LINEAR MODELING OF SWITCHED RELUCTANCE MOTOR BASED ON MATLAB/SIMULINK AND SRDAS ENVIRONMENT

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ABSTRACT

A Matlab/Simulink/SRDaS environment to simulate a 6/4 - Switched Reluctance Motor is presented in this paper. The proposed simulation model of the Switched Reluctance Motor for its linear inductance profile is instigated. All simulations are completely documented by their block diagrams and corresponding Matlab functions. The developed simulation model results were compared with SRDaS software packaged SRM model and its performance were analyzed.

Keywords: SRM, Linear modeling, Simulation, SRDaS Environment.


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1. INTRODUCTION

Switched Reluctance Motor (SRM) is a doubly-salient singly-excited motor, which means that it has salient poles on both the rotor and the stator but only one of them, which is the stator, carries windings. The rotor has no windings or magnet, but is built up from a stack of salient-pole laminations shaped in such a way to maximize the variation of inductance with position [1]-[3].
When compared with the traditional AC and DC machines, SR machines have some advantages in addition to the simple construction, low cost and simple power electronic drive requirements. They are very reliable machines since the phases are largely independent physically, electrically and magnetically from each other. SRM can achieve very high speeds (may reach 100,000 rpm) due to the absence of any conductors or magnet on the rotor. However, the salient structure of SRM causes strong nonlinear magnetic characteristics complicating its analysis and control. The key to a fine control is then a simple but accurate model for the machine.

Most studies concerning dynamic simulation of switched reluctance machines (SRMs) [4] have been achieved from the programming, either in C language, FORTRAN, and also employing differential equation-based languages such as ACSL [5-7]. Even software designed to simulate electric network systems as the EMTDC and EMTP have been used. These techniques, although very useful, have lack of flexibility if new elements are brought, causing the increase of cost because of supplementary programming effort. On the other hand, very few simulation studies of the SRM have been achieved with circuit-based languages such as SPICE, Simulink, Matrix, Tutsim, Vissim, and even MathCAD. The first simulations have been made thanks to the software Spice [8]. Unfortunately, this technique is not “elegant” because Spice is especially adapted to electronic circuit simulation [9]. Lately, there has been considerable progress in simulation software such as Matlab/Simulink, which allows a high flexible modeling environment to electrical machinery, as shown in [10], and in particular for SRMs as shown in [11].

The main benefits to be achieved are as follows. 1) Gain of time for the simulation development; 2) Choice of several techniques of numeric resolution; 3) several available libraries for different domains as for example, fuzzy-logic control, neural networks and signal processing.

The work presented here introduces a linear simulation model of a 6/4 switched reluctance motor drive on Matlab/Simulink Environment and its results and waveforms are compared with SRDaS software package SRM modeled. In Section II gives introducing the linear modeling equation of SRM and its equivalent circuit, flux- linkage characteristics are discussed. Section III shows simulation model of SRM are developed using Matlab function. In section V, the simulation results are presented showing the phase currents, the torque and the motor speed waveforms and these waveforms are compared with SRDaS software SRM model. Finally, the paper is concluded in section VI.

2. SRM LINEAR MODEL

To establish a linear model of switched reluctance machine, L(θ) is defined first. As shown in Figure 1, L(θ) is even symmetric to θ = 0°. Fig.1 shows L(θ) for phase A. Each phase inductance displaced by an angle θs given by

\[ θ_s = 2\pi \left[ \frac{1}{N_r} - \frac{1}{N_s} \right] \]

where \( N_r \) and \( N_s \) are the number of rotor and stator poles, respectively. When the motor has equal rotor and stator pole arcs, \( β_r = β_s \), one has the following angle relations

\[ \theta_x = \left[ \frac{\pi}{N_r} \cdot β_r \right]; \quad \theta_y = \frac{\pi}{N_r} \]

(2)
which are indicated in Fig. 1. The 6/4 SRM has the following parameters: \( L_{\text{min}} = 8 \) mH, \( L_{\text{max}} = 60 \) mH, and \( \beta_r = \beta_s = 30^\circ \). Thus, from (2) one gets \( \theta_x = 15^\circ \) and \( \theta_y = 45^\circ \). The electrical equation of phase A is given by

\[
\frac{d\Psi(0)}{dt} + RI = V
\]

while excluding saturation and mutual inductance effects, the flux in phase A is given by the linear equation

\[
\Psi(0,1) = L(0)I
\]

The total energy associated with the three phases \( (n = 3) \) is given by

\[
W_{\text{total}} = \frac{1}{2} \sum_{i=1}^{3} L((\theta + (n-i-1)\theta_s)^2)
\]

and total torque by

\[
T = \frac{1}{2} \sum_{i=1}^{3} \frac{dL((\theta + (n-i-1)\theta_s)^2)}{d\theta} I_i^2
\]

The mechanical equations are

\[
J \frac{dw}{dt} = T - T_f - f\omega
\]

\[
\frac{d\theta}{dt} = \omega
\]

where \( T_f \) represents the torque load, and \( f \) the machine friction coefficient. The speed is constant value \( (\omega = 180 \text{ rad/sec}) \).

![Figure 1 SRM linear model inductance profile of phase A](image)

### 2.1. Equivalent Circuit

The basic circuit shown in Figure 2 is approximate equivalent circuit of the SRM [12]. \( V(t) \) is the voltage source, \( R \) is the phase resistance, \( L(\theta) \) is the instantaneous inductance and \( e(t) \) is the instantaneous back EMF. Speed \( (\omega = 180 \text{ rad/sec}) \) and voltage source \( (V(t) = 150V, -150V, 0V) \) have constant value in each regions and stages
The simulation is performed for three stages because of the switching the SRM in three regions, as stated in section of commutation strategy. All parameters of a function of rotor position are converted to parameters of a function time (from $\theta$ domain to $t$ domain) by using (9).

From this equation,

$$t=\frac{\theta}{\omega} \left( \text{rad/sec} \right)$$

is defined at all rotor position. Inductance profile for phase A is drawn with time domain. Also switching rotor position angles are converted into time domain by using (9) as follows.

$$\theta_x \rightarrow t_x \Rightarrow t_x=\frac{\theta_x}{\omega}$$

$$\theta_y \rightarrow t_y \Rightarrow t_y=\frac{\theta_y}{\omega}$$

(10)

$$K=\frac{dL}{d\theta}$$

(11)

After domain converting, the new circuit model is defined as shown in Figure 3. In the circuit, $e(t)$ is the EMF of the SRM and it is modeled as a current-controlled voltage source.

2.2. Flux – Linkage of Characteristics of the Switched Reluctance Motor

The double saliency structure of the SRM causes its highly nonlinear motor characteristics, which reflects completely on the flux-linkage characteristics of the motor. The relationship between the electrical torque and the stator currents of the SRM appears to be more complex, compared with the other types of motors. Generally, the generated electrical torque can be approximated by a high order polynomial of the stator currents with an order equal to or larger than two. Even for the simplest case in the linear flux region, the electrical torque is not a linear function of the stator current. That is one reason why the control of the SRM is so difficult. Therefore, studying the motor’s magnetic property is essential for proper control.

Properties of the Flux-Linkage Characteristics of SRM:
If both the stator and rotor poles are symmetrically distributed, it is easy to find that the flux-linkage $\Psi$ has following properties:

- The flux-linkage $\Psi$ of the SRM is a function of both the stator current $i$ (phase A) and rotor position $\theta$.
- For fixed rotor position $\theta$, the flux-linkage $\Psi$ is purely a linear function of the stator current $I$ only under the case when there is no saturation effect. Generally, when the stator current is under certain value (in the linear flux region), the relationship between $\Psi$ and $i$ appear to be linear. As the stator current $i$ increase, saturation occurs, which means $\Psi$ is no longer a linear function of $i$. The larger $i$ is, the heavier the saturating effect.
- For fixed stator current $i$, $\Psi$ is a periodic function of rotor position $\theta$ with periodic equals.
- If the magnetic characteristics is plotted as shown in Figure 4, the flux-linkage $\Psi$ is always bounded between the aligned and unaligned positions. Moreover, for the same $i$, $\Psi$ is symmetric with respect to both the aligned and unaligned position.
- For the same larger $i$, the saturation level differs considerably for distinct for position $\theta$. The closer to the aligned position, the sharper the saturation effect becomes.

![Figure 4 Flux-linkage chart of SRM](image)

### 2.3. SRM Energizing Strategies

There are several possible configurations to energize a switched reluctance machine from a converter. The different energizing structures distinguish themselves by their number of semiconductors and passive components. They also depend on the number of phases and the way of which the stator coils are connected. The maximum control and flexibility is obtained, with the H-bridge asymmetric type converter shown in Figure 5. Each phase has two IGBTS and two diodes. The number of semiconductors is the same that for an inverter of a synchronous machine. However, the structure is completely different. One can also notice that it is not possible to short-circuit the source because the resistance of the coils limits the current.

For switched-reluctance motors, two most used energizing strategies are possible: voltage-source strategy and current-source strategy (Figure 6). Each scheme has its own advantages and drawbacks. Current-source strategy is particularly suitable for low speed operation when the motor torque must be closely controlled with minimum ripple. On the other hand, voltage-source strategy is suitable for high-speed operation when the counter EMF is high and it is difficult to maintain constant currents. It has been pointed out that a current-controlled voltage-source converter is a good compromise for the problem of SRM energizes strategy. Current control operation provides effective torque control and inherent protection. However,
current regulation is no longer effective at very high speeds so that the converter operates in the voltage-source mode. Voltage-source is used in this work.

![Figure 5 H-bridge asymmetric converter](image)

**Figure 5** H-bridge asymmetric converter

![Figure 6 SRM Energizing strategies](image)

**Figure 6** SRM Energizing strategies, (a) Voltage-Source Strategy (b) Current Source Strategy.

### 3. SIMULATION MODEL OF SRM

The Figure 7 shows the simulation diagram used for the SRM linear model. One can note a strong aspect of the SRM simulation using Simulink that is the use of conventional blocks allowing easier understanding of the programmer’s structure. To be more complete, the block named phase1 is described with details that follow.

Figure 8 shows the content of block phase 1. It contains four other blocks, each one associated with a specific Matlab function. They are the following.

- **Switch** permits to assure the power converter commutations at angles $\theta_{on}$, $\theta_{off}$, and $\theta_d$.
- **Inductance** computes the current on the respective phase inductance according to rotor position $\theta$ and phase flux $\psi$. Therefore, one gets phase current $I$ as its output signal, as shown in Figure 7 by output block 3 named current $I$.
- **Torque** computes the torque produced in this phase according to the rotor position $\theta$ and the current value $I$.
- **Modulo $\pi/2$**: Each phase inductance has a periodicity of $2\pi/N_r$ degrees. Therefore, it is appropriate to transform the rotor position angle coming from the mechanical equation so that it is modulo $2\pi/N_r$. To take account of separating angle $\theta_s$, every phase block in Figure 7 will only differ concerning this point.
This file permits us to take account of a general model for the 6/4 SRM, meaning that the user will be able to enter other values than those utilized in this simulation without changing anything in all remaining parts.

To compute each phase electric equation (3), we avoid the derivative action. The simulation diagram in Figure 7 shows how this was achieved by using a block integrator (1/s) with saturation. This is important because it is necessary that the phase flux not become negative since the converter is unidirectional in operation. If a pure integrator had been used, followed by a saturating block, it would not have the same effect. Indeed, when the saturating block fixes the output variable to its maximum value, it does not prevent the block integrator from stopping the integration, which would introduce a false time delay in the SRM simulation results.

To begin the SRM simulation using its linear model, it is necessary to take care of choosing an initial rotor position that was not in the zone where inductance $L$ had a constant value, since there would not be torque produced. When the load torque is zero, variable $\theta$ corresponding to rotor position would not evolve and the machine will be halted all the time. However, when the load torque is not zero, the rotor position will displace to establish a rotor speed where $T_e = T_L$. For our particular machine, an initial $\theta$ superior to 15° was chosen, as we can verify by its inductance profile in Figure 1, in order to avoid the first case of zero torque load.
4. SRDAS SOFTWARE PACKAGE
SRDaS is Switched Reluctance Motor simulation software which is programmed by das commands. To simulate and analyze the electromagnetic performance of different variations of SRMs, in for instance SRDaS, is a general dynamical model derived, which also takes into account SRMs having permanent magnets. The parameters for the models are obtained with 2D-Finite Element Analysis (FEA), measurements from the developed static characterization system and with special developed SRDaS calculation module. This module is based on simple FEA routines together with some classical analytical functions/routines. The different methods to acquire parameters are all compared and it is seen that the 2D-FEA method has problems due to large end-effect, when the rotor is in the unaligned position. With the measured model parameters the developed dynamical model is also verified. A good agreement is seen between dynamic SRDaS simulations and measurements.

![Geometry editor](image)

**Figure 9** Cross section view of editor window of SRM model

5. SIMULATION RESULTS AND WAVEFORMS
The following waveform represent that inductance, current, torque and speed of SRM model at turn on angle, $\theta_{on} = 0^\circ$ and turn off angle, $\theta_{off} = 32^\circ$ and the machine functioning without load applied. In figure 10 and 11 notes that $\theta_{off}$ angle value is enough to avoid that current starts growing when the aligned position is reached. However, the total torque is always positive, as shown in Figure 12, because the negative torque produced in one phase is compensated by the other torque phases. The motor speed signal presents strong oscillations in permanent regime, as shown in Figure 13, since torque ripple is large.
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Figure 10 Inductance waveform of linear model

Figure 11 Current waveform of linear model

Figure 12 Total torque waveform of linear model

Figure 13 Rotor speed waveform
The below results are simulation model of SRM using SRDaS software package model. Here 6/4 SRM model is designed in cross section editor window as shown in Figure 9 and simulated that model as same parameters used in Matlab/Simulink environment. The results (Figure 14 and Figure 15) obtained in this model same as that of Matlab/Simulink.

![Figure 14 Phase current vs. Inductance profile waveform](image1)

![Figure 15 Total torque vs. Inductance profile waveform](image2)

6. CONCLUSION
This paper has presented and elaborated in detail the Matlab/ Simulink simulation environment for a 6/4 Switched Reluctance Motor. The results were also verified and analyzed with SRDaS software package. A simulation study using linear model is analyzed. Several simulation studies have been carried out to study the behavior of SRM using voltage control strategy. The validation study indicated that the optimum influence of turn-off angle $\theta_{off}$ allowed, minimum torque ripple reduction. The study also indicated that using the Matlab/ Simulink /SRDaS model, better accurate results were obtained.

APPENDIX

SRM Modelled Parameters
- Voltage: (150 & -150 & 0) volt
- Current: 15 A
- Base speed ($\omega$): 180 rad/sec
- Stator / Rotor poles: 6 / 4
- Stator Resistance (R): 1.30 $\Omega$
- $L_{min}$: 8 mH
- $L_{max}$: 60 mH
\[ \beta_r = \beta_s = (30^\circ) \times (\pi/180) \text{ rad/sec} \]
\[ \theta_x = (15^\circ) \times (\pi/180) \text{ rad/sec} \]
\[ \theta_y = (45^\circ) \times (\pi/180) \text{ rad/sec} \]
\[ \theta_{on} = (0^\circ) \times (\pi/180) \text{ rad/sec} \]
\[ \theta_{off} = (32^\circ) \times (\pi/180) \text{ rad/sec} \]
\[ \theta_d = (60^\circ) \times (\pi/180) \text{ rad/sec} \]

The speed is assumed to be constant and the initial condition is set to be zero. For \( N_r = 4 \), the rotor is at aligned 45°. The commutation angle \( \theta_{off} \) is chosen 30°

**REFERENCES**


