Modeling and Simulation of External Rotor 6/8 Switched Reluctance Motor for E-Bike

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***Abstract*— Switched reluctance motors (SRMs) have become an alternative for electric vehicles due to their many advantages. SRMs have a non-linear flux characteristic because they have protruding pole structure. Therefore, the modeling of this motor is quite complex. In this study, firstly dynamic analysis of 6/8 external rotor SRM (ER-SRM) designed with finite element method (FEM) for E-bike is carried out in MATLAB/Simulink. Then, speed control is examined for the variable speed and load values of the SRM.**

Keywords—SRM Dynamic Analysis; E-bike; MATLAB/Simulink, Speed Control.

I. INTRODUCTION

In the last decade, environmental pollution caused by greenhouse gas emissions has spurred efforts to save energy and reduce emissions around the world. Electric vehicle (EV) production has gained momentum worldwide to reduce both greenhouse gas emissions and air pollution in cities. With the development of inexpensive and high-capacity batteries, EVs have become an alternative to internal combustion motor vehicles [1]. In this context, many countries have aimed to gradually eliminate internal combustion motor vehicles by 2050. Moreover, it has introduced various incentives for the production and purchase of electric vehicles that will support the development of the electric vehicle industry [2].

Permanent magnet machines are widely used in EV applications as they can provide high efficiency and high output torque with the magnets in their structure [3,4]. However, the high cost of extracting and refining the magnets in the structure of these motors, having limited reserves and environmental impact limit their applications in the EV market [5,6]. Therefore, the researchers aim to design and manufacture more economical, magnetless motors for EVs.

SRMs have a simple and robust structure and don't have magnets and windings in their rotors. Therefore, the production cost and maintenance costs are low. SRMs can be driven with high fault tolerance and wide speed range. All these advantages have made SRM a strong alternative for EV applications [7,8].

The analysis and control of SRM is quite complex due to its non-linear magnetic property. In order to develop different control techniques in EV applications, the magnetic properties of the SRM need to be modeled correctly. In the literature, inductance-based modeling, analytical modeling, artificial intelligent models and look-up table-based modeling approaches are used for modeling SRM [9,10,11]. These different approaches are chosen for different purposes such as precision, computational load, steady state and dynamic behavior of the motor. Among these methods, the look-up table-based approach is quite reliable due to the high accuracy of the magnetic properties obtained. However, using this approach requires either FEM analysis or experimental setup [11].

In this study, the static torque and flux linkage of the 6/8 ER-SRM [12], which was previously designed using FEM, is used. The simulation studies for the dynamic model of SRM in MATLAB/Simulink are explained step by step. A PID controller is used for speed control of the SRM and the steady state of motor is investigated under different speed and load conditions.

II. 6/8 EXTERNAL ROTOR SRM

A. Design Constraction

Electrical and mechanical parameters of the designed motor are given in Table 1 [12].

TABLE I. MOTOR PARAMETERS

Electrical Parameters		Mechanical Parameters	
Number of phases	3	Rotor outer diameter	218mm
Stator pole number	6	Rotor inner diameter	151mm
Rotor pole number	8	Stator inner diameter	80mm
Power	300W	Stator outer diameter	150mm
Rated speed	360rpm	Air gap	0.5mm
Rated torque	8Nm	Stator pole arc	16deg
Battery supply voltage	48V	Rotor pole arc	17deg
Peak of phase current	20A	Machine axial length	22mm
Turn on / Turn off	0^0 / 20^0	Shaft diameter	50.7mm

The material of the stator and rotor M350-50A is selected. The cross-sectional shape of the proposed 6/8 ER-SRM is given Figure 1.

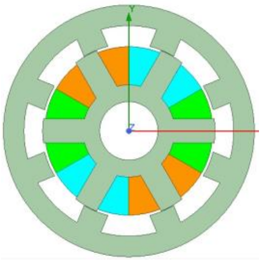
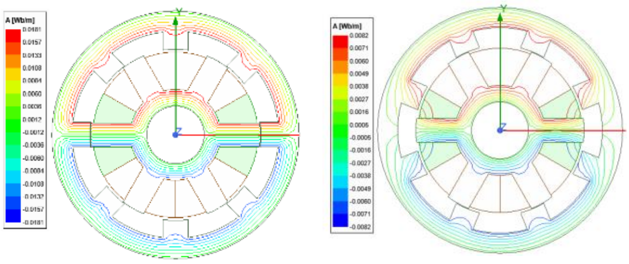


Figure 1. The cross-sectional shape of the 6/8 ER-SRM.

The flux lines for the aligned and unaligned positions of the SRM are given in Figure 2a and Figure 2b, respectively.



(a) Aligned position. (b) Unaligned position.

Figure 2. Flux lines.

In this study, the static torque graph obtained from 0A to 30A at intervals of 2A and rotated from unaligned position (0 degree) to aligned position (22.5 degree) for phase A is given in Figure 3.

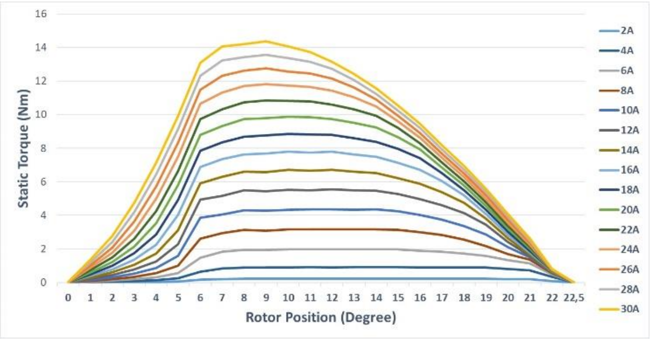


Figure 3. Static torque graphic.

Additionally, the flux linkage - current relationship at different rotor positions is given in Figure 4.

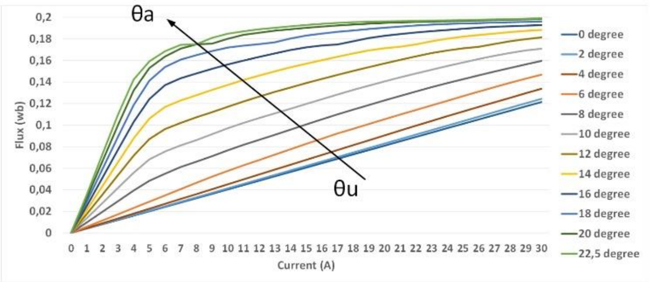


Figure 4. Flux linkage – current relationship.

B. Dynamic Model of SRM

Figure 5 shows the electrical and mechanical models that make up the dynamic model of the SRM [13]. The electrical model can be expressed mathematically by Equation 3.1 and the mechanical model by Equation 3.2 [10, 14].

$$v = R_s i + \frac{d\lambda(\theta,i)}{dt} \qquad (3.1)$$

$$T_e = J\frac{d\omega}{dt} + B\omega + T_L \qquad (3.2)$$

In Equation 3.1, v is phase voltage, Rs is winding resistance, i is winding current, λ is winding flux per phase. In Equation 3.2, Te is the motor torque, J is the total torque of inertia, B is the friction coefficient, ω is the rotor speed, TL is the load torque.

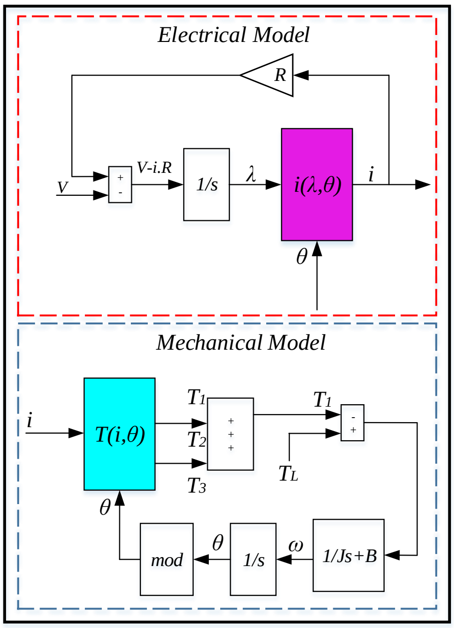


Figure 5. Dynamic model of SRM.

2D lookup tables are used to transfer the FEM data related to the flux and torque, which are the basic characteristics of the motor, to the MATLAB/Simulink. The data of the static torque characteristic are directly transferred to the two-dimensional lookup table in matrix format. However, the data matrix of the flux linkage is not in a form to be transferred to the 2D table. Because the matrix to be transferred to the current lookup table to be used in the motor model should consist of current data. For this reason, it is necessary to convert the obtained $\lambda(i,\theta)$ data to $i(\lambda,\theta)$. For this, the program written in MATLAB M-File is used [15].

III. SIMULATION OF 6/8 EXTERNAL ROTOR SRM

Electrical and mechanical models created in MATLAB/Simulink are given in Figure 6 and Figure 7, respectively.

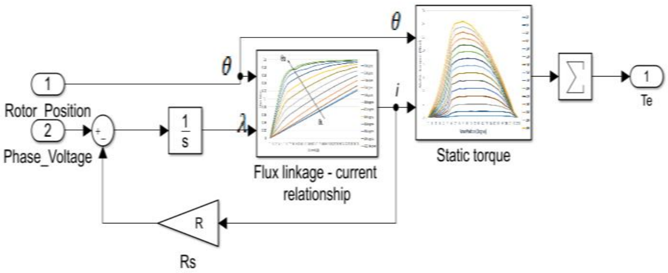


Figure 6. Simulation of electrical model.

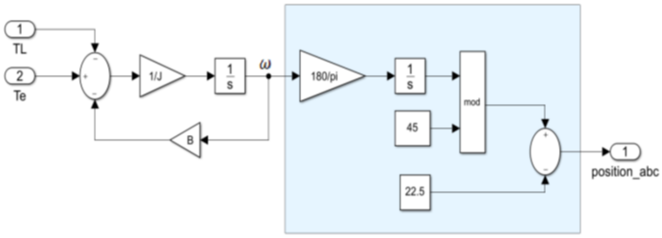


Figure 7. Simulation of mechanical model.

SRMs cannot be run by connecting directly to a resource. Therefore, a driver that performs continuous commutation from one phase to another is needed [16]. In the study, an asymmetric bridge converter, one phase of which is given in Figure 8, is used.

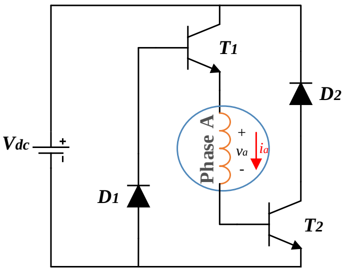


Figure 8. One phase asymmetric bridge converter.

Rotor position information is needed both to determine the switching angles of the driver and to control the current in the phase windings. Therefore, the position sensing unit must be added for system simulation. In Equation 3.3, switching states are given for each phase according to the turn on (θ_{on}) and turn off (θ_{off}) angles [10].

$$v = \begin{cases} +V, & \theta_{on} \le \theta < \theta_{off} \\ -V, & \theta \ge \theta_{off} \end{cases} \qquad (3.3)$$

In this study, θ_{on} angle is selected as 0^0 and θ_{off} angle is selected as 20^0 are determined.

Closed loop speed control is used to keep the speed constant against any change in the system such as load change or reference speed change. Speed and current feedbacks are needed for speed control. The speed control block diagram of the SRM driver is given in Figure 9. In this study, PID controller is used for speed control of SRM. The rotor speed is subtracted from the reference speed and the PID controller generates the reference current signal according to the amount of speed error that occurs. The current error is obtained by comparing the reference current signal with the phase currents at the input of the hysteresis current controller. When the phase current reaches the reference value, the hysteresis controller starts the switching and can keep the phase current at the reference level [10].

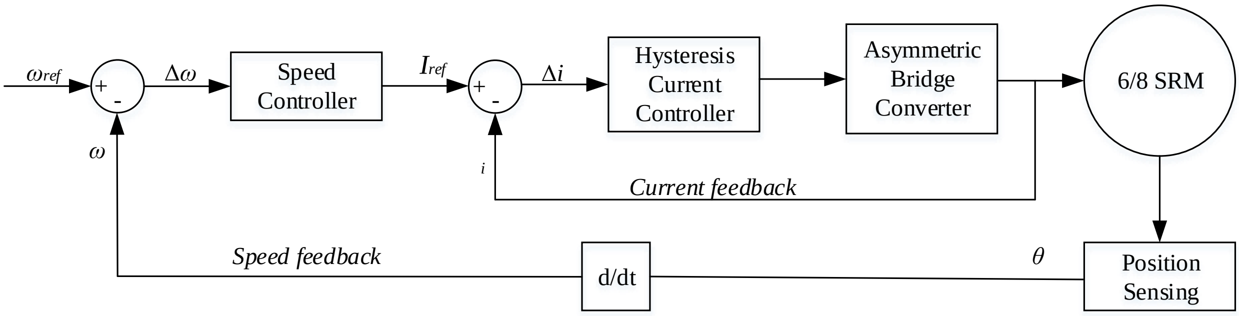


Figure 9. Block diagram of SRM speed controller system.

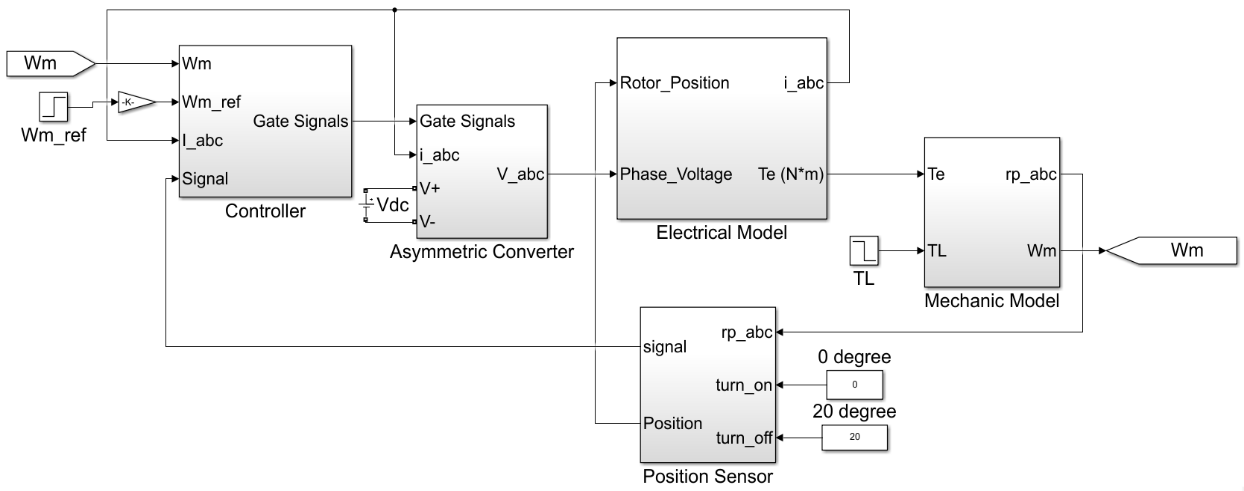
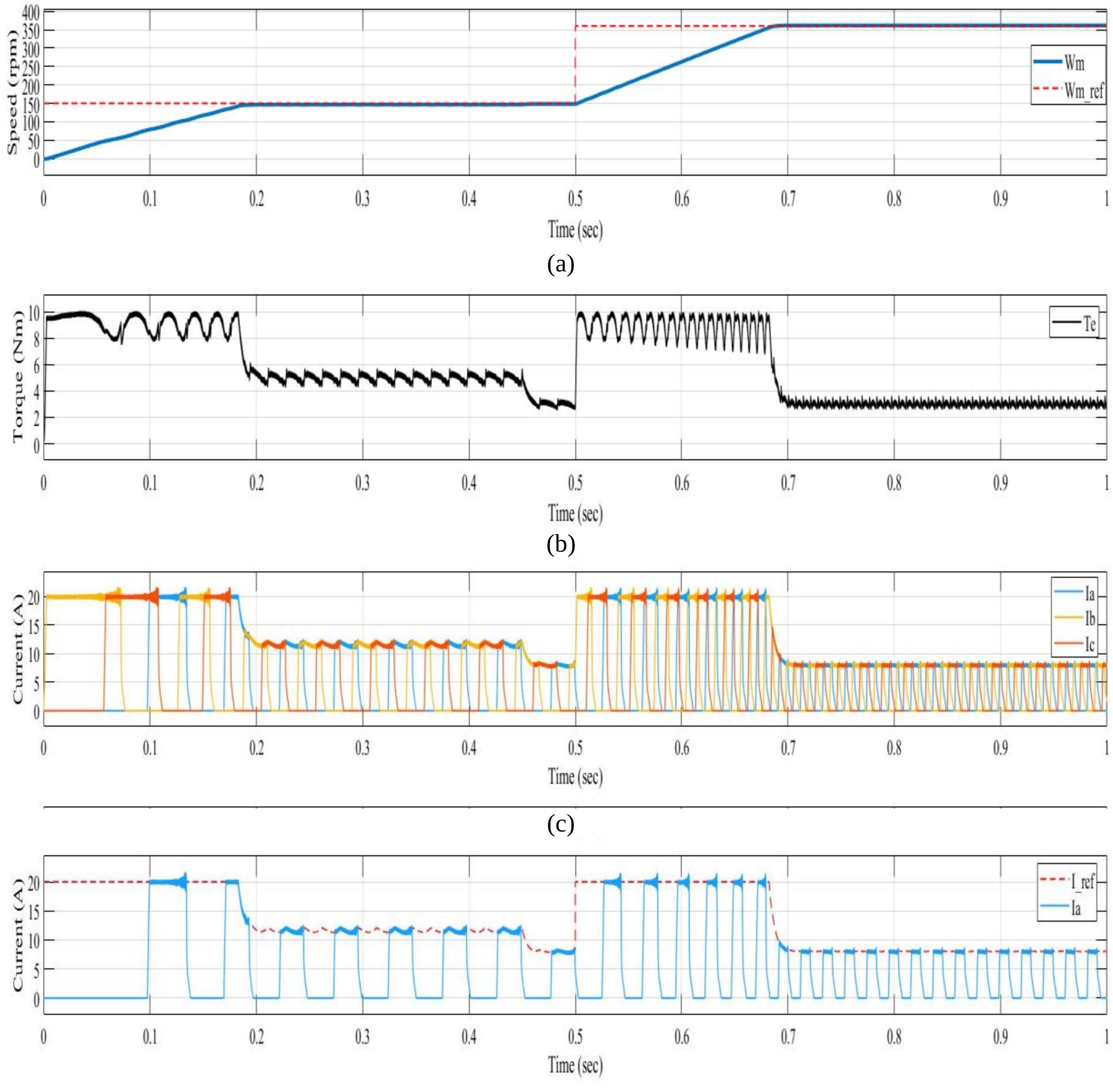


Figure 10. MATLAB/Simulink model of 6/8 ER-SRM.



(a)

(b)

(c)

(d)

Figure 11. Simulation results of transient conditions: (a) Rotor speed; (b) Total torque; (c) Phase currents; (d) Phase current and reference current.

The simulation study performed in MATLAB/Simulink is given in Figure 10. The system has been tested under different speed and load conditions to verify the performance and effectiveness of the implemented model and PID controller. The reference speed is suddenly rised from 150 rpm to 360 rpm in 0.5 seconds. The load torque suddenly reduced from 5 Nm to 3 Nm in 0.45 seconds.

Speed response is given in Figure 11a and total torque is given in Figure 11b. When the speed graph is examined, the SRM catches the reference speed in a short time and reaches a steady state with a small oscillation. When the simulation is started, the phase currents take large values, then the phase currents decrease to normal values. Torque ripple, which is a disadvantage of SRMs, is high at startup. The torque ripple decreased when the SRM reached the reference speed. Three phase current graphs are given in Figure 11c. Figure 11d shows the performance of the current controller when regulating the phase current to monitor the reference current.

IV. CONCLUSION

In this study, modeling and simulation of 6/8 pole ER-SRM designed for electric bicycles in MATLAB/Simulink has been carried out. Due to the non-linear magnetic characteristic of the SRM, the dynamic analysis behavior of the machine is very important to confirm the accuracy of the simulation studies. It is seen that the motor provides the predicted current and torque values during the design phase. Due to its simple and flexible structure, the created simulation study can be easily adapted to different SRMs with known characteristic curves and used for dynamic analysis. In addition, θ_{on} and θ_{off} angles can be optimized to reduce torque ripple over a wide speed range.

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