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Torque Analysis of Switched Reluctance Motor Under Different Loading Conditions

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Abstract

This paper introduces torque analysis of a 4-phase, 8/6 poles, 550W, switched Reluctance motor. In this regard, the influence of varying loads on torque performance is introduced. For the modeling and analysis of this motor's torque, RMXprt (an analytical software) was used in conjunction with Maxwell2D (a finite element method). Because the rotor and stator pole are salient, singly excited, and have nonlinear magnetic characteristics, which creates torque ripple in the motor and complicates analytical procedures. Motor results obtained, such as estimated starting torque, output torque versus speed, torque versus angle versus current, flux linkage versus current versus angle, and torque versus time, were determined by RMXprt and Maxweel2D software. In addition, the simulation results demonstrate that the torque ripple and torque values are greater as the load increases and lower when the load decreases. Finally, the finite element analysis results of torque ripple and torque were compared with the results of the Matlab/Simulink with good agreement.

Keywords: Matlab; Maxwell2D; RMXprt; Switched reluctance motor; Torque ripple

1. Introduction

Switched reluctance motor (SRM) is a type of electric motor, and its operation is viewed as a repetitive process in which the position of the rotor changes from an unaligned position to an aligned position according to the relative position with the stator pole [1]. Due to its features such as simple construction, low inertia, robustness, low cost, and fault tolerance, SRM gained interest in industrial applications such as domestic appliances sectors, aerospace, renewable energy, and automotive [2]-[3]. However, the stator and rotor both have salient poles with nonlinear magnetic properties, singly excited, so SRM produces a large ripple in the torque and hence affects SRM performance[4].

Several research studies have been conducted to study and analyze the torque of SRM. Mehmet analyzed a 2.2kW 8/6 SRM 4-phase by adopting maxwell2D to calculate torque, current, and inductance with open slits in the rotor pole, which leads to an increase in the torque value [5]. Ferková and Suchý [6] analyzed 12/8 and 6/4 SRM using two types of software, Maxwell2D, and Simplorer, to determine motor current, average torque, and torque ripple and assumed that 12/8 poles have better characteristics than 6/4 poles. FEA analyzes different poles of SRM to determine torque versus angle versus current, average torque, torque ripple, and maximum torque, inductance, current, back emf [7]-[10]. Hamouda et al. [11] analyzed three phases using Matlab/Simulink based on TSF to determine torque, current, and efficiency. The proposed method provides low torque ripple and high efficiency. Hao et al. [12] analyzed three-phase 12/8 SRM using a magnetic equivalent circuit and applied the curve fitting method to the magnetization curve of the material. The obtained results are compared with FEA with a good agreement. Labiod et al. [13] analyzed four-phase 8/6 SRM using 2D FEA with dynamic and static analysis under different rotor angles to determine torque, current, flux linkage, and static torque. Kocan and Rafajdus [14] used Matlab/Simulink to calculate torque, torque ripple, efficiency, and losses for a three-phase, 1.5 kW, 6/4SRM with varying speed values. Torque ripple increases considerably as speeds surpass 75,000 rpm. This torque ripple can be reduced by changing the control strategy. As speed increases, winding losses decrease. Iron losses exhibit a recurring pattern of increase up to a rotational speed of 25,000 rpm; however, beyond 75,000 rpm, this increase becomes less significant.

On the other hand, mechanical losses dominate overall losses. While these have been estimated approximately, more accurate values can be obtained through experimental measurement. Antipove et al. [15] analyzed 12/8 SRM and modeled it using Quickfield software and Matlab/Simulink to determine torque and current. Krasovsky et al. [16] analyzed 8/6 SRM by using Matlab/Simulink through the algorithm based on the change in control position to determine torque, and this methodology led to an increase in torque. 12/8 SRM was analyzed using TSF in Matlab/Simulink to calculate current, torque ripple, and torque [17]-[18]. Przybylski [19] evaluated 12/8 SRM by utilizing FEA with three different types of material, somaloy 700HR, somaloy 700, and Fe-Si steel, to calculate inductance versus angle, flux linkage versus angle, versus current, and torque versus angle versus current and assumed that the steel material Fe-Si is better than other steel material. Deepak et al. [20] investigated 8/6, 10/8, and 6/4 SRM by utilizing multi-level converter branches and two-level converters in Matlab to calculate current, torque, flux linkage, and torque ripple, and these findings indicated that the asymmetric bridge converter outperformed other converters. Patel et al. [21] analyzed 8/6 SRM by utilizing FEA with different depths of slots present in the stator tooth to determine torque and flux linkage and prove that the proposed method leads to enhancing the torque value. Sun et al. [22] analyzed 16/10 SSRM and 8/6 SRM using FEA to calculate torque, inductance, and current. Pittam et al. [23] analyzed SRM using the DTFC technique in Matlab to determine torque, current, and flux, and the proposed method leads to improved torque. Marcsa and Kuczmann [24] analyzed 6/4SRM by using 3-D FEA and TSF in Matlab/Simulink, which were skewed in the shape of rotor poles to determine torque. Wang et al. [25] analyzed 12/8 SRM by using PWM and DITC in Matlab/Simulink to calculate current, torque, and ripple torque and proved the proposed method gives good torque ripple. Dawood and Ali [26] analyzed a 0.5hp single-phase induction motor based on two software, MAGNET and AutoCAD, to determine the values of torque and current and compared these values with the nameplate and proved the obtained results have a good agreement. Bahar and Omar studied [27] the control of the PMSM to reduce the torque ripple based on two approaches, predictive torque control, and space vector control, using Matlab. They proved a comparison of the two methodologies shows that predictive torque control has a faster dynamic response.

Previous research explained some of the work, and the rest was not explained, for example, how to obtain the values of some important parameters that MATLAB needs, which were not fully mentioned. The contribution of this paper can be summarized in two points: first, it presents a comprehensive analysis of the SRM torque by RMXprt and 2D FEA and validates from results by using Matlab/Simulink with the absence of test results; second, it makes SRM Matlab model work by feeding it with some necessary input data taken from other two software. This paper aims to analyze the torque of a four-phase, 8/6 poles SRM, 550W with changes in load by utilizing three programs: Matlab/Simulink, RMXprt, and Maxwell2D to offer the trustworthiness and multifariousness to the required results and to make up for the absence of test results.

2. SRM mathematical model

Fig. 1 illustrates the SRM equivalent circuit per phase. Equation 1 represents the equation of voltage based on the equivalent circuit.

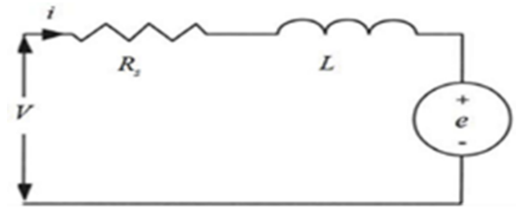

Figure 1 SRM equivalent circuit.

$$V_{ph} = IR_s + \frac{d\ (L(\theta,i))}{dt}$$

$$V_{ph} = I\ R_s + L(\theta,i)\frac{di}{dt} + \frac{d_L(\theta,i)}{d\theta} W_m\ i \quad (1)$$

Where R(Ω) represents the stator resistance per phase, I (A) denotes the current in the phase, θ (rad) indicates the rotor position, Wm(rad/s) corresponds to the motor speed, and L(H) refers to the stator inductance.

The rotor pole pitch (θrp) can be determined by:

$$\theta_{rp} = \frac{2\pi}{N_r} \quad (2)$$

Where Nr is the number of the rotor poles.

The stator pole pitch (θsp) can be computed by:

$$\theta_{sp} = \frac{2\pi}{N_s} \quad (3)$$

Where Ns represent the number of stator poles.

The electromagnetic torque(Te) can be determined by:

$$T_e = \frac{1}{2} i^2 \frac{d_L(\theta,i)}{d\theta} \quad (4)$$

$$T_e - T_L = J\frac{dW_m}{dt} + B\ W_m \quad (5)$$

Where B (N.m.s) is friction, T_L(Nm) is the load torque, and J (kg.m²) is the inertia moment.

The induced emf e(v) is determined by:

$$e(v) = \frac{d_L(\theta,i)}{d\theta}\ i\ W_m = K_b W_m\ i \quad (6)$$

$$K_b = \frac{d_L(\theta,i)}{d\theta} \quad (7)$$

Where kb represents back emf [28].

The equation for determining half rotor pole pitch is given by:

$$\theta 1/2rpp = \frac{360}{2N_r} \quad (8)$$

The equation for determining torque ripple (Tripple) is given by:

$$T_{ripple} = \frac{T_{max} - T_{min}}{T_{avg}} \quad (9)$$

Tav, Tmin, and Tmax indicate the average minimum and maximum torque, respectively [1].

The equation for determining rated torque is given by:

$$T = \frac{P_{out}}{\frac{2\pi N}{60}} \quad (10)$$

Pout and N represent output power and rated speed [29].

3. Modeling and simulation SRM based on Maxwell2D, RMXprt, and Matlab/Simulink.

The RMXprt program is utilized to build and analyze motors using analytical equations. Maxwell2D software, on the other hand, employs the finite element approach to solve field electromagnetic problems in a constrained region by employing Maxwell's equations [30]-[31]. Also, RMXprt is utilized to develop the Maxwell2D model; this study focuses on an SRM featuring an 8-pole stator and a 6-pole rotor. A sectional view of the SRM, designed using RMXprt software, is depicted in Fig. 2. The motor delivers an output power of 550 W at a rated voltage of 240 V and a rated speed of 1500 rpm. The geometric specifications of the motor are summarized in Table 1. The construction utilizes M19-24G silicon steel sheets. Motor specifications were obtained from reference[30], as detailed in Table 1. The trigger pulse width, determined using Equation (10), corresponds to 90°.

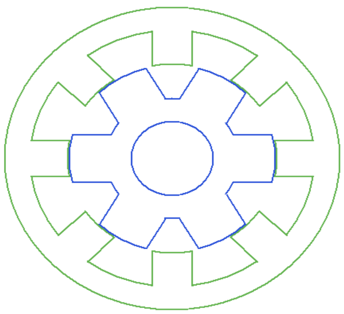

Figure 2. SRM model by RMXprt.

Table 1. The SRM specification under study

Parameter	Value
Stack length	2 V
Inside rotor diameter	30mm
Outside rotor diameter	74mm
Transistor drop	65mm
Rotor yoke thickness	9mm
Stator yoke thickness	9mm
Stacking factor	0.95
Wire thickness	0.08 mm
Outside stator diameter	120mm
Wire Diameter	0.5733 mm
Number of strands	1
Insulation thickness	0.3 mm
Inside stator diameter	75mm
Parallel branch	1
Winding number	142
Frictional loss	12 W
Diode drop	2 V
Trigger pulse width	90

After completing the motor's design in RMXprt and building a 2D model in Maxwell2D, as illustrated in Fig. 3, Fig. 4 clarifies the mesh for SRM and makes its elements and nodes apparent.

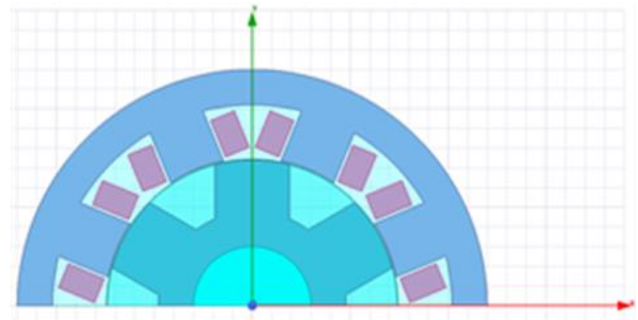

Figure. 3 SRM model in Maxwell2D.

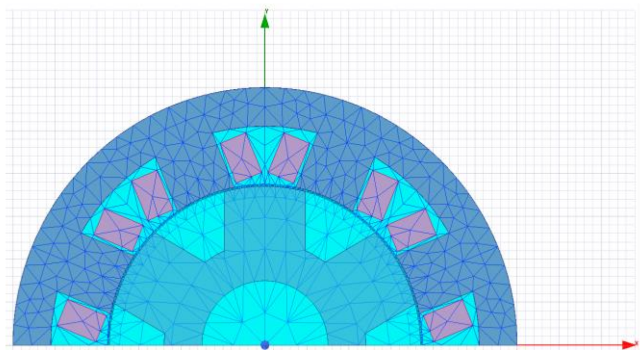

Figure. 4 SRM FEA mesh by Maxwell2D.

The drive circuit is created in Maxwell2D directly. It contains inductors, switches, and diodes with a value of 0.000599669H in each phase and resistors with a value of 4.20481ohm in each phase, as illustrated in Fig. 5.

Fig. 6 shows the Matlab/Simulink model for SRM. The parameters utilized in Matlab/Simulink, such as a turn-off angle equal to 20° and a turn-on angle equal to 0°, the RMXprt result of Fig. 7, and the Maxwell2D result, are entered into Matlab/Simulink as a lookup table, which is utilized to store data of torque, flux linkage, angle, current, and other parameters, which are explained in Table 2.

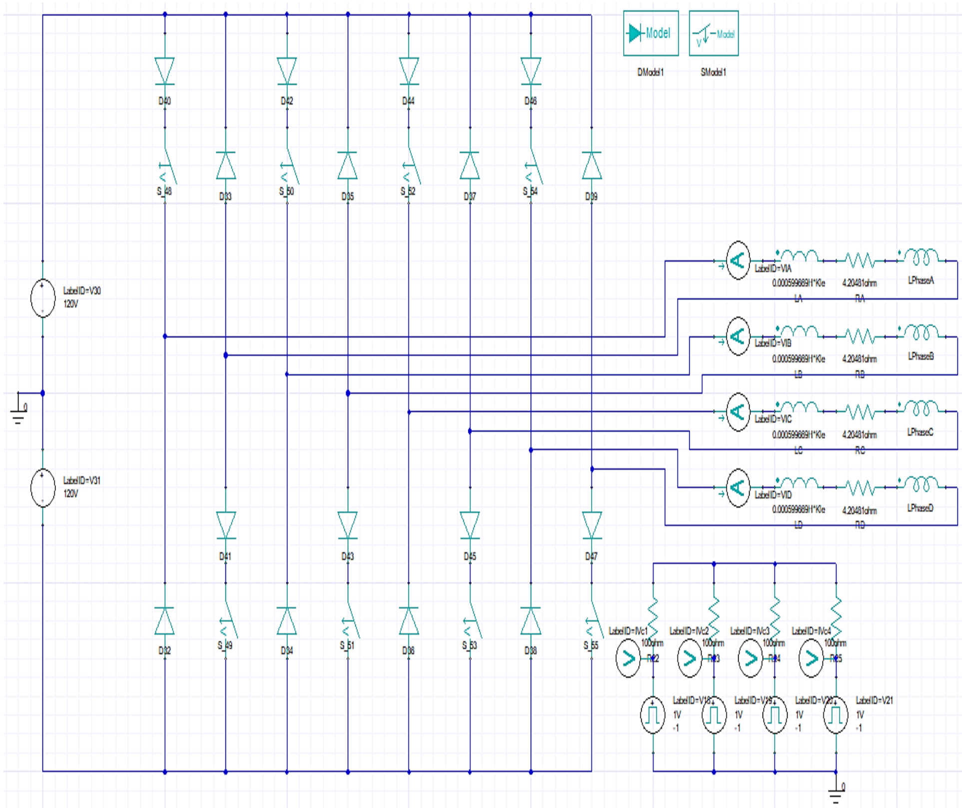

Figure 5 Drive circuit of SRM by Maxwell 2D.

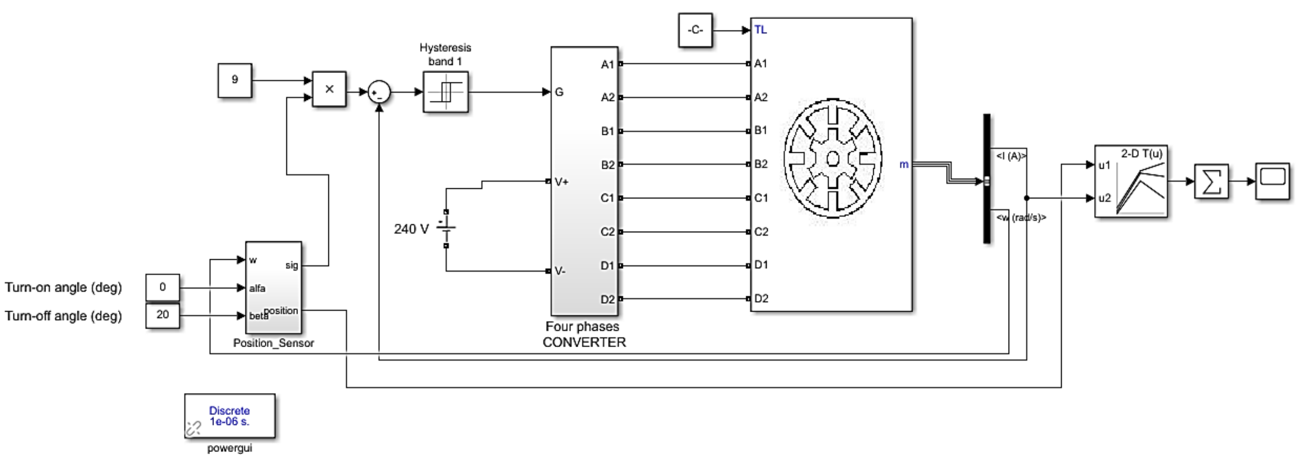

Figure 6. Matlab/Simulink model of SRM.

Table 2 SRM input data for Matlab/Simulink.

Parameter	Value
Load torque	3.72846 (N.m)
Initial speed	147.0694712876 (rad/sec)
Initial position	0.3926990817 (rad)
Inertia	0.00149257 (Kg.m.m)
Stator Resistance	4.20481ohm
Stator poles	8
Rotor poles	6
Friction	0.00203009 (N.m.s)
Reference current	9(A)
Voltage	240 (V)

4. Results and discussion

4.1 RMXprt results

After completing analyzing SRM by RMXprt, Fig .7 clarified the relation between flux linkage, stator current, and rotor position in an electrical degree which stands for inductance at unaligned inductance (Lq) saturated aligned (Ldast), aligned inductance (Ld.), and where the electrical degree reaches to 180deg, maximum flux linkage is equal to 0.6018Wb, maximum current 56.6018A. The starting torque can be calculated by RMXprt, which equals 36.729 N.m.

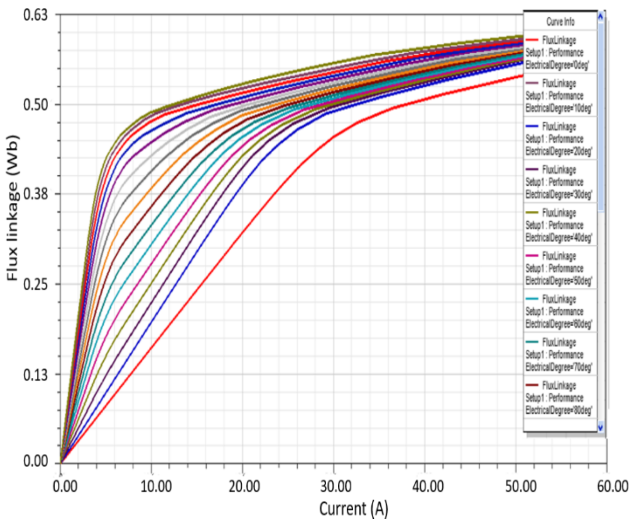

Figure 7 Flux linkage vs. current vs. rotor position by RMXprt.

Fig. 8 clarifies the relation between output torque and speed since it begins at 29.6215 N.m and is progressively reduced with rising speed.

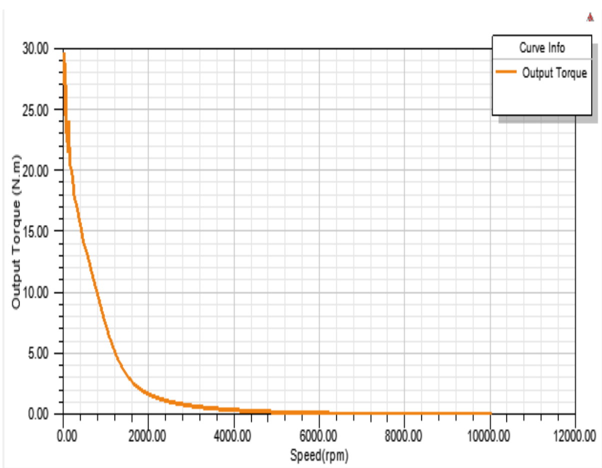

Figure 8 SRM output torque vs speed by RMXprt.

4.2 Maxwell2D results

After completing the SRM analysis in RMXprt, the torque characteristics of the SRM are further evaluated using Maxwell2D. Fig. 9 illustrates the relationship between torque, current, and rotor position, where the position angle is set at 60° and the maximum current is 56.6018 A, varying incrementally by steps of 0.1° and 0.1 A, respectively. The results indicate that the torque is positive as the rotor pole transitions from an unaligned to an aligned position. Conversely, the torque becomes negative when the rotor moves from an aligned to an unaligned position.

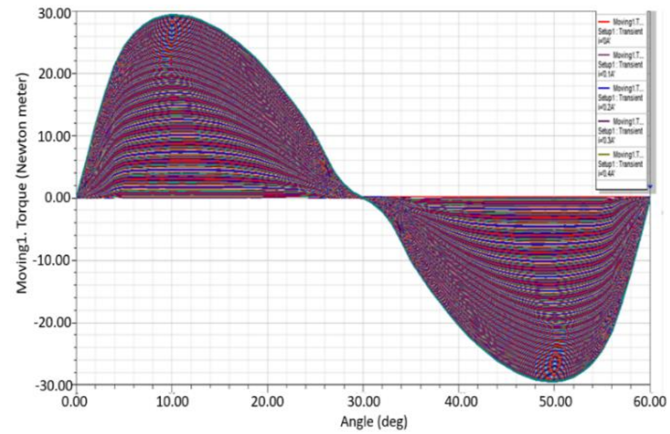

Figure 9 SRM torque vs. rotor position vs. current at rated load by Maxwell2D.

Fig. 10 clarifies the relation of torque versus time. During the switching phase, decaying torque occurs, resulting in a torque ripple, where the torque ripple is 106.46%, the minimum torque is 2.3063 N.m, the average torque is equal to 4.2148 N.m, and the maximum torque is 6.7934 N.m.

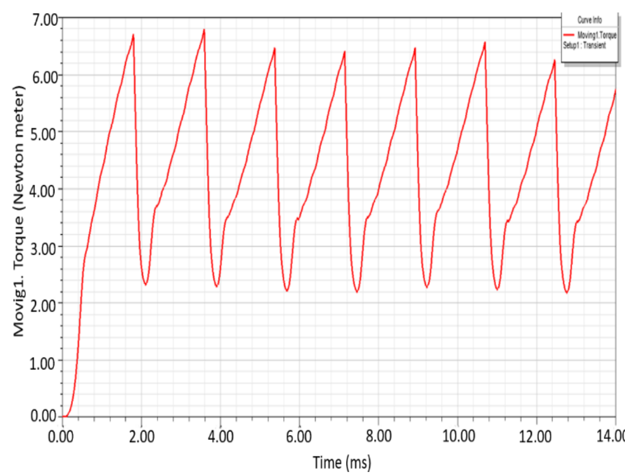

Figure .10 SRM torque curve at rated load by Maxwell2D.

Fig. 11 depicts the relationship between torque ripple and different loads, demonstrating that the torque ripple increases as the load increases.

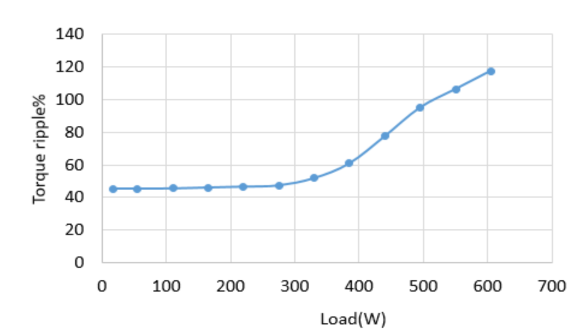

Figure. 11 SRM torque ripple vs load

Fig. 12 depicts the relationship between torque and different loads, with the maximum, average, and minimum torque values increasing as the load rises.

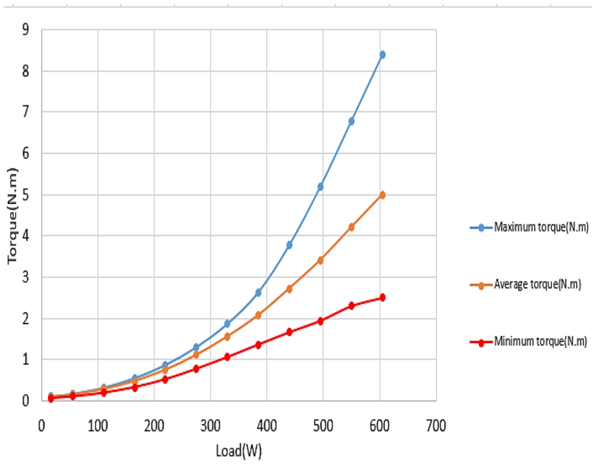

Figure 12 SRM maximum, average, minimum torque vs load

4.3 Matlab results at full load

Fig. 13 depicts the relationship between torque and time, with the highest torque being 6.825 N.m, the minimum being 2.749 N.m, and the average being 4.085 N.m. The torque ripple is 99.779%.

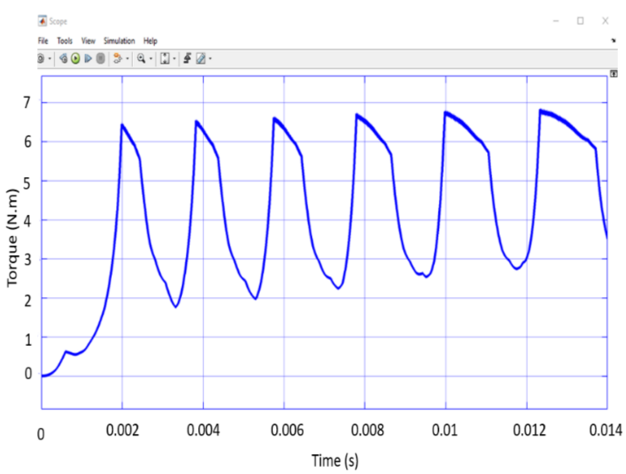

Figure 13 SRM torque curve at rated load by Matlab

Table 3 compares Maxwell2D and MATLAB results for average torque and torque ripple at full load (550W).

Table 3. Torque and torque ripple comparison

Parameters	Maxwell2D	Matlab	Error(%)
Average torque(N.m)	4.2148	4.085	3.079
Torque ripple(%)	106.46	99.779	6.275

4. Conclusions

The SRM torque analysis process was completed successfully by changing the load and simulating it with three RMXprt, Maxwell2D, and Matlab/Simulink to offer trustworthiness and multifariousness to the required results and to compensate for the lack of the test results. From the results obtained, it's clear that alterations in the behavior of torque and torque ripple were evident in our study. Moreover, the impacts of increasing load show that torque and torque ripple are greater at high load compared to low load. RMXprt and Maxwell2D give the performance results of SRM, like flux linkage versus current versus angle, output torque versus speed, torque versus angle versus current, torque versus time, and estimated starting torque. Maxwell2D findings, such as torque and torque ripple at full load, were compared with Matlab/Simulink, and there was a good agreement for additional fidelity. In future work, the effect of varying steel material and poles of stator and rotor in three-dimensional finite element analysis will be studied on the performance of the torque and torque ripple.

Acknowledgments

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Abbreviations

TSF	Torque sharing function
SRM	Switched Reluctance Motor
DTFC	Direct torque and flux control
FEA	Finite element analysis
PWM	Pulse width modulation
DITC	Direct instantaneous torque control

Conflict of interest

The authors confirm that there is no conflict of interest in publishing this article.

Author Contribution Statement

The first author, who is a master's student, carried out the introduction, previous studies, mathematical basis, model modeling, all the calculations, their discussion with conclusions, and writing the paper. The second author reviewed the paper.

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