

SENSORLESS COMMUTATION CONTROL OF SWITCHED RELUCTANCE MOTOR

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ABSTRACT

The control of commutation of switched reluctance (SR) motor without the use of a physical position detector (sensorless detection) has been an area of active research from the late eighties to date. The main drive being to overcome inherent problems associated with and limitations imposed by the physical position sensor used in the operation of SR drives. Most rotor position detection schemes for SR motor based on magnetisation characteristics of the motor use normal excitation or injected current or applied voltage pulses for position detection purposes. The resulting schemes are referred to as passive or active methods respectively. The research effort in sensorless SR rotor position detection being directed at achieving accurate, reliable and robust detector to suit desired application while taking to account economical aspects. This paper present effective and reliable means of generating commutation signals of an SR motor based on inductance profile of its stator windings to define degree of overlap between stator and rotor teeth using active probing technique. The overlap status is used in the motors' commutation control. The scheme has been validated online using a 4-phase 8/6 SR motor and an 8-bit processor.

Keywords: Sensorless, position detection, rotor position, switched reluctance motor

1. Introduction

Most switched reluctance motor controllers at present use optical heads or its equivalent to obtain rotor position needed for position feedback [Mvungi et al 1989, 1992] to indicate the degree of overlap between the stator and rotor poles. Fig. 1

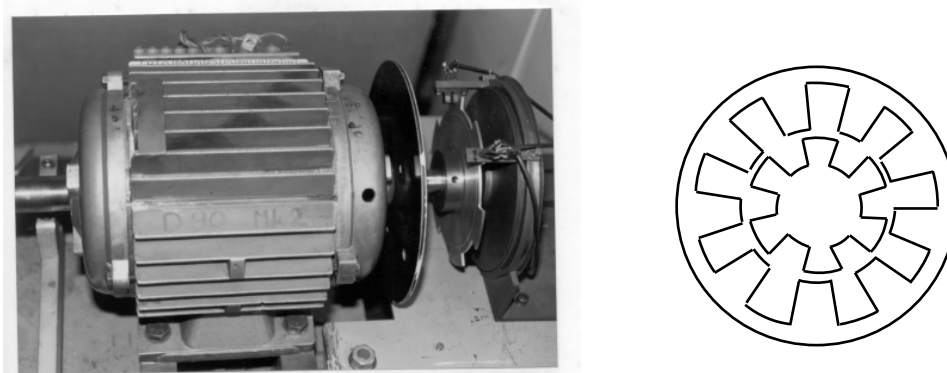


Fig. 1: (a) SR motor with optical head position transducer

(b) The SR motor stator and rotor teeth

shows such a motor, an attached optical position sensor and stator and rotor poles. The presence of physical position sensors presents a number of limitations and problems, hence the need for a sensorless one. However, there is need for the outputs of the developed sensor to be compatible with existing controllers for quick adoption. Therefore, the developed microprocessor based sensorless drive system stores rotor position transfer characteristics (RPTC) of the motor and use it to generate position representing signals during operation equivalent to those produced by conventional optical heads. Fig. 2 shows the signals from optical heads in fig. 1 and the corresponding inductance profiles for a 4-phase 8 stator and 6 rotor poles SR motor [Suresh et al 1998, Ray et al 1994, Panda et al 2000] while fig. 3 shows the general setup of the developed

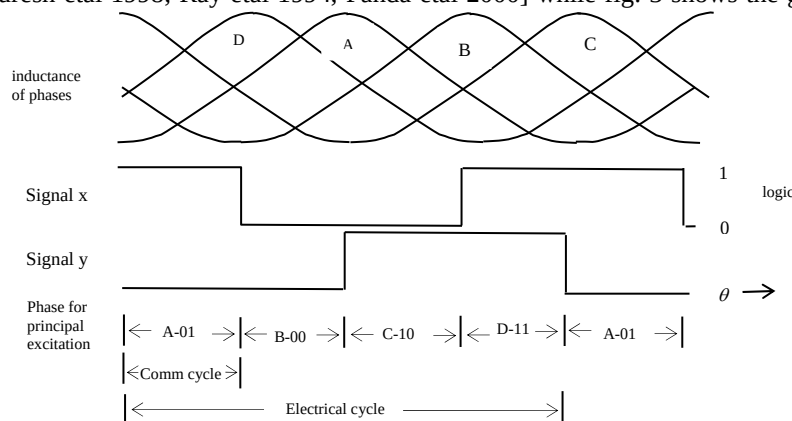


Fig. 2: Stator inductances of a 4-phase SR motor and the relative conventional optical head signals used to control an SR motor to be generated by the new sensing mechanism

method. The new method of generating rotor position signals differ from the conventional one in that it cannot have offset between rotor teeth and the generated position signals since it is based in the inductance characteristics of the motor and does not need any physical attachment to the rotor. Moreover, the extrapolation normally used with optical encoders to predict commutation position is not required since the microprocessor used can advance or retard SR motor commutation signals by any specified amount using the information available within the microprocessor. This can be done at any speed within the motors' operating range. This paper is limited to accurate definition of commutation positions for SR motor, hence does not include SR control strategy.

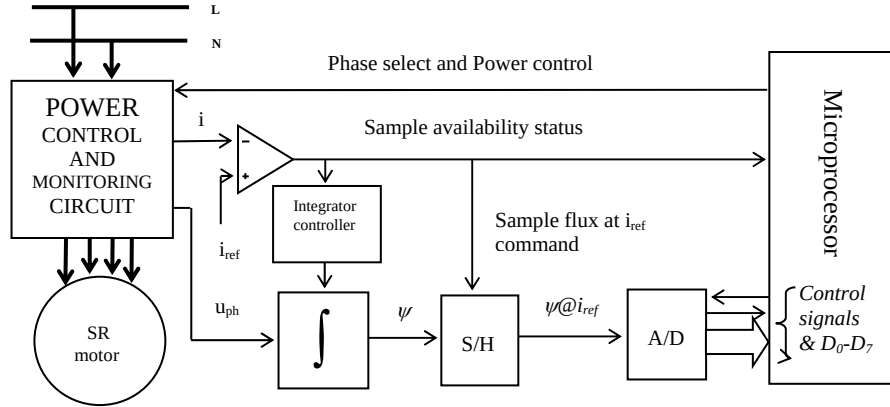


Fig. 3: The general block diagram of a sensorless rotor position detector of a SR motor

There are principally four defined operating regions for the SR motor. These are the stationary, the low-speed, the medium-speed and high-speed regions. These different regions present different challenges and opportunities in relation to rotor position detection. This paper covers the first three regions.

There are a number of schemes that have been developed so far all aiming at removing the necessity of using optical encoder or its equivalent in the control of SR motor. These methods use concepts ranging from those using linear characteristics of phase inductance to non-linear ones using observer or phase permeance [Mvungi et al 1992, Bellini et al 1998, Nagel et al 1998, Young et al 1999, Yang et al 2000, Lumsdaine 1990, Thompson 2000]. 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.

2. 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 was chosen to suit economical consideration of the position transducer, however the choice presents a challenge of working with low resolution. In comparison, an observer-based detector and others [Nagel et al 1998, Young et al 1999, Yang et al 2000, Lumsdaine 1990, Thompson 2000] needed at least a fast 16-bit processor but the performance was not always satisfactory when tested online. The microprocessor kit used had one 8-bit PIO port, two SIO ports and one special 4-bit PIO port. An 8-bit A/D converter was used to digitize flux linkage signal that gave a mechanical position resolution of $\leq 0.12^\circ$ (3.3×10^{-4}) that was considered sufficient.

An excitation voltage of 300V dc was used with two snubberless power MOSFET switches per phase. Only one phase was switched ON at a time for motoring. High-level language was not used in the development stages because the problem is time critical (excitation cycle in the μ s region) requiring utilization of full capability of the microprocessor (clock 8MHz).

The position information is obtained using diagnostic pulses injected in the phase opposite to that used for motoring to generate an inductance profile of any of the phases as shown in figure 4.

3. System Design and Implementation

The design and implementation of the sensorless rotor position detection system for SR motor for condition specified in section 2 can be divided into three basic operations. These are position sampling, starting up and providing commutation during motoring/braking operations. The method used to effect commutation is the same for all speed ranges but the source of position information differed. At low speeds the sampled position information is used directly to control commutation while at medium speeds extrapolated position derived from speed calculated from previous position measurements is used. A reference phase was defined and used for position detection in this new method.

3.1 Using Position Transfer Characteristics

The detected rotor position from the developed method is defined cyclically either in terms of commutation angle or an electrical cycle as illustrated in figure 4. When using an electrical cycle, a reference phase must be defined so that the detected position $\theta = (\theta_n + \theta_{offset})$ where θ_n is the sampled position and θ_{offset} is the fixed relationship between the present diagnostic phase and that of the reference. For every four steps of a 4-phase SR motor, position magnitude cycles between 0° and 360° . This representation is only useful when detection is done simultaneously in more than one phase. When detection is limited to within excitation cycle from one phase, position magnitude is obtained from diagnostic flux-linkage signals directly using the ψ/θ tables without any transformation [Mvungi et al 1992]. The maximum being 180° electrical (see fig. 4). ψ is 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 the position obtained from the diagnostic phase is defined by the initialisation procedure during starting-procedure or by the proceeding position samples.

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 figure 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. Therefore, as can be seen in figure 4 when the motor is running and motoring, the detected position will be in decreasing magnitude to reflect decreasing inductance profile irrespective of direction of rotation.

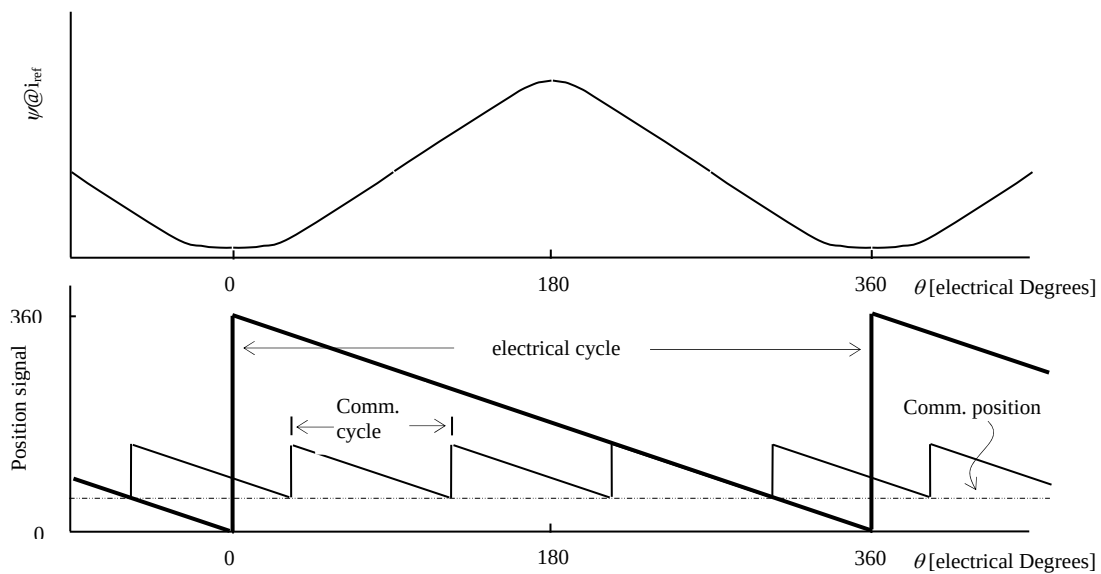


Fig. 4: Position signal definition using constant current RPTC relative to the phase inductance

3.2 Programming the Magnetisation Characteristics into the Processor

To maximise resolution, the variable magnitude of the flux-linkage signal was adjusted to match the A/D converters' input dynamic range. The mis-aligned flux-linkage signal value was offset to zero. Small differences in the inductance of different phases, circuit components and current transducers were compensated for by adjustment of current transducer sensitivities. The adjustment enabled one table of ψ/θ measured from one of the phases to be applicable to all phases. The approach minimised size of memory requirement, and thus costs and access time since it eliminated the need to identify respective table and slope during operation. The maximum error in programmed position realized was 0.5° electrical at the aligned position, which was better than the targeted resolution of 1° electrical.

The constant-current RPTC was stored directly using the microprocessor by assigning every discrete value of the diagnostic flux-linkage signal a corresponding value of position, starting from the mis-aligned to the aligned position. Position information was obtained using both a pointer fixed on the rotor shaft and a position scale fixed on the stator and an optical encoder. The centre of positions between two equal magnitudes of diagnostic flux-linkage signal on either side of the mis-aligned position was used to reliably identify the mis-aligned position. Alternatively a peak of the diagnostic signal using the constant-flux RPTC [Mvungi 1989] was used to indicate the mis-aligned position.

3.3 Overall System Design Strategy

The tasks needed to operate a SR motor without a physical sensor were organised and performed in an interrupt mode with appropriate priority assignment as an effective and efficient way to utilise the processor time. These include monitoring operators' commands and flux-linkage, speed calculations, position extrapolation and provision of commutation signals. The commutation process involves producing signals similar to those produced by conventional optical heads to control

excitation of diagnostic and principal phases. The difference is that changes in the signals from conventional head occur at fixed positions while those from the new method change at the commutation position hence removing the need for extrapolation.

All the external ports of the microprocessor kit were dedicated to specific functions to minimize external circuitry since the inputs signals are few. For safety reasons, the high logic level was conceived as OFF and low as ON state. This allowed controllable power-up and switching off by resetting the processor in case of emergency.

Modest speed A/D converter was used as part of costs control strategy. This was made possible by using constructively part of the processor external access setup as A/D conversion period. This was done by signaling the processor to read in flux-linkage data while at the same time initiating A/D conversion process whenever the diagnostic current reached a defined level following 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. Hence, the need for testing different conditions and looping were minimised. This was done for repetitive events (conditions) that changed less frequently than execution of a particular routine.

3.4 Starting-up Operation

Starting-up operation involves setting-up interface ICs, initialising variables, setting program logic and its flow for low speed operation in a particular direction and the selection of a phase for excitation. Initial position **must be obtained** from the defined diagnostic phase or phases ~~must be obtained~~ before enabling principal excitation. The phase for principal excitation and thus diagnostic is identified by comparison of position magnitudes of adjacent phases when starting from rest. A phase shift is introduced to one of the phases to adjust the actual region of its inductance profile used in the comparison to facilitate identification from any starting position, see fig. 5. The approach was introduced to remove ambiguity of some points. Having defined the phase for principal excitation, the low-speed routine takes over control of

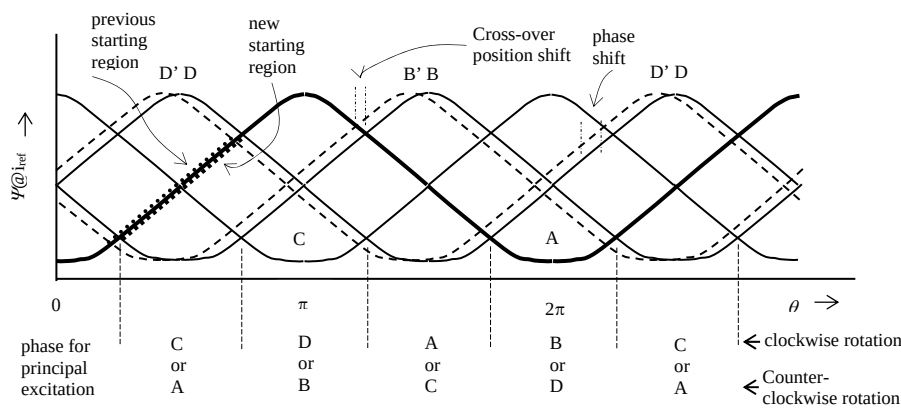


Fig. 5: Defining phase for principal excitation by comparison of position magnitudes of adjacent phases excitation.

3.5 Position Sampling

The microprocessor defines the diagnostic phase while the minimum error conditions occurrence initiates the actual sampling [Mvungi 1992] when operating in both low and medium speeds. For every diagnostic pulse, the microprocessor reads in **flux-linkage position data** when signaled by the RPTC generator of its availability and translate it to position using pre-stored flux-linkage/posotion table. At the time of reading in position data, time and the difference between the current position and the next commutation position given by the extrapolation routine are recorded.

The position sampling routine includes commutation control and its implementation when operating at low speeds to minimise execution time since the events are concurrent. At medium speeds however the timing of the two events do not necessarily coincide since commutation instance is predicted by extrapolation. The two routines are therefore separated. However, partial calculation for determination of speed is done in the sampling routine in both speed ranges to optimise overall execution time by minimising data transfer between routines.

3.6 Commutation

Commutation involves defining and passing to the driver/control board the next phases in the excitation sequence (principal and diagnostic) using two bit codes ~~similar to that from as in~~ conventional optical head ~~signal~~. This is done when the detected or extrapolated instantaneous rotor position signal equals or crosses the set commutation position. At low speeds, the sampled position was used directly while at medium speeds the extrapolated position using previous samples determined when to commute. An effective and efficient method of defining the phases for excitation developed

depended on manipulation of a code in a memory location that was combined with information in another memory location.

3.7 SPEED CALCULATIONS

where x depicts sampled value, n the current value and Δt_n the interval between the samples. A pre-set value of speed determined the switchover from low to medium-speed operating regimes and vice versa. To avoid oscillation of switchover of speed regimes, hysteresis is incorporated. In the medium speed regime, the calculated speed is used to update the extrapolation of rotor position that controls commutation.

The Δt_r is obtained from speed calculations while $\Delta \theta_r$ is considered to be unity. The slope counter is updated with Δt_r value after every position sample. By decrementing the position counter at the end of every timed interval Δt_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 however took into consideration the purpose of the extrapolation, which is to provide commutation signals. Therefore, the value of the position counter is set equal to the position differences between two successive commutation positions θ_{comm} at commutation instance (fig. 6) i.e. position of next diagnostic phase just before commutation less the commutation position magnitude.

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

accuracy and added delay. The compromise was setting the factors of k_1 and k_2 shown in figure 7 that were set to 4 and 0.5 respectively. The resulting compensated value of θ_{comm} is given by equation 6 where n refers to the present sample.

$$\theta'_{comm} = \theta_{comm} - k_1 \theta_{\varepsilon n} + k_2 \frac{\sum_{i=n-8}^n \theta_{\varepsilon i}}{8} \quad (6)$$

However, to minimise execution times, the average commutation position error was evaluated using equation 7.

$$\bar{\theta}_{\varepsilon n} = \frac{\theta_{\varepsilon n} + 7 \theta_{\varepsilon n-1}}{8} \quad (7)$$

Therefore, the compensated commutation position becomes that shown by equation 8.

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

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 figure 7. Hence equation 8 is modified to 9.

$$\theta'_{comm} = \theta_{comm} - k_1 \theta_{\varepsilon n} - k_2 \bar{\theta}_{\varepsilon n} - k_3 \theta_{\varepsilon acc} \quad (9)$$

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.

3.9 Counter Updating Delays

Interpolation of position is made using the two counters that form part of peripheral ICs for the microprocessor system immediately after each position sample using acquired information. A nominal approach being to update the counter when counter value reduces to zero. This introduces a delay of one cycle leading to sluggish decaying or under-damped oscillatory response to a transient error occurrence. A technique was developed that enabled correction of transient error in a single step i.e. one commutation cycle. The method is illustrated in figure 8. 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 involved modification of $\theta_{comm}/2$ in response to detected errors, while the second perceived as a “forget” cycle used the nominal $\theta_{comm}/2$ without modification and no error was detected in this part of the commutation cycle. Therefore, whenever an error θ_{ε} occurs it is compensated for before the next cycle of position error detection takes place. The error is thus detected and corrected within one commutation period. When one omits the “forget” cycle corrections would be introduced but its effect would not be complete by the next error detection time. This is a very significant method introduced that assured good response in manipulations that were limited to 8 – bit resolution therefore, introducing a tendency for over compensation.

4. 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.

The use of position samples directly to control commutation at start-up instead of extrapolated ones proved to be a useful feature that provided setup time needed by the extrapolation routine without loss of controllability or hunting response.

The use of counters to perform extrapolation of rotor position and to indicate when to commute without assistance of the processor except for updating them improved considerably the speed of response of the position detector. The actual commutation was done via the processor although if such information is not needed within the processor, commutation can be done directly by the counters using sequencing circuitry. Updating the counters only at zero count skipped no commutation cycle.

The use of 8-bit accuracy in calculations to minimise delays needed careful planning of the compensator routine, a problem not encountered with higher accuracy computations. The limited accuracy can be seen as an additional disturbance to the controller. The measured and extrapolated positions are compared and the extrapolation process compensated as necessary in each routine, which 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.

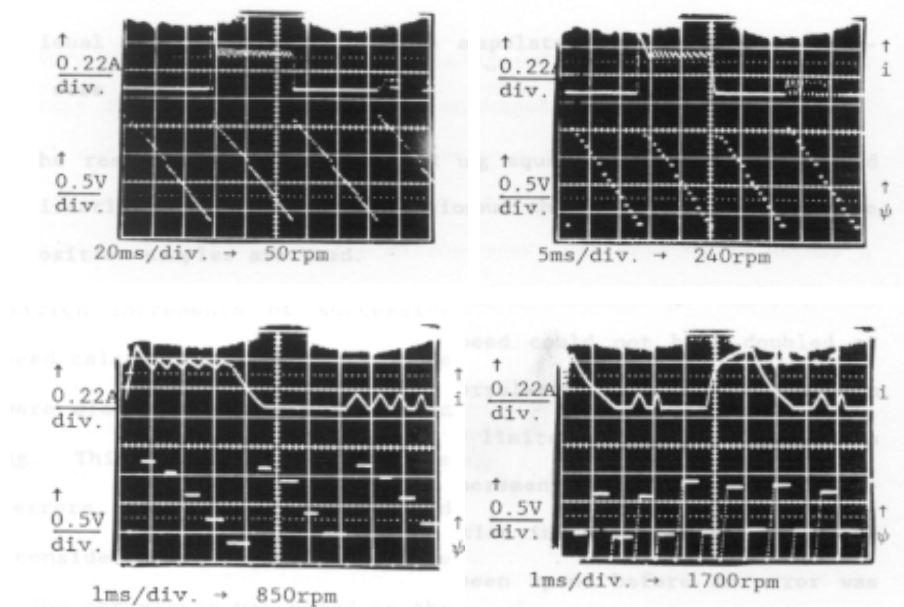


Fig. 9: Oscillograms of diagnostic flux linkage signal and the current in one of the phases for 4

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. 9. However, this occurs in the upper limit of the operating speed range. Compensation is therefore necessary^[2].

5. CONCLUSION

This work has shown that magnetisation characteristics of a SR motor can indicate successfully the phase for principal excitation when starting from any rotor position in any direction. The tests conducted with a prototype showed that the rotor detection scheme developed is reliable for starting motor in any direction with low or high initial slew rates. The method has shown to be suitable for operation 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 limit can be extended by the use of high-speed routine not covered in this paper. The position detector had a resolution of 0.12° mechanical. When magnetic interaction of diagnostic phase with other phases is not compensated for at full-load, a commutation position jitter of 2.5° was observed in an attempt by the position detection scheme to eliminate errors. However, a the maximum error of 0.5° electrical at aligned position was realised at low and medium loading conditions.

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APPENDIX 1: The general Algorithm for the Sensorless Position Detector

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START
INITIALISE:      interface ICs, routines, variables
IF:              not ON command, MONITOR: commands
    SELECT:      phase and energise
    DO:
    {
    MONITOR:      commands, position, interrupt
    IF:           medium speed, COMMUTATE: at position count interrupt
        WHILE:   fresh position sample
        {
        UPDATE:   position, time,  $\theta$  count
        IF:        low speed region
            {
            IF:     Commutation position, ENERGISE: net phase
            CALCULATE:  $\Delta\theta$  and  $\Delta t$ 
            REQUEST: speed calculations
            }
        ELSE:
            CALCULATE:  $\Delta\theta$  and  $\Delta t$ 
            REQUEST: speed calculations
        IF:        position sample correlates
            {
            CALCULATE: speed
            IF:        speed correlates
                {
                CALCULATE: average speed
                UPDATE: position extrapolator
                }
            ELSE:
                TERMINATE: speed calculations
            }
        ELSE:
            TERMINATE: speed calculations
        }
    IF: command "advance commutation position"
        READ: the new position
        ADJUST: program
    ELSE:
        CONTINUE
    IF: command OFF
        EXIT
    ELSE:
        CONTINUE
    }
STOP and MONITOR: commands

```