Applying POWERSYS and SIMULINK to Modeling Switched Reluctance Motor

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Abstract

Although PSPICE is a powerful tool to simulate the circuits, it is a tough job to simulate the electromagnetic behavior of a converter-fed motor drive, particularly the switched reluctance motor (SRM) with many nonlinearities in its constituted components. Therefore, a simulation environment of the SRM drive combining the features of POWERSYS and SIMULINK is developed in this paper. In the establishment of SRM system components, the nonlinear inductance-current-position characteristics are experimentally obtained initially. Accordingly, the variation of the phase inductance with rotor position is approximately represented by Fourier series with the first three terms considered. The coefficients of the Fourier series are determined by the values of the inductance at the aligned position, the unaligned position and the position midway between the two. On the other hand, the variation of phase inductance with winding current for a given rotor position is fitted by a third-order polynomial whose coefficients are derived from experimental results. The construction of other components is also described in detail. Furthermore, how to speed up the simulation is suggested. Some experimental and simulated winding current and rotor speed dynamic responses are compared to validate the effectiveness of the developed simulation environment.

Key Words: Fourier Series, POWERSYS, SIMULINK, SRM

1. Introduction

Owing to the inherent advantages of SRM’s structure [1] and converter circuits [2,3], the researches concerning driving performance improvement in switched reluctance motor (SRM) drives have increasingly attracted attention. Recently, the progress made in the motor design and the power electronic control technology has promoted the capability of SRMs in high-performance industry applications.

It is known that excellent electromagnetic operation of an SRM can be achieved only by the proper excitation and control, and this is not easy to obtain only from experiments. Consequently, the computer simulation becomes indispensable. However, the accurate simulation result is quite difficult to obtain. As for an SRM, its phase inductance is a nonlinear function of winding current and rotor position, and also time-varying. Therefore, as rotor position and winding current change with time, solving the differential methods is not straightforward. Several simulation methods have been proposed in the literature [4–7]. In [4], the basic properties of the SRM drive are simulated by inputting structural parameters into the SABER (by Analogy Ltd.) simulation package to circuit, but the control system is not included. As to [5] and [6], the comprehensive dynamic simulation models for the SRM drive using SPICE and PSPICE are developed respectively, and the latter with graphic representation is friendlier. In the models developed in [5] and [6], for the convenience of simulation, the variation of phase inductance with rotor position is expressed by some Fourier series terms. And the nonlinear relationship be-
 tween phase inductance and winding current is represented by polynomials whose coefficients are derived from finite element analysis results. Concerning [7], a dynamic simulation model of an SRM drive using SIMULINK is developed without a converter circuit included, in which, the average torque equation is expressed as $T_{av} = K i^2$, where $K$ is related to the turn-on and turn-off angles, the structural parameters of the motor, and the phase inductance.

PSPICE is basically a circuit-oriented package. It can be employed to simulate the circuit operation of any type of converter, and its simulation results can be used to determine the ratings of circuit components. However, the flexibility of PSPICE in handling simulation of the electromagnetic device and control system is low. Therefore, to simulate the overall SRM drive system modeled by PSPICE is less efficient and inaccurate. As to SIMULINK, it is a function-oriented package and one of the most effective simulation tools for control system. But it lacks ability to simulate the behavior of a converter-fed electromagnetic device. The ElectroMagnetic Transients Program (EMTP) embedded with a Transients Analysis of Control Systems (TACS) routine is suitable for power electronic system simulation. However, it is not as friendly as a commercialized package, and hence it is not a cinch for power electronic engineers to be familiar with it.

In this paper, POWERSYS manufactured by TESQSIM International Inc. [8] and SIMULINK [9] are employed to establish the simulation environment of an SRM drive, while the former is capable of simulating the converter circuit and the latter can cope with the control system. As generally acknowledged, the performance of the SRM depends basically on its inductance profile. Thus, the inductance-current-position characteristics through experiment are obtained initially. Following that, for the convenience of simulating the overall SRM drive system, the phase inductance is represented as the first three components of Fourier series whose coefficients are obtained by third-order polynomials of phase current. All unknown coefficients are acquired by fitting them to the experimental data using MATLAB. After that, the detailed procedure for developing the proposed simulation model of an 8/6 SRM drive is described. In addition, how to speed up the simulation is also suggested. Finally, some experimental results provided are compared with the simulation results to verify the effectiveness of the proposed model.

2. Governing Equations of the SRM Drive

Before going to this topic, there are some definitions to be given as follows. For phase 1 to be considered, when any pair of rotor poles is exactly aligned with the stator poles of phase 1, phase 1 is said to be in the aligned position; when the inter-polar axis of the rotor is aligned with the poles of phase 1, phase 1 is in the unaligned position. And hence, phase 1 is said to be in the middle position, when the corresponding magnetization curve is intermediate between the aligned and unaligned curves.

As sketched in Figure 1, the phase winding inductance of an SRM is a nonlinear function of rotor position and current level, which can be approximately represented as [3]:

$$L(i, \theta_e) = L_0(i) + L_1(i) \cos \theta_e + L_2(i) \cos 2\theta_e$$

(1)

where

$$\theta_e = N_r \theta_r = \text{electrical rotor angle in radians}$$

(2)

$N_r = \text{number of rotor poles}$

$$\theta_r = \text{mechanical rotor angle in radians}$$

$i = \text{phase winding current}$

And the current-dependent inductance functions $L_0(i)$, $L_1(i)$, $L_2(i)$ are expressed by three-order polynomials as:

$$L_0(i) = \frac{1}{2} \left[ \frac{1}{2} (L_s + L_u) + L_a \right] = \sum_{m=0}^{3} a_{m0} i^m$$

(3)

$$L_1(i) = \frac{1}{2} (L_s - L_u) = \sum_{m=0}^{3} a_{m1} i^m$$

(4)

Figure 1. Nonlinear characteristics of phase inductance.
\[ L_z(i) = \frac{1}{2} \left[ \frac{1}{2} (L_a + L_n) - L_m \right] = \sum_{m=0}^{\infty} a_{2m} i^{2m} \]  

(5)

where

\[ L_a = L(i, \theta_e = 0) = \sum_{n=0}^{\infty} b_{2n} i^{2n} \text{ aligned position inductance} \]  

(6)

\[ L_m = L(i, \theta_e = \pi/2) = \sum_{n=0}^{\infty} c_{2n} i^{2n} \text{ middle position inductance} \]  

(7)

\[ L_u = L(i, \theta_e = \pi) = \text{constant} = \text{unaligned position inductance} \]  

(8)

with \( b_m \) and \( c_m \) being the coefficients to be found by curve fitting. The expressions for the other phase inductances are the same as (1) but shifted by \( 0.5(n - 1)\pi \), where \( n \) represents the \( n^{th} \) phase.

### A. Voltage Equation

Through careful derivation, one can find the voltage equation of every particular phase [3]:

\[ v = Ri + L_z \frac{di}{dt} + L_{cq}(i, \theta_e) \frac{di}{dt} + e(i, \theta_e) \]

\[ = Ri + L_z \frac{di}{dt} + L_{cq}(i, \theta_e) \frac{di}{dt} + e(i, \theta_e) \]  

where the mutual inductance is neglected [10], \( v \) is the terminal voltage, \( R \) is the winding resistance, \( L_z \) is the leakage inductance, \( L_{cq}(i, \theta_e) \) is the nonlinear equivalent inductance and \( e(i, \theta_e) \) is the speed voltage. \( L_{cq}(i, \theta_e) \) and \( e(i, \theta_e) \) can be represented as respectively:

\[ L_{cq}(i, \theta_e) = L_q^* + L_q^* \cos \theta_e + L_2^* \cos 2\theta_e \]

(10)

\[ e(i, \theta_e) = -N_i \omega_s (L_q^* \sin \theta_e + 2L_2^* \sin 2\theta_e)i \]

(11)

with

\[ L_q^* = \frac{1}{2} \left[ \frac{1}{2} (L_q^* + L_n^*) + L_m^* \right], \quad L_1^* = \frac{1}{2} (L_a^* - L_n^*) \]

\[ L_2^* = \frac{1}{2} \left[ \frac{1}{2} (L_q^* + L_n^*) - L_m^* \right] \]  

(12)

\[ L_q^* = \sum_{m=0}^{\infty} (m+1)a_{2m} i^{2m}, \quad L_m^* = \sum_{m=0}^{\infty} (m+1)b_{2m} i^{2m} \]  

(13)

### B. Torque Equation

The developed torque per phase can be derived from its co-energy [3]:

\[ T_e = \frac{dW}{d\theta_r} = \frac{d}{d\theta_r} \int L(i, \theta_e) i \, di \]

\[ = -N_i \omega_s \left( \frac{1}{2} L_q^* \sin \theta_e + L_2^* \sin 2\theta_e \right) \]

(14)

where

\[ L_1^* = \frac{1}{2} (L_q^* - L_n^*), \quad L_2^* = \frac{1}{2} \left[ \frac{1}{2} (L_a^* + L_n^*) - L_m^* \right] \]

(15)

\[ L_q^* = \sum_{m=0}^{\infty} \frac{2b_m}{m+2} i^{2m}, \quad L_m^* = \sum_{m=0}^{\infty} \frac{2c_m}{m+2} i^{2m} \]

(16)

Then, one can obtain the following torque equation:

\[ T_e = \sum_{i=1}^{N} T_{im} = T_L + B_0 \omega_s + J \frac{d\omega_s}{dt} \]

(17)

where \( T_e \) is the sum of the torque developed by all phases, \( N \) is the number of phases, and \( J \) and \( B \) denote the total inertia moment and the total damping ratio respectively.

### C. Motor Drive Configuration

The complete system configuration of the SRM drive system is shown in Figure 2. It comprises an 8/6 pole motor, a converter, the commutation timing scheme, the PWM switching scheme and the associated control system. As generally recognized, the SIMULINK is not convenient for simulating such a circuit. In this paper, the simulation electromechanical model of the SRM, based on the above governing equations, is created. The converter leg/motor phase is approximately modeled using POWERSYS while the dynamic equations, the rotor position sensing and the control strategy are modeled using SIMULINK.

### 3. Proposed Simulation Model

The configuration of the proposed simulation model
representing the overall SRM drive system shown in Figure 2 is illustrated in Figure 3. The hierarchy way to construct all modules is utilized herein. The converter feeding power to the SRM is modeled by POWERSYS using the built-in blocks such as Diodes, Mosfets, Series RLC Branches, Controlled Voltage Sources, Voltage Measurements and Terminators. And, all the remaining modules in Figure 3 are modeled using SIMULINK, in which, the equations describing the electromagnetic and mechanical dynamic behaviors of the motor drive, the generation of gate driving signals for the switches, and the controllers in speed and current loops are all realized by Demuxes, Muxes, Constants, Sums, Repeating Sequences, Gains, Logical Operators, Products, Dot Products, Saturations, Integrators or Fcn. The transmission of signals among modules is controlled by In1s and Out1s, or Froms and Gotos. Considering phase 1, the various modules used for their realization are described below. All blocks used in all modules are plotted according to the notations defined in POWERSYS and SIMULINK.

A. Parameter Estimation and Representation of Nonlinear Inductance

Before establishing the proposed simulation model, the parameters of the motor’s governing equations listed in (9) and (17) are first obtained experimentally. The experiments performed in the estimation of parameters are described as follows:

1) DC test

Powering the stator winding with different values of DC voltage leads to various corresponding values of current. Thus, by calculating the sets of readings and averaging their results, the reasonable value of stator winding resistance is obtained to be \( R = 0.96 \Omega \).

2) Blocked-rotor AC test

With the rotor being blocked at a specific position, the stator phase winding is excited with a variable frequency AC source. The source frequency is varied from 35 Hz to 60 Hz in steps of 5 Hz while the current is held constant. At each frequency, the input power, frequency and rms values of input current and voltage are recorded. Similarly, readings are taken at different constant currents by increasing the current by 1A till 10A. The same procedure is repeated with an increment of 2° for the next rotor position till one rotor pole pitch is covered, namely, from the aligned to unaligned position of the rotor with respect to the excited stator. From the above sets of readings, the phase winding inductance at a specified excitation current and rotor position is obtained as:

\[
L = \frac{2\pi f}{[(I/V)^2 - (1/R)^2]^{1/2}} 
\]

\[
P = V_d I \cos \phi, \quad \tilde{V} = V_d - IR, \quad V = \sqrt{V_d^2 + (IR)^2 - 2PR} \]

\[
P_c = P - I^2 R, \quad R_c = V^2 / P_c
\]

where \( \tilde{V} \approx V \leq 0^\circ, \tilde{I} \approx I \phi, \) and \( P_c \) and \( R_c \) denote the core loss and core loss resistance respectively. The results show that the value of the inductance varies be-
tween 14 mH and 125 mH, the effect of variation of excitation frequency has a slight impact on the inductance profile, and the higher the excitation frequency is, the less the effect on the inductance. Furthermore, the experimental values of inductance do not vary with either current or frequency at the unaligned position. However, at the aligned position, the value of the inductance remains almost constant with excitation frequency but decreases with increment in current. This is due to the saturation in the bulk of magnetic material at the aligned position.

According to the state above, the measured data at excitation frequency of 60 Hz are used to fit the phase inductance listed in (1). The measured inductance-current-position characteristics are plotted in Figure 4(a). The coefficients of the third-order polynomial functions for $L_a(i)$, $L_m(i)$ and $L_d(i)$, which represent the inductances at the aligned, unaligned and middle positions respectively, are first obtained using MATLAB through measured data fitting. After that, the current-dependent inductance polynomials $L_a(i)$, $L_i(i)$ and $L_d(i)$, used as the coefficients of the Fourier series terms of $L(i, \theta_s)$, can be acquired from (3) to (8) as:

$$L_a(i) = (7.38 \times 10^{-5})i^3 - (1.46 \times 10^{-3})i^2 + (5.63 \times 10^{-3})i + 5.53 \times 10^{-2}$$

$$L_i(i) = (1.03 \times 10^{-5})i^3 - (1.92 \times 10^{-3})i^2 + (6.53 \times 10^{-3})i + 5.01 \times 10^{-2}$$

$$L_d(i) = (3.09 \times 10^{-5})i^3 - (5.03 \times 10^{-3})i^2 + (1.18 \times 10^{-3})i + 8.43 \times 10^{-3}$$

And hence

$$L_a(i) = (2.08 \times 10^{-4})i^3 - (3.88 \times 10^{-3})i^2 + (1.33 \times 10^{-2})i + 1.14 \times 10^{-1}$$

$$L_m(i) = (4.29 \times 10^{-5})i^3 - (1.96 \times 10^{-3})i^2 + (4.45 \times 10^{-3})i + 4.69 \times 10^{-2}$$

$$L_d(i) = (1.7 \times 10^{-6})i^3 - (4.3 \times 10^{-3})i^2 + (2.8 \times 10^{-4})i + 1.36 \times 10^{-2}$$

The calculated winding inductances for various rotor angles and excitation currents from the fitted nonlinear inductance function $L(i, \theta_s)$ are shown in Figure 4(b) using MATLAB along with SYMBOLIC. The comparison between the results in Figures 4(a) and 4(b) indicates that they are well-matched.

3) Other parameters

It is known that the leakage inductance of an electromagnetic device is not easy to accurately estimate. Generally this inductance is accounted to be 5~10% of the self-inductance. According to the estimated magnetizing inductances plotted in Figure 4(a), $L_i = 1$ mH is chosen herein. The mechanical parameters in (17) are $B = 0.007$ kgm$^2$ / s / rad and $J = 0.02$ km$^2$, which are obtained from the machine data sheets.

B. Converter-Fed SRM Model by POWERSYS

The power circuit simulation model for the phase 1 of the converter-fed SRM shown in Figure 2 is drawn in Figure 5. It has two power switches, two diodes, one equivalent resistance, one leakage inductance and the calculated value of the flux linkage derivative. The voltage drop across the resistance and the voltage drop across the leakage inductance are utilized to calculate the phase current and the derivative of the phase current, respectively. The time derivative of the flux linkage, $\dot{\phi}_{L1}/dt = L_m(i_1, \theta_s)(di_1/dt) + e(i_1, \theta_s)$, is regarded as a voltage
source and connected in series with the converter leg/motor phase.

C. Representation of the Time Derivative of the Flux Linkage

The blocks shown in Figure 6 are a representation of the phase 1 equation of $\frac{di_1}{dt}$ in (9). The key variables required are the instantaneous phase winding current $i_1$ and its time derivative $\frac{di_1}{dt}$, rotor position $\theta$, and speed $\omega_r$. It should be noted that the equivalent inductance term in (10) and the speed voltage term in (11) depend on both the rotor position and the phase current to take into account the effect of saturation. Besides, $C_1$ and $C_2$ are obtained from (13), and for the convenience of the calculation of the back EMF, $L_{eq}$ is divided into $L_{eq1}$ and $L_{eq2}$.

D. Gate Driving Signal Generator

The gate pulses for the two switches of each phase are decided mainly according to the sensed rotor position. The commutation logical and PWM generators shown in Figure 2 are simulated by the blocks shown in Figure 7. In order to imitating the position sensing behavior used to determine the switch-on and switch-off instants for the switches, the sine and cosine functions of the actual rotor position, together with an offset, are utilized. The generated signal $S_1$ is used to drive the lower switch and ANDed with the PWM switching signal to create the signal $T_1$ employed to drive the upper switch. The turn-on and turn-off instants of the switches for the different phases are obtained by changing the offset values. The general expressions for the gate functions to create commutation timing signals are given by:

$$G_{i1}(\theta_r) = \sin(N_r \theta_r - \phi_i) + \sin \theta_{offset 1}$$  \hspace{1cm} (27)

$$G_{i2}(\theta_r) = \cos(N_r \theta_r - \phi_i) - \sin \theta_{offset 2}$$  \hspace{1cm} (28)

where $G_{ij}(\theta_r)$ = gate function for the $i^{th}$ phase, $j = 1, 2$

$\phi_i = 0.5(i - 1)\pi$ = reference angle for the $i^{th}$ phase

$\theta_{offset 1}, \theta_{offset 2}$ = angles to decide turn-on and turn-off instants respectively

As $G_{i1}(\theta_r) > 0$ and $G_{i2}(\theta_r) > 0$, the corresponding $i^{th}$ gate pulse is created, which is generated according to the strategy one would wish to adopt. Considering phase 1,
\( \phi_1 = 0, \ G_{11}(\theta_1) = \sin(N_1\theta_1) + \sin \theta_\text{offset}_1 \) and \( G_{12}(\theta_1) = \cos(N_1\theta_1) - \sin \theta_\text{offset}_2 \). The drawings shown in Figures 8(a) to 8(d) are utilized to further illustrate how to create the commutation timing signals.

**Case 1:** \( \theta_\text{offset}_1 = \theta_\text{offset}_2 = 0 \)

**Case 2:** \( \theta_\text{offset}_1 = \pi/6 \) and \( \theta_\text{offset}_2 = 0 \)

**Case 3:** \( \theta_\text{offset}_1 = 0 \) and \( \theta_\text{offset}_2 = -\pi/6 \)

**Case 4:** \( \theta_\text{offset}_1 = \pi/6 \) and \( \theta_\text{offset}_2 = -\pi/6 \)

The commutation timing signal \( S_1 \) in case 1 is applied to single excitation and the others to multiple excitation. It is obvious that the turn-on instant in case 2 is forward shifted with respect to that in case 1, the turn-off instant in case 3 is backward shifted with reference to case 1, and the result in case 4 combines those in cases 2 and 3.

### E. Torque and Mechanical Equations

The developed torque by a particular phase expressed by (14) to (16) is simulated in Figure 9(a). Then based on (17), the mechanical dynamic behavior is simulated in Figure 9(b). All the phase developed torques are added to get the resultant electromagnetic torque \( T_e \). By inputting the load torque and the mechanical parameters \( B \) and \( J \), the rotor speed and position are solved. Besides, \( A_3 \) and \( B_3 \) are obtained from (16).

### F. Current Command Generator and Controllers

In the cascade control structure displayed in Figure 2 the control operation behaviors of current and speed loops are: (i) the speed error existing between the rotor speed and its command is regulated by the speed controller \( G_{c_\text{cm}}(s) \) to yield the current command magnitude, and then multiplied by the commutation timing signal \( S_1 \) to generate the current command \( i_{c1} \); (ii) the current controller \( G_{ci}(s) \) regulates the current feedback error \( (i_{c1} - i_1) \) to yield the control voltage \( v_{c1} \) which is compared with a triangular wave to create the PWM switching signal. Although any types of controller can be simulated by the proposed simulation environment, the proportional-plus-integral (PI) control type is adopted herein as an illustration. The transfer functions of \( G_{c_\text{cm}}(s) \) and \( G_{ci}(s) \) are:

\[
G_{c_\text{cm}}(s) = \frac{k_{m}}{s}, \quad G_{ci}(s) = k_{p} + \frac{k_{i}}{s}
\]  \hspace{1cm} (29)

Detailed block diagrams to simulate the speed and current control loops are drawn in Figures 10(a) and 10(b).

The developed simulation environment can be employed to perform the simulation of the converter-fed motor drives with different constituted circuit components and control system structures. For example, the DC-link voltage boosting and its control scheme [11] shown in Figures 11(a) and 11(b) can be utilized to promote the high-speed driving performance of an SRM.
drive. This circuit and controller can be successfully simulated by the proposed method. Detailed description of this voltage boosting circuit can be referred to [11].

4. Simulation and Experimental Results

To verify the effectiveness of the proposed simulation model based on POWERSYS and SIMULINK, some simulation and experimental results are provided and compared with each other. The configuration of the overall SRM drive system is shown in Figure 2, where the DC-link voltage source is replaced by the voltage boosting circuit [11] shown in Figure 11, i.e., $V_{dc}$ in Figure 2 is replaced by $V_t$ in Figure 11(a). Let the speed control loop be opened and $T_L = 1.5$ Nm is estimated at $R_L = \infty$. $R_L$ is the load resistance of the DC generator with its rotor mechanically coupled on to the SRM. The parameters of the current controller $G_{ci}$ are chosen to be $k_{pi} = 75$ and $k_{ii} = 10000$. The DC sources in Figure 11(a) are set as $V_{dc} = 300$ V and $V_b = 160$ V. Figures 12(a) and 12(b) display the simulated DC-link voltages, phase 1 current commands and phase 1 winding currents under the current command $I_c = 2.5$ A without and with voltage boosting, respectively. Under the same conditions, the experimental results are shown in Figures 13(a) and 13(b). Furthermore, Figures 14(a) and 14(b) display the simulated DC-link voltages, phase 1 current commands and phase 1 winding currents under the current command $I_c = 2.5$ A: (a) without voltage boosting; (b) with voltage boosting.
winding currents under the current command $I_c = 3.5\text{A}$ without and with voltage boosting, respectively. Under the same conditions, the experimental results are shown in Figures 15(a) and 15(b). Therefore, the results show that the proposed simulation environment is able to faithfully simulate the operations of the converter circuit and control system for an SRM drive.

5. Conclusion

A proper simulation environment for a motor drive is helpful in the design of its system components. In this paper, a simulation model for an SRM drive using POWERSYS and SIMULINK has been developed, where POWERSYS is appropriate for simulating the drive circuit while SIMULINK is capable of simulating the control system. First, the inductance-current-position characteristics of the SRM are obtained experimentally and then the curve fitting of phase inductance follows by using a limited number of Fourier series terms. The data generated by the fitted functions closely match those obtained experimentally. After that, the detailed procedure for establishing the modules of the proposed simulation

![Figure 13](image1.png)

**Figure 13.** Measured DC-link voltages, phase 1 current commands and phase 1 currents under the current command $I_c = 2.5\text{A}$: (a) without voltage boosting; (b) with voltage boosting.

![Figure 14](image2.png)

**Figure 14.** Simulated DC-link voltages, phase 1 current commands and phase 1 currents under the current command $I_c = 3.5\text{A}$: (a) without voltage boosting; (b) with voltage boosting.

![Figure 15](image3.png)

**Figure 15.** Measured DC-link voltages, phase 1 current commands and phase 1 currents under the current command $I_c = 3.5\text{A}$: (a) without voltage boosting; (b) with voltage boosting.
model is described. The simulated winding current and speed dynamic responses by the developed simulation model indicate that they closely match the experimental results. Finally, some comments on how to speed up the simulation are suggested.

References


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