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ROTOR POSITION OF SWITCHED RELUCTANCE MOTOR USING SENSORLESS METHOD

[1]RAMESH PALAKEERTHI AND [2]Dr. P. SUBBAIAH
[1]Research scholar, Dr. MGR Educational and Research Institute University, Chennai, INDIA
[2]Professor, sriSunflower College of Engineering & Technology,Challapalli, INDIA

Email: [1]rams.palakeerthi@gmail.com,[2]subbaiah_nani45@gmail.com

ABSTRACT

Switched reluctance motor (SRM) is an energy converter that converts an electrical energy to mechanical energy in motoring operation and vice-versa in generating operation. When the rotor is out of alignment, the inductance is very low and the current also increase rapidly. The rotor is aligned with the stator then the inductance become very large. In the simulation results, how the rotor minimizes the reluctance position during excitation in a magnetic circuit is presented in this work.

Keyword: *Switched Reluctance Motor (SRM), Rotor Position, Sensorless Method, Flux linkage.*

1. INTRODUCTION

SRM can be classified on the basis of the nature of motion. SRMs are further differentiated by the nature of the magnetic field path as to its direction with respect to the axial length of the machine. If the magnetic field path is perpendicular to the shaft, which have been seen along with the radius of the cylindrical stator and rotor, the SRM is classified as radial field [1]. When the flux path is along the axial direction, the machine is called an axial field SRM. It can be divided into shorter and longer flux paths based on how a phase coil is placed [2].

The SR machine torque produce a phase which is excited by applying a voltage and the current in the coil produces a magnetic flux through its stator poles and this flux flows through the pair of nearest rotor poles and exist magnetic reluctance [2]. The reluctance of the flux path is at its minimum in the aligned position and maximum in the unaligned position. The rotor poles of an SR machine do not require magnetic poles to produce torque [8]. The radial magnetic attraction in SR machine becomes ten times larger than the circumference forces produced by machine position. However, the rotor is displaced to either side of the unaligned position, there appears a torque and attracts towards the next aligned position. The torque is proportional to the square of the current; hence the current can be unipolar to produce unidirectional torque. The direction of rotation can be reversed by simply changing the sequence of stator excitation. Torque and speed control is achieved with converter control. The variation of reluctance with respect to rotor position is shown in Figure 1.

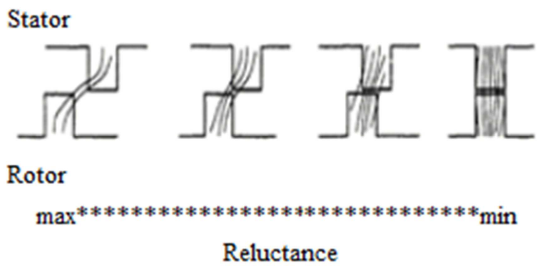

Fig. 1 Variation of Reluctance with respect to Rotor Position

The knowledge of rotor position is essential for the speed control of a SRM drive, since with the rotor position, can determine which phase should be supplied to provide positive or negative torque. Moreover, another feature affects torque control: current reference for hysteresis control. The block diagram of SRM control is given in Figure 2 and the control can be divided in two parts,

(i) Current reference settling and
(ii) Choice of the phase to be fed.

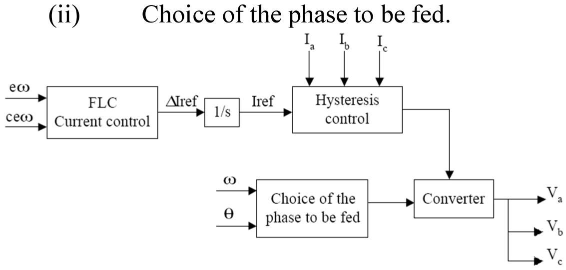

Fig. 2 Block diagram of the SRM control

The structure of SRM drive System is shown in Figure 3. A typical SRM drive system is made up of four basic components are,

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(i) Power converter,
(ii) Control logic circuit and
(iii) Position sensor.

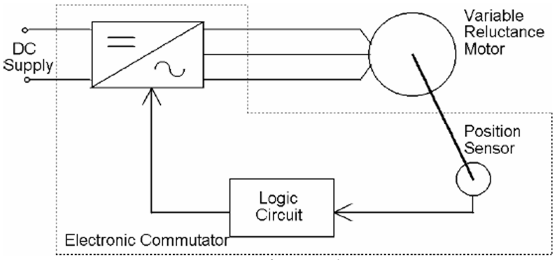

Fig. 3 Structure of SRM drive System

2. PREVIOUS WORK

Cheok, AD and Ertugrul, N [1995] presented the position sensors are to obtained rotor position measurements that can eliminate the sensors. JP Lyons, et al., [1991] proposed flux/current methods for SR motor rotor position information. Vikas S. et al., [2009] presented to investigate the fast on-line training back propagation algorithm for feed-forward ANN, which is suitable to identify the status of a SRM to minimize the torque ripple. Gupta, et al., [2010] proposed sensorless control of switched reluctance motor drive with fuzzy logic based rotor position estimation. Ibrahim [2008] presented a rotor position which is based on a phase-by-phase basis and measuring the flux linkage and current when the estimated position is reached. C. Elmas, et al., [1994] proposed modelling of a nonlinear switched reluctance drive based on artificial neural networks. Kopecký, M. [2002] proposed high efficiency of SRM to use the motor in application of the runabout with battery source. I. Husain et al., [1996] proposed torque ripple minimization in SR motor drives by PWM current control and distributes the desired torque to adjacent phases during predetermined commutation interval using the torque distribution function. Y.J. Zhan, et al., [1998] proposed a novel position and velocity observer for robust control of switched reluctance motors. Wei and Fahimi [2014] presented to sensorless methods with the occurrence of phase faults and introduce strategies for sensorless operation of SRM under single and multiphase faults. J.P. Lyons, et al., [1991] proposed SR motor position estimation schemes for a numerical table of measured static motor is used to describe the motor and measured motor data that provide a numerical model of the static angle versus flux linkage and current characteristics. A.D. Cheok [1998] proposed a new fuzzy logic based sensorless rotor position estimation algorithm for SRM. Traore, D., et al., [2008] proposed high-order sliding-mode controller and adaptive interconnected observer for sensorless induction motor. DiRenzo and Khan [1997] proposed to use an intermediate magnetization curve for rotor position estimation. Jun and Zhiquan [2014] presented to estimate switching-on and switching-off flux linkage from the switching angles range and measured phase current that obtained for sensorless control and rotor speed estimation. J. Bu and L. Xu [2001] proposed eliminating starting hesitation for reliable sensorless control of switched reluctance motors. Hongwei Gao, et al., [2004] proposed SRM is modeled by equations based parameters such as flux, current and torque, speed and inductance.

3. ROTOR POSITION ESTIMATION OF SRM

To model a fuzzy rotor position estimator for SRM, the SRM magnetization curve (Flux linkage-current-rotor position) is used in a fuzzy rule base, where several rotor position data's are stored in fuzzy rule-base tables. The position information can be taken from the rule base tables during operation. This rule base table provides several values of rotor position from the inputs of the fuzzy model. This rule is used for mapping the input values of flux linkage and current to output value of rotor position in terms of an angle. A variable in fuzzy logic has sets of values, which are characterized by linguistic labels, such as small, medium, and large etc. Each set is again characterized by membership function varies from 0 to 1. Thus, fuzzy sets can have mathematical representation of linguistic values. The fuzzy logic system is represented in four parts;

(i) The fuzzifier,
(ii) The rule base,
(iii) The interference engine and
(iv) The defuzzifier.

In controller, the estimated angle is compared with measured angle and fuzzy rule base is updated according to the error. In this case, the input are flux linkage and current [0–1] and [0–20A] respectively. Similarly, the angle is defined as 0–30 degrees and the fuzzy sets are chosen to be isosceles triangular shapes.

3.1 Rotor Position Detection

In salient-pole motors the rotor asymmetry leads directly to differences in the magnetic reluctance values in the rotor direct axis (*d*-axis), which is the axis of permanent magnet flux, compared to the values available in the quadrature

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axis (q-axis) which is the axis perpendicular to d-axis. Therefore, measuring both the values, the initial rotor position can be derived. However, the majority of permanent magnet drives are of non-salient nature, (e.g. bread loaf or radial magnet design) where the values of L_d and L_q are nearly equal. The rotor position detection technique is caused by magnetic saturation in the stator laminations and found in every permanent magnet motor. The reason for this is that, almost every electric motor design targets its cost minimum. It leads to high magnetic loading inside the motor, (i.e. magnetic flux densities from 1.5T up to 1.8T in the stator tooth areas) to achieve high drive efficiency and good utilization of the motor materials. Flux densities of that level cause light up to middle saturation in the electromagnetic paths of the stator windings. Since, the motor windings are equally distributed within the stator bore; the teeth belonging to one phase have different locations within in the stator bore relative to the teeth of the next phase. Hence, the degree of saturation of the teeth belongs to a phase, which depends on the rotor position.

4. SENSORLESS CONTROL METHOD

The sensorless control method is to determine the appropriate moment when the motor winding should be commutated by the rotor position [17]. The initial rotor position is not necessary for the start-up and for a proper compensation in the observer equation. The sensorless control system is rotor flux oriented vector control, which is shown in Figure 4. The d-axes current is controlled to be zero which gets the largest torque with the smallest phase currents. Since, the terminal voltages of motor are hard to measure; the voltages are used instead of the real voltages.

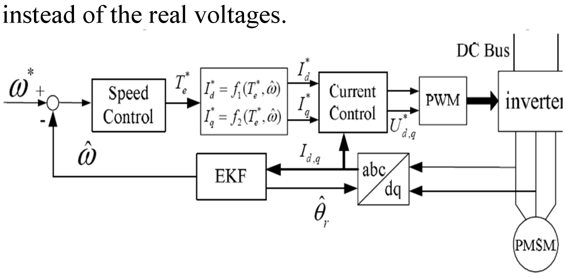

Fig. 4 Block diagram of the sensorless system

The sensorless control of the SRM approach can be classified within the magnetization-data based methods that form a very efficient mapping structure for the nonlinear SRM using ANN. The ANN training data set comprises of magnetization data of the SRM for which flux linkage (λ) and current (i) are inputs and the corresponding position (θ) is the output. Given a sufficiently large training data set, ANN can build up a good correlation among λ, i and θ using appropriate network architecture. It is evaluated against a test data set which has different λ – I values. The sensorless control algorithm is shown in Figure 5.

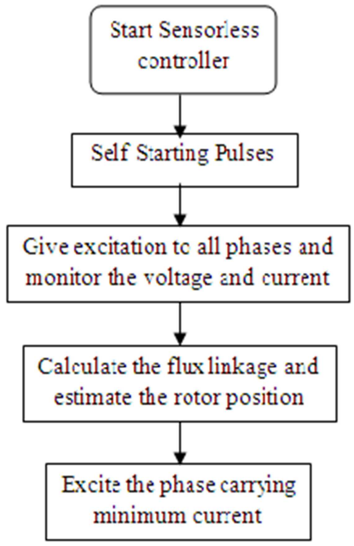

Fig. 5 Sensorless Control Algorithm

4.1Principles of the Sensorless Scheme

4.1.1 Impedance Sensing Method

The principles of the position estimation scheme, which refer to as impedance sensing have the voltage equation of each stator phase voltage given by eqn. [1],

$$v = iR + \frac{Li}{dt} = iR + L\frac{di}{dt} + i\,\frac{\partial L}{\partial i}\frac{di}{dt} + i\omega\frac{\partial L}{\partial \theta} \ldots (1)$$

where, L = phase inductance,
R = phase resistance,
i = phase current,
ω = dθ/dt = speed and
θ = rotor position.

The impedance sensing scheme requires only discrete rotor positions to be detected for successful commutation. The rotor positions sensing is accomplished by comparing Δi to a threshold value as shown in Figure 6. Each phase is assumed to be active for30° (120° elec.) and only one phase is excited at one time. For example, while phase A is the active phase, the last phase C is injected with pulse voltage, the response current i_c is compared with the threshold current. While i_c is greater than the threshold, phase A is turned off and phase B is turned on. The commutation can be advanced by reducing or increasing the threshold.

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In this way, when one phase is active, last phase is sensed to generate the signal for commutation. The rotor speed is estimated by the interval of the commutation signal.

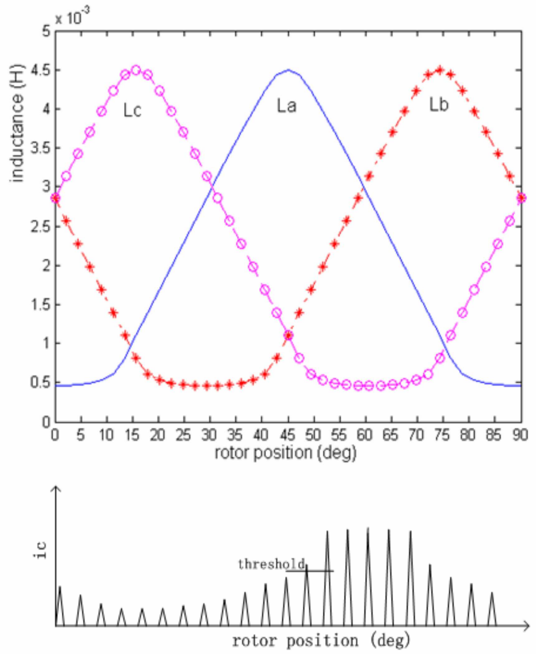

Fig. 6 6/4 SRM inductance profiles and sensing current for phase [14]

4.2 Advantages for Sensorless Algorithm

Rotor position sensors add hardware complexity, connectivity problems and reliability issues that make the drive system prone to failure. The removal of the SRM position sensors is to improve the robustness of the system by developing control algorithms that eliminate rotor position sensors. These systems are typically called sensorless drives, which have no position sensors. If sensorless SRM drives are to become replacement technology for induction drive applications, sensorless schemes for SRM drives must have the same robustness and reliability as induction drives. To achieve the goal, robustness must be designed into the algorithm because sensorless techniques are noise and error sensitive. However, inherent reliability occurs just by the omission of the sensors as well as the reduction of hardware therein.

The SRM structure gives electrical states with respect to rotor position, whether the sensorless technique uses a lookup table for flux-linkage, active current probing are the typical quantities used to derive rotor position. The various genres by which sensorless SRM algorithms can be classified are,

(i) Hardware-intensive methods,
(ii) Lookup table methods,
(iii) Model-based methods and
(iv) Adaptive methods (fuzzy controllers are computationally intensive).

5. IMPLEMENTATION WORK

5.1 Initial Rotor Position Estimation Method

The motor currents and voltages are zero, the system of rotor position estimation using EKF algorithm gives no information for the initial position. Therefore, another technique has to be used for rotor position estimation to achieve a stable start. It is based on the inductance of phase that is a function of the rotor position. This approach is estimating the initial rotor position by using the inductance variation due to the magnet position and an impressed stator current. However, to estimate the initial rotor position, two kinds of suitable sequence dc voltage rectangular pulses are applied from the inverter to the stator windings of the motor are,

(i) Voltage pulse is applied with a short time duration, and
(ii) Voltage pulse is applied with long time duration.

The motor is fed by a continuous current source, the phase current peaks I_u, I_v, I_w of the motor are sinusoidal functions of the rotor position given in equations [2], [3] and [4] respectively,

$$I_u = I_0 + \Delta I_u = I_0 + \Delta I_0 \cos(2\theta) \qquad \ldots (2)$$

$$I_v = I_0 + \Delta I_v = I_0 + \Delta I_0 \cos\left(2\theta - \frac{2\pi}{3}\right) \qquad \ldots (3)$$

$$I_w = I_0 + \Delta I_w = I_0 + \Delta I_0 \cos\left(2\theta + \frac{2\pi}{3}\right) \qquad \ldots (4)$$

where, I_0 = (1/3) (I_u, + I_v, + I_w) is the dc current component and ΔI_0 is the amplitude of a fluctuated component. It measures the phase current peaks I_u, I_v, and I_w and calculate the difference $\Delta I_u = I_u$, - I_0, and ΔI_v = Iv - I_0, and $\Delta I_w = I_w - I_0$.

An expression for the rotor position is generated by using trigonometric identities from the eqn. [2] to eqn. [4] and isolating the angle terms for θ as given in eqn. [5],

$$tg(2\theta) = \frac{\sqrt{3}\,(\Delta I_v - \Delta I_w}{2\Delta I_u - \Delta I_v - \Delta I_w} \qquad \ldots (5)$$

The rotor position is calculating the inverse tangent and dividing the remaining angle by two. For small angles, an approximation of tg(2θ) to the first order

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tg(2θ) = (2θ), obtains, the expression (2θ) of the estimated initial electrical rotor position according to the current fluctuations peak.

5.2 Rotor Position Estimation Using Flux Linkage

The flux linkage estimator plays a major role for rotor position estimation. The quantity flux is generated by flux linkage estimator block, which calculates flux linkage based on the phase voltage and current in the active phase winding. The flux-linkage of any phase is computed by using Faraday's law as given in eqn. [6],

$$\Psi = \int (V - IR)\ dt\ (1) \qquad \dots (6)$$

The calculation of flux linkages by equation is helpful in computing estimated angle for the operation of sensor less SRM drive.

6. ANN-BASED ROTOR POSITION ESTIMATOR IN SR MOTOR

The rotor estimation in SRM is performed in this study to design the position observer are built on the 4 phases, 5.5HP, 1500 rpm and 8/6 poles SRM are shown in Figure 7.

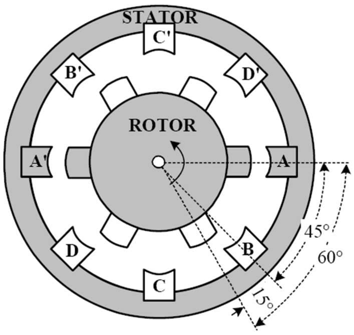

Fig. 7 Cross section of 8/6 poles SRM [5]

The network structure is used for estimating the rotor position by using ANN is shown in Figure 8. The inputs of the networks i_j and ψ_j are the phase current and the flux linkage data are obtained from the non-linear full model of the SRM. The output of network is the actual rotor position per phase θ_j computed according to the inputs. $\theta_j$is the desired rotor position per phase, while *e* is the error between actual and desired rotor position values. The network is composed of 4 layers: an input layer (*P*), two hidden layers (*R, S*) and an output layer (*T*).

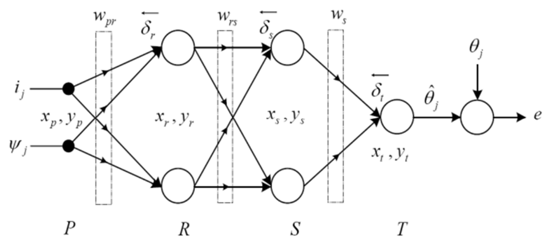

Fig. 8 Architecture of the neural network for modeling of the inductance and flux linkage [2]

In nodes at the *R, S,* and *T*, the output of the nodes is calculated by using activation function is given in eqn. [7],

$$y(x) = exp\left(-\left(\frac{x-c}{\sigma}\right)^2\right) \qquad \dots (7)$$

Here, *x* represents input of the nodes, *y* represents output of the nodes related to *x*, *c* center of Gaussian function, and σ its width. Feedforward model of the layers can be described as follows.

6.1 Feedforward Algorithm

P layer: It is the input layer and the entry of this layer, i_j and ψ_j are the values of the current and flux linkage data, respectively. The inputs and the outputs of this layer are obtained as given in eqn. [8],

$x_p = \{i_j, \psi_j$, and $y_p = x_p$ where $p = 0...P$ … (8)

R layer: It is the first hidden layer, the inputs and the outputs of this layer are given in eqn. [9],

$$x_r = \sum_{p=0}^{P} y_p . w_{pr}\ , and\ y_r = y(x_r) \qquad \dots (9)$$

Where, r=0…R

S layer: It is the second hidden layer, the inputs and the outputs of this layer are given in eqn. [10],

$$x_s = \sum_{r=0}^{R} y_r . w_{rs}\ , and\ y_s = y(x_s) \qquad \dots (10)$$

Where s= 0…S

T layer: It is the output layer, the inputs and the outputs of this layer are given in eqn. [11],

$$x_t = \sum_{s=0}^{S} y_s . w_s\ , and\ y_t = y(x_t) \dots (11)$$

While the terms layers are combined; inductance model is given in eqn. [12], 6

$$\theta_j = y\left(\sum_{s}^{S} y\left(\sum_{r=0}^{R} y\left(\sum_{p=0}^{P} y_p . w_{pr}\right). w_{rs}\right). w_s\right) \qquad \dots (12)$$

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The estimated rotor position model is obtained as a result of the feedforward algorithm has been completed and the backpropagation learning algorithm is realized for the optimization of the weights in the network.

6.2 Backpropogation Learning Algorithms

The learning algorithm of the ANN using the supervised gradient method, the energy function *E* is chosen as given in eqn. [13],

$$E(k) - \frac{1}{2}e^2\,(k), where\ k = 1, \dots, K \qquad \dots (13)$$

K denotes total number of input-output patterns and error value for each pattern as given in eqn. [14],

$$e(k) = \theta_j(k) - \theta_j\,(\mathrm{k}) \qquad \dots (14)$$

where, (*k*) *j*θ is the desired value (*k*) *j* θ actual value.

7. RESULTS AND DISCUSSION

In this work, the nonlinear method is used for rotor position to find out controlled or uncontrolled process and analyze the variations are shown in Figure 9.

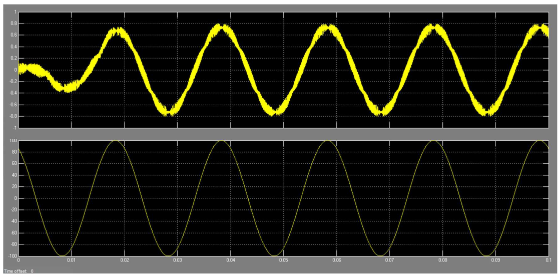

Fig. 9 Variations between control and uncontrolled process for rotor position estimation system

The comparison between controlled and uncontrolled nonlinear process for rotor position estimation shows the variations are shown in Figure 10.

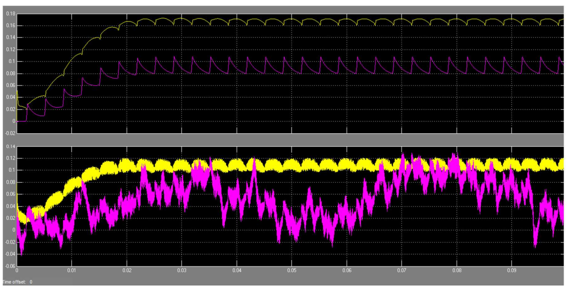

Fig. 10 Comparison between Control and Uncontrol nonlinear process in rotor position estimation

8. CONCLUSION

In this work, SRM are rotary machine is dependent on the magnetic field path which has direction with the axial length of the machine. The magnetic field path has perpendicular to the shaft that is seen as the radius of the cylindrical stator and rotor which is classified as radial field by SRM. The phase voltage and current in the active phase winding is based on the quantity flux which is generated by flux linkage estimator and calculates flux linkage. The results of this research work are presented the comparison between control and uncontrol nonlinear process and measure the phase flux linkages and phase currents estimation using rotor position and achieved a stable current start is presented.

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