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Elimination of Discrete Position Sensor For Synchronous Reluctance Motor

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Abstract **- A new discrete position sensor elimination technique for a sinusoidally wound synchronous reluctance motor drive is presented. The proposed technique determines the rotor position at zero crossing of the phase currents. The rotor position between the zero crossings is determined by applying extrapolation. The proposed technique works well at all speeds, including zero speed. This technique can be used in both vector controlled and conventional constant Volts/Hertz type of motor controllers.**

I. INTRODUCTION

Synchronous reluctance motor (SynRM) drives have recently received renewed attention[1]. This interest is mainly due to modern field oriented control strategies, which have recently been applied to these motors [2,3]. In particular, it has been shown that a properly designed and field oriented SynRM can perform as well as an induction motor drive when the field weakening range is not too wide[3]. However, the inherent characteristics of the SynRM makes it preferable for some applications. Some of the desirable characteristics are as follows [2],

1. The stator of the SynRM is constructed from a cylindrical structure identical to an induction motor. Hence the stator of both machines can be constructed from the same assembly line.

2. No starting cage is necessary with an inverter supply. The rotor can therefore be designed purely for synchronous performance.

3. Electronic control makes the motor auto-synchronous and can assure an optimum torque angle at all loads and torques, consequently giving the motor a very high pull-out torque.

4. No damping winding is necessary. This makes it possible to design the motor for the highest reluctance difference $X_d - X_q$, thereby increasing the power density of the machine.

5. The torque pulsations and the acoustic problem are not as severe as those for variable reluctance machines.

6. Vector control techniques can be applied in order to achieve high performance.

However, field orientation control of SynRM requires position sensor information as is common for all ac machines. However a discrete position sensor reduces the reliability and ruggedness of the drive and increases its cost. The SynRM however possess unique features which make position sensing much simpler and reliable than either conventional squirrel cage induction machines or variable reluctance machines. In contrast to induction machine the SynRM possess saliency which permits the rotor position to be sensed since the inductance per phase is a function of rotor position. This allows sensing position at zero speed which is impossible for an induction machine. Secondly, in contrast to the variable reluctance motor, the stator windings of the SynRM are magnetically coupled. Hence, voltages are induced in the stator winding upon open circuit of a phase, which allows sensing of the emf. These two features in combination make the task of sensing position easier than for either an induction or variable reluctance motor. A new indirect rotor position sensing technique for SynRM, utilizing only the input variables (voltages and phase currents) and the rotor saliency information, is presented in this paper.

II. EQUIVALENT CIRCUIT

For purposes of analysis, a 2-pole, 3 phase wye connected SynRM is considered as shown in Fig.1. The performance of the SynRM can be described by the equations given below,

$$V_{as} = r_s i_{as} + \frac{d}{dt}(\lambda_{as}) \tag{1}$$

$$V_{bs} = r_s i_{bs} + \frac{d}{dt}(\lambda_{bs}) \tag{2}$$

$$V_{cs} = r_s i_{cs} + \frac{d}{dt}(\lambda_{cs}) \tag{3}$$

where, v_{as}, v_{bs} and v_{cs} are the applied terminal voltages, r_s is the stator winding resistance and λ_{as}, λ_{bs} and λ_{cs} are the flux linkages of the individual phases. The flux linkages can be expressed as ,

$$\lambda_{as} = L_{aa} i_{as} + L_{ab} i_{bs} + L_{ac} i_{cs} \qquad (4)$$

$$\lambda_{bs} = L_{ab} i_{as} + L_{bb} i_{bs} + L_{bc} i_{cs} \qquad (5)$$

$$\lambda_{cs} = L_{ca} i_{as} + L_{bc} i_{bs} + L_{cc} i_{cs} \qquad (6)$$

where the self and the mutual inductances of the machine can be written as, [4]

$$L_{aa} = L_{ls} + L_A - L_B \cos 2\theta_r \qquad (7)$$

$$L_{bb} = L_{ls} + L_A - L_B \cos 2(\theta_r - \tfrac{2\pi}{3}) \qquad (8)$$

$$L_{cc} = L_{ls} + L_A - L_B \cos 2(\theta_r + \tfrac{2\pi}{3}) \qquad (9)$$

$$L_{ab} = -\tfrac{1}{2} L_A - L_B \cos 2(\theta_r - \tfrac{\pi}{3}) \qquad (10)$$

$$L_{ac} = -\tfrac{1}{2} L_A - L_B \cos 2(\theta_r + \tfrac{\pi}{3}) \qquad (11)$$

$$L_{bc} = -\tfrac{1}{2} L_A - L_B \cos 2(\theta_r + \pi) \qquad (12)$$

where, $L_{mq} = 3/2\ (L_A - L_B)$ and $L_{md} = 3/2(L_A + L_B)$. Equations 4 through 6 show the coupling between different phases and the equations 7 through 12 show the dependence of the mutual and self inductances on the rotor position, θr. The proposed technique utilizes these facts to determine the rotor position as described in the following section.

III. THE PROPOSED TECHNIQUE

The rotor position information embedded in the SynRM equations above will be obtained by employing a special switching technique for the current regulated pulsewidth modulated (CRPWM) converter. In a regular CRPWM converter the phase switches are normally turned on and off in order to make the individual phase currents follow the desired reference within a desired band. However, in the modified switching technique, both the switches of that phase are turned off when the current of a particular phase; e.g., phase A crosses zero. The remaining two phases (in this case phases B and C)are excited in series by turning on alternate pairs of switches (the lower switch of phase B and the upper switch of phase C (see Fig.2a) or the lower switch of phase C and the upper switch of phase B (Fig.2b)). This modified switching pattern will extend the zero crossing interval of phase A for a short interval. The currents in phases B and C can be controlled to follow a constant reference during this period. The description of this constant reference PWM of the phases B and C is explained later with simulation results. Although current of phase A during this extended zero crossing period will be zero, a voltage will be induced in phase A due to the currents in other two phases, which can be obtained by setting $i_{as} = 0$ in Eq.1 in which case,

$$V_{ind} = \frac{d}{dt}(L_{ab}\, i_{bs} + L_{ac}\, i_{cs}) \qquad (13)$$

Since phase B and phase C are now effectively in series, $i_{bs} = -i_{cs}$ and $d/dt\ (i_{bs}) = -\ d/dt\ (i_{cs})$ and the Eq.13 becomes,

$$V_{ind} = (L_{ab} - L_{ac})\frac{d}{dt} i_{bs} + i_{bs}\frac{d}{dt}(L_{ab} - L_{ac}) \qquad (14)$$

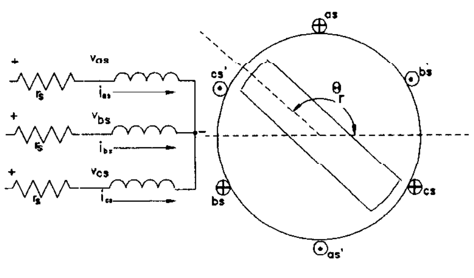
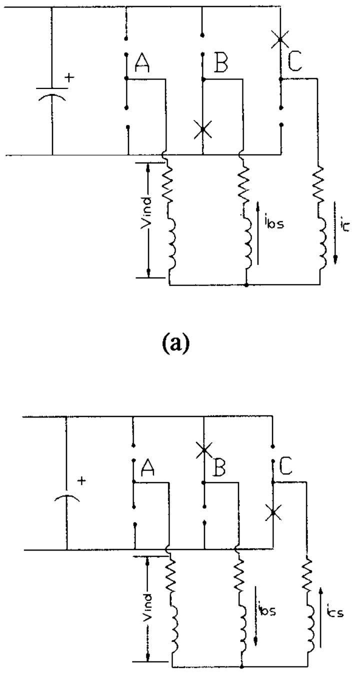


Fig.1 Equivalent circuit of a 2 pole SynRM.



(a)

(b)

Fig.2 Circuit configurations during the extension of the zero crossing period of phase A current.

Using Eq.10 and Eq.11, the induced voltage can consequently be written as,

$$V_{ind} = K_1 \sin(2\theta_r) + K_2 \cos(2\theta_r) \qquad (15)$$

where,

$$K_1 = -(2 L_B \sin \tfrac{2\pi}{3}) \tfrac{d}{dt} i_{bs}$$
$$K_2 = -(4 L_B \omega_r \sin \tfrac{2\pi}{3}) i_{bs}$$

In Eq.15, ω_r is the rotor speed in hertz, which is equal to the frequency applied to the stator divided by the number of pole pairs. Thus, by knowing the induced voltage V_{ind}, the slope and the instantaneous value of the current i_{bs} and using ω_r, it is theoretically possible to compute instantaneous value of the rotor position θ_r.

Figure 3 shows a trace of the phase A current of a simulated SynRM drive wherein the zero crossing period of the phase A current is extended by applying the proposed technique. During the extended zero crossing period of phase A current, phases B and C of the converter are switched in a special diagnostic manner for a short interval. This diagnostic switching interval consists of following a constant reference current, in each phase, by means of hysteresis control. The level of the constant reference currents in phases B and C are exactly the instantaneous values of these currents, respectively, at the instant of phase A current zero crossing, as shown in Fig.4.

During this diagnostic PWM interval, the instantaneous slopes and the magnitudes of phases B and C currents become equal and opposite. The voltage induced in phase A due to the currents flowing through phases B and C is shown in Fig.5. The sequence of coupled voltage pulses, shown in Fig.5, have the instantaneous rotor angle encoded in their amplitudes, according to Eq.15. Each individual pulse amplitude sample can deliver one rotor angle sample by use of a look-up table. The table contains the inverse function of Eq.15, solved for θ_r, in discrete form. Thus, several samples of the rotor angle are obtained during each diagnostic PWM interval. These samples can be used for two purposes. The multiple samples can be used in an error reduction and noise elimination algorithm. The change of θ_r from sample to sample can also be used to enhance speed and rotor angle extrapolation algorithms between two zero crossings when the change of speed is very high, such as during start-up.

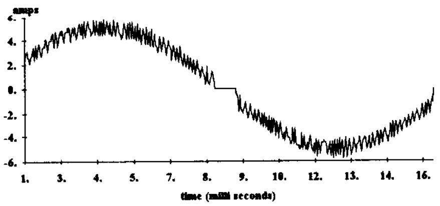


Fig.3 Extension of the zero crossing period of phase A current.

Although the proposed technique has been described only for phase A, the same technique can clearly be applied for phases B and C. Thus, for the six zero crossings within one electrical cycle of a three phase machine this technique gives six rotor position measurements. At this point it should also be mentioned that the zero crossing window of phase A current, Fig.3, has been made longer than necessary in order to illustrate the concept of the new switching technique. In a practical implementation of a SynRM drive this window will be much smaller than shown here because a very high frequency PWM will provide the required number of voltage pulses as shown in Fig.5 within a very short interval and consequently the zero crossing window can be made very small. These zero crossing windows must be kept as small as possible in order to avoid excessive torque pulsations.

The proposed technique nominally requires access to the center point of the stator of the machine. This requirement can be avoided with a simple modification of the switching technique. When the center point is not available, the controller will read the induced voltage between phase A and either of the remaining two conducting phases. It is possible to formulate the induced voltage expression similar to Eq.14 for this modified form of switching. For the simulation the

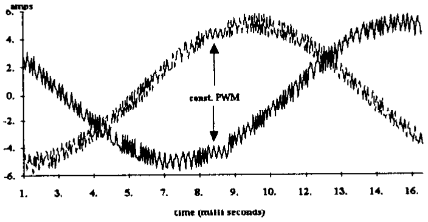


Fig.4 Phase B and phase C currents go into constant PWM during the extended zero crossing period of phase A.

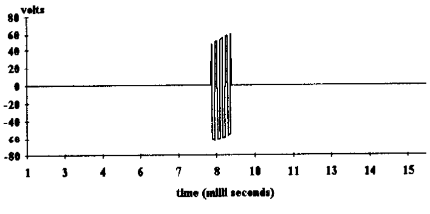


Fig.5 Phase induced voltage during the constant PWM of phase B and phase C.

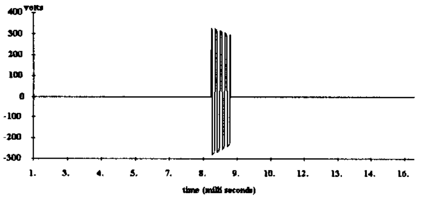


Fig.6 Line to line induced voltage (phases A & C).

induced voltage is measured between the phases A and C and is shown in Fig.6. Pulses of the coupled voltages shown in Fig.6 contains the rotor position information as explained previously.

IV. STARTING ALGORITHM

It is important to note that the proposed technique can determine the rotor position even at zero speed. At zero speed all phase currents are zero. This provides one with the luxury of inducing the diagnostic PWM signals on any pair of phases while the current in the other phase is controlled to experience zero current. The additional advantage is that the zero crossing can be made to persist for as long as one wishes the diagnostic interval to be. Furthermore, speed term $i_{bs}\frac{d}{dt}(L_{ab} - L_{ac})$ in Eq.14 is eliminated in the look-up table for θ_r, which can now be derived from the simple form given below,

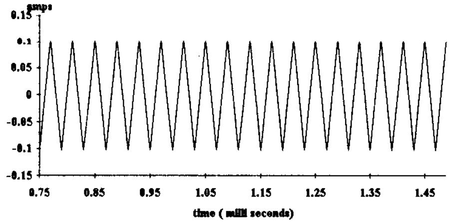


Fig.7 Current through phase B and phase C when the induced voltage is measured across phase A at zero speed.

$$V_{ind} = (L_{ab} - L_{ac})\frac{d}{dt}i_{bs} \qquad (16)$$

Figure 7 shows the diagnostic current of phases B and C during the induced voltage measurement of phase A.

To determine the rotor position uniquely, the induced voltages from all three phases have to be read. Induced voltage for phase A should be read by diagnostically energizing phases B and C. Similarly the induced voltages of phases B and C should be read by diagnostically energizing the remaining two phases. The induced voltages for three phases (when the rotor was at 25 mechanical degree) are shown in Fig.8.

It can be noted that the phase inductances of a SynRM is a function of twice the rotor angle θ_r i.e., $2\theta_r$. Hence, for every electrical cycle the phase inductance goes through two cycles. For this reason, the induced voltages at 205 mechanical degree as shown in Fig.9 will be same as those of shown in Fig.8.

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 SynRM has no preferred polarity due to the absence of any kind of winding on the rotor. Thus, during the startup operation the controller can be set to pick always the lower or the higher angle.

V. THE COMPLETE DRIVE SYSTEM

In order to verify key predicted results, an experimental self-synchronized SynRM drive has been implemented. The experimental machine has an axially laminated rotor of the type described in [1-3]. The stator is actually a standard configuration for a 7.5 hp three phase induction machine. The block diagram of the complete SynRM drive including the different controller segments is shown in Fig.10. IGBT's are used as the power semiconductor devices and are driven by high voltage integrated circuit gate drivers, FUJI EXB841. The controller is configured to take the induced

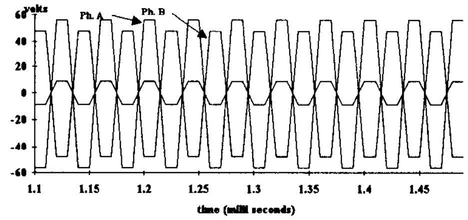


Fig.8 Induced voltages at zero speed when the rotor is at 25 mechanical degree.

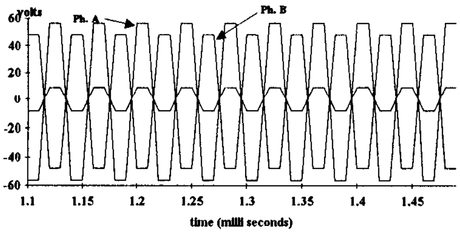


Fig.9 Induced voltages at zero speed when the rotor is at 205 mechanical degree.

voltage and the phase currents and generate the gate switching signals for the three phases. The remainder of the drive system consists of the induced voltage sensing circuit which is interfaced with the phase coils. Isolation of the sensing circuit from the power circuit is accomplished by using a high frequency isolation transformer. The control algorithm routinely measures the rotor angular positions and makes the experimental drive self synchronized by advancing or retarding the phase currents.

VI. EXPERIMENTAL EVALUATION

Throughout these tests case the SynRM operated at 1000 RPM under a lightly loaded condition. Figure 11 shows a measured trace of the phase A current with the extended zero crossing period corresponding to Fig.3. Note that the zero current interval is obtained, in this case only one per cycle. Figure 12 shows the constant current PWM interval of the phase B current during that extended zero crossing period of phase A. Figure13 shows the induced voltage measured in phase A. Very good correlation with simulation, Fig.5, is apparent. During the tests, the experimental drive was made self synchronized by advancing or retarding the phase currents depending on the rotor position. In order to calculate the starting rotor position, two phases were diagnostically energized and the induced voltage was read across the third phase. Figure 14 shows the diagnostic constant current regulation flowing through the phases B and C of the experimental drive. Figure 15 shows the voltage induced across phase A during this diagnostic interval. A strong, easily measurable signal is clearly evident.

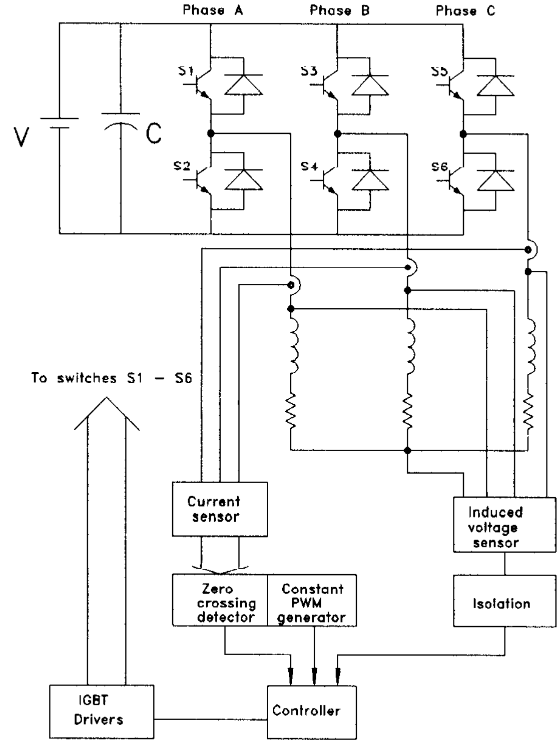


Fig.10 Drive circuit and the control block diagram of the proposed technique.

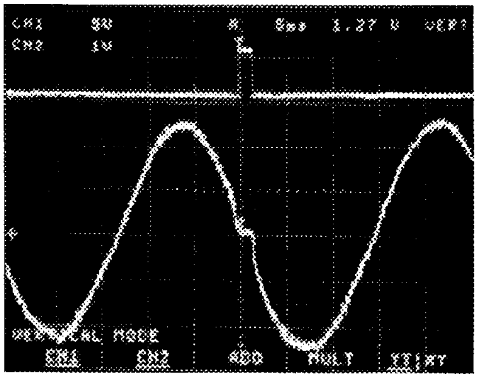


Fig.11 Lower trace: phase A current with extended zero crossing period. Upper trace: control pulse for disconnecting phase A .

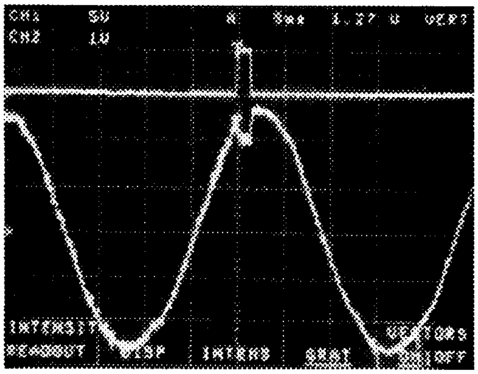


Fig.12 Phase B current (lower trace) goes into constant PWM during the extended zero crossing of phase A.

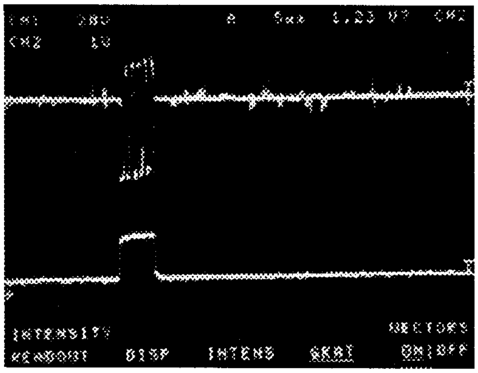


Fig.13 Induced voltage measured in phase A. Upper trace: Induced voltage. Lower trace: control pulse.

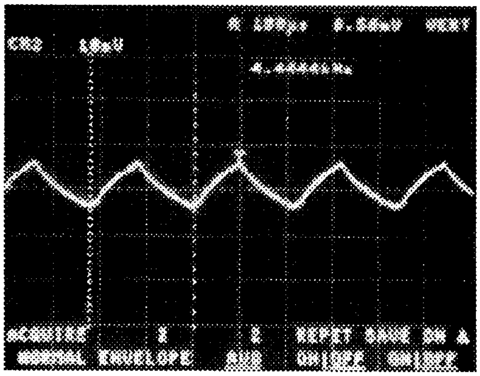


Fig.14 Diagnostic current flowing through the phases B and C during the start-up operation.

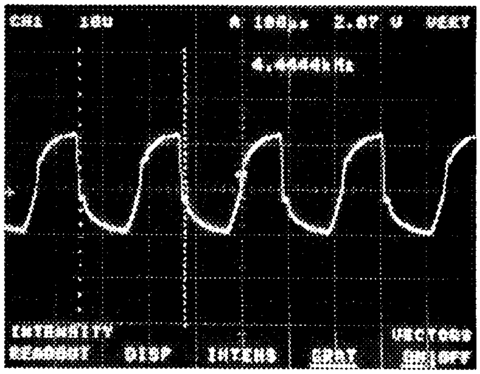


Fig.15 Induced voltage in Phase A during the start up.

VII. CONCLUSIONS

A new indirect rotor position sensing method for synchronous reluctance motor drives has been presented. This measurement technique can produce smooth rotor angle data all the way to zero speed, with increasing rather decreasing accuracy. Although the proposed technique provides the rotor position information only six times in one electrical cycle, rotor positions between two zero crossings can be readily calculated using simple interpolation.

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