Sensorless Rotor Position Estimation For Switch Reluctance Motor: A Review

T. M. Shubham, Pramod Pal
M.Tech Scholar, Department of Electrical Engineering,
Maulana Azad National Institute of Technology Bhopal

Amit Ojha
Assistant Professor, Department of Electrical Engineering,
Maulana Azad National Institute of Technology Bhopal

***Abstract*- Rotor position information in SRM is important for steady state operation because nature of torque depends entirely on inductance profile of machine. Inductance at any instant depends on rotor pole position with respect to stator pole of energized phase. So, it is necessary that information of rotor position should be specific throughout operation right from starting of motor. Easiest way of collecting rotor position information is using position sensors but it reduces reliability and putting further mechanical constraints. Efforts being made to replace position sensors and proper position estimation techniques are being applied called as sensorless techniques. In this paper, different sensorless position estimation techniques are discussed with their shortcomings.**

Keywords- AC- DC convertor, Asymmetric H-bridge, Reluctance torque, State observer, SRM

I. INTRODUCTION

Nowadays Switched Reluctance Motors (SRM) is becoming popular in the field of automation industry due to its several advantages. It has simple structure and has good mechanical strength due absence of rotor winding and permanent magnet rotor. SRM does not contain conductors which permits it to achieve high efficiency especially in high speed region for prolonged operation. Also the copper losses are less in SRM then any motor. The main agenda in motor drives is to obtain a low cost, high performance motor drive but both are contradictory parameter, therefore main focus of researchers is to obtain an optimal solution. Now the problem faced during operation of SRM is torque ripple, accuracy in position estimation and stored reactive power.

Torque ripple can be minimized by increasing the number of stator phase but consequently it increases the cost. Stored reactive power is handled by using capacitors.

This paper is focused on rotor position estimation. Position of rotor is defined in terms of the position of rotor poles with respect to stator poles. It can be done either by use of sensors (like encoder, hall sensors) or by use of mathematical modeling (sensorless) for position estimation. Obviously sensorless techniques are cost effective but accuracy is an issue. Due to non linear magnetic structure, it exhibit variable inductance. Torque will also be variable in nature as it is proportional to the rate at which inductance is varying so it may be positive, negative or zero (positive torque is the torque which drive rotor in required direction) at any instant of operation as shown in figure 1. The nature of starting torque will depend on position of rotor accordingly it can move forward or backward. Sensorless operation in running condition can't be implemented without proper starting technique. Proper algorithm is desired which will give better estimation of position during running. There should be proper technique to start motor conveniently. In this paper different sensorless techniques both for starting and steady state running are discussed.

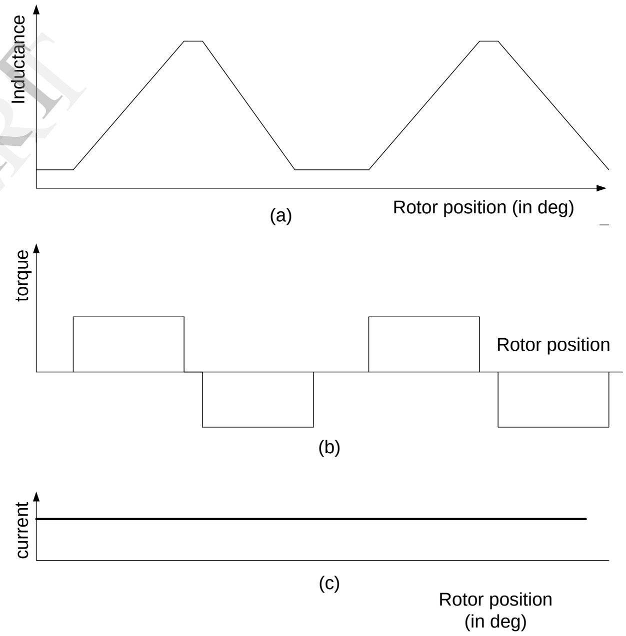

Fig 1(a) inductance variation v/s rotor position (b) torque variation v/s rotor position (c) current v/s rotor position

II. BASIC MODELLING OF SRM

SRM is an electric machine that operates due reluctance torque. In SRM, both stator and rotor have salient-poles, which contributes to produce a reluctance torque

The basic principle of SRM operation is that when a stator phase is excited, the rotor of the SRM always rotates to the nearest position of minimum reluctance (when stator and rotor poles aligned). To minimize reluctance of flux path rotor poles tend to align with stator poles by producing reluctance torque. When stator pole becomes nearly aligned

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with rotor pole, the excitation of active coils is removed because after that rotor will move further and there is decrease in inductance. As the rate of change of inductance will become negative the torque will produce in negative direction. And hence opposes the normal motion of machine. Therefore the adjacent winding will be energized and the previous winding will be de-energized and same process goes on further. By selectively exciting the stator pole pair continuous synchronous motion can be produced. The number of poles on SRM stator is usually unequal to number of poles on rotor to avoid the possibility of zero initial torque.

The fundamental equations of an SRM can be generated in terms of phase voltage and torque as follows

$$V = R.i + L(\Theta_{rms}, i)\frac{di}{dt} + i\frac{dl(\Theta_{rms}, i)}{d\Theta_{rms}}\omega_{rms} \qquad (1)$$

$$T_m = \frac{1}{2}i^2\frac{dl(\Theta_{rms}, i)}{d\Theta_{rms}} \qquad (2)$$

where, R : resistor of phase winding,

Θ_{rms} : rotor position,

ω_{rms} : rotor speed,

$L(\Theta_{rms}, i)$: inductance is linearly varying with rotor position for a given current

Now in equation (2) it clearly observed that motor torque is directly proportional to rate of change of inductance. As the rotor pole approach to the stator pole, inductance increases and slope is positive and hence the torque. But as rotor pole get completely aligned with stator pole and starts moving away from stator pole it's inductance starts decreasing and slope become negative thus making torque negative.

So firstly we have to find the position of rotor at standstill and should apply the supply in such a way so that positive torque is produced

Where R_n, I_n, v_n and are the resistance, current, and voltage of the n^{th} phase respectively. It is assumed that each phase is magnetically decoupled from every other phase. The rotor angular position and velocity are denoted by Θ and ω, respectively. T_L is the load torque.

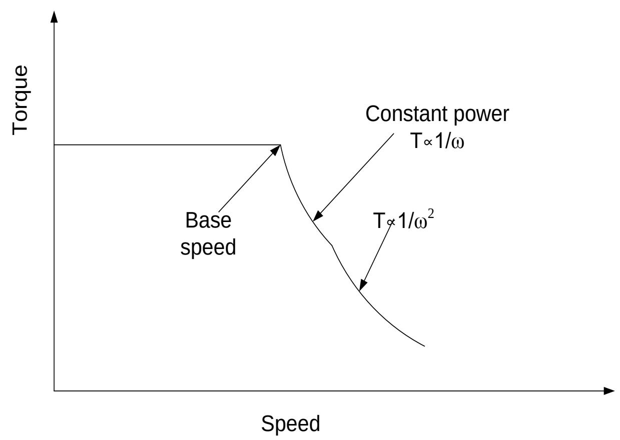

Fig 2 Speed Torque characteristics of SRM

III. STARTING OF SRM

Different methods are discussed for starting of motor without using sensors.

A. Feed Forward Open Loop Method

The motor is controlled feed-forward in open loop as a stepper motor. In this method a train of pulses of fixed frequency is applied to each phase of motor in a sequence. Each phase pulse train is phase shifted by 22.5 degree. Now frequency is increased linearly in order to increase the rotor speed.

Shortcomings- It is neither efficient nor optimal, but it permits a reliable start even under load.

B. Locking the rotor along a particular phase axis

In this method one phase is excited for sufficient time so that rotor may experiences a force and rotor poles get aligned to one of stator poles. Once the rotor poles get aligned to any stator poles the position of all the phases with respect to rotor can be obtained and with suitable switching logic motor can be started.

Shortcomings- The inductance profile of SRM is such that there is no- torque zone near aligned and non-aligned region in which even if we excite rotor winding, motor will not experience any torque. So if rotor is positioned in that region then motor cannot be started.

C. Flux Computation Technique

In this method, voltage pulse is injected in any phase and flux linkage is computed. Using the value of current and flux, position of rotor in starting can be obtained by using flux linkage characteristics same as in running condition. Theoretically, in this method excitation of one phase may not give the accurate result, so two phases will be excited at a time to get a better and accurate result. Besides if particular phase is in the no-torque zone then estimated position will be error prone.

Shortcomings- Before the actual start, rotor may move backward and hence hesitation is observed.

D. Three Phase Excitation Method

This method is most reliable for estimation of rotor position for starting of SRM. In this method test signals are given to excite all the phases simultaneously. By exciting all the phases' up to a moderate value of flux and current such that there will be no appreciable rotor movement. Now during excitation current of all the phases are measured. The phase will have maximum inductance with which rotor poles are aligned. So that phase will have minimum current among all phase.

Shortcomings- Extra care has to be taken while choosing the time duration for excitation of phases because if we excite the motor for long time the rotor will experience a force, which may be negative or positive so again there will be change in rotor position.

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IV. SENSORLESS METHOD FOR RUNNING

Running of SRM requires a DC source, power convertor like asymmetric H-bridge. DC source can be obtained by using any AC- DC convertor. There are many power convertors which are used for driving SRM. Controllers are used to control timing and width of switching pulses given to power switches of power convertor. Due to its non linearity SRM produce all three types of torques i.e. zero, positive and negative torque.

Pulses should be given to power switches at the instants when rotor is in such position that machine can give positive torque to rotor. So basis of controller is position sensing. Now position sensing can be done by either using sensor or without sensor i.e. sensorless. In sensorless methods position of rotor is to be estimated. More accuracy in position sensing leads to good performance as accuracy increases machine performance also improves. Methods of position sensing are classified as follows:

The sensorless methods of estimation can be classified into modern control-based and inductance-based estimation schemes.

The inductance-based estimation methods exploit the inherent unique characteristic of the three-dimensional relationships among the flux linkages or inductance, current, and rotor position,. And the availability of the first two variables leads to resolution of the third unknown, i.e. rotor position. A number of methods does exist using inductance-based estimation. They can be further divided into direct and indirect forms of inductance measurement. The salient difference between these methods lies in which either the inductance is measured directly or by monitoring other variables.

The modem control methods are based on observer and intelligent control techniques. The observer-based methods use a state observer or a sliding mode observer, both of which essentially depend to an extent on the inductance slope for their convergence and functioning. The observers are computationally intensive and have the problem of convergence in terms of the time taken to converge to the correct estimates. The intelligent control methods encompass estimators based on artificial neural networks and fuzzy control. These methods are computationally less intensive compared to observer methods but due to their learning capability provide adaptive control. The accuracy of the rotor position estimation is not sufficient for high-performance applications, such as a position servo control application, but is acceptable in many other industrial applications. Most of the sensorless methods require phase currents and applied voltages for their estimation.

A. Inductance-based estimation method

Machine has inherent property of variable inductance. Inductance is a function of rotor position. Reluctance torque is a function of inductance and current but DC source is used in operation so torque is solely depends on rate of change of inductance.

Here flux linkage is used for estimation of rotor position. Flux linkage is also proportional to inductance as current is constant so with the help of flux linkage also rate of change in inductance can be traced since inductance is not measured directly. This method can be called as indirect method

This method is based on the comparison of the estimated flux linkage and the reference flux linkage in order to define turn-off (commutation) position. This is called on-off control method. In this method, actual flux linkage value is compared with reference value. When the estimated flux linkage is nearly equal to the reference flux linkage, it indicates that the switching position has been reached and the commutation can be performed .Gate pulse is removed, convertor switch is turned off and the following phase is turned on. Reference flux linkage is obtained from the magnetization characteristic as a function of phase current for the desired commutation position. The reference flux linkage is obtained from the flux linkage in the aligned position of the rotor. Flux linkage is calculated and it is compared with the reference level from the reference magnetization curve.

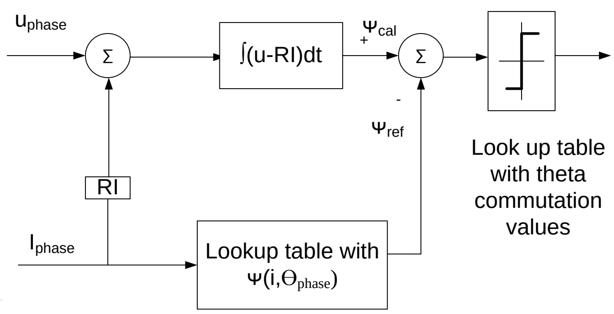

Fig 3 Block Diagram for angle control method

Voltage equations, neglecting the saturation and the induced voltage, can be expressed as follows:

$$V = RI + L(\theta)dI/dt \qquad (3)$$

$$\Psi = \int_0^t (V - RI)dt \qquad (4)$$

Using equation (4) flux linkage (reference value and actual value) can be calculated

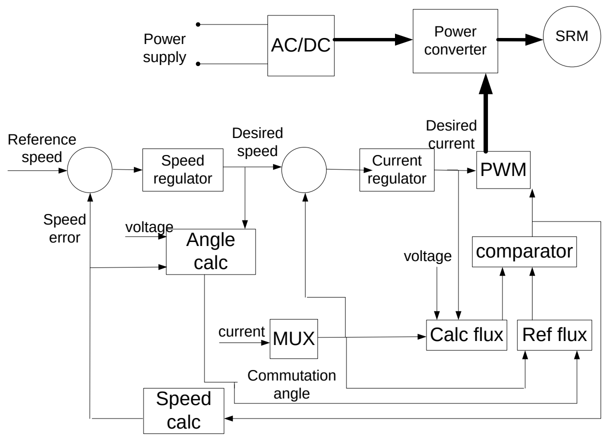

Fig 4 Speed Control of SRM

B. Sliding mode observer

The magnetic nonlinearities of an SRM can be taken into account by appropriate modeling of the nonlinear flux-current- angle (ϕ-i- Θ) characteristics of the machine. The output electromagnetic torque of the machine can also be described by nonlinear torque-current-angle (T-i- Θ) data.

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The machine model may be described by

$$\Phi = \Phi\,(I,\theta) \quad (5)$$

$$T = T\,(I,\theta) \quad (6)$$

The state-space differential equations of the SRM to be solved are

$$\frac{d\phi_n}{dt} = -R_n I_n(t) + v_n \quad (7)$$

$$\frac{d\Theta}{dt} = \omega(t) \quad (8)$$

$$\frac{d\omega}{dt} = -\frac{D}{J}\omega\,(t) + \frac{1}{J}\sum_n T_n(\Theta,\phi_n) - \frac{1}{J}T_L \quad (9)$$

Sliding mode observer or state observer depends up to an extent on the inductance slope for their convergence and the sliding-mode observer incorporates a state-space model of the SRM to estimate rotor position and velocity. The sliding-mode observer estimates rotor position and velocity from phase current and terminal voltage measurements. An error correction term is computed based on the difference of the motor flux computed from the mathematical model and that derived from motor measurements.

$$\Phi_n(t) = \int_0^t [v_n(t) - I_n(t)R_n]dt \quad (10)$$

Consider a second-order sliding-mode observer for the SRM of the form

$$\widehat{\Theta} = \widehat{\omega} + k_\Theta \mathrm{sgn}(e_f) \quad (11)$$

$$\widehat{\omega} = k_\omega \mathrm{sgn}(e_f) \quad (12)$$

Where $\widehat{\Theta}$ and $\widehat{\omega}$ are the estimated rotor position and velocity, respectively, and e_f is an error function based on measured and estimated variables.

$$e_\Theta(t) = \Theta(t) - \widehat{\Theta}(t) \quad (13)$$

$$e_\omega = \omega(t) - \widehat{\omega}(t) \quad (14)$$

Differentiating both sides of (13) yields

$$\frac{de_\Theta}{dt} = \frac{d\Theta}{dt} - \frac{d\widehat{\Theta}}{dt} \quad (15)$$

Substituting eq. (11) and eq. (13) in eq. (15) produces

$$\frac{de_\Theta}{dt} = \omega(t) - \widehat{\omega}(t) - k_\Theta \mathrm{sgn}(e_f)$$

And using (12) yield the position error dynamics

$$\frac{de_\Theta}{dt} = e_\omega - k_\Theta\,\mathrm{sgn}\,(e_f) \quad (16)$$

Similarly velocity error dynamics become

$$\frac{de_\omega}{dt} = -k_\omega\, sgn(e_f) \quad (17)$$

Thus, (16) and (17) describe the convergence properties of the observer. Once the sliding surface $e_\Theta = 0$ is reached, the error dynamics become

$$\frac{de_\Theta}{dt} = 0$$

$$\frac{de_\omega}{dt} = -\frac{k_\omega}{k_\Theta}e_\omega$$

To keep the system in the sliding regime, a proper equation must be defined for the sliding surface as a function of the system states, in this case the equation of sliding surface is $e_\Theta = 0$.

Slide Mode Controller (SMC) forces the system states to slide on $e_\Theta = 0$ surface in the state space. If the states slide on the desired surface that means that the system is under control. If the numerical value of $e_\Theta = 0$ is equal to zero, than the system is on the sliding surface, otherwise, not. The numerical value of $e_\Theta = 0$ is calculated by entering the actual values of the states. When $\sigma(x)$ is greater than zero, this means that a control signal must be applied to decrease the value of $e_\Theta = 0$. The opposite occurs when $e_\Theta = 0$ is less than zero.

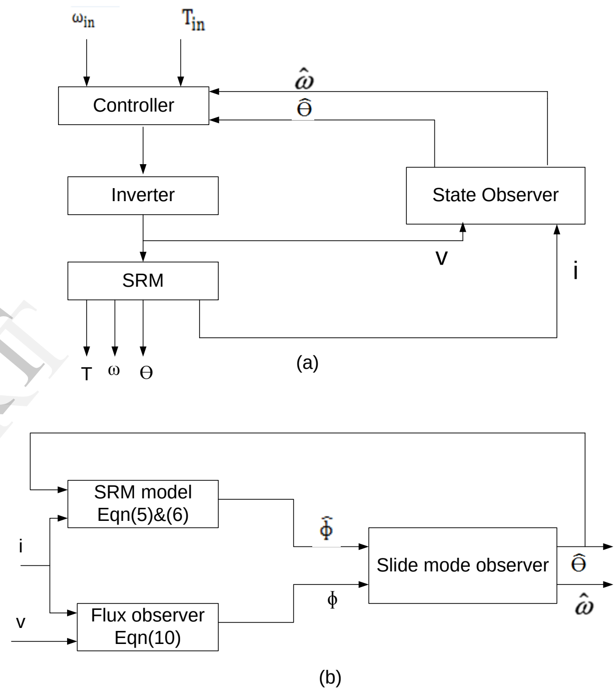

Fig 5 (a) Block diagram of model based sensorless controller. (b) Sliding mode observer theory based observer

V. CONCLUSION

Of all the methods used to start SRM, three phase excitation method is most effective but care should taken while implementing because if we give keep supply for long time the rotor will change the position. In sensorless methods used for steady state operation, inductance based estimation method is more reliable because it easy to implement. While state observer are computationally intensive and have the problem of convergence in terms of the time taken to converge to the correct estimates. Still it has been studied extensively to tackle problems of the nonlinear dynamic control systems.

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