

Multi Quadrant Operated Speed and Torque Control of Switched Reluctance Motor

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Abstract—The switched reluctance motor (SRM) is receiving renewed attention as a viable candidate for various adjustable speed and high torque applications such as in the automotive, traction and aerospace industries. The unique feature of a switched reluctance motor is its relatively simple mechanical structure; the rotor does not carry any windings, commutators or permanent magnets. The maintenance free usage makes it a good choice over other DC or AC drives. The four-quadrant operation, and the development of an optimum commutation angle controller for low output current ripple, The experimentally obtained commutation angles are compared with the data table generated from simulation results.

Index Terms—Four-Quadrant Operation, Speed control, switched reluctance motor

1. INTRODUCTION

The SRM has the simplest structure of any electric machine. It is a doubly-salient and singly-excited reluctance machine with independent phase windings on the stator, which is usually made of magnetic steel laminations. The rotor is a simple stack of laminations, without any windings or magnets. The basic 3-phase SRM structure has 6 stator and 4 rotor poles. A 3-phase 12/8 SRM is a two-repetition version of the basic 6/4 structure within the single stator geometry. Each stator and rotor pole has pole arc of 30° and 45° mechanical, respectively. The two-repetition machine can alternately be labeled as a 4-poles/phase machine.

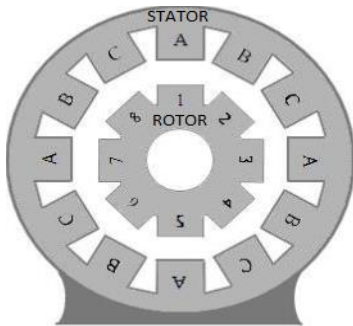


Figure 1: A typical 12/8 switched reluctance motor cross-sectional diagram.

The stator windings on diametrically opposite poles are connected either in series or in parallel to form one phase of the motor. When a stator phase is energized, the most adjacent rotor pole-pair is attracted toward the energized stator to minimize the reluctance of the magnetic path. Therefore, by energizing consecutive phases in succession, the SRM develops reluctance torque in either direction of rotation. The unsaturated phase inductance is maximum (L_a) in this position. The phase inductance decreases gradually as the rotor poles move away from the aligned position in either direction. When the rotor poles are symmetrically misaligned with the stator poles of a phase, the position is said to be the unaligned position. The phase has the minimum inductance (L_u) in this position. The extent of unaligned/aligned inductance region depends on the width of stator and rotor poles, which further reduces the torque ripple. The model is the geometry based machine model by A. Radun, which is used to develop the operation logic for four-quadrant control of a three-phase 12/8 pole SRM.

2. MATHEMATICAL EQUATIONS GOVERNING SRM

The general expression for the phase voltage of the SRM is [1, 2]:

$$V_{ph} = I_{ph} * R_{ph} + \frac{d\lambda}{dt} \dots (1)$$

where, „ V_{ph} “ is the DC-bus voltage, „ i_{ph} “ is the instantaneous phase current, „ R_{ph} “ is the winding resistance, and „ λ “ is the phase flux-linkage.

The SRM is always driven into saturation to maximize the utilization of the magnetic circuit, and hence, the flux-linkage (λ) is a non-linear function of stator current and rotor position.

The phase flux-linkage can be obtained from voltage and current measurements as follows:

$$\lambda(i, \theta) = \int (V_{ph} - i_{ph} * R_{ph}) dt = \frac{1}{\omega} \int (V_{ph} - i_{ph} * R_{ph}) d\theta \dots (2)$$

The electromagnetic profile of an SRM is defined by the λ - i - θ characteristics of the machine. The stator phase voltage in Equation (1) can be expressed as

$$V_{ph} = I_{ph} * R_{ph} + \frac{d\lambda}{dt} * \frac{di}{dt} + \frac{d\lambda}{d\theta} * \frac{d\theta}{dt}$$

$$V_{ph} = I_{ph} * R_{ph} + L_{inc} * \frac{di}{dt} + K_v * \omega$$

..... (3)

Where „Linc” is the incremental inductance, „Kv” is the current-dependent back-emf coefficient, and $\omega = \frac{d\theta}{dt}$ is the rotor angular speed. Assuming magnetic linearity (where, $\lambda = (i, \theta) = L(\theta) * i$), the voltage expression in Equation (1) can be simplified as,

$$V_{ph} = I_{ph} * R_{ph} + L(\theta) * \frac{di}{dt} + I_{ph} * \frac{dL(\theta)}{dt} * \omega$$

.....(4)

The last term in the equation above is the “Back-emf” developed in the SRM, which is similar to the back-emf in a DC motor.

3. SRM INDUCTANCE PROFILE AND MACHINE OPERATION

The shape of the inductance profile of a SRM along the air-gap between stator and rotor poles depends on the reluctance along the gap and pole-widths of stator and rotor as shown in Figure 3.1. The control algorithm is developed based on this inductance profile with respect to rotor position. Motoring can be achieved between unaligned to aligned pole positions, because of the positive slope of inductance. Similarly, along the negative slope from aligned to unaligned pole positions, generating torque can be produced.

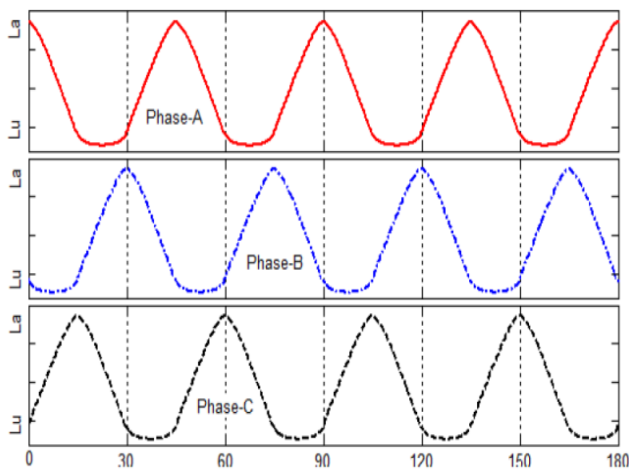


Figure 2: Phase inductance profile of a 12/8 pole SRM with respect to rotor position in mechanical degrees.

However, the current profiles for the motoring and generating modes are exactly the mirror image of each other along the aligned pole position for the same speed and symmetrical turn-on and turn-off angles as shown in Figure 3.

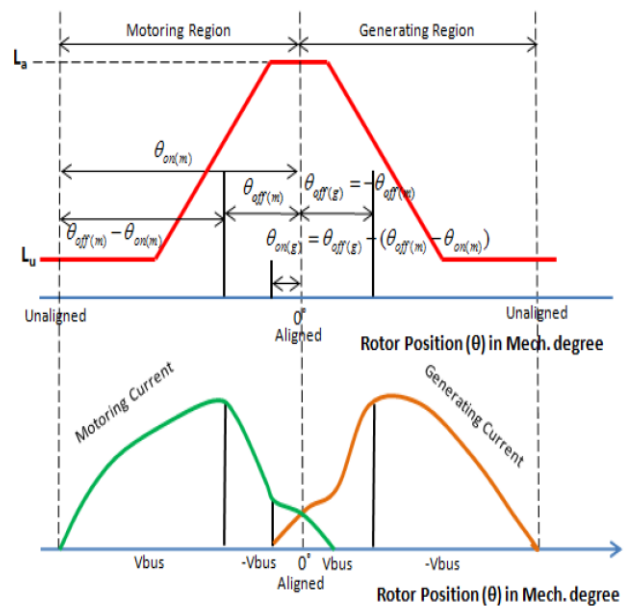


Figure 3: Motoring and generating current waveforms describing the phase inductance principle of SRM [11].

The maximum inductance in the phase inductance profile corresponds to the minimum reluctance pole-aligned position. When a stator phase is energized with the transistor switches turned ON, the most adjacent rotor pole-pair is attracted towards the energized stator in order to minimize the reluctance or maximize the inductance of the magnetic path. Therefore, by energizing consecutive phases in succession, a constant torque is developed in either direction for continuous rotation. During this operation, the inductance along the air-gap between the stator and rotor poles varies.

4. CLASSIC CONVERTER TOPOLOGY

The torque developed in a SRM is independent of the direction of current flow. Unlike induction motors or synchronous motors that require bidirectional currents to flow through the power devices, the SRM has the added advantage of reduced hysteresis losses due to the unidirectional current flow.

The converter circuit is connected to a DC source for the operation of the SRM. The most flexible and versatile four-quadrant SRM can be achieved with the classic bridge converter topology, which has two transistors and two freewheeling diodes per phase as shown in Figure (4) [1]. The transistor switches are turned ON and OFF in each phase based on controller outputs for torque and speed control of the SRM. The converter switching options for the various modes of phase operation are given in the following section.

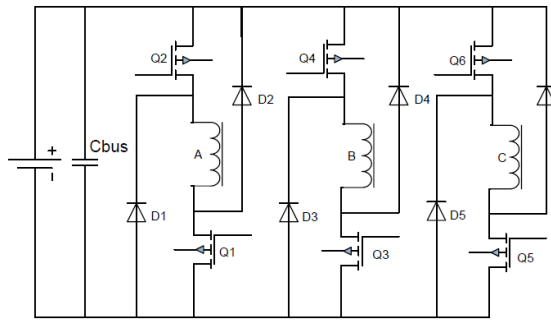


Figure 4: Four-quadrant classic converter for a 3-phase SRM.

5.CONVERTER LOGIC FOR MOTORING AND GENERATING OPERATION

There are three modes of converter operation in each phase: magnetization, freewheeling and demagnetization.

1.Magnetization period for motoring are when both the switches are turned ON and the energy is transferred from the source to the motor phase winding as shown in Figure. 5(a). For generation, the phase winding of the motor is excited initially to generate higher back-emf than the DC-link voltage (+Vdc) with the machine driven by a prime mover

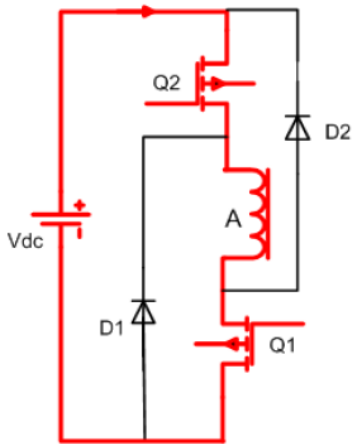


Figure.5(a):Magnetization (Q1&Q2 on)

2. Freewheeling, for motoring operation at lower speeds is accomplished by keeping one of the switches ON and switching the other switch as shown in Figure. 5(b). With only one switch ON, the motor phase gets slowly demagnetized through the respective anti-parallel freewheeling diode. For generating operation, one of the switches is turned OFF, while the other switch is turned ON and OFF. With only one switch ON, the motor phase gets slowly magnetized through the respective anti-parallel freewheeling diode.

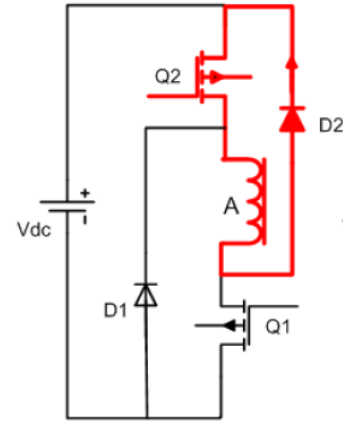


Figure.5 (b): Freewheeling (Q2&D2 on)

3. Demagnetization is achieved by applying negative DC-link voltage to the phase winding with the two switches turned OFF as shown in Figure. 5(c), helps in fast decay of current flowing through both the diodes.

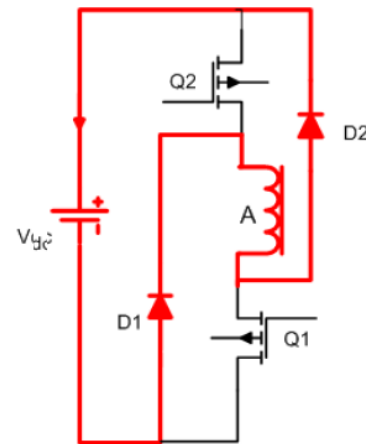


Figure.5(c):De-magnetization (D1&D2 on)

The chopping operation involves switching of the transistors connected to the phase winding accordingly for current regulation depending on the motoring or generating operation. The possible phase voltages in this PWM operation would be +Vdc (for magnetization), 0V (for freewheeling) and -Vdc(for demagnetization). The phase current control is set by 3 levels which include the reference current value (Iref) and the upper and lower hysteresis band limits. The hysteresis band value is chosen based on the peak phase current value of the machine. The chopping operation is implemented for torque control below the base speed.

The single-pulse mode of operation is possible when the machine is operated at high speeds. The possible phase voltages in this operation would be +Vdc (for magnetization) and -Vdc (for demagnetization). The current regulation is not possible in

this operation because in motoring there may not be sufficient time to reach the desired current level at high speeds or in occurs, there is no control over the diodes.

6.Four-Quadrant Operation with SRM

There are four quadrants that exist with respect to speed polarity vs. torque polarity. From the table, the each quadrant can be defined with the speed and torque.

Table 6: Four-Quadrant Operation

| Function | Quadrant | Speed | Torque |
|---------------------------------------|----------|-------|--------|
| Forward Motoring (CW Motoring) | I | + | + |
| Forward Regenerating (CW Braking) | IV | + | - |
| Reverse Motoring (CCW Motoring) | III | - | - |
| Reverse Regenerating (CCW Braking) | II | - | + |

For convenience, forward motoring is called CW motoring, reverse motoring is called CCW motoring, and regenerating can be called braking.

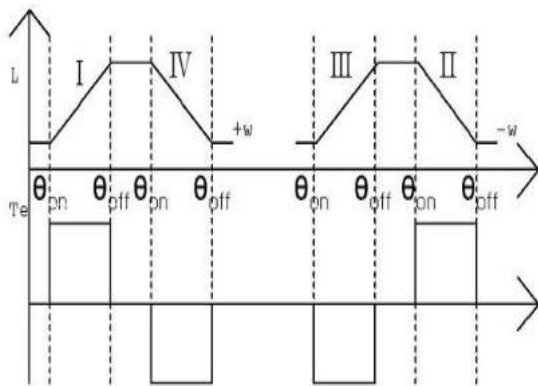


Figure 6: Four-quadrant operation with firing angle [1]

Figure .6, shown inductance profile and torque polarity with speed polarity, present a waveform, derived table 6.

generating when demagnetization

7.SIMULATION OF 12/8 SRM WITH GEOMETRY BASED MODEL

The geometry based SRM machine model by A.Radun has been used to develop the SRM simulation model in Matlab/Simulink. The block diagram of the simulation model is shown in Figure 7.0. The inputs to the machine model are the phase voltages, and the outputs are the phase currents, rotor position and electromagnetic torque.

The fundamental inputs used for this simulation are the geometric parameters and operating conditions of the machine as given in Table 7.0. The controller generates the turn-on, turn-off and phase command current based on a control algorithm, and rotor position feedback information. The sequence of phase turn-on and turn-off logic for each phase is simplified by wrapping the angles for one rotor pole period i.e., -22.5° to 22.5° (mech.) based on the 12/8 pole SRM configuration.

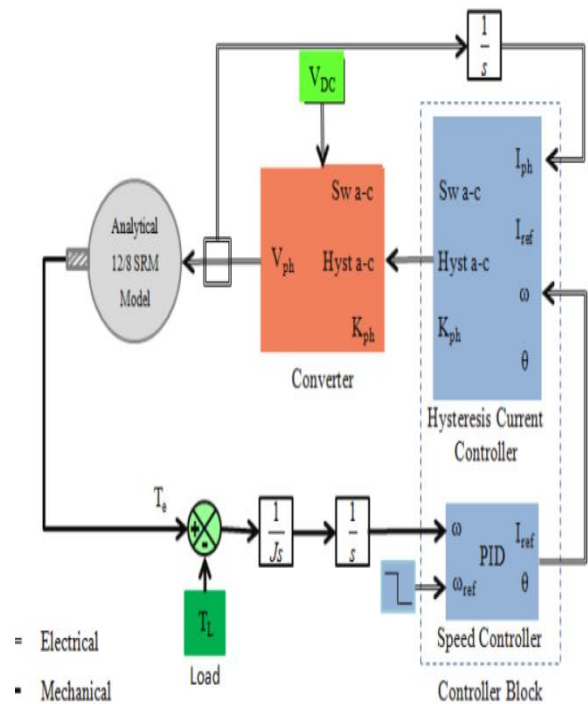


Figure .7: Simulation block diagram of analytical SRM model.

Table .2: 12/8 SRM parameters and operating conditions used in the simulation.

| Machine description | | Geometry | | Machine magnetic and phase parameters | |
|---------------------|------------|----------|--------|---------------------------------------|------------------|
| Nph | 3 | Lstk | 1.846 | Bsat | 1.8T |
| Np | 175turns | Ag | 0.015 | μ_o | $4\pi * 10^{-7}$ |
| Nrep | 2 | Rag | 1.6325 | μ_r | 3300 |
| θ_p | 15° mech | Rry | 1.2025 | Rph | 2.1 |
| Nser | 4 | Rsy | 2.233 | Imax | 5.5 |
| Npar | 1 | STF | 0.9 | ω | 1000 |
| θ_u | 22.5° mech | PULstk | 1 | | |
| θ_a | 45° mech | | | | |
| θ_{sep} | 30° mech | | | | |

Since the machine has 12 stator and 8 rotor poles, the pole arc of each rotor pole is 45°; therefore, the position is periodic within -22.5° to 22.5° or 22.5° to -22.5° (mech.) depending on the direction of rotation (forward or reverse directions, respectively). Similarly, the position wrapping for phase B and C are shifted by 30° (mech.) and 60° (mech.), respectively.

7.1 MOTORING OPERATION OF THE SRM

The best turn-on and turn-off angles are tuned for proper current and speed control based on the inductance profile of the machine. The various operations involved in modeling the closed-loop control of the 12/8 SRM for motoring are active phase determination, phase switching, hysteresis current chopping and PID speed control

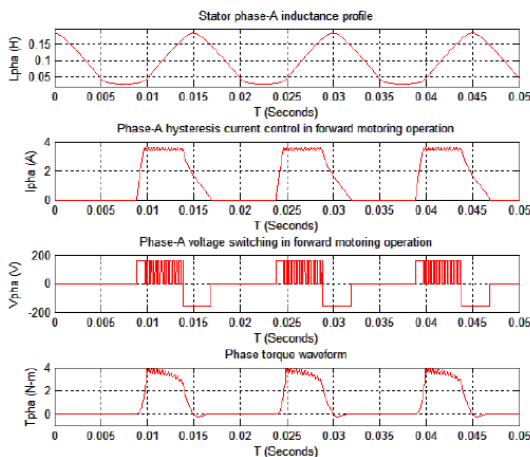


Figure .8: Motoring operation of the SRM in forward direction.

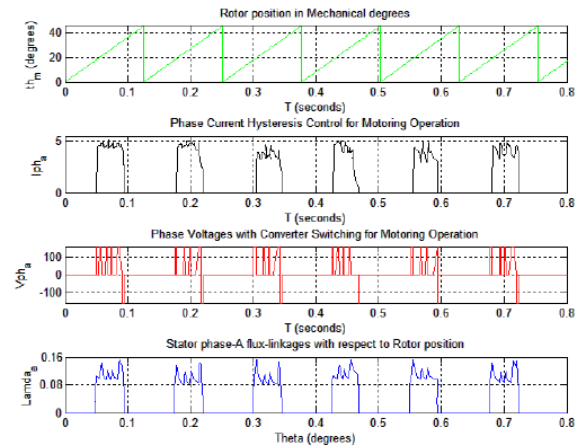


Figure .9: Motoring operation of phase-A with hysteresis current control.

7.2 GENERATING OPERATION OF THE SRM

During generation, the SRM is mechanically coupled and driven by the prime mover at constant speed as shown in Figure 2.6. The various operations involved in modeling the braking operation of a SRM are active phase determination, phase commutation, hysteresis current chopping and single-mode operation.

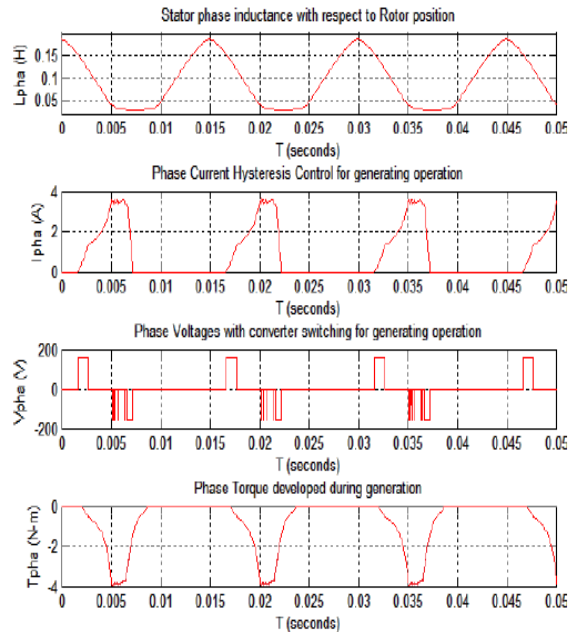


Figure .10: Generating operation of the SRM in forward direction.

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