

A Hybrid Analysis of Brushless DC Motor

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Article Info	Abstract
Received 26/10/2022 Revised 16/06/2024 Accepted 23/06/2024	Brushless DC (BLDC) motors have gained popularity because of numerous advantages. This motor application is achievable since permanent magnet (PM) technology has advanced. This motor has higher efficiency, reliability, and power density and requires less maintenance due to the absence of brushes. A higher torque-to-mass ratio and long life are two of this motor's most attractive characteristics, making it appropriate for high-performance applications. This study describes the hybrid methodology for analyzing a three-phase, four-pole, 1500 W, brushless DC (BLDC) motor with an inner rotor. This paper uses PI controllers and PWM in Matlab/Simulink and the chopped current control in Maxwell 2D. BLDC motor modeled by rotation machine export (RMxprt) analytical software and analyzed with a finite element method (FEM) Maxwell 2D software to calculate motor performance, such as torque, speed, and efficiency. The FEM results were verified by comparing them with the results taken from the Matlab/Simulink program and with the aid of the RMxprt software to supply some missing data. The results from Maxwell 2D and Matlab show good agreement. Despite lacking motor test data, this paper successfully applied a hybrid FEM-analytical approach to study a BLDC motor using three software packages RMxprt, Maxwell 2D, and Matlab/Simulink. The RMxprt program offers missing data like stator resistance, stator inductance, and torque constant. It is provided in the design sheet to help us with motor modeling. The successful adoption of the proposed hybrid FEM-analytical methodology will provide a good starting point for future BLDC motor research work.

Keywords: Ansys Maxwell- 2D; Finite element analysis; Flux density; MATLAB/Simulink; Permanent magnet

1. Introduction

Brushless DC motors are used more frequently in various applications, particularly computers, aerospace, military, automobiles, industrial, and household appliances [1]-[2]. The Permanent Magnet Synchronous Motor (PMSM) and the Permanent Magnet Brushless DC (PMBLDC) motor are the two BLDC motors [3]-[4]. They differ in characteristics, particularly at the output wave back-EMF. A sinusoidal wave is the typical output of PMSM motors. The back-EMF result on PMBLDC motors has a trapezoidal waveform [3]-[4]. The copper loss and core loss of BLDC motors are significantly lower than those of ordinary DC motors due to the use of permanent magnets (PMs) in the rotor to create field flux, which raises the total efficiency of motor drive [5]. A BLDC motor's operation is based on internal shaft position feedback. The hall sensors and encoders are the most accessible kinds of sensors. According to the hall sensor-effect principle, the charge carriers encounter a force based on the voltage between

the conductor's sides when exposed to a magnetic field. The generated voltage will change

suppose the magnetic field's direction is inverted. When the magnetic poles (N or S) approach hall sensors, they produce a signal that can be used to calculate the position of the shaft [6]. Fig. 1 depicts the basic layout of how a BLDC machine operates. To gain a complete understanding of the motor's operation and to create control based on that understanding, it is frequently necessary to model the engine under study [7].

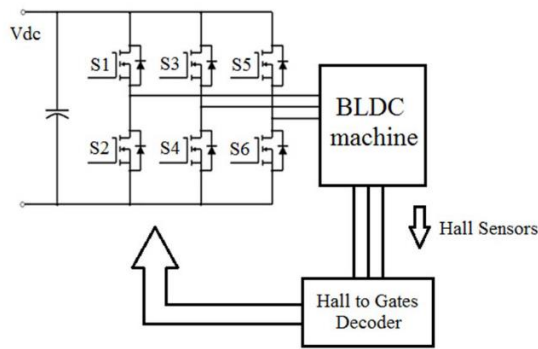


Figure 1. Circuit diagram of BLDC motor [4].

Numerous studies have focused on BLDC motor modeling, simulation, and analysis: Zheng estimated and assessed the performance of the BLDC motor. The calculation employs finite element and circuit methods, which provide the torque and loaded back-EMF curves [8]. Mujianto discovered that a slotted BLDC motor has more torque than a slotless one, and the power and speed are nearly equal. However, the slotless version of a BLDC is ten times faster than the slotted version. [9]. Vipin designed and tested a 1.5 kW permanent magnet brushless DC motor for solar and hybrid electric vehicles. The FEM is used to determine a motor's performance characteristics, so it is analyzed by changing the lead angle in the control circuit; when the lead angle increases, the rated speed of the BLDC motor also increases [10]. Pawar utilized RMxpert for the basic design, then the BLDC motor's overall performance was optimized using (FEM) analysis. Due to modern electrical systems, the demand for electrical power in automobiles will still increase. Less current consumption, smaller electrical systems, and lower losses are examples of the benefits of the 48V system [11]. Thirunavukkarasu examined the speed control of Brushless DC (BLDC) motors for feed drives using Matlab/Simulink. The analysis considers rated, overrated, and underrated speeds [12]. In the MATLAB/Simulink environment, Kumar discussed both open-loop and closed-loop control of BLDC motors with real-time simulation. The relevant results are also shown [13]. Kelek used Maxwell and Matlab/Simulink to compare full-load currents. The currents are nearly identical, which indicates the precision of the simulation. The motor's mechanical and electrical characteristics are derived using the BLDC's physical characteristics motor. These models can be used to manage numerous applications, including industrial robots, electric vehicles, and the environment [14]. According to the research studies listed above, the majority of them analyze BLDC motor output behavior, including current, torque, speed, and efficiency, while the motor is operating. They also make use of a variety of software tools, like Matlab/Simulink and Maxwell 2D, to achieve their objectives. This paper aims to simulate and analyze a BLDC motor with three software to fill the gap in the results. RMxpert software is used for motor modeling, and Maxwell-2D will be used for FEM analysis. Finally, the FEM results of Maxwell 2D will be compared with the analytical results of Matlab/Simulink.

2. Mathematical Background

The FEM has taken over as the primary tool for determining the magnetic fields in electrical motors. The Engineers used it for solving issues that are challenging to resolve using traditional analytical techniques. The technique also enables the researchers to conduct deep analysis inside the motor. The FEM is a mathematical method based on computers that uses a numerical approach to determine machine parameters like torque, flux density across various motor parts, and flux linkage. In ANSYS software, FEM formulations are derived from Maxwell's electromagnetic field equation. The mathematical formulas for Maxwell's equations, on which FEM is based, are indicated below [15]-[17].

$$\nabla \cdot D = \rho \quad (1)$$

$$\nabla \cdot B = 0 \quad (2)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (3)$$

$$\nabla \times H = \frac{\partial D}{\partial t} + J \quad (4)$$

Where:

(D) represents the electric flux density ($C.m^{-2}$)

(ρ) represents the volume charge density ($C.m^{-3}$)

(B) is the magnetic flux density vector term in (tesla)

(E) is the electric field intensity in ($V.m^{-1}$)

(H) is the magnetic field intensity in ($A.m$)

(J) is the current density in ($A.m^{-2}$)

The torque is calculated by using mathematical equations and FEM. Mechanical power can be determined by measuring the machine's torque and speed. The direct method efficiency calculation is provided below[18]:

$$Efficiency (\eta) = \frac{mechanical\ output\ power}{electrical\ input\ power} \times 100\% \quad (5)$$

the first equation mentioned above (the direct method) is written as shown below:

$$\eta = \frac{T \omega}{V_s I_s} \quad (6)$$

Where:

(T) represented the output torque in (N. m).

(ω) represented the angular speed in (rad/sec).

(Vs) represented the voltage source in (V).

(Is) represented the current in (A).

3. Modeling of BLDC Motor

The initial step in any motor's design and control is modeling and analysis[19]. A three-phase BLDC motor is modeled by three software listed below:

RMxprt is a tool that uses templates to help machine designers improve their work. RMxprt can calculate machine parameters and make initial decisions. RMxprt automatically generates the entire Maxwell 2-D for electromagnetic analysis. The design sheets contain a graphic waveform and a list of the important inputs and parameters. To determine performance, it mixes a magnetic circuit approach with traditional electric machine theory [5]. This paper focuses on the fundamental motor design by RMxprt. This tool accepts fixed specifications for the motor, stator, and rotor from[10] as an input; the motor is simulated using the data provided in the paper's tables[10]. The external circuit is edited, as shown in Fig. 2. The driving circuit automatically generates a 6-leg inverter to excite the stator winding with a 100V source.

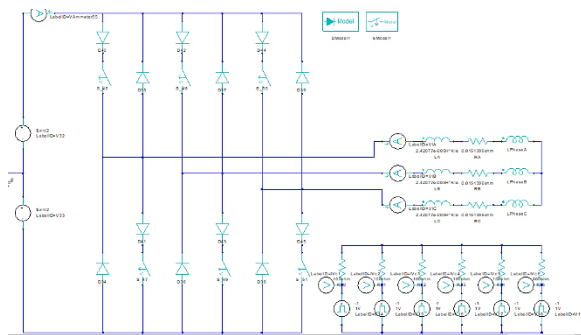


Figure 2. External circuit with DC control

Fig. 2 shows that the stator resistance was very low and equal to 0.015Ω , and when the voltage is applied to this winding, that will cause a high current, so the control type must change to chopped current control (CCC). Fig. 3. Shows the (CCC) control type, so the current measured and additional switches control the current within the defined band. It is almost like PWM control in MATLAB.

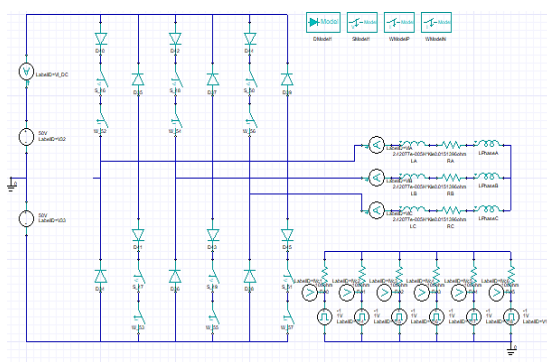


Figure 3. External circuit with chopped current control

As the conditions of the inverter or driver is controlled; we can change the voltage, frequency, and the lead angle of switching to obtain different speeds, output power, and torque. The finite element method is the numerical approach used to solve physics and engineering problems. FEM means the body of the machine was divided into more minor elements and the numerical integration is used at each component [13]. By using the RMxprt model, the 2D -FEM can be exported. Fig.4 shows the finite element mesh of the analyzed model.

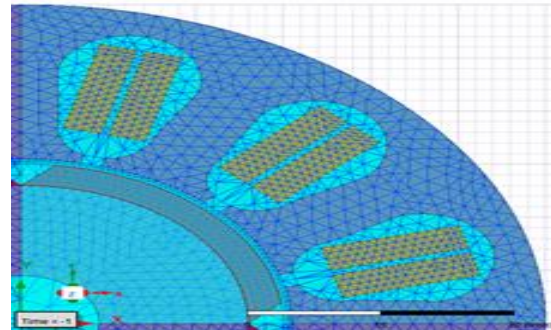


Figure 4. Finite element mesh of BLDC motor

It's clear that with this same motor, different source voltages and field angles between the rotor and stator field will cause other operation points. Then Maxwell 2D results will be compared with MATLAB results for the same motor at a single speed of (2000) rpm. Although a constant supply voltage is linked to the inverter's input, the BLDC motor is connected directly to the output terminals. The inverter is assumed to have no power losses, and the machine winding is connected in a star pattern. Two control loops control the BLDC motor's speed. The inside loop synchronizes the inverter's gate pulse and EMF, while the other loop adjusts the speed by changing the DC bus voltage[20].

First, we have to model the machine and its driver in Matlab. The simulation schematic was taken from the math work indicated in Fig.5. Matlab requires additional parameters and variables. The control types of Matlab components also vary. The parameters used in Matlab were taken from the RMxprt design sheet and the external circuit in Fig. 3, as indicated in Table 1.

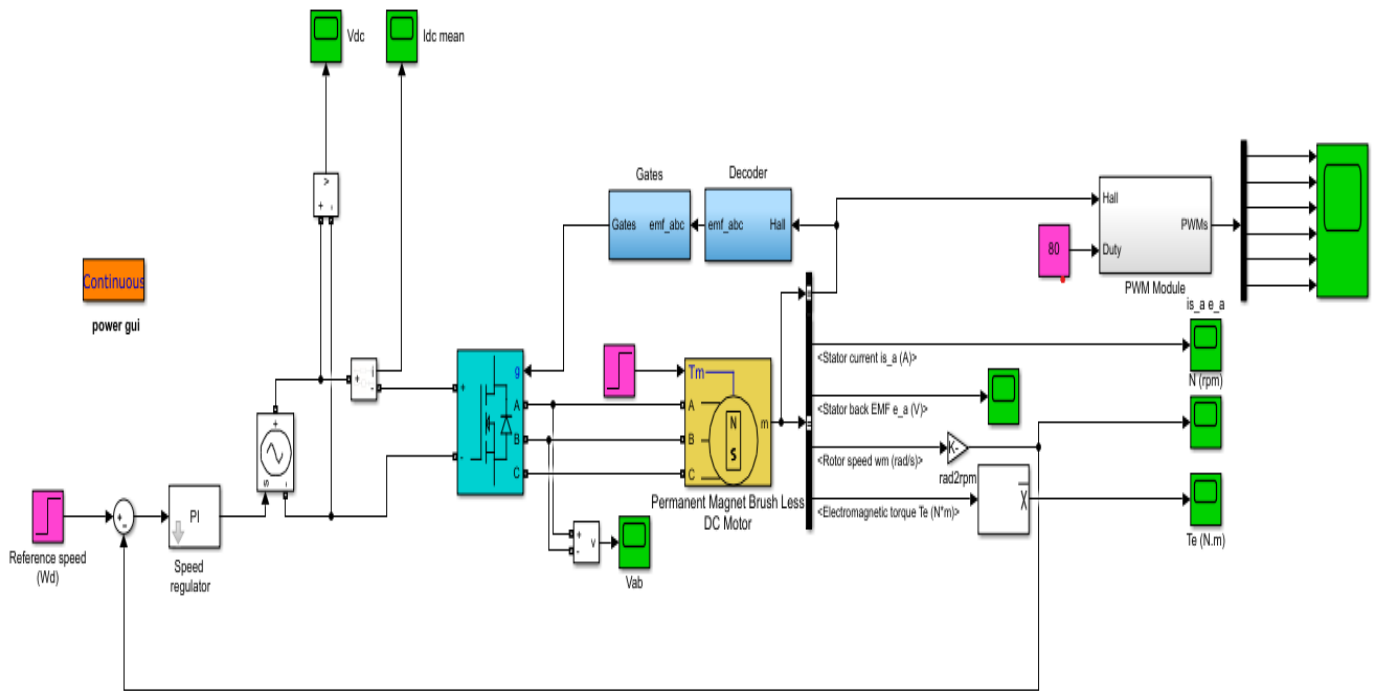


Figure 5. Matlab model of 3_ phase BLDC motor

4. Result and Discussion

4.1. RMxpert Results

After analyzing the BLDC motor by RMxpert, different results are obtained like the relation between torque and speed, as shown in Fig.6, which shows how torque changes with the change in speed where the torque increases by reducing the speed, Fig. 7 shows the relation between the output power and speed.

Table 1. Matlab parameters of 3-phase BLDC motor

Parameter	Value	Unit
No. of Pole pairs	2	-
Resistance/phase	0.0151	Ω
Inductance/phase	2.42077e-005	μH
Torque constant	0.322	[Nm/A]

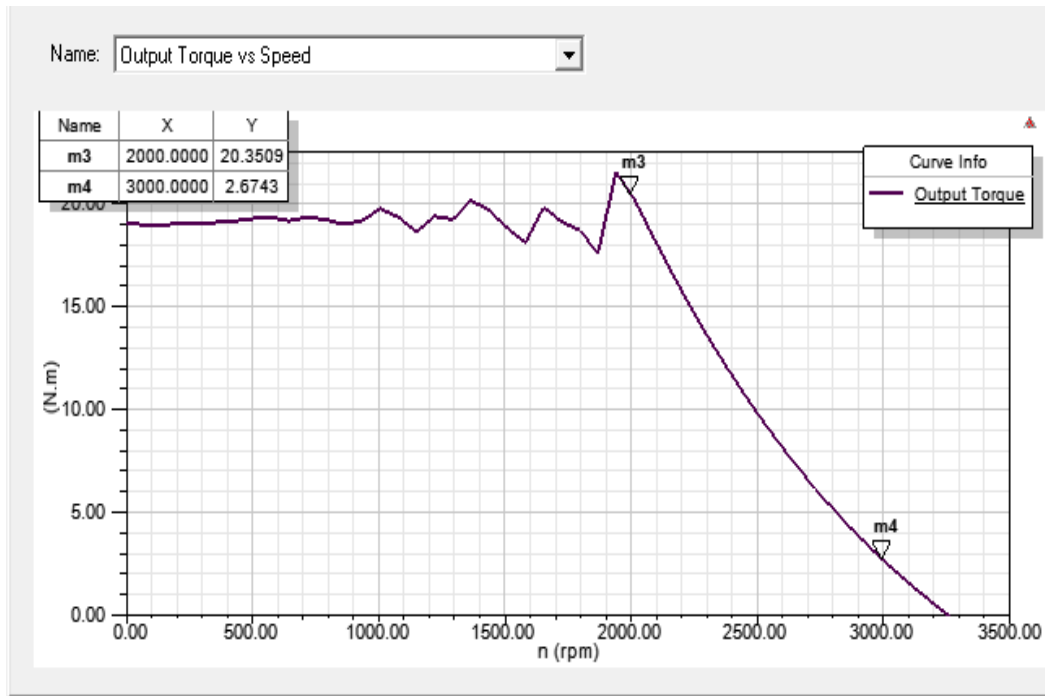


Figure 6. Output torque vs. speed

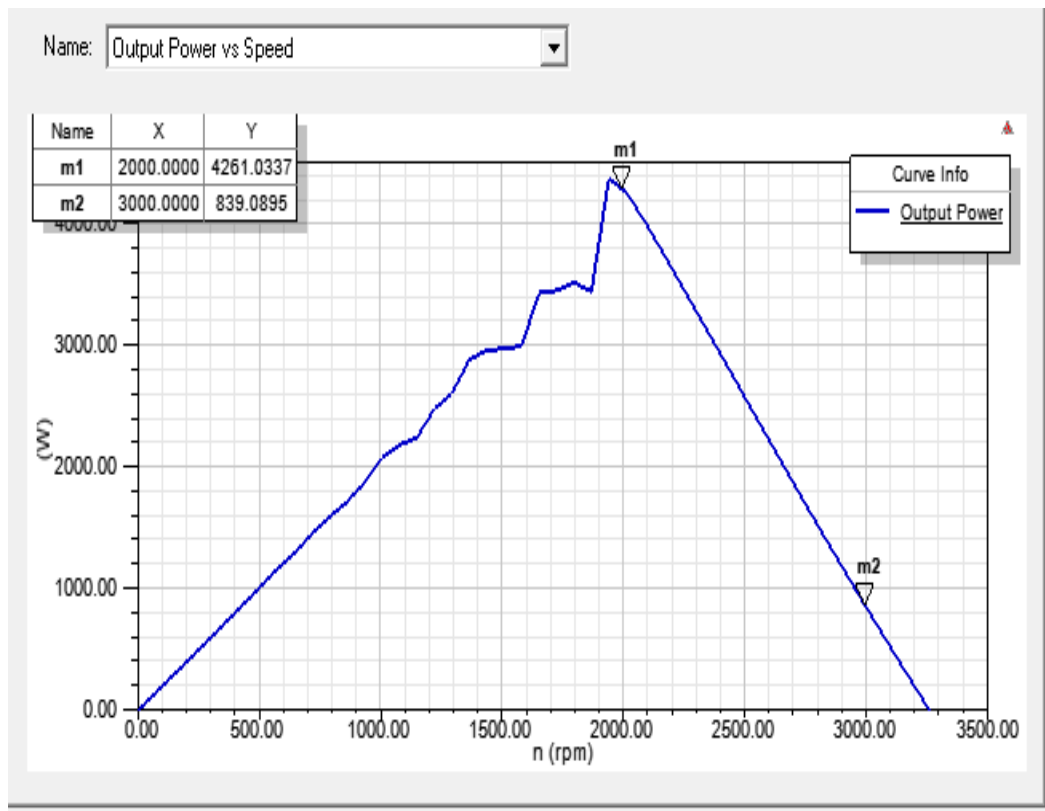


Figure 7. Output power vs. speed

4.2. Maxwell 2D Results

After solving the BLDC motor model in RMxpert for the exact machine specifications in [10], at 100 volts and 2000 rpm with (CCC) control, the average torque taken from Maxwell 2D is illustrated in Fig.8 and is equal to 14.2 N.m.; the average input current is 32.26 as shown in Fig.9.

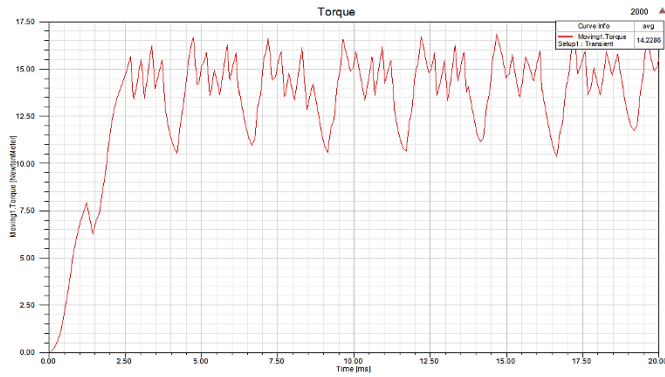


Figure 8. BLDC motor torque by Maxwell 2d

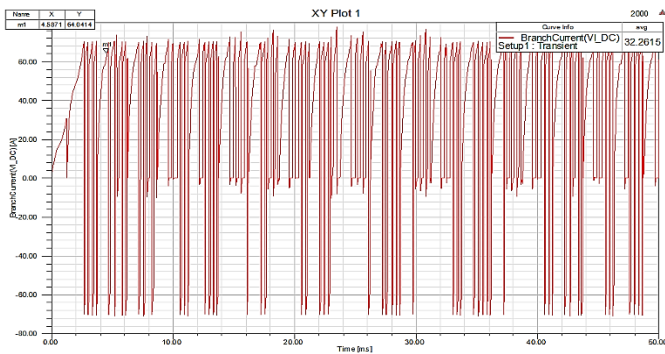


Figure 9. DC source current of BLDC motor by Maxwell 2d

The flux density distribution is displayed in Fig.10. The blue color indicates the lowest flux density, while the red has the highest flux density.

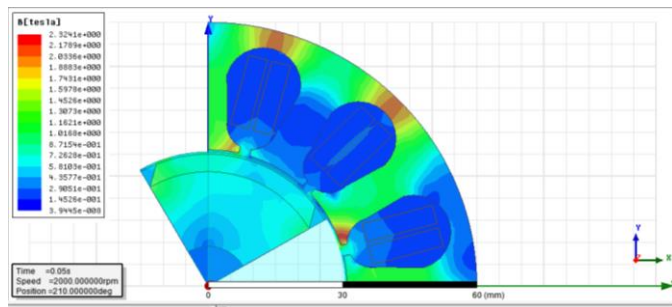


Figure 10. The flux density of the BLDC motor

Fig. 11. depicts the location of the magnetic flux lines inside the BLDC motor.

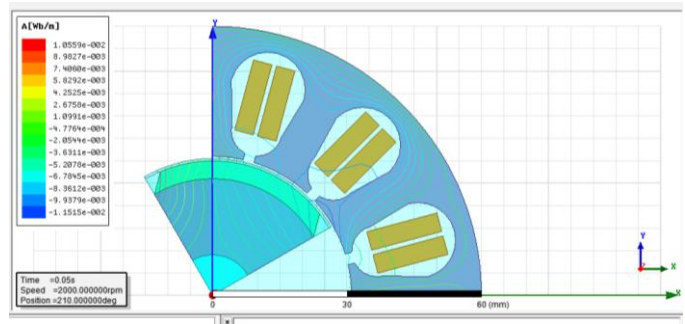


Figure 11. Magnetic flux lines of BLDC motor by Maxwell 2D

4.3. MATLAB simulation results:

The drive uses PWM control in Matlab, but the default Maxwell 2D driving circuit connects the DC source to the stator winding and disconnects it by position feedback. This difference causes the current results to have some differences. This issue is that the voltage is very high and the resistance is very low, so the DC control must be changed to chopped current control (CCC) to avoid the high current. This issue can be solved using an external circuit, as indicated in Fig.3. By inserting the parameters in Table 1 for a 3-phase BLDC motor, 2000 rpm, results were obtained. As shown in Fig. 12, the average DC input current is 48 A. Fig. 13 depicted an average DC input voltage of 69V, Fig. 14 depicted a speed of 2000 rpm, and Fig. 15 depicted an output torque equal to 14.5 N. m.

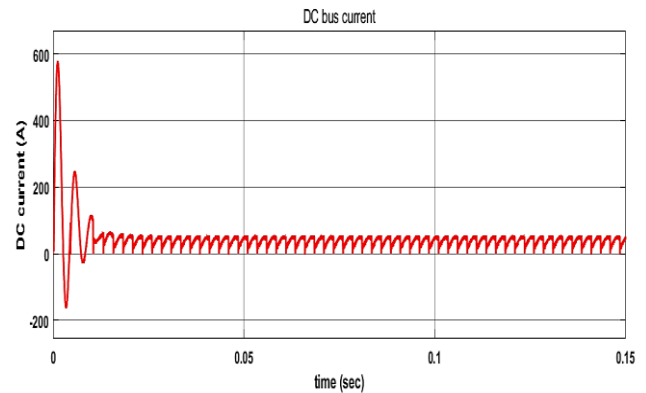


Figure12. Input DC bus current of BLDC motor in Matlab

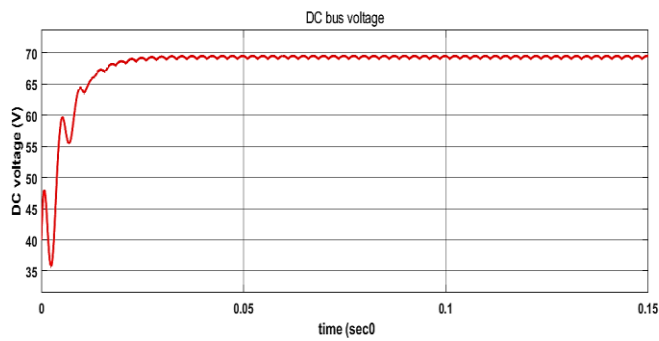


Figure13. Input DC voltage in Matlab

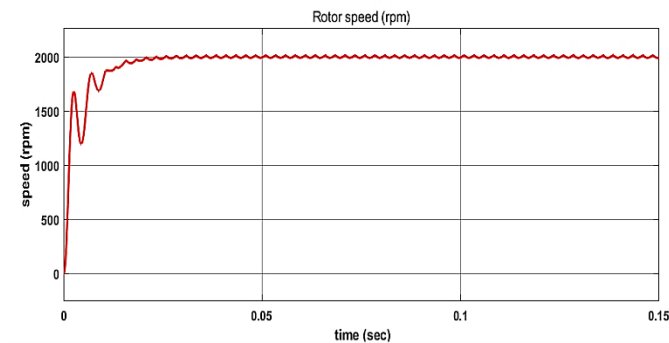


Figure14. Speed of BLDC motor in Matlab

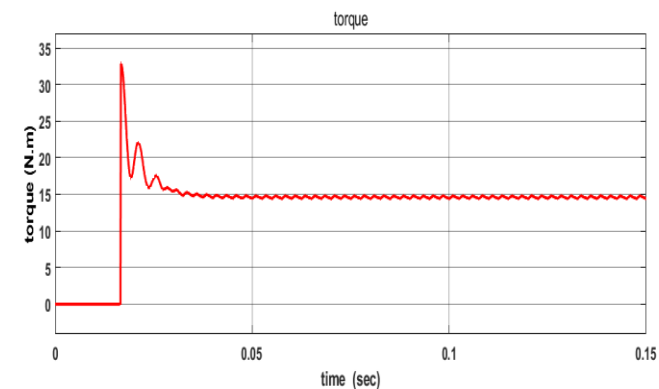


Figure 15. Torque of BLDC motor in Matlab

4.4. Results Comparison:

Table 2. represents the torque, speed, and efficiency results taken from Maxwell 2D and Matlab for the same motor at 2000 rpm

Table 2. Results comparison of 3-phase BLDC motor

parameter	Maxwell 2D	- Matlab	Error (%)
torque	14.22	14.5	1.9
efficiency	92.2	91.6	0.65

At 2000 rpm, it is evident that the results from the two software are comparable when motor torque, speed, and efficiency results are compared. These results support the validity of the motor's analytical hybrid methodology adopted in this paper model as a reliable starting point for any other analytical work.

4. Conclusion

This paper successfully adopted a hybrid FEM–analytical methodology to analyze a BLDC motor. (RMxpert, Maxwell 2D, and Matlab/Simulink) are three software packages used to achieve this methodology: RMxpert software used to assist with motor modeling by providing some missing parameters from the design sheet like stator resistance, stator inductance, and torque constant, while Maxwell 2D was used to obtain FEM results; Then, Matlab results used to compare them with FEM results. The motor torque and efficiency were calculated by Maxwell 2D (FEM) and compared with the analytical results of Matlab with good agreement. and also computed the parameters and operating characteristics of the motor. The simulation model expanded the analysis and identified the motor's properties. In addition to discovering the powerful simulation tool FEM for field analysis, Despite the lack of motor test results, the proposed methodology provides a good starting point for future BLDC motor research.

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Conflict of interest

The authors declare that there are no conflicts of interest in reading.

Author Contribution Statement

Authors: Estabraq A. Abbas^{1*} and Amer M. Ali² share each step in the paper. The contribution to the paper is adopting a hybrid FEM–analytical methodology to analyze a BLDC motor based on RMxpert, Maxwell 2D, and Matlab/Simulink software. RMxpert software also assists motor modeling by providing missing parameters from the design sheet, such as stator resistance, stator inductance, and torque constant. The proposed methodology provides a good starting point for future BLDC motor research.

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