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# Sensorless Commutation Control of Switched Reluctance Motor

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***Abstract*—**This paper addresses control of commutation of switched reluctance (SR) motor without the use of a physical position detector. Rotor position detection schemes for SR motor based on magnetisation characteristics of the motor use normal excitation or applied current /voltage pulses. The resulting schemes are referred to as passive or active methods respectively. The research effort is in realizing an economical sensorless SR rotor position detector that is accurate, reliable and robust to suit a particular application. An effective and reliable means of generating commutation signals of an SR motor based on inductance profile of its stator windings determined using active probing technique is presented. The scheme has been validated online using a 4-phase 8/6 SR motor and an 8-bit processor.

***Keywords*—**Position detection, rotor position, sensorless, switched reluctance, SR.

## I. Introduction

MOST switched reluctance motor controllers at present use optical heads or its equivalent to obtain rotor position needed for position feedback [1,2] to indicate the degree of overlap between the stator and rotor poles. Fig. 1 shows such a motor and an attached optical position sensor. The physical position sensor has problems and limitations, hence the need for a sensorless one. However, by developing a sensor that is compatible with existing controllers making outputs of the, adoption is quicker. The developed microprocessor based sensorless drive system stores rotor position transfer characteristics (RPTC) of the motor and use

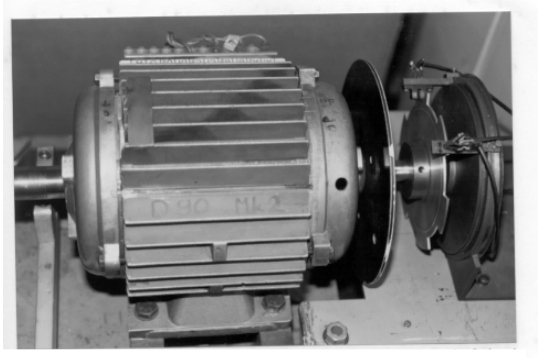

Fig. 1 SR motor with optical head position transducer

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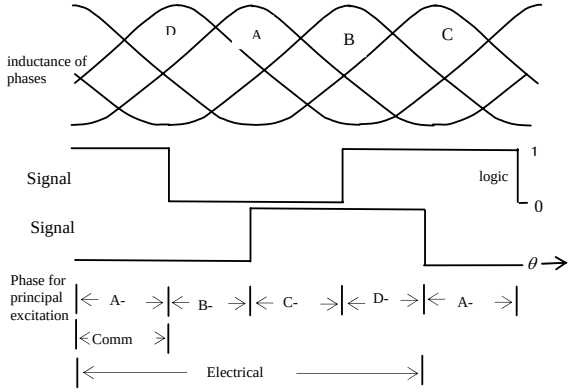


Fig. 2 Stator inductances of a 4-phase SR motor and the relative conventional optical head signals

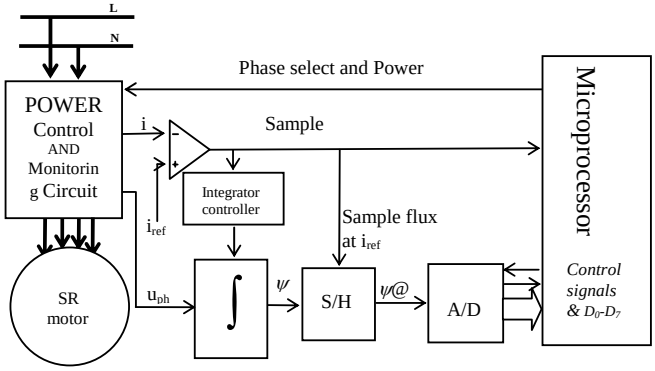


Fig. 3 The general block diagram of a sensorless rotor position

it to generate position representing signals during operation equivalent to those produced by conventional optical heads. Fig. 2 shows phase inductances and corresponding optical sensor position signals for a 4-phase 8 stator and 6 rotor poles SR motor [3,4,5]. Fig. 3 shows the general setup of the developed method. This method of generating rotor position signals differ from the conventional one in that there cannot be an offset between rotor teeth and the generated position signals since it uses the inductance characteristics of the motor. Moreover, the extrapolation normally used with optical encoders to predict commutation position is not required since that information is in the microprocessor. This paper does not include SR control strategy.

A number of schemes that have been developed aiming at removing the necessity of using optical encoder or its equivalent in the control of SR motor. These schemes use concepts ranging from those using linear characteristics of phase inductance to non-linear ones using observer or phase permeance [2, 6, 7, 8, 9, 10, 11]. The basic difference between the different methods is in the technique used in extracting and in processing phase inductance or its inverse to obtain position information. Each method has its advantages and disadvantages. The method being presented is based on simplicity hence low cost, while aiming for high reliability and accuracy.

## II. Design Environment

A 4-phase SR motor with eight stator poles and six rotor poles was chosen to test the developed rotor position detection method. An 8-bit microprocessor (8 MHz clock) was used; however the choice presents a challenge of working with low resolution. In comparison, an observer-based detector and others [7, 8, 9, 10, 11] needed at least a fast 16-bit processor but the performance was not always satisfactory when tested online. An 8-bit A/D converter was used to digitize flux linkage signal representing position that gave a mechanical position resolution of ≤ 0.12° ($3.3\times10^{-4}$) that was considered sufficient.

One phase was switched ON at a time for motoring using two snubberless power MOSFET switches per phase. The problem is time critical, hence low level language was used to utilize the full capability of the microprocessor.

The position information was obtained by injecting diagnostic current pulses in the phase opposite to that used for motoring to generate an inductance profile as shown in Fig. 4. There are interactions between phases that lead to significant detection errors as shown in Fig. 5.

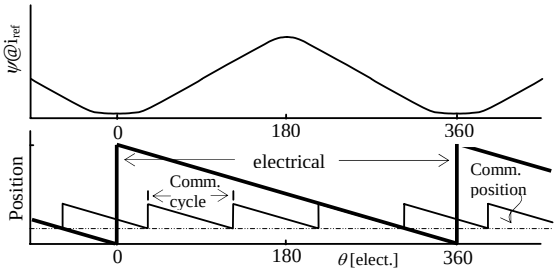


Fig. 4 Position signal definition using constant current

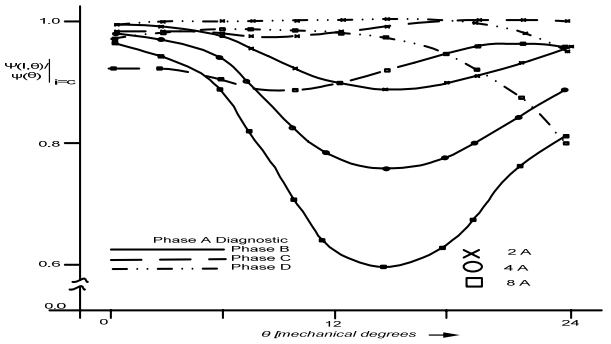


Fig. 5 Effects of magnetic coupling between phases and that of back core saturation

## III. System Design and Implementation

The design and implementation of the sensorless rotor position detection system for SR motor was divided into three basic operations namely; position sampling, starting and providing commutation during motoring/braking operations. Commutation is effected in the same way for all speed ranges using different information sources. Sampling position and commutation control are common at low speeds while differing at medium speeds where position is extrapolated from previous measured positions. Position detection in this new method defines a reference phase.

### *A. Using Position Transfer Characteristics*

The detected rotor position is defined cyclically in terms of commutation angle or in an electrical cycle as illustrated in Fig. 4. A reference phase is defined in electrical cycle so that the detected position $\theta=(\theta_n+\theta_{offset})$ where $\theta_n$ is the sampled position and $\theta_{offset}$ is the angle between the diagnostic phase and the reference. For every four steps of a 4-phase SR motor, position magnitude cycles between 0° and 360°. This is used when detecting simultaneously in more than one phase. When detecting within excitation cycle from a phase, position magnitude is obtained from diagnostic flux-linkage signals directly using the $\psi/\theta$ tables without any transformation [2], $\psi$ being flux-linkage. The detected position varies between that of commutation and the commutation position plus fixed phase displacement between adjacent phases (i.e. 90° electrical) during operation. The detected position can be used directly to control commutation since initialisation was done during starting.

To translate diagnostic flux-linkage signal to position magnitude, the flux-linkage at aligned position was assigned 180° and that at mis-aligned position 0° as shown in Fig. 4. This representation was chosen over the conventional use of leading and trailing edge of the rotor pole to avoid the use of signed numbers. The detected position during motoring will be in decreasing magnitude to reflect decreasing inductance profile irrespective of direction of rotation.

The constant-current RPTC $\psi/\theta$ table used in position detection was programmed directly using position information from an optical encoder and the flux-linkage signal that

mapped its variable magnitude to that of input dynamic range the A/D converter used. The differences in the inductance of different phases, circuit components and current transducers were compensated for by adjustment of current traducer sensitivities to enable the use one table of $\psi/\theta$ for all phases. The memory requirement, costs and access time were thus optimised. The $\psi/\theta$ table lowest position resolution was 0.5° electrical, which was better than the targeted resolution of 1° electrical.

### *B. System Design Strategy*

The tasks necessary to operate a sensorless SR motor were performed in an interrupt mode with appropriate priority assignment to effectively and efficiently utilise the processor time. These are monitoring operators' commands and flux-linkage, speed calculations, position extrapolation and provision of commutation signals. In the commutation process, signals similar to those of conventional optical heads were produced (Fig. 2) to control excitation of principal and diagnostic phases. From the conventional head signal changes occur at fixed positions while in the new method the change occurs at the commutation position.

There were few external inputs; hence each external port of the microprocessor kit was dedicated to specific function to minimizing external circuitry. The high logic level was conceived as OFF and low as ON state hence switching off power could be effected by resetting the processor in case of emergency.

To control costs, modest speed A/D converter was used. Part of the processor external access setup was used as A/D conversion period. The processor was signaled to read in flux-linkage data while initiating A/D conversion process whenever the diagnostic current reached a defined level after application of diagnostic voltage pulse to a phase winding. The execution speed was optimised, and the necessary program storage area minimised by changing parts of the program code during its excitation. This was done for repetitive events (conditions) that changed less frequently than execution of a particular routine.

### *C. Operation*

The starting-up routine involved setting-up interface ICs, initialising variables and setting program logic for low speed operation in a particular direction and defining the phase for excitation. Information from the diagnostic phase(s) is used to enable principal excitation. Comparison of position magnitudes of adjacent phases is used for this when starting from rest. A phase shift is introduced to one of the phases before comparison to facilitate starting from any position since there were a few ambiguous points. Once started, the low-speed routine takes over excitation control.

When the diagnostic phase is defined the actual sampling [2] is initiated by the minimum error conditions. The microprocessor reads in flux-linkage data when signaled by the RPTC generator of its availability that is translated into position using pre-stored $\psi/\theta$ table. When reading in position data; time and the difference between the current position and the next commutation position given by the extrapolation routine are recorded.

At low speeds position sampling and commutation control were implemented in the same routine to minimise execution time. However, at medium speeds two routines were necessary since the two events do not necessarily coincide in time because commutation instance is predicted by extrapolation. However, partial speed calculation is done in the sampling routine in both speed ranges to optimise overall execution time since data transfer between routines is minimised.

The commutation function defines and passes to the driver/control board the next principal and diagnostic phases for excitation using two bit codes similar to that from conventional optical head. This is done whenever the detected or extrapolated instantaneous rotor position signal equals or crosses the set commutation position. The sampled position was used directly at low speeds while extrapolated position using previous samples was used at medium speeds for this.

### *D. Position Extrapolation*

Position extrapolation starts with continuous calculation of rotor speed following acquisition of a position sample. The low speeds region is used to setup operation in medium speed regime. The concept used to determine speed taking the ratio of incremental position over its sampling interval.

The switchover from low to medium-speed operating regimes and vice versa was determined by a pre-set value of speed including hysteresis. In the medium speed regime, the calculated speed updates the extrapolation of rotor position for commutation control.

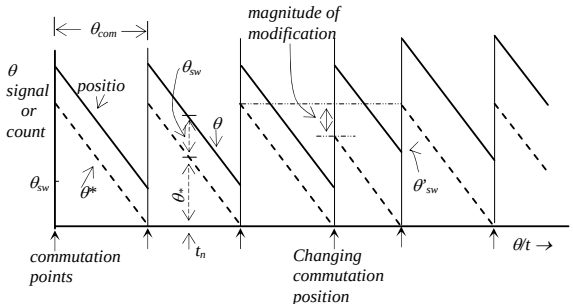


Fig. 6 Position extrapolaion using counters relative to measured ones and changing that of commutation

The magnetic coupling between different phases was assumed negligible since opposite phase was used, but as shown in Fig. 5 errors in adjacent phases is very significant. All other residue error sources were assumed to be random in speed calculations. Hence, as a compromise between delay and extrapolated position errors an average of 4 successive samples was used for position extrapolation. To eliminate sporadic large errors tests were made to correlate position and

speed changes of successive position samples before adoption for speed calculations. The concept used is based on the fact that inertia of moving parts limits acceleration/deceleration hence magnitude of rate of change. Correlation tests on both speed and position increased reliability of the limited resolution (8-bit) system used while saving processor time.

Equation 1 gives the concept used in extrapolation of rotor position. The minimum number of diagnostic pulses required per excitation cycle to extrapolate rotor position reliably is two. CTC counters of the microprocessor kit are used to integrate speed during extrapolation to free the processor. Two counters were used, one contained position information and the other speed information (i.e. inverse of speed). The value of the speed counter is defined as $\Delta t_r/\Delta\theta_r$ where $\Delta\theta_r$ is the resolution of the speed detector and $\Delta t_r$ is the time required for the motor to move by the resolution amount assuming constant speed operation.

$$\hat{\theta}_{x_{n+1}} = \int_{t_n}^{t_{n+1}} \omega dt + \theta_{x_n} \tag{1}$$

The $\Delta t_r$ is obtained from speed calculations while $\Delta\theta_r$ is consider to be unity. The slope counter is updated with $\Delta t_r$ value after every position sample. By decrementing the position counter at the end of every timed interval $\Delta t_r$ as determined by the slope counter, the contents of the position counter reflect relative rotor position. Instantaneous position can be obtained by initialising position counter with measured value of position. The initialisation method adopted took into

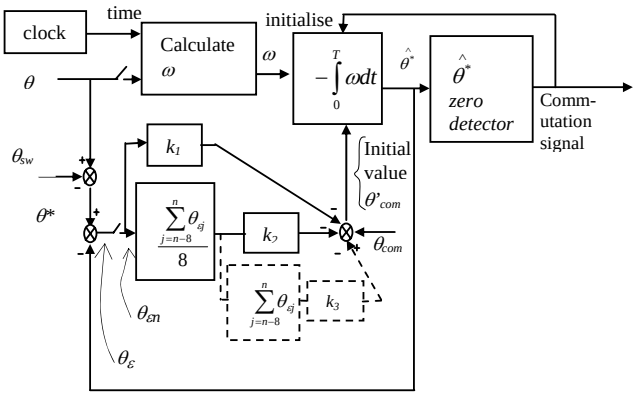


Fig. 7 Schematic diagram of position extrapolation process that accommodate transient and measurement characteristics errors

consideration that extrapolation defines commutation instance. Therefore, the value of the position counter was set equal to the position differences between two successive commutation positions $\theta_{comm}$ at commutation instance (Fig. 6) which is position of next diagnostic phase just before commutation less the commutation position magnitude.

The value $\theta^*$ contained in the position counter is the difference between the instantaneous position magnitude given by the diagnostic phase and $\theta_{sw}$ the commutation position. When the 8/6 poles four phase SR motor is operated under fixed conduction angle of one phase excitation at time control method (principal excitation) the position change between commutations $\theta_{comm}$ is 90° electrical. Therefore, position $\theta$ in fig. 6 for an error free operation is given by equation 2.

$$\theta = \theta_{sw} + \theta^* \tag{2}$$

The position counter was set to generate interrupt at zero count when operating in the medium speed regime to signal the processor to generate commutation signal. Note that the curve for position magnitudes looks similar to that of $\theta^*$ because the phase inductance of diagnostic phase decreases with position during motoring operation.

In an error free operation, initialisation need be made once in the low speed regime. However, errors are expected therefore they must be checked and corrected cyclically to prevent accumulation. The last position from diagnostic pulse prior to entering the commutation routine was used for this. Position error expressed in equation 3 is removed by subtracting it from $\theta_{comm}$ for the next cycle only. The corrected value $\theta'_{comm}$ given equation 4 is loaded to position counter instead of $\theta_{comm}$ to restore the commutation position to its correct value in the next commutation.

$$\theta_\varepsilon = \theta^* - \theta + \theta_{sw} \tag{3}$$

$$\theta'_{comm} = \theta_{comm} - \theta_\varepsilon \tag{4}$$

This technique eliminated transient errors in a single step and accumulation of persistent ones. The factor $\theta_\varepsilon / \theta_{comm}$ needed to remove errors could not be implemented directly in the limited accuracy system used. Increasing calculation to 16 bit would increase significantly delays degrading performance. An alternative approach used added amplified persistent errors to the detected transient ones as shown in the feedback control system diagram in Fig. 7. Persistent errors were detected by averaging 8 successive samples. Higher number could be better but for the limited accuracy and added delay. The compromise was setting the factors $k_1$ and $k_2$ shown in Fig. 7 to 4 and 0.5 respectively. The resulting compensated value of $\theta_{comm}$ is given by equation 5 where n refers to the present sample.

$$\theta'_{comm} = \theta_{comm} - k_1\theta_{\varepsilon n} + k_2 \frac{\sum_{i=n-8}^{n} \theta_{\varepsilon i}}{8} \tag{5}$$

However, to minimise execution times, the average commutation position error was evaluated using equation 6.

$$\bar{\theta}_{\varepsilon n} = \frac{\theta_{\varepsilon n} + 7\,\theta_{\varepsilon n-1}}{8} \tag{6}$$

Therefore, the compensated commutation position becomes that shown by equation 7.

$$\theta'_{comm} = \theta_{comm} - k_1\theta_{\varepsilon n} - k_2\bar{\theta}_{\varepsilon n} \quad (7)$$

The selection of compensator gain $k_2$ is compromise between position error and transient response, therefore an alternative method was developed and used to take care of persistent errors whose source had cumulative effect without the use of high gains. A third term using accumulated average position error was thus introduced shown dotted in Fig. 7. Hence equation 8 is modified to 8.

$$\theta'_{comm} = \theta_{comm} - k_1\theta_{\varepsilon n} - k_2\bar{\theta}_{\varepsilon n} - k_3\theta_{\varepsilon acc} \quad (8)$$

where, $\theta_{\varepsilon acc} = \sum_{i=0}^{n} \theta_{\varepsilon i}$

The values for $k_1$, $k_2$, and $k_3$ were set at 0.75, 2.0, and 1.0 respectively. The additional term provided a dynamic pre-set position displacement between phases that must be altered to maintain the commutation position at set value in the event of continuous position error. Extrapolation of position is not made entirely in a separate routine but is a result of execution of three or four routines depending on the operating speed range.

Two counters that form part of peripheral ICs for the microprocessor system are used in position extrapolation immediately after each position sample. A nominal approach of updating the counter when counter value reduces to zero introduces delay of one cycle leading to sluggish decaying or under-damped oscillatory response to a transient error. A technique was developed that enabled correction of transient error in a single step i.e. one commutation cycle. The method divides the commutation cycle into two extrapolation cycles each with a nominal position change of $\theta_{comm}/2$, although equality in the magnitudes is not obligatory. The first cycle modificated $\theta_{comm}/2$ in response to detected errors, while the second perceived as a "forget" cycle used the nominal $\theta_{comm}/2$ and no error was detected in this part of the commutation cycle. Therefore, whenever an error $\theta_{\varepsilon}$ occurs it is detected and corrected within one commutation before the next cycle of position error detection takes place. When one omits the "forget" cycle introduced corrections would not be complete by the next error detection time. This method introduced assured good response for the limited to 8 – bit resolution.

## IV. Test Results

The sensorless position detection method developed based on the magnetisation characteristics of the motor was used to control excitation of the 4 phase SR motor. The phase for principal excitation was indicated successfully in any position and direction. The starting process proved reliable in either direction irrespective of motors' initial slew rate. The motor could start and operate at very low speeds and extend to the entire medium speed range. The maximum speed attained when diagnostic current magnitude was set at 1% of the rated value was 2220 rpm that decreased to 1700 rpm when increased to 1.3% because the maximum diagnostic pulse rate reduced from 2.4kHz to 1.7kHz.

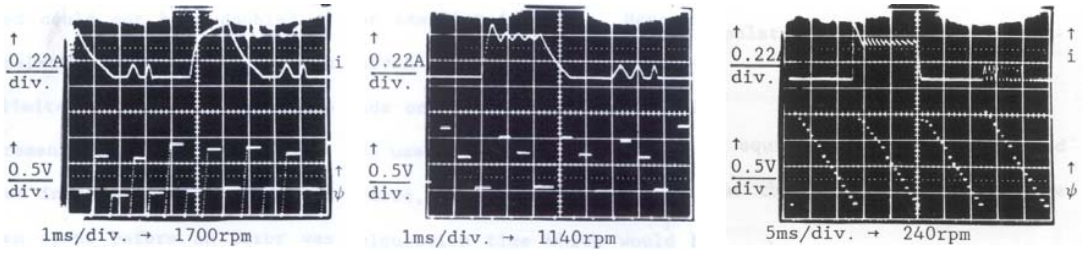


Fig. 8 Oscillograms of diagnostic flux linkage signal and the current in one of the phases for 4

The effects of back core saturation on position detection indicated clearly as shown in Fig. 5 that adjacent phases does degrade serious the precision of the detector if no corrections are made. The effects become stronger as the diagnostic phase inductance increases. These problems were addressed in the elegant speed extrapolation routine. Fig. 8 shows the current and flux-linkage position signals at three different speeds.

The technique used made the speed of response of the position detector to be very good.

Careful planning of the compensator routine was very useful for the 8-bit accuracy in calculations in minimizing delays. The limited accuracy can be seen as an additional disturbance to the controller. The comparison of measured and extrapolated positions and the compensation done in extrapolation process ensured detector robustness. The scheme is superior to that of fixed optical heads since extrapolation can be done in between commutation instance as position samples becomes available thus higher bandwidth. At light loads and low speeds the detected position is not influenced by changes in the excitation status of other phases. However, at medium speeds the interaction of the diagnostic phase with other phases cannot be ignored. The current decay time in the just OFF phase is relatively long compared to the commutation interval. The just OFF phase being adjacent to the diagnostic phase has stronger influence to diagnostic phase than was the opposite phase, see Fig. 8. However, this occurs in the upper limit of the operating speed range. Compensation is therefore necessary [2].

## V. Conclusion

The magnetisation characteristics of a SR motor detected from the phase windings can indicate successfully the phase for principal excitation to start the motor in any direction. The rotor detection scheme developed is reliable for starting motor in any direction with low or high initial slew rates. The detector can operate motror from standstill to 2220 rpm without loss of synchronisation or hunting. The upper speed limit is determined by the magnitude of the diagnostic current used relative to that of full-load. The position detector had a resolution of 0.12° mechanical. The magnetic interaction of diagnostic phase with other phases is important that needs to be compensated for. If not compensated for at full-load, a commutation position jitter of 2.5° was observed. The maximum error was 0.5° electrical at aligned position when operating at low and medium loading conditions.

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