{LCM(N_s, N_p)} \qquad (5)$$

Results:

The results of this study provide a detailed evaluation of various slot-pole configurations in BLDC motors for ceiling fan applications, focusing on cogging torque, back electromotive force (EMF), efficiency, and overall performance. This section presents a comparative analysis of simulation results, including torque profiles, back-EMF waveforms, and efficiency trends for each configuration. The findings highlight the trade-offs between cogging torque reduction, energy efficiency, and manufacturing feasibility, offering insights for optimizing energy-efficient BLDC ceiling fan motors. Figure 3 illustrates the winding patterns. Transient analysis in Ansys Maxwell shows that the 24-slot/22-pole combination has the highest inductance value due to its greater number of slots and turns.



(a)



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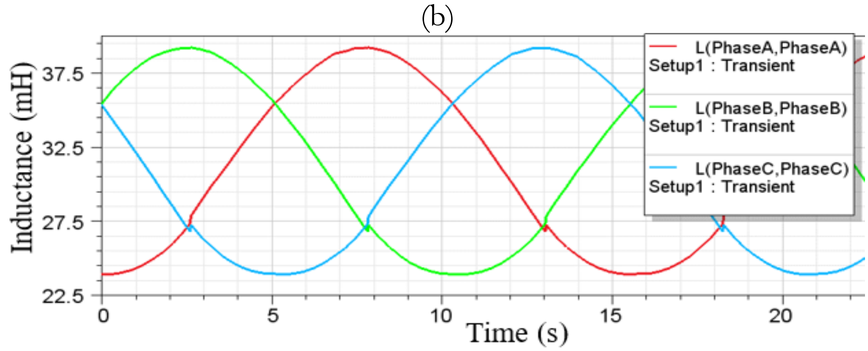


(c)

Figure 3. Winding patterns of BLDC motor with (a) 12-slot, 14-pole, (b) 18-slot, 16-pole, and (c) 24-slot, 22-pole combinations.

The analysis of Figure 3 shows that the BLDC motor with a 12-slot/14-pole configuration exhibits waveform irregularities, leading to torque ripples and unstable performance. Similarly, the 18-slot/16-pole motor still shows non-uniformity in its waveforms. In contrast, the 24-slot/22-pole BLDC motor maintains a stable, sinusoidal waveform, resulting in lower torque ripples, improved stability, and optimal efficiency.

Table 2 shows that the 24-slot/22-pole BLDC motor has the lowest cogging torque periodicity. Using Equations (1-5), the efficiency parameters for the 12/14, 18/16, and 24/22 slot-pole combinations are presented in Table 2.

Table 2. Calculated efficiency of different slot-pole combinations

N_s	N_p	q	z	k_w	f_{cog}	P_{cog}
12	14	0.29	2	0.93	84	4.29
18	16	0.38	3	0.94	144	2.5
24	22	0.36	4	0.95	264	1.36

Table 2 shows that the 24-slot/22-pole BLDC motor generates lower cogging torque while producing higher magnetic flux and back EMF. Figure 4 illustrates the cogging torque for different slot-pole BLDC motor configurations.

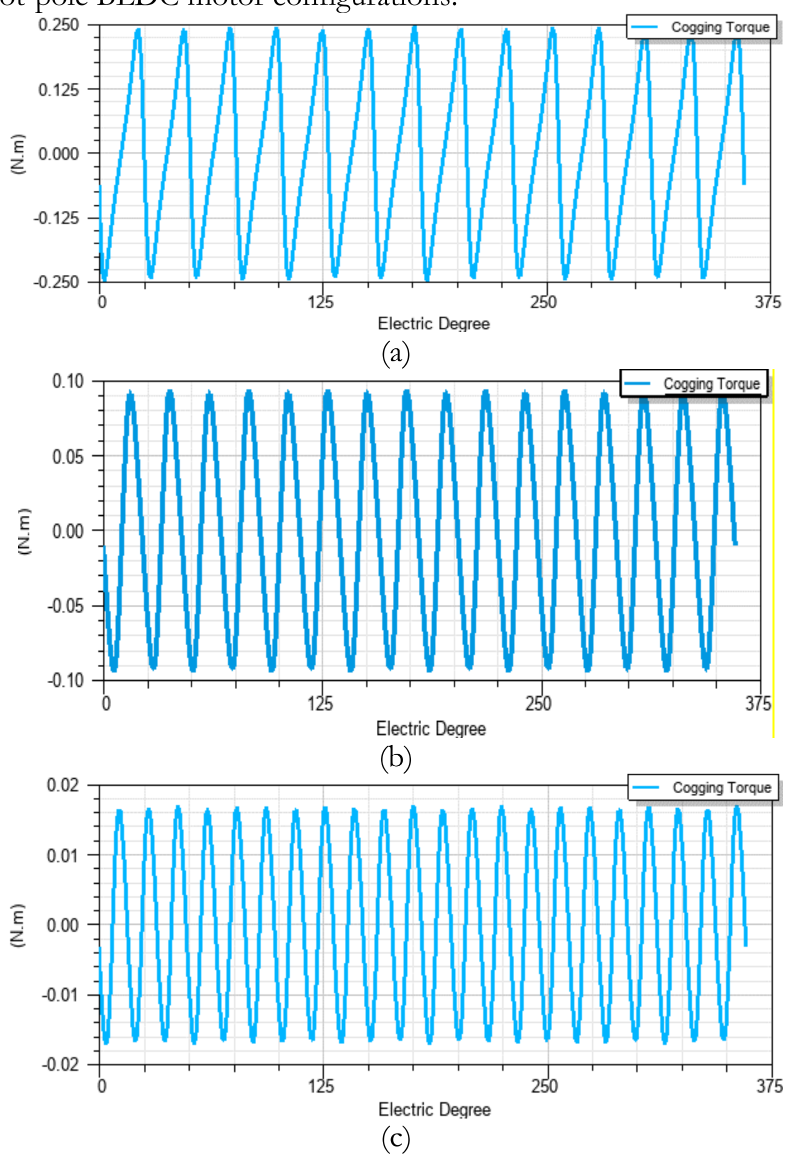


Figure 4. Cogging torque generated by (a) 12-slot, 14-pole, (b) 18-slot, 16-pole, and (c) 24-slot, 22-pole combinations.

Figure 4 shows that the 24-slot/22-pole BLDC motor has the lowest cogging torque of 0.18 Nm, while the 12/14 and 18/16 slot-pole combinations produce 0.24 Nm and 0.9 Nm, respectively.

Torque Production:

When the stator magnetic fields interact with the rotor's permanent magnet fields, torque is generated in the motor. In the 24-slot/22-pole BLDC motor, more stator and rotor magnetic fields interact, resulting in higher torque. Due to its high q value, this combination has smaller torque ripples compared to the other two configurations.

Using FEM, the torque generated by the three motor designs is shown in Figure 5. Torque instability leads to inefficiency and excessive heat generation.

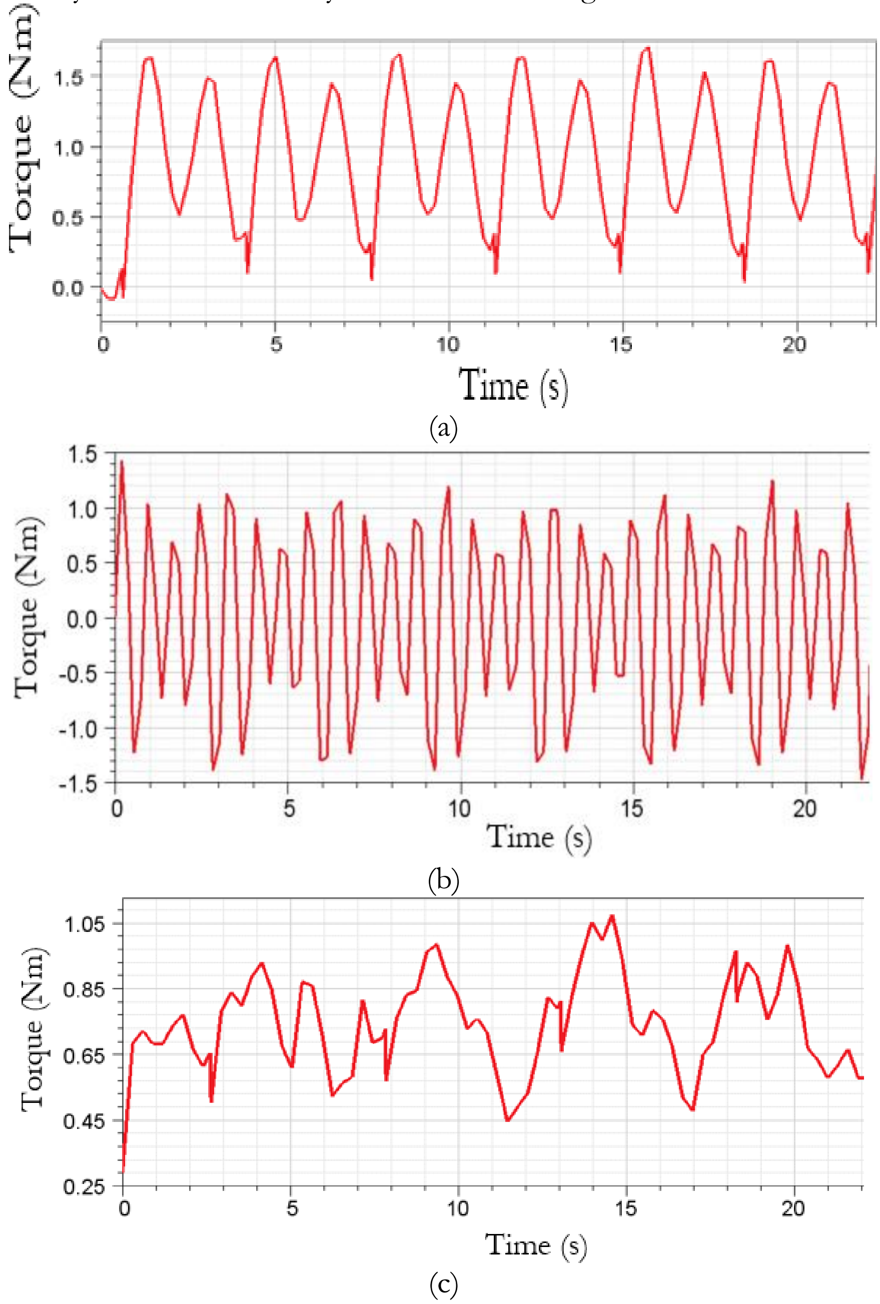


Figure 5. BLDC motor torque is generated by (a) 12-slot, 14-pole, (b) 18-slot, 16-pole, and (c) 24-slot, 22-pole combinations.

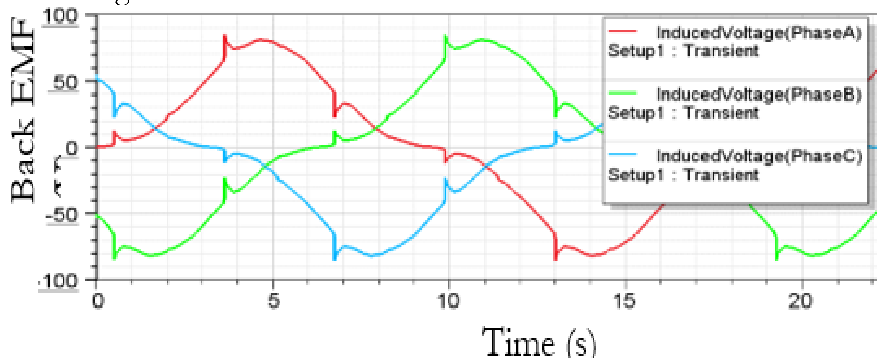
Figure 5 shows that the 12-slot/14-pole BLDC motor produces unstable torque, oscillating between 0.2Nm and 1.5Nm. This instability can lead to inefficient motor rotation and high torque ripples. Similarly, the 18-slot/16-pole BLDC motor exhibits torque fluctuations, making it unsuitable for ceiling fan applications.

In contrast, the 24-slot/22-pole BLDC motor provides the most stable torque output, making it a better choice for ceiling fan applications.

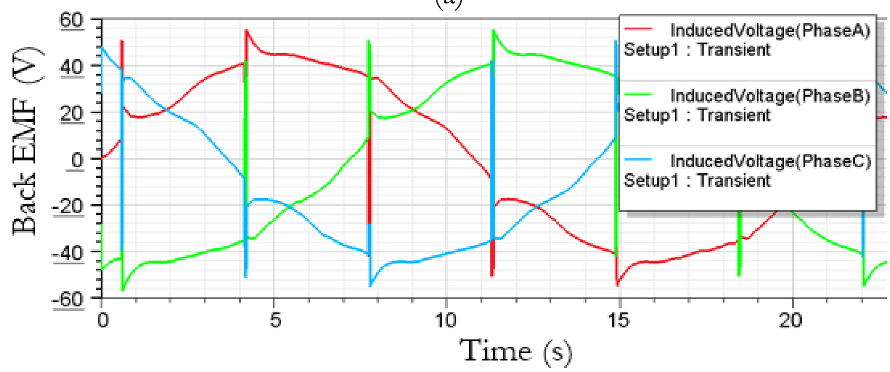
Back-EMF:

The FEM results from Ansys Maxwell illustrate the back EMF generated by the three different slot-pole combinations, as shown in Figure 6. A higher back EMF corresponds to a higher rotational speed (rpm) but lower torque production.

Figure 6 indicates that the BLDC motor with a 12-slot/14-pole combination produces the highest back EMF at 80V, followed by the 24-slot/22-pole motor at 62V, while the 18-slot/16-pole motor generates the lowest back EMF at 42V.



(a)



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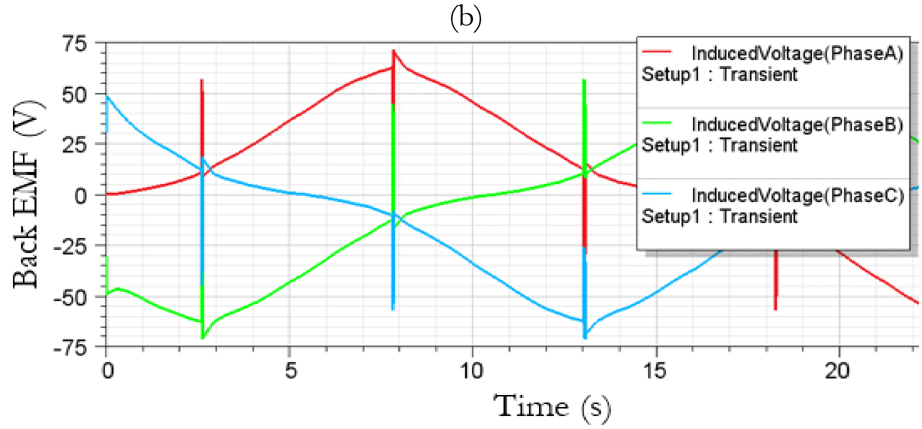

(c)

Figure 6. Back-EMF of BLDC motor with by (a) 12-slot, 14-pole, (b) 18-slot, 16-pole, and (c) 24-slot, 22-pole combinations

The waveforms in Figure 6 indicate that the BLDC motors with 12-slot/14-pole and 18-slot/16-pole combinations exhibit quasi-sinusoidal back EMF (BEMF). In contrast, the

24-slot/22-pole BLDC motor produces a pure sinusoidal BEMF waveform, making it an optimal choice for field-oriented control (FOC) commutation topology [33].

24-Slot and 22-Pole BLDC Motor Design:

The literature review suggests that the 24-slot and 22-pole BLDC motor offers superior efficiency due to its low cogging torque, high winding factor, reduced back EMF, and increased torque production. A practical demonstration of the 24-slot and 22-pole BLDC motor is illustrated in Figure 7.

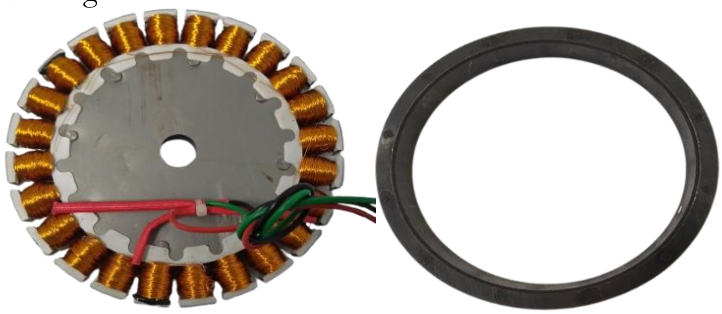

Figure 7. BLDC motor with (a) 24-slot stator, and (b) 22-pole rotor.

Table 3 presents the measured parameters of the proposed 24-slot and 22-pole BLDC motor when operating at 220V. These parameters include torque, efficiency, cogging torque, back EMF, and overall performance characteristics, confirming its superior efficiency and stable operation compared to conventional configurations.

Table 3. Measured parameters of 24-slot, 22-pole BLDC motor

Measured values	Parameters
220V	V_{in}
0.17A	I_{in}
40W	P_{in}
0.15A	Phase current
0.8N.m.	Average Torque

Table 3. shows the measured parameters of the 24-slot and 22-pole BLDC motor.

Discussion:

Your conclusion effectively summarizes the study, highlighting key findings and their implications. However, there is a contradiction: earlier, the 24-slot/22-pole configuration was presented as the best-performing option, but the conclusion states that the 18-slot/16-pole configuration provides the best balance. You may want to clarify this point. Additionally, you could briefly reinforce why the 24-slot/22-pole setup, despite its advantages, faces practical challenges. Would you like me to refine or streamline this section for better clarity?

Conclusion:

A BLDC motor with a 24-slot and 22-pole combination is proposed for ceiling fan applications. This configuration is compared with the commonly used 12-slot/14-pole and 18-slot/16-pole combinations. Using Finite Element Method (FEM) analysis, key efficiency parameters are evaluated. Since ceiling fans require high torque for optimal performance, an outer rotor BLDC motor is utilized.

The proposed slot-pole combination demonstrates high torque production, a high cogging frequency, and an improved winding factor while maintaining a sinusoidal back EMF. Additionally, it produces a lower back EMF, which enhances torque generation while operating at a lower input voltage. This research focuses specifically on ceiling fan applications. For high-torque applications such as electric vehicles (EVs), BLDC motors with a greater number of slots and poles should be considered.

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