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The Status of Indirect Rotor Position Sensing in SR Drives

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Abstract

The performance of Switched Reluctance (SR) motor drive systems using rotor position transducers has been satisfactory, but the potential of SR drives for providing economical, robust, compact and reliable drive systems which can operate in harsh environments, has made the development of sensorless system desirable. A system which can detect rotor position without a conventional position sensor should avoid the above limitations. Furthermore, the detection system can reside with the control electronics board away from the hostile environment in which the motor may have to be installed. There are various methods of sensorless rotor position measurement developed over several years of research and each of the methods has its own limitations and drawbacks. Much recent and current research is directed at determining rotor position from winding magnetisation data. These magnetisation data either normally available during actual phase energisation or they are specially injected for the purpose of sensorless position estimation. It is the aim of this paper to discuss these sensorless rotor position measurement methods and their limitations.

Keywords: SR drive, intelligent sensing

1 Introduction

Accurate knowledge of the rotor position ensures that the phase current is switched at the desired points with certainty and, therefore, that the desired operating characteristics of the motor are reliably obtained.

The rotor position for SR motor drive control has usually been measured using an incremental rotor position transducer attached to the rotor shaft. The performance of SR drive systems using rotor position transducers has been satisfactory [1], but the potential of SR drives for providing economical, robust, compact and reliable drive systems which can operate in harsh environments, has made the development of sensorless system desirable.

There are various methods of sensorless rotor position measurement developed over several years of research and each of the methods has its own limitations and drawbacks. The methods and their limitations will be discussed in this paper. In general, most of these methods are based on direct use of the SR motor magnetisation data [ψ-i-θ curve] of the phase. Either on the idea of injecting a small current signal to one of the phases during the time the phase is normally off, or using the actual current signal waveform. The methods which are based on injecting diagnostic signals have not succeeded at high speeds operation, because there is no sufficient region of unenergisation in the phase period in which to inject the signal, or because of the limitations of the back emf and mutual effects. On the other hand, methods used the actual current signal waveforms and not by injecting a small current signal to the off phase have overcomed the limitations of high speed, back emf and mutual effect.

The magnetic characteristics of the motor [2, 3] are represented by the static non-linear relationships between flux-linkage ψ(θ,i) or inductance L(θ,i) for a motor phase and the phase current i and rotor position θ. Typical characteristics are shown in figure 1 where θ_1 represents the unaligned rotor position of minimum inductance and θ_n represents the aligned position of maximum inductance. Provided the iron losses in the machine are relatively small the characteristics apply for changing currents and position - i.e. for dynamic excitation under rotating conditions. The general principle for most sensorless methods is that if at a given instant ψ (or L) and i are measured then θ can be calculated from the pre-stored characteristics.

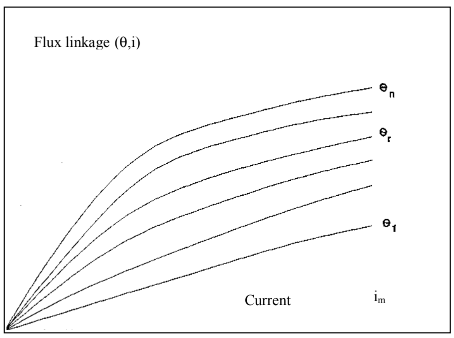

Fig. 1 Typical flux-linkage ψ(θ,i) characteristics for an SR motor phase winding

The methods provide a repetitive measurement of rotor position. These can be effectively continuous with many identifications of position during each

phase cycle. Alternatively only one rotor position indicator per phase cycle may be determined generally by finding when the flux or inductance passes through a particular threshold value which represents a particular reference rotor position. This latter case is equivalent to the rotor position sensor signal used at present in most applications. Intermediate positions can be obtained from a phase locked higher frequency signal [4]. In many cases the threshold position is that of minimum or maximum inductance although the sensitivity with rotor positions is less than during the rising inductance part of the characteristic.
The methods mainly fall into two groups covered below in sections 2 and 3. In the first group, test signals of different kinds are introduced during the time when a phase is normally unenergised. For motoring operation this is generally during the falling or, at low speeds, around the minimum inductance periods. The test signals need to be of low amplitude for a number of reasons:

a) to avoid negative torque production
b) to avoid back-emf effects
c) to avoid saturation effects (i.e. dependence of L on i in addition to θ)
d) to minimise the size and cost of additional injection circuitry where this is necessary.

Reasons (b) and (c) are further discussed in section 2. The low amplitude test signals are susceptible to mutual interference from the excitation currents in other phases, which is the main problem with these methods. Furthermore since at high speeds the excitation waveform occupies the majority of the phase period, injection of test signals is very restricted and hence these methods are more suited for lower speed operation (chopping mode).
The second group of methods utilises the actual excitation current waveform. Sufficiently accurate measurement of total flux-linkage when chopping is difficult (see section 2.2) and hence these methods are more appropriate for higher speed (single-pulse mode). The use of the chopping current waveform is examined in section 2.1.

The sensorless position detection methods reviewed in this paper [5-36] are limited to rotating SR machines with no additional motor connections for sensing purposes. Some methods [37-39] have advocated the use of additional phase windings for position sensing. The aim of the review is to examine and compare the basic principles and ideas of the various methods rather than experimental results. In many cases experimental verification is very limited and no systematic comparison of accuracy has been made. Very often the position detection is an integral part of the control and the verification lies in whether or not the system will operate without direct position sensors whilst still producing the same or approximately equivalent performance.

2 Sensorless Low Speed Operation

These methods generally make use of an unenergised phase winding for position calculation - i.e. position testing is executed whilst the phase is not required for torque production. Often the tested phase is the one due to be energised next in the sequence and from the tests a position threshold can be established for switching the energisation to this phase. The tests utilise chopping waveforms, or injected high frequency test signals, or a sequence of diagnostic pulses. The current level is relatively small and such that any negative torque produced is negligible and such that the measured inductance $L(\theta,i)$ is effectively the unsaturated inductance $L(\theta,0)$ and the same as the incremental inductance. Furthermore back emf effects are generally negligible.

Since the testing can be effectively continuous provided the frequency is relatively high, continuous position information can be obtained. This may be important at low speeds where excitation current profiling as a function of rotor angle may be required.
However, these methods are generally difficult to implement at high speed since at high speed the excitation current waveform generally occupies the majority of the electrical cycle for a phase and hence there is little unenergised space for position testing.
These methods also suffer from interference due to mutual effects whereby current in the energised phase(s) induce voltages in the testing phase which distort the test current waveform.

2.1 Based on Chopping Waveforms

The first major publication concerning sensorless rotor position detection for SR motors was by Acarnley [5, 6] who proposed three methods, the first two of which utilised chopping current waveforms with a fixed current excursion and mean current. Firstly the main torque producing chopping waveform may be used. However this suffers from various disadvantages. The range for which position detection is possible is restricted to low speeds else the back emf affects the accuracy. The need for a fixed mean current whilst chopping results in rather inflexible control. Furthermore at high current the incremental inductance can reduce as the rotor and stator align giving a double peaked L-θ characteristic.

Further work by Panda [7-10] demonstrated that the method was viable but suffered from the restrictions referred to above. To lessen the effect of back emf Panda fixes the commutation point towards the end of the rising inductance period where $dL/d\theta$ is less. This, however, results in appreciable loss of torque as the speed increases, as is shown by his measurements. Panda also attempts with difficulty to extend the method to single pulse control although the outcome appears to be the same as operation synchronously from an oscillator with the rotor taking up an appropriate load angle.

To avoid the effect of back emf on the relationship between chopping period and rotor angle, Acarnley secondly proposed [5] using a "mini" chopping current waveform in a non-torque productive phase, i.e. when the phase is normally unexcited. This method can be easily implemented in systems utilising chopping or PWM for current profiling in the active phases -the same hardware is used to create a small constant-level current in the inactive phase.

The major difficulty, as previously mentioned, is the mutual coupling with currents in the active phases and this is particularly significant at the higher frequencies associated with PWM. However, a satisfactory elimination of the mutual effect has been found by Egan [11] by using different PWM frequencies for the active torque producing phase and for the probing phase, and by using frequency selective synchronous demodulation of the chopping waveform. The measured inductance profile thereby obtained is free from distortion due to mutual coupling effects. However, a fairly sophisticated demodulation system is required.

2.2 Based on Frequency Injection

As in the above section, the idea is to measure inductance in an unenergised phase and to commutate when the inductance exceeds a threshold value. However, rather than using chopping waveforms Ehsani [12] connected the phase winding to an oscillator designed such that the frequency is inversely proportioned to the phase inductance. Comparison with the threshold value for frequency is made either using an F to V converter or digitally using a binary counter. The main problem of disconnecting the oscillator from the power circuit during energisation is overcome by using photo-voltaic BOSFET switches. Circuits and details of suitable oscillators are provided in the associated patent [13]. The method requires a separate oscillator for each phase and significant analogue circuitry. It may also be susceptible of corruption of the test signal by mutual effects. The authors recommend measurement around the minimum inductance region here mutual effects are less - however, the sensitivity of inductance to rotor position is also less in this region. In a later paper [14] Ehsani provides a modification to the frequency injection method. In this case a sinusoidal signal of a fixed frequency and amplitude from an oscillator is connected to the phase winding via a resistance. As the inductance of the phase changes, the phase displacement between oscillator voltage and current varies. This can be measured using a phase sensitive demodulator. The current amplitude also varies and may be used as an alternative measurement. It is claimed that this method is extremely robust to switching noise that is present in the sensing phase due to mutually induced voltages.

A further variant to the frequency injection methods is provided by Goetz [15]. This method of detecting resonance seems viable in concept but it is unclear how the phase windings are de-energised since there is only one switch per phase and no return current diodes.

The main disadvantage of methods using frequency injection to unenergised phases, apart from limitations at higher speeds and possible mutual effects, is the additional signal processing analogue and digital circuitry required which can be quite significant.

2.3 Based on Diagnostic Pulses

The idea is similar to the previous section. By using the existing power switching circuit to provide voltage pulses of short duration in an unenergised phase and measuring the consequential current, the inductance $L(\theta,0)$ can be calculated and θ either determined from L or from the measured flux-linkage $\psi(\theta,i)$. The methods follow from Acarnley's third proposal [5] which is that whilst one phase is being energised, for the next phase in the sequence V is switched on and di/dt is measured which is a function of θ (since $di/dt=V/L(\theta,0)$). If di/dt is not the correct value then V is turned off and the current allowed to decay to zero. The process is repeated until di/dt exceeds the threshold value when V is left on and phase changeover occurs. Acarnley's third method is basically the use of diagnostic pulses in an unenergised phase and has subsequently been investigated and improved by various other researchers. The pulses are generally of a fixed duration dt at frequency in the range of 3 to 15 kHz.

Dunlop [16] experimentally investigated the method and found the waveforms for position monitoring were seriously affected by currents in the driving phases and this made absolute rotor position detection very difficult.

Macminn [17, 18] proposed measuring the current rise di for a fixed dt and comparing this with a threshold to detect whether the reference position had been reached. There is no difference in principle to measuring di/dt as proposed by Acarnley. However, McMinn does suggest monitoring variations of the supply voltage V and adjusting the threshold value for di accordingly to give the same reference position. He also samples in two phases simultaneously to detect corruption due to switching noise or mutual coupling.
Harris [19] uses the same method but arranges the diagnostic pulses to occur within 15 deg period before

minimum inductance for a phase - presumably to lessen mutual effects. The relatively large pulses generated significant negative torque.

Hedland [20] uses an approximate law to compensate for the mutual effect. He uses a diagnostic pulse to measure the apparent inductance. $L_a(\theta,i_b)$ of phase a in the presence of a current i_b in phase b (which is also measured) and corrects this according to the equation $L_a(\Theta,0) = (1+Ci_b)L_a(\Theta,i_b)$.

$L_a(\theta,0)$ is then compared with a threshed value to determine the phase commutation point as before.

Mvungi [21, 22]] improved the method of correcting for mutual effects to obtain a continuously sampled measurement of position rather than a threshold value. The significant corruption of the test pulses due to mutual coupling is well illustrated by figure6 of [22]. The measured flux ψ is corrected for the mutually coupled currents in other phases (i_2, i_3, … according to the linearised law)

$$\Psi_1(i_1,\Theta) = \Psi - \{(d\Psi/di_2)i_2 + (d\Psi/di_3)i_3 \ldots\}$$

where i_1 is the test current and dψ/di are the mutual coupling coefficients, which, to avoid a multiplicity of look up tables, are taken to be a simplified function of rotor angle. On obtaining the corrected value of flux ψ_1 for current i_1, θ can be calculated from a 2-dimensional look-up table. The method was demonstrated to work using a 4-phase 8-6 motor with acceptable position accuracy for speeds up to 1200 rpm on load and 1750 rpm on light load.

Ray and Al-Bahadly [23] introduced the use of single diagnostic pulse instead of a train of diagnostic pulses. The single diagnostic pulse could be of larger amplitude to minimize the effect of mutual coupling yet not large enough to produce unwanted torque.

3 Sensorless High Speed Operation

Since diagnostic current pulses in an unenergised 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.These 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.

If at given instant the flux-linkage y(θ,i) or inductance L(θ,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.

The main problem is accurately measuring the flux by integration of V-Ri. For single pulse operation this is not difficult and if V»Ri integration of voltage or even multiplication of V by time may suffice to obtain sufficient accuracy. However, under chopping conditions with repetitive reversals of the phase voltage over a relatively longer time the Ri effect is very significant since it provides volt-seconds continually of the same polarity whereas the positive and negative excursions of V are largely self-cancelling. For this reason these methods are considered more suited to higher speeds single pulse operation.

The first proponent of this method appears to Hedland [24] who was able to simplify the idea to avoid the use of multidimensional look up tables. The aim is to identify a particular rotor position θ_{ref} for each phase where θ_{ref} corresponds to a point in the rising inductance region. Values of ψ against i are stored for the particular θ_{ref}. From the commencement of energisation for a phase, the current i and flux ψ are continuously sampled and the flux $\psi_{ref}(\theta_{ref}, i)$ is calculated - i.e. the flux for i if the position θ was equal to θ_{ref}. Initially the measured $\psi<\psi_{ref}$ eventually, when θ passes θ_{ref}, ψ becomes $>\psi_{ref}$ This transition is detected to identify the reference or threshold position. A rotor position indicator is thus obtained for each phase period from which the excitation can be timed. For acceptable resolution in defining θ_{ref} at high speeds a high sampling frequency is required. The sampling and comparison may therefore require a dedicated microprocessor or equivalent circuitry.

Exactly the same method is proposed by Lyons [25-29] with the measurement regime restricted to a 60 degree electrical band (for a 3-phase motor) at the beginning of the rising inductance period or the end of falling inductance [25, 28]. Some additional features are proposed. Firstly [25, 26] mutual effects can be corrected by using a multi-dimensional look up table or map for calculating $\Psi_{ref} = f(I_1, I_2 \ldots)$ using constant mutual coupling coefficients where I_1 is the current in the active phase and I_2… are the other phase currents. Alternatively [25, 29] a lumped parameter reluctance network model of the motor including all the mutual coupling effects can be used. The network is very complex and many of the reluctance elements are functions of rotor angle θ so this would be difficult to implement in practice. A method [27] of checking whether the measurement is within bounds - ie the position detection sequence is in lock - is also proposed. The position estimation algorithm was tested on an off-line basis (i.e. from recorded measurements of voltage, current, speed and rotor position) and is claimed to give good agreement between measured and estimated angles.

Al-Bahadly [30] made one position measurement for each phase per phase period. The measurement system is a direct replacement for the existing incremental position sensor and no change need to be made to the existing control strategies. 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. Note that only two 2-D look up tables are required irrespective of the number of rotor phases. 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 an additional microprocessor or a more powerful digital signal processor.

The rotor position in [31] 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. 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, at the expense of increased computational requirement.

It should be noted that [31] involved large mathematical computation and require large numerical look-up tables. Therefore [32, 33] suggested the use of fuzzy logic based motor model. The advantage of developing a fuzzy logic based model is no complex mathematical model is required and simple mathematical calculation used for processing. Neural network has also been used to model the SR motor for sensorless position estimation [34], but they needed a longer learning time.

Much more extensive testing and published results of performance and positional accuracy will be necessary before a preferred method (if any) will be apparent. It is also likely that improvements will be made to the existing methods and that further new methods will be forthcoming. More recent work [35, 36] explored more integrated approach at low speeds and high speeds operation. Depending on the operational region of the SR motor, an appropriate version of the phase voltage equation is then used for the sensorless measurement purpose.

4 Conclusion

It is evident from the number of publications that research activity in the area of sensorless position detection is widespread and considerable further work will be required before a reliable and commercially applicable method is fully developed. Much recent and current research is directed at determining rotor position from winding magnetisation data. These magnetisation data either normally available during actual phase energisation or they are specially injected for the purpose of sensorless position estimation. It is also evident that either significant computation is required to obtain the information from existing or readily created waveforms, or significant additional circuitry is required to implement the less sophisticated schemes. It is possible that the most appropriate method may differ according to the application - for example, a more expensive drive with high dynamic performance as compared with a simpler drive for domestic or pump/fan applications.

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