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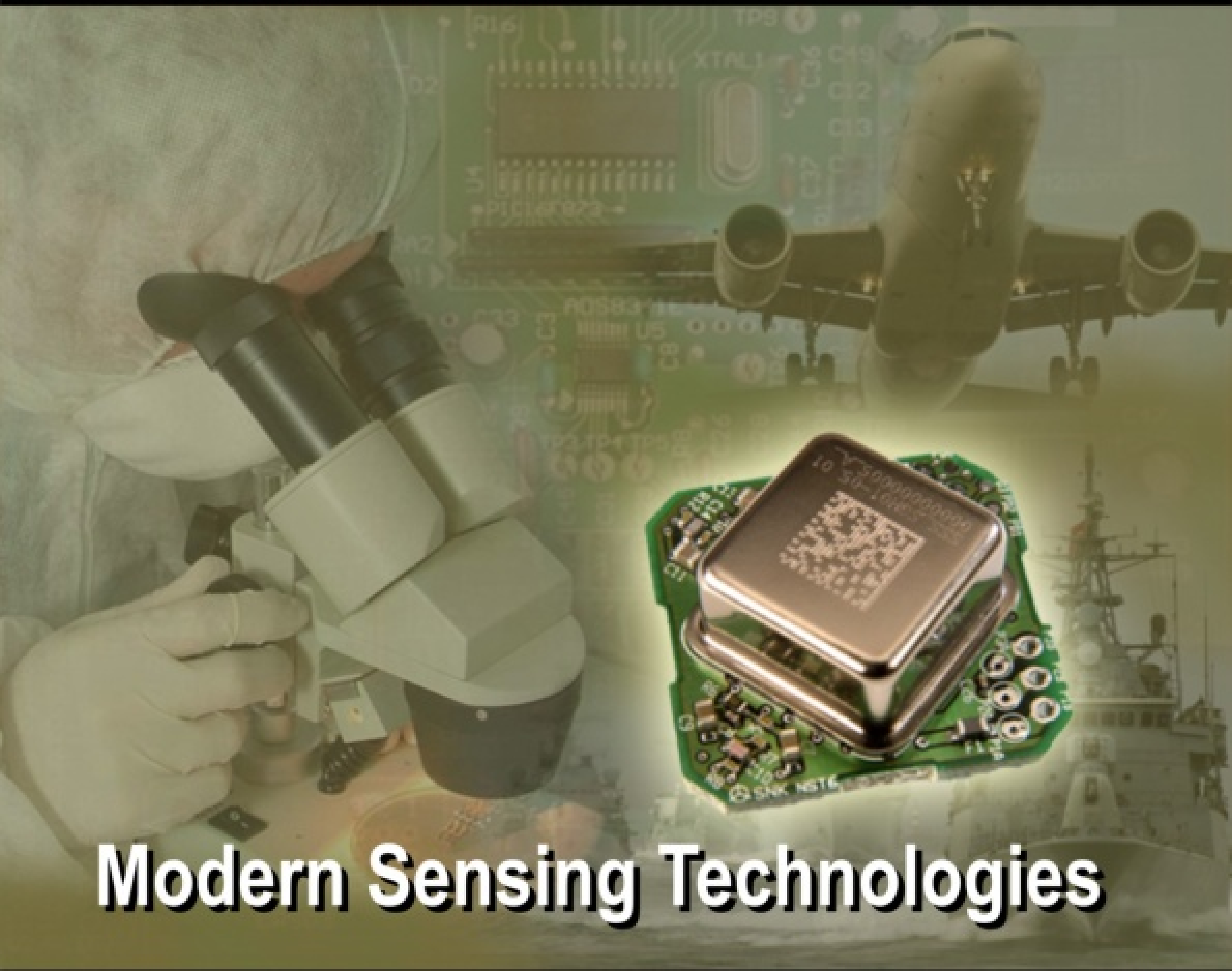

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Actual Excitation-Based Rotor Position Sensing in Switched Reluctance Drives

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Abstract: The sensing of the rotor position for Switched Reluctance (SR) motor is necessary for excitation control so as to obtain the best performance. The rotor position for SR motor control has usually been measured using a physical rotor position transducer attached to the rotor shaft. The fitting of a rotor position transducer on an SR motor requires additional electrical connections and additional cost, it is also a potential source of unreliability. Considerable attention has recently been applied to various methods for sensorless rotor position measurement, generally based on measurement of phase current and flux and a preknowledge of the magnetic characteristics. This paper presents two methods which deduce sensorless rotor position information by monitoring the actual excitation signals of the motor phases. This is done without the injection of diagnostic current pulses and has the advantages that the measured current is large and mutual effects from other phases are negligible. *Copyright © 2008 IFSA.*

Keywords: Rotor position sensing, Sensorless control, Switched reluctance motors

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1. Introduction

The structure of the switched reluctance motor is simple, robust and very reliable in operation. The machine has a salient pole stator with concentrated excitation windings and a salient pole rotor with no conductors or permanent magnets. Unlike induction motors or DC motors the SR motor cannot run directly from an AC or DC supply [1]. The flux in the SR motor is not constant, but must be established from zero every working step. A power converter circuit must supply unipolar current pulses, timed accurately to coincide with the rising inductance period of each phase winding. It is therefore advantageous to feed rotor position information from a shaft mounted sensor back to the control board (see Fig. 1(a)). Much has been made of the undesirability of the shaft sensor, because of the associated cost, space requirement, and possible extra source of potential failures.

Operation without the shaft sensor (see Fig. 1(b)) is possible and several schemes have been reported. But to achieve the performance possible with even a simple shaft sensor, considerable extra complexity is necessary in the controller, particularly if good starting and running performance is to be achieved with a wide range of load torques and inertias. Much the same is true for the permanent magnet brushless motor and the induction motor variable speed drives.

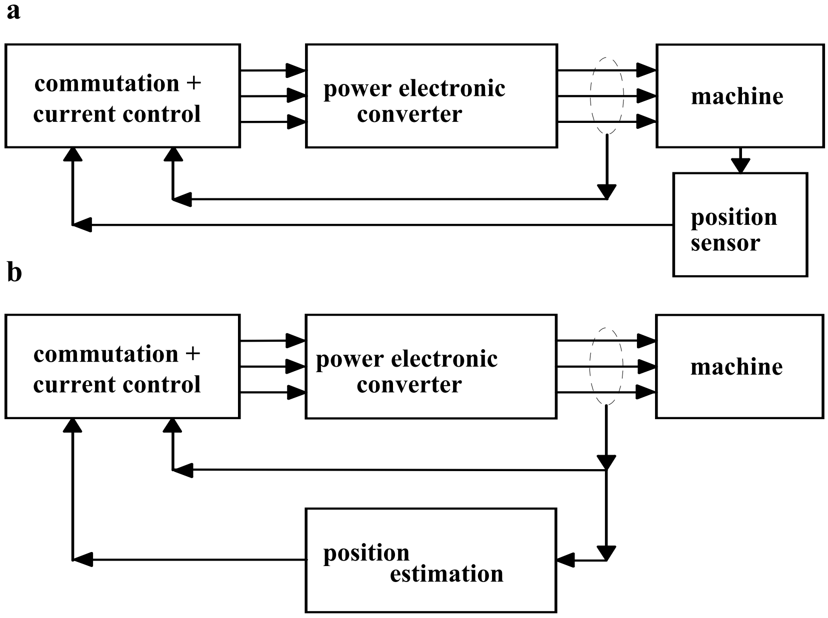


Fig. 1. Schematic arrangement of the switched reluctance drive: (a) with position sensors, (b) with sensorless position estimator.

Much recent and current research is directed at determining rotor position from winding currents and/or voltages, either those normally occurring or from those specially injected for this purpose. The early proposed methods were to identify a position during the period for which the phase incremental inductance is rising (or falling) by measuring the current rise times with constant amplitude chopping (or vice versa). A high chopping frequency is necessary to obtain sufficient resolution at high speed. Furthermore, the mutual effect of other phase currents and the back emf at other than very low speeds are very significant and can not be neglected. So far, there is no such technique reported that has been successful in covering the entire speed range.

This paper reports the development of two new methods based on using the actual motor excitation signals, not an injected signals for sensing purposes. The first method, described in section 4, is especially suited to medium and high speed operation (single pulse mode), but can be extended to low speeds. The second method, described in section 5, can cover the entire speed range, at the expense of increased computational requirement. This has been made practicable with the recent advances in digital signal processor (DSP) and their continuous decrease in cost.

2. Sensorless Position Estimation

Various methods have been proposed to eliminate the rotor position transducer, the majority of which aim to deduce rotor position by the measurement and examination of the current and flux-linkage (or inductance) in one or more phases of the motor. Comprehensive reviews of these methods have been published in [2]-[4].

The methods fall mainly into two groups. In the first group [5]-[8] test signals of different kinds are introduced during the time when a phase is normally not energized. For motoring operation this is generally during the falling inductance period or, at low speeds, around the minimum inductance periods. The test signals need to be of low amplitude to;

1) avoid negative torque production;
2) avoid back-emf effects;
3) avoid saturation effects (i.e. dependence of inductance on current in addition to rotor position) and
4) minimize the size and cost of additional injection circuitry where this is necessary.

These low amplitude test signals are susceptible to mutual interference from the excitation currents in other phases and this is the main problem with these methods. At high speeds the excitation waveform occupies the majority of the phase period which, seriously restrict the injection of test signals. Thus, these methods are more suited for lower speed operation.

The second group of methods [9]-[13] utilizes the excitation current waveform. Since diagnostic current pulses in a non-energized phase are of necessity small and suffer from mutual effects, it is sensible to examine the use of the main excitation current waveform for the purpose of rotor position sensing. This current already exists and does not require additional switching or injection circuitry.

If at a given instant the flux-linkage $\psi(\theta,i)$ or inductance $L(\theta,i)$ is known and the current i is known, then this defines the rotor position θ provided, it is also known whether the inductance is rising or falling. The latter is generally obvious from the positioning of the excitation which will be predominantly in the rising inductance region for motoring operation. The position can be looked up in pre-stored tables of ψ or L against θ and i .

These two groups cover the main-stream methods for sensorless detection of SR rotor position. However, there are a number of other proposals and published work which do not fit directly into these groups; such as the use of a state observer [14], monitoring back emf [15] and monitoring mutually induced voltages [16]. It is evident from the number of publications that research in the area of sensorless position detection is very active but that considerable further work will be required before a reliable and commercially applicable method is fully developed.

3. Rotor Position Sensing Based on Actual Excitation

This section introduces two different methods of rotor position measurements for the control of switched reluctance motors without the use of optical or magnetic sensors. Both methods utilize stored magnetic characteristics for a motor phase and estimate rotor position by monitoring the excitation signals.

The main advantages of these methods are:

1) the injection of additional signals into the machine windings are not needed;

2) the position measurement is based on flux linkage / current / position data, so that saturation and back emf do not introduce errors in the position estimation;
3) the measurements take place during the rising inductance period which is the most sensitive region for rotor angle discrimination and it is not necessary to specify mechanical load parameters;
4) the rotor position estimation is less susceptible to mutual effect from other phases.

One method involves a 3-dimensional lookup tables and requires continually repetitive comparison of measured and stored values. This method will be described in more detail in section 5. Whilst the other method makes one single position measurement per phase cycle and need only 2-dimensional lookup tables of magnetic data. This method is described in section 4. Both of these methods are verified experimentally.

4. Method Based on Single Measurement per Phase Cycle

This method is based on estimating a particular rotor position on a phase by phase basis and measuring flux-linkage and current when this estimated position is reached. By comparing the measured flux-linkage with the stored flux-linkage corresponding to the particular (reference) position for the measured current, the angular difference between the estimated position and the reference position can be calculated.

One position measurement for each phase per phase period will be made. The measurement system will therefore be a direct replacement for the existing incremental position sensor and no change need to be made to the existing control strategies. Consider the schematic phase current and voltage waveforms shown in Fig. 2.

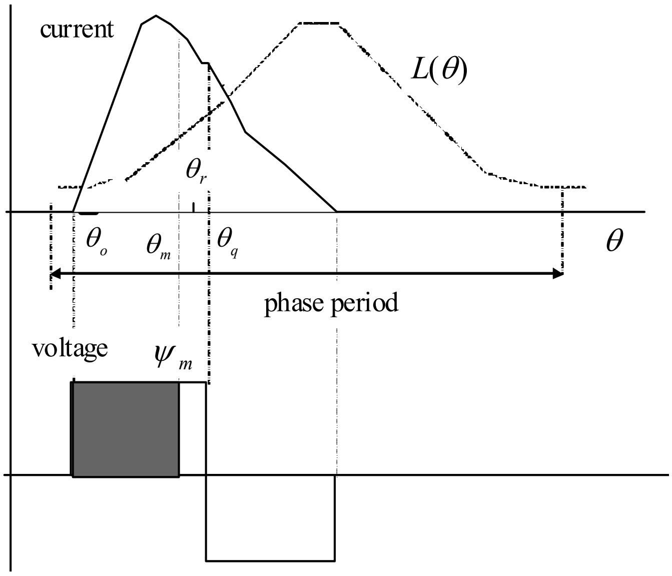


Fig. 2. Typical current and voltage waveforms at high speed in relation to the inductance profile.

The reference angle θ_r is the prechosen position for which the 2-dimensional characteristic is stored, and is preferably fixed for the entire speed range.

The measurement angle θ_m is the actual position at which the measurement is made - ideally, the measurement angle should coincide with the reference. The measurement angle may be situated after the commutation point θ_q although it is preferred to be before the commutation angle as shown in the figure above. At the previous measurement angle $\theta_{m'}$ (for the previous phase), and knowing the speed, the time to the next θ_r can be calculated. When this time has elapsed the measured flux-linkage ψ_m and current i_m are recorded.

The flux-linkage is best measured by integrating from the time corresponding to θ_o in Fig. 2 - i.e.:

$$\psi_m = \int_{\theta_o}^{\theta_m} (V - iR)dt, \tag{1}$$

where V is the phase voltage and R is the phase resistance.

The integrator for ψ_m will be started at θ_o when the phase is switched on. In general, due to error in the calculation or acceleration/deceleration effects, the position θ_m will be different to θ_r.

Having obtained the measured flux-linkage and current at the unknown position θ_m (but assumed to be reasonably close to the reference position), the expected value ψ_e for the flux-linkage corresponding to the measurement current i_m and the reference angle θ_r can be obtained from the look up table. This is shown in Fig. 3.

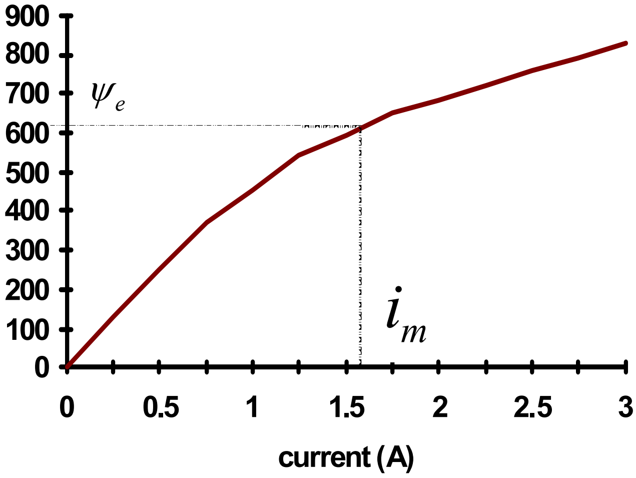


Fig. 3. Flux-linkage v current characteristic for rotor angle θ_r.

The ψ_e will differ from ψ_m, unless $\theta_m = \theta_r$.

For small variation, $\Delta\theta$ about θ_r for a particular i_m.

$$\Delta\psi(i_m) = \psi_m - \psi_e \tag{2}$$

$$\Delta\theta = \left(\frac{\partial\theta}{\partial\psi}\right)_m \Delta\psi(i_m) \tag{3}$$

and

$$\Delta\theta = \theta_m - \theta_r \tag{4}$$

The partial derivative $\frac{\partial\theta}{\partial\psi}$ is a function of current as shown in Fig. 4 and can be stored as a 2-D look up table.

The position θ_m may now be estimated using equations (3) and (4);

$$\theta_m = \theta_r + (\frac{\partial\theta}{\partial\psi})_m \Delta\psi(i_m) \tag{5}$$

Note that only two 2-D look up tables are required irrespective of the number of rotor phases.

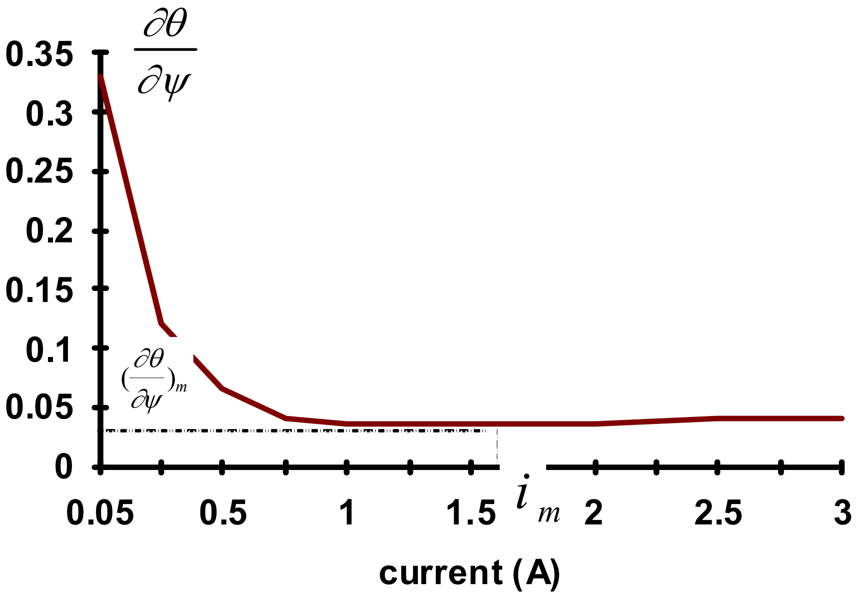


Fig. 4. $\partial\theta / \partial\psi - i$ characteristic for rotor angle θ_r.

A 0.3 kW 10,000 rpm 3-phase 6 stator/4 rotor pole SR motor drive was used to test the above position detection method. The experimental system is shown schematically in Fig. 5.

The aim was to directly replace the signals generated by the SR drive incremental position sensors. To avoid modification to the SR controller a separate TMS320C25 digital signal processor was used to execute the sensorless measurement. The program was prepared on and down loaded from a PC. A multiplex arrangement was used so that the SR drive could operate either from its optical position sensors or from the sensorless position signals. The SR drive system was run up to a predetermined speed using the optical sensors and the sensorless program then initiated. Control was then transferred to the sensorless signals. Fig. 6 shows the experimental sensorless position signals for three phases and one position signal from one of the head sensors.

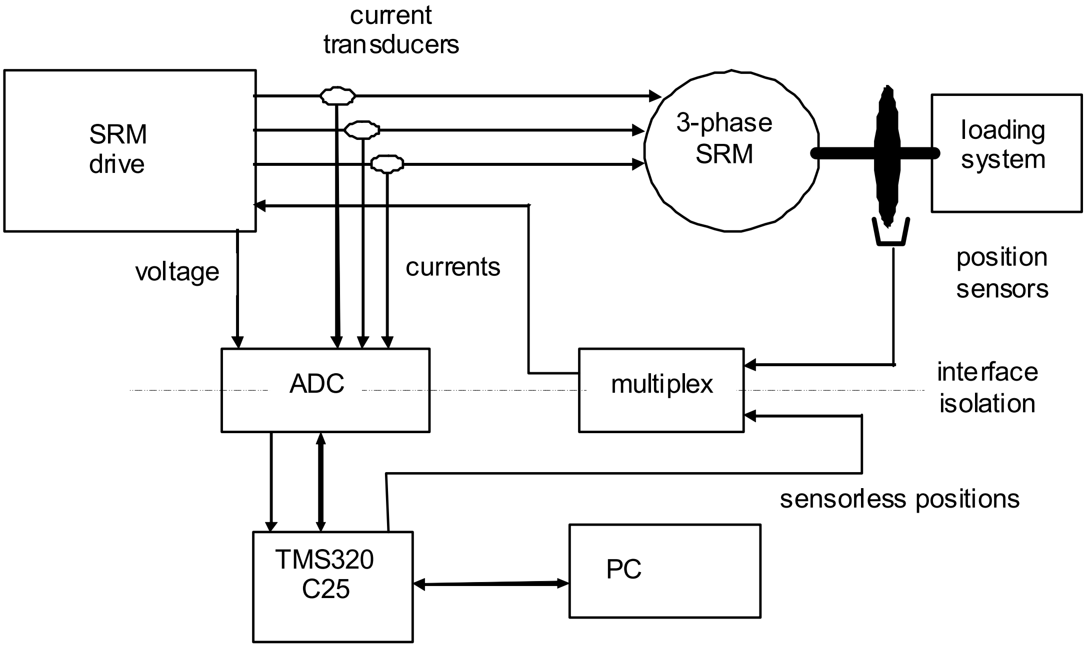


Fig. 5. Schematic diagram for the experimental test system.

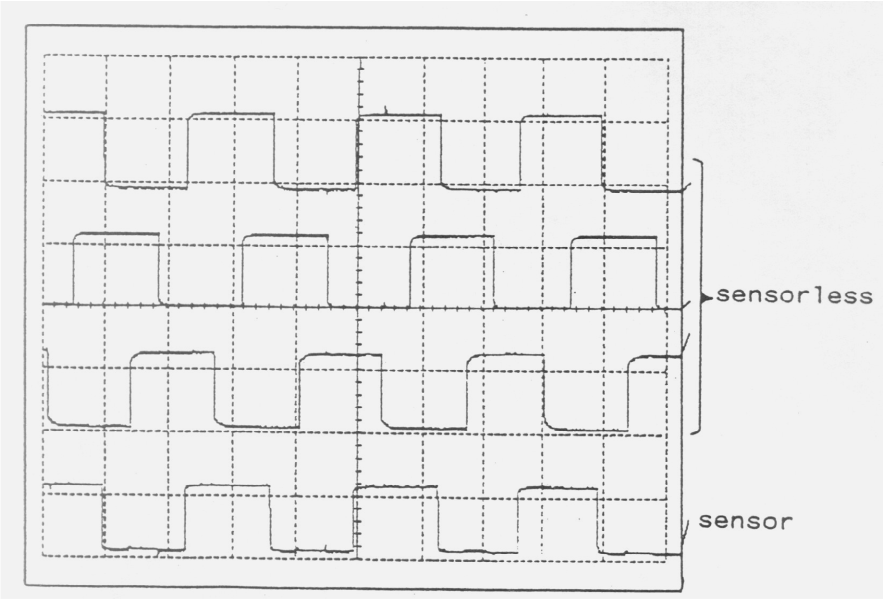


Fig. 6. Experimental sensorless position signals
(Voltage scale: 5 volt/div, Time scale: 1 ms/div).

The presence of the optical sensors enabled a comparison to be made between the optical position indicators and those from the sensorless method under different conditions of speed and torque. For a high resolution comparison, the maximum inductance angle has been indicated for both signals. Fig. 7 shows a typical oscilloscope waveform with the sensorless position indicators on the bottom trace, and those from the optical sensors on the top trace. The time difference between these represents the measurement error. This could be obtained by expanding the time scale on the oscilloscope or displaying a third high frequency waveform as shown in Fig. 7.

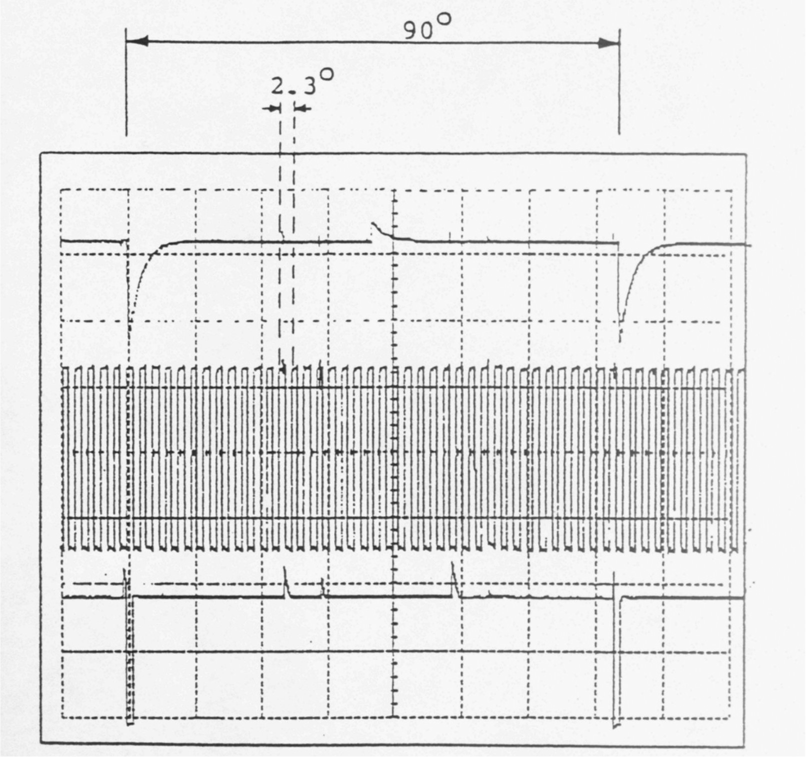


Fig. 7. Comparison of optical and sensorless-method position indicators for one phase
Top trace - sensor signal 5 volt/div; Middle trace - HF comparison signal 2 volt/div;
Bottom trace - sensorless signal 2 volt/div; Time scale - 500 microsecond/div.

The SR drive was demonstrated to operate in satisfactory manner with sensorless position measurement over a significant speed range (100 to 10,000 rpm) and with different levels of load torque. The positional error was measured to be within +/-1.1 degree which did not significantly reduce the drive performance. The method however only works provided the current pulse is of sufficient duration for a measurement to be made - i.e. it does not work at very low or zero torque levels. This major deficiency which must be corrected.

The aim of this method was to produce a simple algorithm such that the measurement computation may be achieved by the existing SR drive microprocessor/controller without requiring additional microprocessor or a more powerful digital signal processor.

5. Method Based on Continuous Measurements

This method is based on earlier work by Acarnley et. al. [17], [18] for permanent magnet motors. The rotor position in this method is estimated continuously using a predictor/corrector routine which performs the following stages; firstly, the flux-linkage can be predicted from voltage and current measurements. Then, combine the predicted flux-linkage with predicted rotor position based on the previous measurement and using the look up stored flux linkage/current/rotor position, estimated current can be obtained. Compare estimated and measured currents to derive a current error, then translate this current error to a position error using stored machine characteristics. Finally, the predicted position can be corrected using the position error. The algorithm is illustrated schematically in Fig. 8.

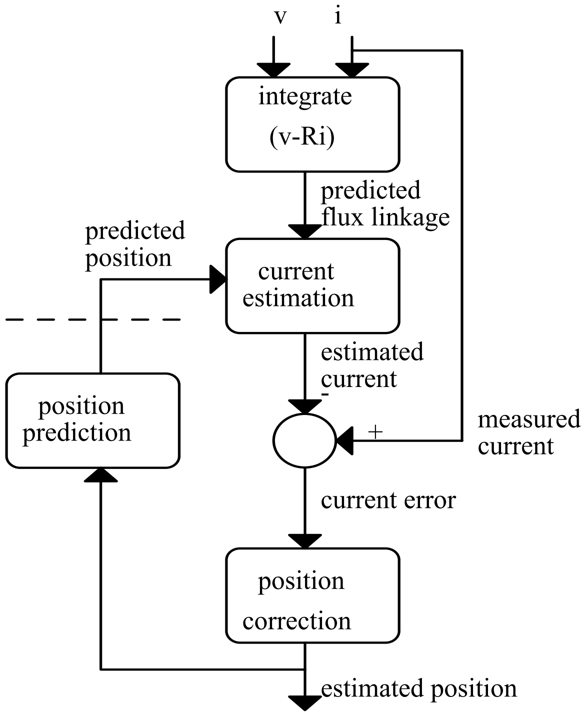


Fig. 8. Simplified position estimation algorithm signal flow.

The experimental set up (Fig. 9) is based on a TMS320C31 digital signal processor. The drive controller/position estimator is implemented in 'C'.

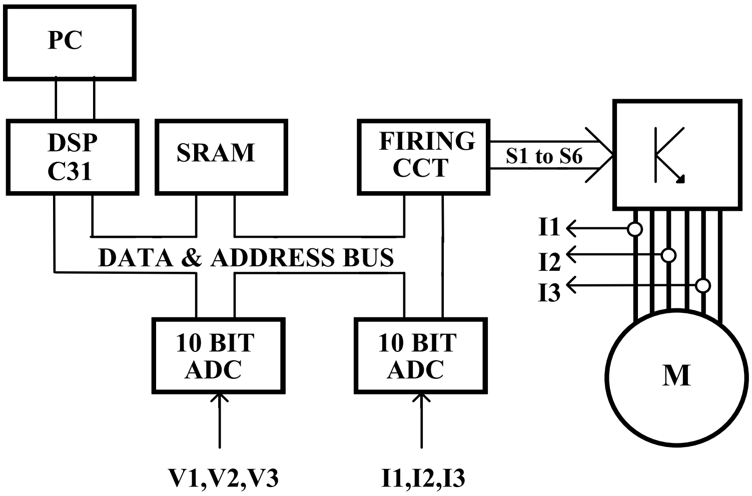


Fig. 9. Experimental setup system overview.

Experimental results were obtained using a commercial 7.5 kW 3-phase SR motor with 12 stator poles and 8 rotor poles. Machine magnetic characteristics are stored at rotor positions in the range 0-22.5 deg at 2.5 deg intervals and at flux-linkage values in the range 0 to 1600 mWb at 20 mWb intervals. Values of phase current at intermediate flux linkage and rotor positions are calculated using linear interpolation. Fig. 10 illustrates the general form of this data in the more familiar format of flux-linkage expressed as a function of rotor position at various phase currents.

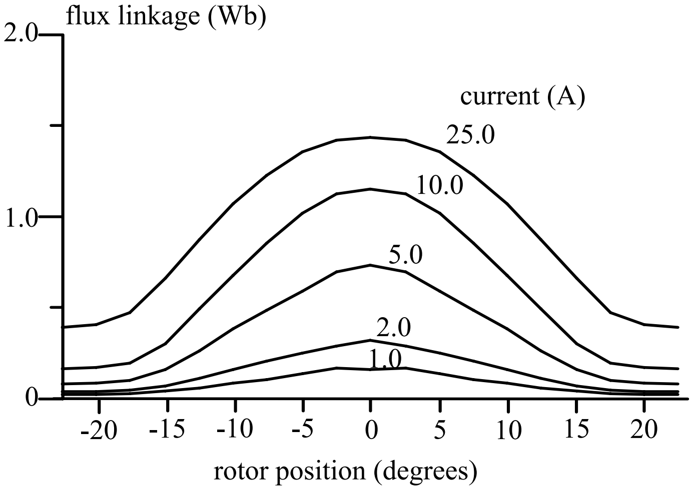
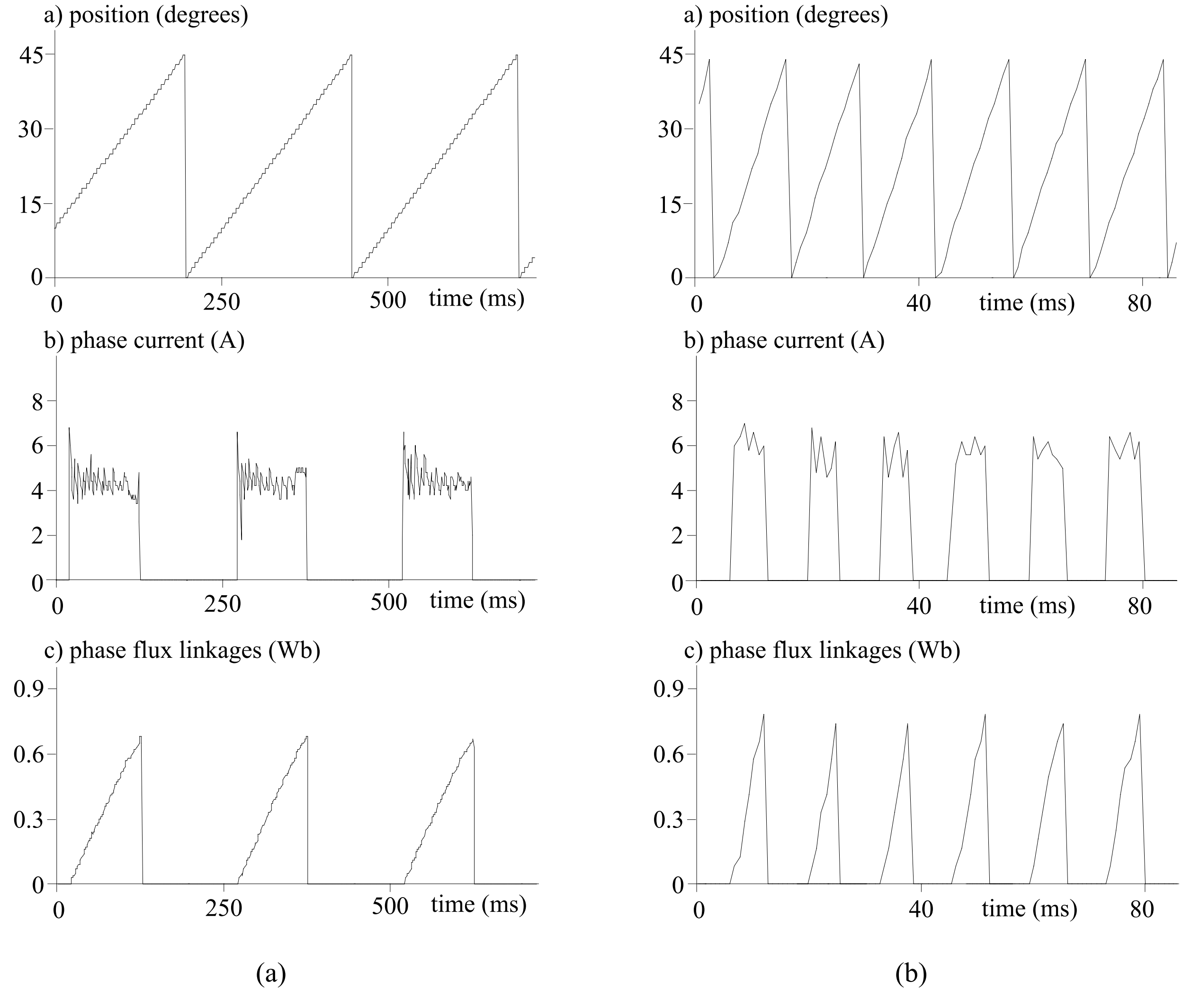


Fig. 10. Flux-linkage versus rotor position at various phase current.

Fig. 11 shows typical results from the position estimation algorithm when the drive is operating at a constant speed. The results have been obtained with the position being estimated in real-time and being used as a feedback signal to initiate commutation between phases.



(a) (b)

Fig. 11. Estimated rotor position, phase current and flux-linkage at: (a) 30 rpm, (b) 500 rpm.

In this method, there are no limits imposed on operating speeds apart from starting up from standstill. Also, since the estimation procedure produces a continuous position signal, it is a straightforward matter to implement for variations in conduction angles with speed and load. Further testing of performance and positional accuracy needs to be carried out.

In the development of this method it has been assumed that the cost of processing power will continue to fall. Therefore the emphasis has been placed on the development of a method which is flexible and applicable to wide applications and operating conditions covering the entire speed range [19] and [20], at the expense of increased computational requirement.

6. Conclusions

The majority of sensorless rotor position measurement methods involve the insertion of diagnostic current signals into the phases whilst these are normally not energized. These diagnostic signal methods are limited to low speed operation.

It is preferable to utilize the excitation current. Why inject diagnostic current pulses if a measurable current already exists? This also has the advantage that the measured current is large and mutual effects from other phases are negligible.

The two methods discussed in this paper produce rotor position measurement utilizing the excitation signals. One method makes a single measurement each phase cycle as a direct replacement for the existing incremental position sensors. It was a simple algorithm so that the measurement computation may be achieved by the existing SR drive microprocessor/controller without requiring an additional microprocessor or a more powerful digital signal processor. This method can not cope with very low speed/low torque operation. Additional improvement is necessary to make it cover the entire speed range. The method is suitable for well defined torque/speed characteristic applications such as fan and pump operations.

The other method makes continuous measurements of rotor position. It covers the entire speed range. It does however require a powerful digital signal processor to implement the extensive computational requirement. The development of such a method was based on the assumption that digital signal processor prices will continue to drop, a realistic assumption.

The accuracy in both methods depends on the accuracy of characterizing and measuring the flux-linkage. To minimize the error the same method of measuring flux-linkage for characterization purposes, should be used for the measurement under operating conditions. Provided sufficient accuracy is achieved in measuring and characterizing flux-linkage, then an acceptable accuracy of position measurement for SR drive control purposes can be achieved.

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