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Indirect Startup Rotor Position Sensor For Synchronous Reluctance Motor

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Abstract - **This paper presents a new indirect method of sensing the rotor positions in Synchronous Reluctance Motor (SynRM) at zero speed. The method is based on a special diagnostic switching control of the drive converter. The induced phase voltages and currents from this diagnostic signal is used to determine the position of the rotor. Variations of the method also works accurately and with robustness at all speeds. This method requires no additional hardware, other than the drive circuitry and microcontroller.**

The theoretical foundations of the method are presented and the experimental results are shown to verify the practicality of the method.

I. INTRODUCTION

Synchronous reluctance motor drives have recently received renewed attention. This interest is mainly due to modern field oriented control strategies, which have recently been applied to these motors. In particular, it has been shown that a properly designed and field oriented synchronous reluctance drive can perform as well as an induction motor drive when the field weakening range is not too wide. However, field orientation control requires position sensor information as is common for all ac machines. These discrete position sensors reduce the reliability and ruggedness of the drive and also increase the cost of the drive. Recent trends to estimate rotor positions of ac machines involve detecting the voltage induced in the stator windings from the rotor. However, at the startup, the rotor is motionless, with no induced voltage and no position information. This makes the rotor position sensing at stand still very difficult for commonly used ac drives (induction, brushless etc. drives). Thus these motors operate in open loop until the motor induced voltage is large enough to be sensed. Also, the sensed voltage is often noisy and very difficult to sense. The synchronous reluctance motor however possess unique features which make position sensing much simpler and reliable [1] even at stand still. In contrast to an induction machine the synchronous reluctance machine has saliency which permits the rotor position to be sensed from the inductance per phase which is a function of rotor position. This allows sensing position at stand still which is impossible for the induction machine. An indirect startup rotor position sensing technique for synchronous reluctance motor drive which involves use of electrical quantities at the motor terminals is presented in this paper.

II. EQUIVALENT CIRCUIT

For purposes of analysis a 2 pole, 3 phase wye connected synchronous reluctance machine is considered. The performance of the synchronous reluctance machine can be described by the equations given below,

$$v_{as} = r_s i_{as} + \tfrac{d}{dt}(L_{aa} i_{as} + L_{ab} i_{bs} + L_{ac} i_{cs}) \qquad (1)$$

$$v_{bs} = r_s i_{bs} + \tfrac{d}{dt}(L_{ab} i_{as} + L_{bb} i_{bs} + L_{bc} i_{cs}) \qquad (2)$$

$$v_{cs} = r_s i_{cs} + \tfrac{d}{dt}(L_{ac} i_{as} + L_{bc} i_{bs} + L_{cc} i_{cs}) \qquad (3)$$

where, v_{as}, v_{bs} and v_{cs} are the applied terminal voltages, r_s is the stator winding resistor, i_{as}, i_{bs} and i_{cs} are the stator phase currents. L_{aa}, L_{bb} and L_{cc} are the mutual inductances between different stator phases. L_{ab}, L_{bc} and L_{ac} are the mutual inductances between different stator phases. The self and mutual inductances of the machine are dependent on the rotor position, θ_r, and can be written as [2],

$$L_{aa} = L_{ls} + L_A - L_B \cos(2\theta_r) \qquad (4)$$

$$L_{ab} = L_{ls} + L_A - L_B \cos 2(\theta_r - 2\pi/3) \qquad (5)$$

$$L_{cc} = L_{ls} + L_A - L_B \cos 2(\theta_r + 2\pi/3) \qquad (6)$$

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$$L_{ab} = -\tfrac{1}{2}L_A - L_B \cos 2(\theta_r - \pi/3) \tag{7}$$

$$L_{bc} = -\tfrac{1}{2}L_A - L_B \cos 2(\theta_r + \pi/3) \tag{8}$$

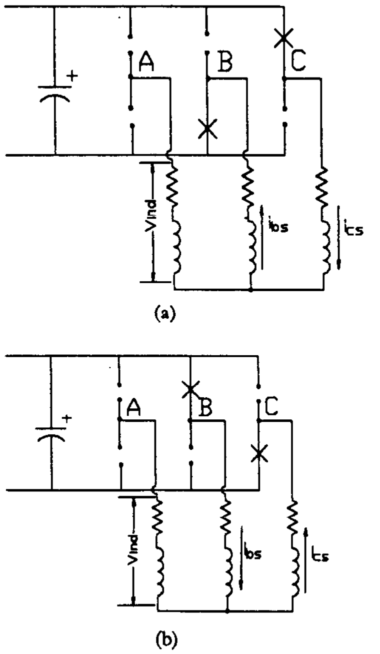
$$L_{ac} = -\tfrac{1}{2}L_A - L_B \cos 2(\theta_r + \pi) \tag{9}$$

where, $L_{mq} = 3/2(L_A - L_B)$ and $L_{md} = 3/2(L_A + L_B)$.

The sensorless startup technique presented in this paper, utilizes these synchronous reluctance machine characteristics to determine the rotor position at stand still as described in the following sections.

III. SENSORLESS STARTUP TECHNIQUE

The startup technique proposed detects the induced voltage in the stator windings from the rotor, when a stator phase pair is diagnostically energized for a brief interval of time. Figure 1(a) and (b) shows the circuit configuration of a particular case when phases B and C are diagnostically energized to measure the induced voltage across phase A. Since phases B and C are now effectively in series $i_{bs} = -i_{cs}$ and $\frac{d}{dt}i_{bs} = -\frac{d}{dt}i_{cs}$, moreover the current in phase A, i_{as}, remains zero. Thus, using Eq.(1) the induced voltage in phase A can be written as,



(a)

(b)

Fig. 1 Circuit configurations during the measurement of the induced voltage across phase A.

$$v_{ind} = (L_{ab} - L_{ac})\tfrac{d}{dt}i_{bs} \tag{10}$$

Using Eqs. (7) and (9), the induced voltage given by Eq.(10), can be expressed as,

$$v_{ind} = K_1 \sin 2\theta_r \tfrac{d}{dt} i_{bs} \tag{11}$$

where, $K_1 = -2L_B \sin 2\pi/3$ is a constant dependent only on a physical parameter of the motor. Similar equations can be developed for the other two stator phase pairs (phases C and A to measure voltage across phase B or phases A and B to measure voltage across phase C). Note that the induced voltage expressed by Eq.(11) does not contain the speed term and depends only on the rotor position θ_r and the slope of the diagnostic current. Figure 2 shows the simulated diagnostic current flowing through the phases B and C of a 2 pole, 3 phase synchronous reluctance motor drive. Figure 3 shows the corresponding induced voltage in phase A. The coupled voltage induced in phase A, has the rotor angle encoded in its amplitude. This induced voltage amplitude can be used to estimate the startup rotor position, by using a look-up table. The table contains the inverse function of Eq.(11), solved for θ_r in discrete form.

It can be noted that the phase inductances of the synchronous reluctance motor is a function of $2\theta_r$. Hence for every electrical cycle the phase inductance goes through two cycles. This apparent problem during the startup operation has a simple solution. It does not matter for this particular case whether the algorithm picks the higher or the lower angle, because the rotor of a synchronous reluctance machine has no preferred polarity due to the absence of any type of wind-

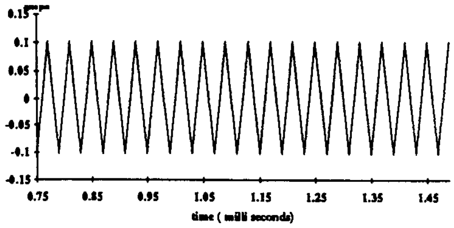


Fig.2 Current through phase B and phase C when the induced voltage is measured across phase A at zero speed.

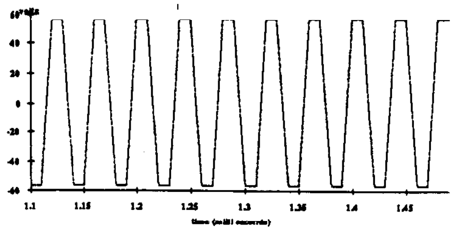


Fig.3 Induced voltage measured across phase A.

ing on the rotor. Thus, during the startup operation the controller can be set to pick always the lower or the higher angle. It should also be mentioned that to determine the startup position uniquely, the induced voltages from all three phases have to be measured. The induced voltages from all three phases (when the rotor is at 25 mechanical degrees) are shown in Fig. 4.

IV. ERROR ANALYSIS

The variation of induced voltage is a nonlinear function of rotor position and only the average sample error in the digitizing process can be obtained. The error results from conversion of the induced voltage v_{ind} and the current slope, $\frac{d}{dt}i_b$ to their integer digital representation and is always equal to 0.50 LSB. Using Eq.(11), the startup rotor position θ_r, can be written as a function of the measured variables (induced voltage and the slope of the current):

$$\theta_r = \theta(v_{ind}, i^\circ)$$

The error in the rotor position can be approximated by the first terms of its Taylor expansion in terms of errors in the variables:

$$\Delta\theta_r = \frac{\partial\theta_r}{\partial v_{ind}}\Delta v_{ind} + \frac{\partial\theta_r}{\partial i^\circ}\Delta i^\circ \tag{12}$$

where, ΔV_{ind} and Δi^0 are the individual variable errors which depend on the A/D converter resolution and the full scale range of the individual variables. If V_{max} is the maximum induced voltage, then the error for the induced voltage measurement, Δv_{ind},becomes, $V_{max}/2^n$ where, n is the number of output bits of the A/D converter. Similarly, with the maximum phase current I_{max}, the error for current measurement, Δi, becomes, $I_{max}/2^n$.

The slope of the current, i°, required for the startup rotor position estimation is calculated by measuring the phase currents at the switching instants of the phase pair and then dividing the difference of the measured currents by the time interval between the switching instants. If i_1 and i_2 are the currents at the two switching instants of the phase current, then with the error of Δi, the worst case current difference becomes,

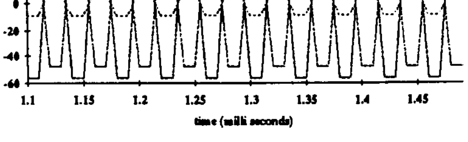


Fig.4 Induced voltages across all three phases (rotor is at 25 mechanical degrees).

$$i_2 - i_1 + 2\Delta i$$

Consequently, the worst case error for current slope measurement (assuming linear current variation between i_1 and i_2 becomes,

$$\frac{2\,\Delta i}{1/(2f_s)} = 4\Delta i\, f_s$$

where, f_s is the diagnostic switching frequency applied to a phase pair in order to measure the induced voltage across the remaining unenerzied phase.

Using Eq.(12), the error in startup rotor estimations can be expressed as,

$$\Delta\theta_r = \frac{\partial\theta_r}{\partial V_{ind}}\frac{V_{max}}{2^n} + \frac{\partial\theta_r}{\partial i^\circ}4\Delta i\, f_s \tag{13}$$

The error of the individual startup samples can now be calculated according to the data obtained from an experiment. In our experiment, the maximum measured induced voltage was 40 volts and our A/D converter had an 8 bit resolution. This makes the error of the induced voltage measurement Δv_{ind}, equal to 0.16 volts. The rated phase current of the experimental motor is 10 amps, making the quantization error for current measurement equal to 0.04 amps and with the diagnostic switching frequency of 1.5 kHz, the error in current slope measurement Δi^0becomes 240 amps/sec. Equation (13) gives the worst case error, $\Delta\theta_r$, in terms of quantization error alone with the assumption that the accuracy of the analog voltage and current probes and their interface electronics are less than their respective quantization errors. In order to calculate the worst case error given by Eq.(13) it is necessary to calculate the maximum $\frac{\partial\theta_r}{\partial V_{ind}}$ and $\frac{\partial\theta_r}{\partial i^\circ}$. The maximum of $\frac{\partial\theta_r}{\partial V_{ind}}$ and $\frac{\partial\theta_r}{\partial i^\circ}$ can be found from analytically or numerically maximizing those two terms in the possible range of the two dimensions V_{ind} and i°. The numerical value of the worst case position error at the startup is found by substituting the system parameters L_B, n, V_{max}, I_{max} and the ranges of v_{ind} and i°. In the experiments for startup operation the values for different parameters were as follows:

V_{max} = 40 volts I_{max} = 10 amps.
v_{ind} = 0 to 40 volts

$n = 8$ $L_B = .0035$

Therefore, the worst case error for startup rotor position estimation was found to be,

$$\Delta\theta_r \le 0.50$$

V. EXPERIMENTAL EVALUATION

In order to verify the key predicted results, the startup technique has been implemented on an experimental synchronous reluctance drive. The experimental machine has an axially laminated four pole rotor of the type described [3-5]. The stator of this machine is actually a standard configuration for a 7.5 hp three phase induction machine. The microcontroller (INTEL 196) is configured to measure the induced voltage and the phase current within a brief time interval. The measured input variables are then used to estimate the starting rotor position from a look-up table. The size of the look-up table was determined by the number of rotor poles as explained below.

Figure 5 (a) and (b) shows a 2 pole and 4 pole rotor at different mechanical angles. Since the rotor of a synchronous reluctance machine has no winding or polarity, a 2 pole rotor will induce the same voltages between 0 to 180 and 180 to 360 mechanical degrees. Similarly, a 4 pole rotor will induce the same voltages between 0 to 90, 90 to 180, 180 to 270 and 270 to 360 mechanical degrees. This suggests that in either case (2 or 4 pole rotor), the look-up table need not be 360 degrees long. For a 2 pole rotor machine it is sufficient to have a look-up table 180 degrees long and, similarly, a 4 pole rotor machine will need a look-up table 90 degrees long. The synchronous reluctance machine used for experimental evaluation has a 4 pole rotor, thus the corresponding look-up table is made 90 degrees long.

Figure 6 shows the diagnostic regulated constant current flowing through phases B and C of the experimental drive. Figure 7 shows the voltage induced in phase A during the diagnostic period. A noise free and easily measurable induced voltage is clearly evident. Also note that only the positive portion of the induced voltage (Fig. 7) was fed to the microcontroller and was used to determine the initial rotor position. The negative portion of the induced voltage was rectified and was not used for position estimation. The use of

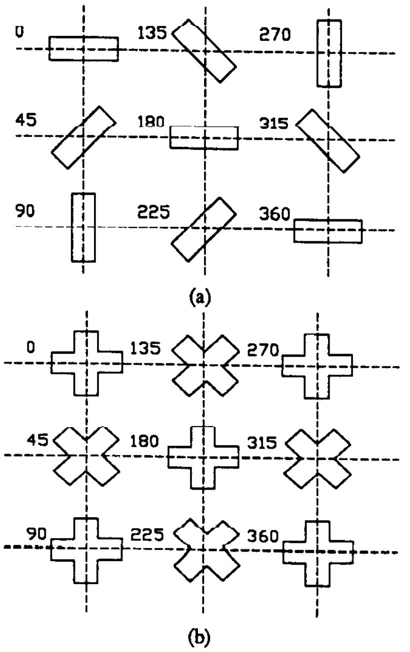


Fig.5 Different rotor positions of (a) 2 pole rotor and (b) 4 pole rotor

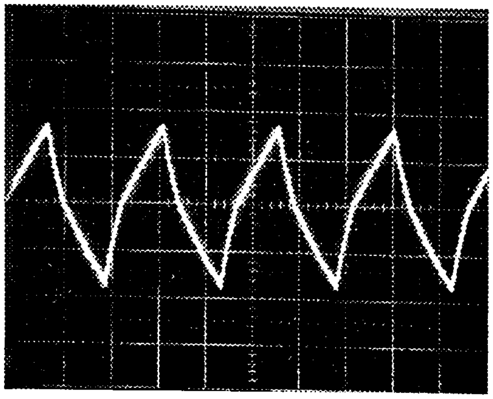


Fig.6 Diagnostic current flowing through phases B and C when the voltage is measured across phase A at zero speed.

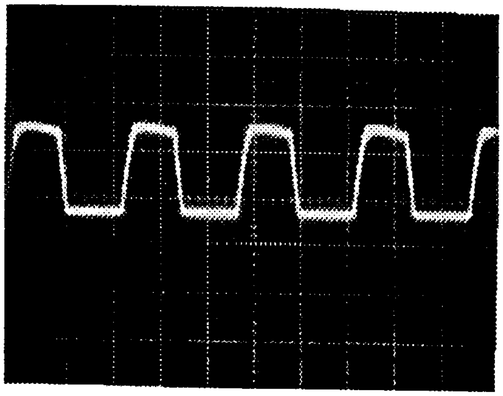


Fig.7 Induced voltage measured across phase A at zero speed.

only the positive portion of the induced voltage simplified the hardware implementation. The measured induced voltage and the current slope was then utilized to estimate the rotor position at zero speed. The accuracy of the estimated rotor positions were within the error margin developed in the Error Analysis section.

VI. CONCLUSIONS

An indirect startup technique for synchronous reluctance machine has been presented. The salient rotor and the high mutual coupling between stator and rotor phases of a synchronous reluctance machine make startup rotor position estimation easy and reliable. Moreover, the absence of rotor windings reduce the size of the lookup table needed for the rotor position estimation and also eliminate the apparent problem of the phase inductance being a function of twice the rotor angle. Easily measurable noise free induced voltage can be obtained with a phase current which has low amplitude, high frequency and zero average value. Thus, estimation of the startup position for a synchronous reluctance machine is possible without producing any torque ripple. Finally, the key results were verified by simulation and hardware evaluation.

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