REVIEW OF POSITION ESTIMATION FOR LINEAR SWITCHED RELUCTANCE MOTOR

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ABSTRACT

Position estimation is very important in operation of Linear Switched Reluctance Motors (LSRMs). With increasing application of LSRMs, the position estimation techniques would get more and more attention. This paper compares LSRMs to Rotary Switched Reluctance Motors (RSRMs) with regard to position estimation and surveys various existing position estimation methods for RSRMs. Because of the similarities and differences between LSRMs and RSRMs, these position estimation methods have significant reference values for LSRMs.

KEY WORDS

Linear switched reluctance motor, switched reluctance motor, position estimation, sensorless.

1. INTRODUCTION

Recently Linear Switched Reluctance Motors (LSRMs) have been obtained more attention for position or velocity control due to their low-cost and simple structures, ruggedness and reliability in harsh environments. Compared to the method of rotary motors with transformation components for producing linear motion, LSRMs also have many advantages, such as quickly response, high sensitivity and tracking capability, moreover, the structure of LSRMs can reduce the room requirement for its installation. According to the principles of LSRMs, the phase excitations of LSRMs need to be synchronization with the position for effective control. The mechanical sensors or optical encoders are usually used to obtain the position information. However, these sensors not only add complexity and cost to the system but also reduce the reliability of the drive system. The alternative to these sensors is indirect position sensing based on measurements of other motor parameters.

Several methods of position estimation have been reported for Rotary Switched Reluctance Motors (RSRMs) [2-19]. But for LSRMs, there are few literatures referring to position estimation so far. RSRMs and LSRMs are similar in term of principle of operation, while they are different in mechanical structures. Therefore, the position estimation methods for RSRMs can be referred or applied on LSRMs. This paper compares LSRMs to RSRMs with regard to position estimation and reviews various position estimation methods.

2. FUNDAMENT OF POSITION ESTIMATION FOR LSRM

The force production mechanism of a LSRM is based on the tendency to minimize the reluctance between mover and stator. In a LSRM, the reluctance depends on its air gap; hence the minimum reluctance of a phase is sited in full alignment with a stator tooth. To energize an unaligned phase will make this phase move till it is fully aligned. Therefore, the desired performance can be achieved by energizing each phase in appropriate positions. As an example, Fig.1 shows a schematic of a set of three-phase LSRM. The three coils are with same dimension. The body of the moving platform is manufactured with aluminum, so that the total weight of the moving platform and its inertia are low and the magnetic paths are decoupled [1].

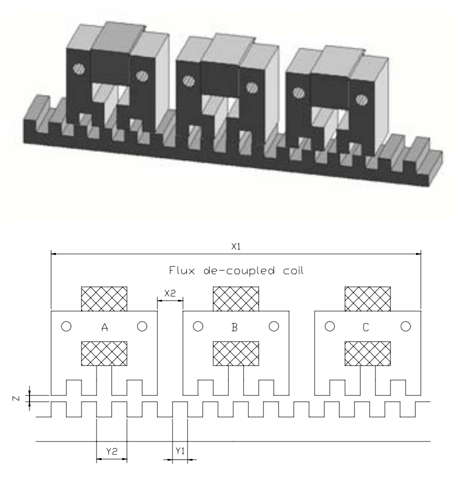

Fig. 1 Schematic of a three-phase LSRM.

Because of the decoupling of the magnetic paths for LSRMs, the basic voltage balancing equation of each phase is given by,

$$\begin{aligned} v_j &= r_j i_j + \frac{d\lambda_j}{dt} \\ v_j &= r_j i_j + L_j \frac{di_j}{dt} + i_j \frac{\partial L_j}{\partial i_j}\frac{di_j}{dt} + i_j \frac{\partial L_j}{\partial x}\frac{dx}{dt} \end{aligned} \tag{1}$$

where v_j is the voltage applied to the terminals of phase j, i_j is the current of phase j, r_j is the winding resistance, λ_j is the phase flux linkage of phase j, $L_j(i_j, x)$ and x represent the self-inductance of phase j and position of the mover, respectively. The equivalent model of a phase for LSRMs is showed in Fig. 2. The flux linkage of each phase can be obtained as (2) by integrating both sides of equation (1). And Fig. 3 depicts a typical flux linkage vs current and position for LSRMs. In the low current level and unaligned position region the flux linkage is almost linear, while in high current level and near aligned position region the flux linkage is easy saturated.

$$\lambda_j = \int_0^T (v_j - r_j i_j)dt \tag{2}$$

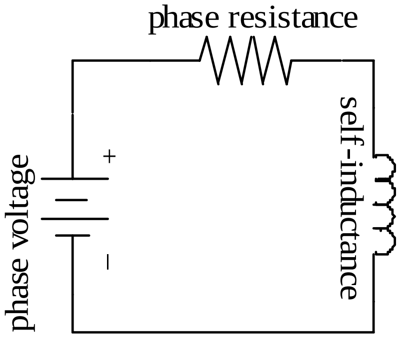

Fig. 2 Equivalent model of a phase for LSRMs.

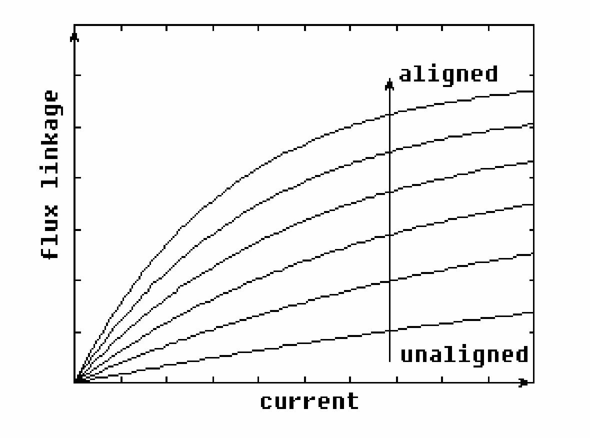

Fig. 3 A typical flux linkage vs current and position for LSRMs.

It is known that both of the phase flux linkage and self-inductance are functions of phase current and position. Therefore, position information is contained in the flux linkage, inductance and back-emf. Most of the existing position estimation methods are based on the voltage balancing equation to extract position information. The voltage equation is so complicated that analytic solving the voltage is very difficult. Usually, it is used in different simplified forms for various conditions. The different forms are presented in term of operation speed region [2, 3, 4]. This is mainly resulted by the changing weights of the each term in right hand of the phase voltage equation for different speed region.

From the phase voltage equation LSRMs and RSRMs are similar. But there are important differences with regard to position estimation. (a) Most RSRMs operate under speed control mode, while LSRMs are usually applied in position control and trajectory control. The position estimation of LSRMs, therefore, requires wider speed range. (b) Driving electrical signals and mechanical structures for RSRMs are cyclic in nature, but LSRMs can only operate in a linear movement. Due to the integration error, estimation in this case is difficult. (c) Since the mover phases are separated to each other in space, the mutual inductance is very low. These differences should be considered in position estimation for LSRM.

3. CLASSIFICATION OF POSITION ESTIMATION METHODS

In this section, various position estimation methods will be reviewed in the following four classes.

A. Incremental Inductance Measurement

The basic principle of incremental inductance was originally proposed in [5] and an analytical model of incremental inductance in term of Fourier series was reported in [6]. By investigating the chopping characteristics of phase current waveforms, this method mainly considers the relationship between incremental inductance and position. In term of incremental inductance, the voltage equation can be rewritten as follows,

$$v_j = r_j i_j + l_j \frac{di_j}{dt} + i_j \frac{\partial L_j}{\partial x}\frac{dx}{dt} \quad (3)$$

where l_j represents incremental inductance for phase j and is equal to $L_j + i_j \frac{\partial L_j}{\partial i_j}$. Then the rate of current $\frac{di_j}{dt}$ can be represented as,

$$\frac{di_j}{dt} = \frac{v_j - r_j i_j - i_j \frac{\partial L_j}{\partial x}\frac{dx}{dt}}{l_j}. \quad (4)$$

It can be seen that the rate of current is relative to phase voltage and incremental inductance if the voltage drop in phase resistance and back-emf can be neglected in low speed region. In general the phase voltage is invariable, therefore, the position information can be extracted from the incremental inductance. However, the position estimation will be effected when the back-emf increase with speed.

B. Flux Linkage Based Estimation

In paper [7], a non-intrusive rotor position estimation was proposed, which relies on the machine's inherent flux/current magnetic characteristics to infer rotor position from measurements of stator flux linkage and current during normal phase excitation. Considering the eddy effects, a correction factor was introduced [8]. And a principle of high resolution position estimation was proposed in [9], which uses either flux linkage or current to correct for errors in rotor position through correlation of current, flux linkage and rotor position.

The mechanism of this estimation method is based on the fact that flux linkage in phase is made function of current and position. The flux linkage can be estimated as (2) by using measured phase voltage and current [7]. This non-intrusive method can operate in a wide speed range. However, error will be resulted in low current level due to not setting up flux linkage.

C. Methods of Signal Injection

During the operation of switched reluctance motor, there is at least one phase unexcited. Phase inductance can be estimated by injecting signals into the unexcited phase. A chopped current approaching to zero was proposed to inject to the unexcited phase [7], in which the resistance drop and back-emf are very small and can be ignored. In this case, the incremental inductance is inversely proportional to the rate of current as (5).

$$\frac{di_j}{dt} = \frac{v_j}{l_j}. \quad (5)$$

Another group of this kind of methods is based on modulated frequency injection. By applying a small high frequency sinusoidal voltage to a idle phase, the phase inductance will be encoded in the amplitude and phase of the sensing current. In [2, 10], the phase modulation (PM) and amplitude modulation (AM) techniques were proposed. And a resonance based high frequency injection was proposed [11], in which the resonant frequency was selected at the unaligned position of the rotor. Since the phase impedance varies from the unaligned to the aligned, the position information was obtained from the measured impedance. The complexity of the demodulation circuit may limit the application of this algorithm but this is still one of the best methods for rotor position estimations in VRMs [12].

D. Modern Control Theory Based Methods

With the help of modern control theory, the rotor position information can be estimated using analytical models. A state observer based on a nonlinear model of SRM with the state variables of flux linkage, speed and position was proposed in [13], a reduced-order extended Luenberger type nonlinear observer model along with the load torque was reported in [14] and in [15] an observer based sensorless with adaptive fuzzy controller was presented for switched reluctance motors. But these estimation methods heavily depend on motor parameters such as the stator winding resistance and accurate phase voltage and current measurement. On the other hand, intelligent control based estimations such as neural networks is employed to overcome the parameter dependency problem [16, 17] but the accuracy and speed operating range need to further investigated [12]. Fuzzy logic control scheme with minimal motor parameter information is adopted to provide a wide speed operating range and satisfactory performances are shown in [18, 19]. Due to mass computation, this method requires high speed microprocessors such as digital signal processor (DSP).

4. CONCLUSION

This paper compares LSRMs with Rotary Switched Reluctance Motors (RSRMs) with regard to position estimation and surveys various existing position estimation methods for RSRMs. These existing methods can be divided into four classifications: (a) incremental inductance measurement, (b) flux linkage based estimation, (c) methods of signals injection and (d) modern control theory based methods. From the view of foundation, the basic phase voltage equation is the root of most existing methods. Because of the similarities and differences between LSRMs and RSRMs, these position estimation methods have significant reference values for LSRMs.

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