Affordable Reference in Different Techniques of Switched Reluctance Motor Driving and Controlling

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Received: Jan 2013 Revised: Feb 2013 Accepted: May 2013

ABSTRACT:
The presented paper studies different types of strategies for Switched Reluctance Motor (SRM) controlling. In SRM control, the rotor position is the most important parameter which all controlling methods try to achieve it. Two strategies are used in SRM driving: direct and indirect strategies. Direct strategies use position detection sensors in order to detect the rotor position. Indirect techniques don’t use any detection sensor and rotor position find out by using the relationship between some parameters of the motor like phase current, coil flux, etc. Indirect strategies have many advantages over direct strategies but their implementation is more complex. The most attractive SRM controlling methods are studied and explained in this paper and at the end the best methods are introduced based on the best efficiency, simplicity and cost.

KEYWORDS: SRM, Control, Sensorless, Direct method.

1. INTRODUCTION
SRMs are one type of special machines which have many advantages like simplicity, low cost, high efficiency, ability to work in harsh environment, etc. The rotor poles have no winding which means the rotor is able to achieve higher speed. On the other hand, the machine cooling is much easier. The simplicity of these families of machines causes they require less maintenance [1], [2]. These machines are divided in two general types of rotary SRM and linear SRM. The linear SRM has two types of single stack and multi stack SRM. The rotary SRM is divided in two families of axial field and radial field SRM each has two types of internal rotor and external rotor SRM. The radial field SRMs with internal rotor which are so favorable have different types like doubly- salient cylindrical, salient pole flux path, single phase, multi layer, and SRM with field assisted. [3-7]

For SRM driving, the rotor pole position respect to stator pole is required. The stator phase should be turned on at the start of the rotor and stator alignment region and turned off before the fully aligned position. In this way, positive torque is generated and the rotor rotates. The driver uses some power electronic devices and transistors; as a result SRM wasn’t a favorite motor for many of years till improvement in power electronic in last decades. By now, a lot of driver types and methods are presented which causes SRM to be used in many homelike and industrial applications. In general, two methods are used in SRM driving and controlling: direct and indirect (sensorless) strategies. In this paper, the most famous SRM driving strategies are studied in order to select the best strategies presented so far. In direct strategies, position detection sensors like optocoupler, hall effect sensors, etc are used in order to detect the rotor position. In sensorless strategies no detection sensor is used and rotor position information is obtained using some specific parameters of the motor like current, coil flux, etc. Sensorless strategies have some advantages over direct strategies but they are more complex. In sensorless method, the motor control algorithm is changed in different speed which makes it harder.

Section one of the paper presents the mathematical model of the SRM phase which shows the relationship between different parameters of the motor. Section two presents the SRM driving method types. In section three, direct control strategies is studied and section four presents different sensorless strategies. At the end the results and conclusions are declared.

2. SRM PHASE MATHEMATICAL MODE
In general, a phase of a SRM can be modeled as RL circuit. So by applying the voltage to the phase, the equation(1) is written as:

\[ V = \frac{d\lambda}{dt} + Ri \]  

Where \( V \) is the applied voltage, \( R \) is the coil resistance, \( i \) is the phase current and \( \lambda \) is flux and written as:
\[ \lambda(\theta, i) = L(\theta) i \] (2)

Where \( \theta \) is the rotor position angle respect to the stator pole and \( L \) is the coil inductance and varies with rotor position variation in the form of Fig.1. So \( \lambda \) depends on both \( i \) and \( \theta \) which is shown as magnetization curve in Fig. 2.

In order to use the SRM as a motor the phase should be turned on in positive torque region at which torque can be generated and rotated the rotor. So rotor position is the most important parameter that is required in SRM driving.

\[ V = L \frac{di}{dt} + i \frac{di}{dt} + Ri \] (3)

The angle speed of the motor is \( \omega = \frac{d\theta}{dt} \), so equation (3) can be written as:

\[ V = L \frac{di}{dt} + i \omega \frac{d\theta}{dt} + Ri \] (4)

The expression \( e = i \omega \frac{d\theta}{dt} \) is the back EMF voltage of the motor. [8]

3. SRM CONTROLLING

In order to drive and control SRM, the rotor position information is required. By detecting the rotor position, the adequate fire pulses can be generated and sent to each phase of the motor. There are two strategies for SRM controlling:

1. Direct controller.
2. Indirect (Sensorless) controller.

3.1. Direct controller

As it’s mentioned, detecting the SRM rotor angle is the biggest problem in SRM control. One strategy of rotor angle detecting is to use position detector sensors like optocoupler, Hall Effect sensors, using additional coils, etc. Using optocoupler is the most famous strategy. As an example, for a 6 by 4 SRM, three optocouplers are installed at the back of the motor where a plate which has some wings and similar to the rotor is installed to the motor shaft. By shaft rotating, the plate moves through the optocouplers generating pulses. These pulses are used in order to determine the rotor position and produce command fire pulses. [9]

3.2. Sensorless controller

Using position sensors in the motor construction causes the motor needs more maintenance. It increases the motor wires. On the other hand, the sensor price increases the cost. The installation of the sensor on the motor is another problem as well. The sensors have some limitations which decreases the system confidence. These disadvantages cause researchers work on sensorless strategies in SRM control. Equation (4) is the general equation for SRM which shows that SRM phase has a nonlinear mathematical model and depends on different parameters. By using the equation, different sensorless methods of SRM controlling can be creates.

In this section we are going to study the different SRM sensorless driving strategies. The valuable goals in the strategies usually includes less estimation errors, high stability, less sensitivity to environment noise, disturbance and also the internal and external parameters of the driver itself. As well, improving the efficiency is preferred to be done by the controller sometimes.

Nonlinear characteristics of SRMs, high variation in value of some parameters like inductance and the speed variation cause the SRM sensorless controlling to be so complex and need high speed microcontrollers or processors to estimate and produce phase fire pulses. But the advantages of sensorless controller cause many researchers work hard to achieve an affordable SRM sensorless driver with high efficiency and low cost.

In order to control a SRM, the torque-speed characteristics should be studied at first. According to equation (4), in low speed, the back EMF voltage is negligible. So the SRM drive can be done by a simple current controller and the goals like high efficiency and minimization of torque ripple are easily achieved. In this region, the conduction pulse width is
generally put at the maximum value and is not used as a control parameter. The current curve in this region is shown in Fig. 3.a.

In average speed the back EMF voltage starts to rise up causing the rising and falling time of the phase current to be longer. This decreases the motor generated torque. This region is shown in Fig. 3.b. By controlling the conduction pulse width, we can improve the torque. In high speeds, we have a little time for the phase conduction so there is only one conduction pulse for each phase. This mode illustrated in Fig. 3.c is called one pulse mode. In this case, as turning on the phase, the voltage faces with a low inductance in the phase causes the current rises up with a high slope. When the phase is turned off, the phase which is near to alignment region has a high inductance which causes the current falls down with low slope. Since the high speed, the next phase must to be turned on so fast but the later phase is not discharged completely yet. In other word, when the next phase is turned on, the current tail of the later phase exists. Each of them magnet the rotor to themselves but the next phase has higher current which produced more torque but the later phase generated torque works as a negative torque causing torque ripple. A large number of researchers worked on the strategies in minimization of torque ripple in SRMs.

![Fig. 3. Current and inductance curves versus rotor position in different speed](image)

Sensorless strategies are divided for three ranges of speed.

1. Starting the SRM from standstill
2. Control in low speed
3. Control in high speed

### 4. STARTING THE SRM FROM STANDSTILL

#### 4.1. Lock rotor strategy

Exiting of one phase in SRM for particular time is able to align the rotor pole with the stator pole. At this time the position of the rotor is completely declared and by energizing the next phase by a sufficient logic of switching, the motor starts rotating.

Exiting of one phase may not align the rotor with stator pole sometimes because of no-torque zone which is a case when all rotor poles are not at the position in which exiting the stator pole cause alignment. As a result no torque is generated. In this situation, two phases should to be energized. This strategy may cause reverse movement of rotor at starting time [10].

### 4.2. Training pulse strategy

In this strategy a train of pulse with a constant frequency is applied to each winding of stator poles based on the desired direction of motor rotation. The frequency is then linearly increased and the rotor follows the pulses and starts rotating. This strategy can also be used in low speeds but there is no control on the motor since it’s an open-loop method. Training pulse strategy is neither optimal nor efficient but generally used in sensorless control since it simply starts the motor even under load [11].

### 4.3. Pulse detection technique

By injecting high frequency pulse to the phase of the motor at standstill situation and calculating the flux from the produced voltage and current in the winding, the position of rotor can be detected. As it’s mentioned before the inductance and as a result the flux of the phase winding is proportional to the rotor position. The frequency of pulses is selected between 3 to 15 KHz generally. Estimation of the rotor position cannot be accurate by exiting one phase. In order to accurately detect the rotor position at standstill, two phases should be exited.

This technique is also used in low speed applications. As one phase is energized, another un-energized is exited with detective pulses and at the proper rotor position it’s turned on and the later phase is turned off. Since the un-energized phases are seriously under the effect of the energized phase current the rotor position estimation is so hard in this case. To solve the problem, it’s suggested that the pulse detection technique is applied to two un-energized phases which decreases the estimation errors significantly [12].

### 5. CONTROL IN LOW SPEED

#### 5.1. Modulation based strategies

In these strategies, the rotor position detection is based on the information obtained from the modulated signal in the phase winding.

- Frequency modulation technique (FM)

In this strategy, signal with high carrier frequency is applied to the un-energized phase winding. A resistance with low value is put in series with phase winding and the current signal can be obtained. The resulting signal includes the inductance information of the phase. In fact it has some variation in the frequency in compare with the applied signal so the value of the phase inductance and the rotor position can be estimated after a simple FM demodulation shown in Fig. 4.
The phase inductance changes the frequency of the generated signal according to the equation (5):

\[ T = \frac{L}{(R_s+R_{loss})} \left[ \ln \frac{1+a_v}{1-a_v} + \ln \frac{1+a_v}{1-a_v} \right] \]  

(5)

Where \( R = \frac{R_1}{R_2} \cdot V_{o1} \) and \( V_{o2} \) are the positive and negative saturated voltages of the amplifier. \( T \) is the period of the resulting signal. The saturated voltages are assuming constant for simplicity, so the phase inductance value can be calculated as:

\[ T = K_1 L \rightarrow L = \frac{1}{K_1 T} \]  

(6)

By obtaining the inductance value, the rotor position can be detected. The accuracy and the simple logic in this strategy are its best advantages. The modulator and demodulator need some isolator components in order to isolate them from the power section which is a disadvantage in this method [13].

- Amplitude modulation technique (AM)

In this strategy, a high frequency low level sinusoidal signal is applied to the phase winding. The phase current signal is obtained by AM demodulation and filtering of the winding current as it’s shown in Fig. 5.

The current amplitude varies by phase inductance variation according to equation (7):

\[ I = \frac{V_{in}\sin(\omega t+\phi)}{\sqrt{R^2+(\omega L)^2}} \]  

(7)

By obtaining the current value the inductance can be calculated as:

\[ L = \frac{1}{\omega} \sqrt{\frac{V_{in}^2}{I_m^2} - R^2} \]  

(8)

And after that the rotor position can be estimated.

This method is optimal but since AM demodulation it needs high speed processor. There have to be well isolation between the digital and power sections in this method as well [14].

- Phase modulation technique (PM)

A high frequency low level sinusoidal signal is applied to un-energized phase in this technique. Since this voltage signal \( V_{in} \) is applied to a variable inductance, the resulting voltage \( V_{out} \) signal has some phase difference in compare with applied voltage as is shown in Fig.6 and Fig.7. The difference can use in order to calculating the inductance, therefore the position angle.

As it’s illustrated in the figures the phase difference is at its maximum value when the rotor and stator poles are in alignment position and the inductance value is at its maximum value. The phase difference has the minimum value in non-alignment position where the inductance value is minimum.

The inductance value is:

\[ L = R \tan \frac{\alpha}{\omega} \]  

(9)

Where \( \alpha \) is the phase difference in radian and \( \omega \) is the signal frequency in rad/s.

The phase difference can be obtained using zero crossing detector or even level crossing detector. The strategy is so resistant against switching noise [15].

![Fig. 4. FM demodulator](image)

![Fig. 5. The input (a), filtered (b) and demodulated (c) current signal](image)

![Fig. 6. V_in and V_out signal in aligned position](image)
5.2. Chopping strategy

In this strategy a current hysteresis controller is used to keep the current in a hysteresis band of $I \pm (\Delta I/2)$. Note that in current hysteresis controller the pulse width of the transistor gate signals or in other word the conduction angle of the phase is controlled as is shown in Fig.8. According to Fig.9, in chopping strategy, the rise time ($t_{\text{rise}}$) and the fall time ($t_{\text{fall}}$) of the current waveform vary since the phase inductance variation. So they are able to be parameters to detect the rotor position. The rise time ($t_{\text{rise}}$) and the fall time ($t_{\text{fall}}$) of the current waveform are calculated as:

$$t_{\text{rise}} = \frac{L(I(\theta), \Delta I)}{v - R_1}$$  \hspace{1cm} (10)

$$t_{\text{fall}} = \frac{L(I(\theta), \Delta I)}{R_1}$$  \hspace{1cm} (11)

5.3. Observer based strategy

In this strategy, a complete mathematical model of the motor which is based on the linear model of the motor simultaneously starts working with the real SRM. The linear model of SRM is:

$$\dot{\theta} = -R \cdot H(\theta) \cdot \bar{\phi} + v_{ph} + F_{\phi}(\bar{\phi}, \theta). (i - i) \hspace{1cm} (12)$$

$$\frac{d\phi}{dt} = -\frac{B}{J} \cdot \dot{\phi} - \frac{1}{2J} \cdot H(\theta) \cdot \dot{\theta} + F_{\phi}(\bar{\phi}, \theta). (i - i) \hspace{1cm} (13)$$

$$\dot{i} = H(\theta) \bar{\phi} \hspace{1cm} (14)$$

The input parameters are used for the both model and the output parameters are measured and compared with each other and the errors are used in order to control the machine. The control block diagram of observer based strategy is shown in Fig. 10.

The method has high accuracy, efficiency and performance. It can be also used in high speed. But the complex control algorithms and a high frequency
processor demand are the main disadvantages of the strategy. [18], [19]

5.4. Mutual voltage strategy

As the motor rotates and the phase inductance varies, the mutual voltage of the energized phase in other unenergized phases differs. So this parameter can be used in rotor position detection. The mutual voltage is calculated as:

\[ V_m = \frac{d\lambda_m}{dt} \] (16)

Where \( \lambda_m = M(\theta) \) and \( M(\theta) \) is the mutual inductance. By calculating \( M(\theta) \) and using the equation (4) at the on time, the equation (18) and at the off time the equation (19) is obtained:

\[ V_{m1} = \frac{M(\theta)}{L(\theta)} \left( V - \frac{M(\theta)}{L(\theta)} i \frac{dL}{d\theta} \theta - iR \frac{M(\theta)}{L(\theta)} + i \frac{dM(\theta)}{d\theta} \theta \right) \] (17)

\[ V_{m2} = - \frac{M(\theta)}{L(\theta)} i \frac{dL}{d\theta} \theta - iR \frac{M(\theta)}{L(\theta)} \] (18)

As it’s illustrated in the equations the mutual voltages does not depend on the rotor position only. They also depend on the current which makes the calculation so complex [20].

5.5. Resonate strategy

In this method, a signal with special frequency is applied to an un-energized phase. The frequency is designed so that in alignment position the phase faces to a resonance. The phase impedance model includes a resistant and a variable reactance. In low speed the reactance is inductive reactance but in higher speed is capacitive reactance because in higher speed, capacitive characteristics create between the winding of the phase. The signal frequency has to be lower than the frequency in which the inductive reactance changes to capacitive reactance [21].

5.6. Series capacitance strategy

In this technique a small capacitance is put in series with phase winding as is shown in Fig. 11. High frequency low level pulses are applied to the phase. Since the variation in the winding inductance, the rise time of the voltage in the capacitance varies in different rotor positions. By measuring the rise time and with a proper logic, the rotor position can be detected [22].

6. CONTROL IN HIGH SPEED

6.1. Flux calculation strategy

In this strategy the flux is calculated from the phase current and voltage. By using flux and the magnetization curve of \( \lambda - i - \theta \), the rotor position is found [23], [24].The flux is calculated as follows:

\[ V = Ri + \frac{d\lambda}{dt} \rightarrow \lambda = \int (V - Ri) \, dt \] (19)

6.2. Back EMF calculation strategy

As it’s declared before in equation (4), the expression \( i \omega \frac{dL}{d\theta} \) is the back EMF voltage which is highly under the effect of the motor speed. In low speed, we can connivance the voltage. In high speed, back EMF voltage is increased so it can be used in rotor position detection [25].

6.3. Current waveform strategy

In this method, the current waveform is used directly in rotor position detection. As it’s shown in Fig.12 the current slope is high at first which is because of the low inductance of the phase. As the rotor and the stator start aligning, the inductance increases. This decreases the current slope. The note is that in the alignment starting point the current slope is zero which is used in rotor position detection in this strategy [26-28].
6.4. Intelligent control strategy
These methods use accurate and powerful estimator based strategies like neural networks, fuzzy control. Fig.13 shows the block diagram of a SRM sensorless controller based on neural networks. In this method the flux is calculated from the phase current and voltage. Then the rotor position is estimated from the magnetization curve [29], [30].

7. CONCLUSION
This paper presented different types of SRM controlling strategies. In SRM control, the position of the rotor pole to stator pole is required. Direct strategies use position detection sensors like optocoupler, hall effect sensors, etc to detect the rotor position. Sensorless techniques don’t use any detection sensor and rotor position find out by using the relationship between some parameters of the motor like current, coil flux, etc. Sensorless strategies have many advantages over direct strategies but their implementation is more complex. Each Sensorless technique is used for specific limited range of speed. There is no method which is able to control the SRM in all ranges of speed. One type of sensorless methods classification is based on the speed they are able to operate in.

Among the presented sensorless strategies, the training pulse method and pulse detection technique can be selected as the best methods in starting motor from the standstill position. Training pulse method although is an open loop method, is able to start the motor even under load. In pulse detection strategies, the desired phase is detected and motor can start rotating properly. At low speed, modulation strategies are good choice. Although they are so complex but their accuracy makes them favorable. At high speed current waveform strategy is so simple and efficient. Intelligent control strategy is so accurate but they need a robust and high frequency processor for their calculation. Researching on a sensorless strategy in which SRM can be controlled in all ranges of speed is proposed as future work. In the method the complete equation of the SRM which includes the behavior of the SRM in all ranges of speed should be used.

REFERENCES


