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Sensorless Operation of an Ultra High-Speed Switched Reluctance Machine

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Abstract – The most advanced vacuum cleaners are now using brushless drives, with operating speeds in excess of 100,000 revs/min. The drives are very sophisticated, but must also maintain low-cost. Sensorless control is desirable, but most sensorless methods involve extensive computation, which is prohibitively expensive at such high speeds. This paper looks at a 100,000r/min, 1,600W switched reluctance machine and drive system using the current gradient sensorless scheme and analyses parameters that affect the stability of the system.

Commercial products require very robust control schemes: effects such as motor magnetic saturation, speed variations, changes in advance angle and changes in DC link voltage are examined to determine the boundaries within which the current gradient sensorless scheme is stable. Both simulation and measurements are used, demonstrating measures which ensure stable operation over the entire operating range.

Index Terms—Electric machines, electric variables measurement, motors, motor drives, position measurement, reluctance machines, reluctance motors, reluctance motor drives.

I. NOMENCLATURE

V_{ph}	Phase voltage (V)
i_{ph}	Phase current (A)
R_{ph}	Phase resistance (Ω)
L_{ph}	Phase inductance (H)
ψ_{ph}	Phase flux-linkage (Wb)
θ_e	Electrical angle ($^\circ$)
ω_e	Electrical speed (rad/s)
t	Time (s)
t_s	Sample time (s)
k	Sample number (integer value: 1,2,3...)

II. INTRODUCTION

The use of brushless machine topologies in domestic products is becoming ever more prevalent. Higher speeds can be achieved, reliability is improved and brush wear is eliminated. Switched reluctance machines (SRMs) can be

very attractive for certain applications: the lack of magnets on the rotor leads to reduced manufacturing complexity and cost. Extremely high speeds can be achieved and the machine type is very robust and reliable, though it has lower torque density than permanent magnet machines.

For good dynamic control of any machine, knowledge of the rotor position is required. In a traditional brushed machine this is inherently known by the commutator. In a brushless machine some form of rotor position sensor is required and electronic switching circuitry is used to commutate the machine's windings. The position sensor can be an expensive part of a drive system and, because it will normally be subject to a hot and electrically noisy environment, it can also be unreliable. It increases manufacturing complexity, as the sensor needs to be mounted into position and electrical connections have to be run between the sensor and the main drive. This complicates an otherwise very reliable, robust, low-cost machine topology. Clearly using a 'sensorless' method of control is appealing: manufacturing complexity is reduced, there is the possibility of improved reliability and costs can be reduced – cost being of major importance in mass market domestic applications.

A sensed 1,600W, 100,000r/min 4-2 SRM is currently in several products produced by Dyson Ltd, including hand dryers and cylinder vacuum cleaners. An opto-sensor is used for rotor position feedback. A light beam produced by the sensor is broken by a chopper plate mounted on the rotor, as shown in Fig. 1 below:

Fig. 1. Opto-sensor and chopper plate used on the sensed 1,600W SRM drive system

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This research investigates conversion of the drive to operate using a sensorless control system for the benefits discussed previously. This paper extends previous research into sensorless methods and analyses the effects of machine speed, advance angle and DC link voltage on the stability of the chosen scheme. A brief overview of the chosen scheme is presented, followed by simulation and measured results along with a detailed analysis of the results.

III. REVIEW OF SENSORLESS SCHEMES

There are many existing sensorless control strategies for switched reluctance machine and drive systems; in this paper they will be categorized into the following four categories: open-loop methods, signal injection methods, passive waveform monitoring and computationally intensive methods.

Open-loop control is the only true sensorless control strategy as there is no feedback whatsoever. Switching signals are applied to the machine at a suitable frequency and it is assumed that the rotor will follow the applied signals. The frequency of the applied signals is applied at a rate the rotor can follow and current control is usually achieved by hysteresis or PWM techniques. Reliability of this type of scheme is always a concern: if the rotor loses synchronism with the applied signals there is no way of knowing. Miller and Bass [1, 2] propose a modified open-loop scheme to improve stability, which adjusts conduction angles with load torque to keep the torque angle constant and maximize machine efficiency; this is done by measuring the average DC link current. Oldenkamp [3] adds additional circuitry to allow changes in speed and direction. An alternative to this approach is to fix the conduction angle and adjust the advance angle as is demonstrated by Vukosavic [4]. Open-loop schemes are extremely low-cost, but the schemes generally have poor dynamic performance and are mostly suited to constant speed and load applications [2].

Signal injection methods usually use inactive phases to determine rotor position. If the machine is running slowly, the phases in the machine will have periods where they are inactive long enough to inject signals into them, retrieve the resultant signals and process them to determine the rotor position. The injected signals must have a small amplitude so that braking torque is kept to a minimum. Acarnley *et al* [5] show that the relationship between rate of change of current and inductance allows rotor position to be determined, enabling sensorless control. Panda *et al* [6] show that current rise and fall times can be used to indicate rotor position. By applying voltage to an idle phase and measuring the rise or fall time of current, or by measuring the rise and fall times of hysteresis chopped current, the position of the rotor can be determined, allowing sensorless control to be achieved. Various modulation techniques have been presented: Ehsani *et al* [7-10] present a frequency modulation approach where the phase inductance forms part of a baseband oscillator. The FM signal contains inductance variation information, which is position dependant. Suresh *et al* [11] and Laurent *et al* [12] propose a similar method using amplitude modulation.

Passive waveform approaches use signals, including phase currents and voltages in the active phases of the machine to determine the rotor position. These methods are more suitable for high-speed operation, compared to the signal injection methods discussed previously. This is because the amount of time a given phase is not producing torque is substantially less at high-speed. Lyons *et al* [13-17] use the flux/current/position characteristics of the SRM to determine rotor position. An estimate of phase flux-linkage is made by subtraction of the resistive loss from the measured phase volts and this is integrated. The estimated flux-linkage along with the phase current can be used to determine rotor position using the flux/current/position characteristics. Kjaer *et al* [18] and Gallegos-Lopez *et al* [19] present the current gradient sensorless method which only requires use of the phase current to determine rotor position. It is shown that the current gradient decreases when the rotor and stator poles begin to overlap as they come into alignment – detection of this point provides a known rotor position, making sensorless control possible. Other approaches include solving the phase equation for phase inductance (assuming the machine is operating linearly) and using the inductance information to determine rotor position, as shown by Miki *et al* [20]. Mutually induced voltage measurement is another technique employed by Hussain *et al* [21], Austermann *et al* and Lui *et al* [22, 23].

Computationally intensive methods such as state observer techniques [24] and fuzzy logic or artificial neural network approaches [25-34] have also been researched greatly.

In this paper it is the high speed operation of the presented machine which is of interest. Computationally intensive approaches were ruled out due to cost, PCB space constraints and difficulties in processing the data fast enough at 100,000r/min. Open-loop and signals injection approaches are well suited for low-speed control, but for high speed control there was one existing passive waveform method that was of particular interest: the current gradient sensorless (CGS) scheme. There are two variants of this technique: one is presented by Kjaer *et al* [18] and the other by Gallegos-Lopez *et al* [19]. The CGS scheme was selected because it only requires knowledge of the phase currents to operate; no prior knowledge of the SRM parameters or the phase voltages are required, allowing the scheme to be implemented at very low-cost.

IV. THE CURRENT GRADIENT SENSORLESS SCHEME

A. Current Gradient Sensorless Variants

The current gradient sensorless scheme looks for position information within an SRM's current waveform. When the rotor moves from the unaligned to the aligned position, the inductance will start-off being relatively low and will rise as the rotor approaches the aligned position. It is shown in [2, 18, 19] that the gradient of the current will decrease when the rotor and stator poles begin to overlap – if this point can be detected the rotor position will be known, allowing sensorless control to be achieved.

Kjaer *et al* [18] proposes differentiating the current to obtain its gradient, followed by a peak-hold and compare circuit to detect when the gradient begins to decrease, thus detecting when overlap between the rotor and stator poles occurs. The analogue detection circuit presented uses a combination of 7 operational amplifiers, a comparator, plus a one-shot circuit – relatively low-cost circuitry, but when PCB space is at a premium, this is still considered to be a lot of parts to accommodate.

Gallegos-Lopez *et al* [19] proposes a similar technique, but for simplicity, the current ‘peak’ in the waveforms is detected. At high speeds, this point is relatively close to the point where the current gradient begins to decrease and is an accurate enough position reference to enable sensorless control. The only constraint is that the current waveform must have one peak per electrical cycle [19]. The analogue detection circuitry presented uses four operational amplifiers, one comparator and a one-shot circuit; suggestions are also made on how the circuitry can be further reduced if necessary.

B. Choice of Current Gradient Sensorless Variant

It was decided to investigate the use of the current peak detection variant presented by Gallegos-Lopez *et al* for high-speed control of the 1,600W SRM. Either variant of the scheme could have been chosen, but with cost always being an issue, the variant which could be implemented at the lowest cost, using fewest parts, was selected and investigated first. The downside to this scheme is that the location of the current peak may not necessarily indicate the point where the rotor and stator just begin to overlap. Also, a current peak must occur during each conduction period for the scheme to operate correctly. Preliminary tests showed that this scheme could operate the 1,600W SRM, but some problems, discussed in this paper, were encountered. Some of the problems encountered could be eliminated by using the original CGS scheme presented by Kjaer *et al*. After a prototype drive was developed and the current peak detection scheme was tested, several interesting observations were made which are shared in this paper.

C. CGS Theory for Peak Detection Variant

When a phase winding is initially energised the rotor and stator poles are not overlapping and the inductance is low and relatively independent of position: current therefore rises quickly. Once the poles begin to overlap the inductance starts to increase and a motional EMF ($\frac{\partial \psi_{ph}}{\partial \theta_e} \omega_e$) arises, opposing the applied voltage, as shown in (1). There is therefore a reduction in the rate of rise of current. The SRM phase voltage equation can be re-arranged to give $\frac{di_{ph}}{dt}$ as shown in (1) and (2):

$$V_{ph} = i_{ph} R_{ph} + \frac{\partial \psi_{ph}}{\partial i_{ph}} \cdot \frac{di_{ph}}{dt} + \frac{\partial \psi_{ph}}{\partial \theta_e} \omega_e \quad (1)$$

$$\frac{di_{ph}}{dt} = \frac{V_{ph} - i_{ph} R_{ph} - \frac{\partial \psi_{ph}}{\partial \theta_e} \omega_e}{\frac{\partial \psi_{ph}}{\partial i_{ph}}} \quad (2)$$

If the point where $\frac{di_{ph}}{dt}$ begins to decrease is detected, the rotor position will be known, allowing sensorless control to be achieved. As discussed previously, the current peak point (the point where $\frac{di_{ph}}{dt} = 0$) is detected for simplicity in this

version of the scheme [19]; this happens when the motional EMF term exceeds $V_{ph} - i_{ph} R_{ph}$. This process is demonstrated more clearly in Fig. 2-4 on the following page. Fig. 2 shows the rotor unaligned with the energised red phase. Current rises fast due to low inductance when phase is initially switched on. Fig. 3 shows the rotor teeth coming into alignment and overlapping the stator teeth, the current gradient decreases due to the rising inductance. The motional

EMF term can be written as $\omega_e i_{ph} \frac{dL_{ph}}{d\theta_e}$ assuming no magnetic nonlinearity. When the machine is running at high-speed, the motional EMF will abruptly rise to a large value when the rotor and stator teeth begin to overlap and $\frac{dL_{ph}}{d\theta_e}$ increases. Providing the motional EMF exceeds $V_{ph} - i_{ph} R_{ph}$, the current will form a peak as the rotor comes into alignment. The current decreases rapidly once the phase is switched off as shown in Fig. 4. At high-speeds the current peak point is very close to where $\frac{di_{ph}}{dt}$ begins to decrease.

Earlier work has shown that the current peak occurs at the same electrical angle in each electrical cycle, except when low-pass filter phase delays come into effect at higher speeds. In these circumstances, adjustments can be made by a commutation angle controller, which is a function of speed [19].

Fig. 2. 4-2 1,600W SRM - unaligned with red phase

Fig. 3. 4-2 1,600W SRM - rotor beginning to overlap stator pole, di/dt decreases due to rising inductance

Fig. 4. 4-2 1,600W SRM - rotor aligning with stator pole, di/dt goes negative forming a current peak

To ensure a current peak forms, the motional EMF term must rise to a sufficient level to exceed $V_{ph} - i_{ph}R_{ph}$, otherwise phase currents as shown in Fig. 5 may occur; this variant of the CGS scheme will not be able to obtain a position reference from them, leading to instability. Fig. 5a and 5b show the shape of the current when the back EMF just matches $V_{ph} - i_{ph}R_{ph}$ and when the back EMF is lower than $V_{ph} - i_{ph}R_{ph}$ respectively.

Fig. 5. Typical current waveforms when the motional EMF does not exceed $V_{ph} - i_{ph}R_{ph}$

It is essential to run the machine at a suitable speed to ensure the motional EMF rises to exceed $V_{ph} - i_{ph}R_{ph}$. The rotor

must also begin to overlap the stator within the conduction period and the current peak must occur within the conduction period, so that it can be detected and a position reference obtained.

V. THE 1,600W SR SENSORLESS DRIVE AND MACHINE

A. Open-loop Startup

An overview of the prototype sensorless drive is shown in Fig. 6. The sensorless drive uses an open-loop start-up routine to accelerate the machine to 60,000r/min. The high-speed closed-loop CGS scheme then takes over to accelerate the machine to rated speed.

Fig. 6. System overview of the sensorless drive and machine system

The SRM has asymmetry added to it by introducing a taper on the rotor (see Fig. 2-4). This gives the rotor the ability to always start and it encourages the rotor to start turning in the correct direction. The open-loop method begins by chopping one phase of the machine and gradually increases the PWM duty ratio to align the rotor with the chopped phase. After a certain amount of time has elapsed the alternate phase is energized to start the rotor turning. Switching signals, defined by lookup table values, are then applied to begin accelerating the rotor.

During open-loop control, a PWM signal is modulated with the high-side switching signals on the drive for current control. The duty ratio of the PWM is modified throughout the acceleration process to adjust the level of current (hence torque) in the phase windings as the machine accelerates.

B. CGS Peak Detection Hardware

The sensorless controller uses two current sensors to measure the two phase currents and scale them. The signals are buffered and fed to two separate differentiators. Pure differentiators tend to be unstable and amplify high frequency noise, to prevent this an additional pole was added to prevent high frequency noise amplification. Each differentiator has

an inverting action, which is counteracted by high-gain inverting amplifiers at the next stage, giving a scaled $\frac{di_{ph}}{dt}$ signal for each phase. The resulting signals are filtered by a 2-pole Sallen-Key 100 kHz low-pass filter. Kjaer [18] notes that the low-pass filters can cause phase shifting of the resulting current peak points. The filter used here phase shifts the signals by about 3° (electrical) at rated speed; this can easily be compensated in software by using a speed indexed lookup table. The final stage of the analogue detection uses comparators to detect zero voltage crossing points in the two filtered $\frac{di_{ph}}{dt}$ signals. When the rate of change of current is zero, a current peak will have occurred, causing the corresponding comparator output to toggle. The two comparator outputs are then fed to a microcontroller.

C. DC Link Setup and H-Bridge Configuration

The drive has a very small DC link capacitance of 9.9μF. DC link capacitors add substantial cost to a drive system, particularly when they have to be rated at high DC voltages; hence, the capacitance is kept to a minimum. For the tests shown here the drive can be considered to be run from a fixed DC supply voltage. The small capacitance means that the phase voltage varies across the conduction period – a typical characteristic of low-cost, mass market, commercial drives.

The drive has two asymmetric H-bridges which use two IGBTs each.

VI. SIMULATION

The simulation for the presented drive and machine is based in MATLAB and Simulink. Static flux-linkage tests were performed on the actual machine and the data is stored in lookup tables in the simulation, with i_{ph} a function of ψ_{ph} and θ_e . The CGS hardware and microcontroller are modeled purely in the Simulink part of the simulation. The speed can be dynamically changing and dependant on load parameters. For a given time step, k , the simulation finds the phase flux-linkage by using the following formula:

$$\psi_{ph(k)} = \int_0^t (V_{ph(k)} - i_{ph(k-1)} R_{ph(k)}) \cdot dt \quad (3)$$

The calculated flux-linkage for the sample time, along with the rotor position value, is used in conjunction with the lookup table of flux/current/position to determine the new phase current value, $i_{ph(k)}$. The new current value, along with rotor position, is used to determine the torque of the machine by using a torque lookup table, developed from the static flux-linkage results. The torque value is used to determine the new speed and position of the rotor and these values are fed back into the simulation, ready for the next time step.

The switching signals are dependent on rotor position and speed. The on and off angles are determined from speed indexed lookup tables.

Current control is achieved by selecting a modulation index value from another speed indexed lookup table. The appropriate switching signals are modulated with the PWM signal, so that the phase voltage is switched between 0V and +V depending on state of the PWM signal. A similar switched reluctance, Matlab/Simulink based model is presented by Soares and Costa Branco [35].

VII. RESULTS AND DISCUSSION

The purpose of this paper is to show what effect changing the level of flux-linkage and advance angle has on the shape of the current waveform and the placement of the current peak; thus, the impact the parameters have on the control of the machine using the peak detect CGS scheme. The level of flux-linkage in the machine is proportional to the DC link voltage (and hence, supply voltage) and inversely proportional to rotor speed. Sensorless results, measured from the actual prototype drive, are first presented along with simulation results. This is to validate the simulation and show the effects that speed, voltage and advance angle have on the system. Further simulation results are then presented to highlight these effects more clearly.

1) Variable DC Link – Simulation and Measured Results from Sensorless Drive

For the current peak to be used as a position reference, ideally it should occur at the same angle in each electrical cycle – independent of speed, advance angle or voltage. If the position of the peak is dependent on these parameters, careful mapping of the peak shifting will be necessary for good control of the SRM. The measured results from the prototype sensorless drive, along with the corresponding simulation results, are shown in Fig. 7-10:

Fig 7. Measured sensorless results and simulation results at 70,000r/min, 9.9μF DC link capacitance, varying supply voltage and advance angle

Fig 8. Measured sensorless results and simulation results at 80,000r/min, 9.9 μ F DC link capacitance, varying supply voltage and advance angle

The previous set of results shows several important features. Firstly, the results show good correlation between the simulated and measured results for all the tests performed; secondly, the position of the current peak is not static – it varies depending on speed, DC link voltage (hence supply voltage) and advance angle. In order to understand the underlying causes of the current peak variation a large amount of simulation work was conducted and is presented in the following section.

B. Fixed DC Link – Simulation Results

The validated simulation was used to further investigate the effects seen in the measured results. The DC link was held constant to eliminate any ripple present, reducing the complexity of the system. This was achieved by running the simulation with a large DC link capacitance. The following results show the effect of increasing advance angle, keeping speed and supply voltage constant; reducing supply voltage but keeping advance angle and speed constant and increasing speed, keeping advance angle and voltage constant. The conduction angle was fixed at 160° for all the simulations. As mentioned previously, changing voltage and speed alters the level of flux-linkage in the machine; therefore, this section examines how the current peaks are influenced by peak flux-linkage and advance angle.

Fig. 9 shows the profile of the phase current in one phase of the SRM over one electrical cycle. The input voltage is fixed at 240Vrms, 50Hz and is rectified to a steady DC link voltage in the simulation. The speed of the machine is fixed at 90,000r/min and the conduction angle is set to 160°. Each current profile shown is for a different advance angle – from 0° to 90° at 10° intervals.

As shown, the current profile forms a current peak, providing the advance angle is below about 60°; at angles exceeding 60°, no current peak forms. The results for 90,000r/min were chosen to show an important point: at some advance angles the current gradient sensorless peak detection system will have a current peak to detect; at advance angles greater than 60° the system will not have a position reference and could become unstable. It is essential that the advance

angle applied is accurately known and does not exceed levels that would cause instability.

1) Effect of Increasing Advance Angle

Fig 9. Phase current over one electrical cycle at 90,000r/min fixed speed, 240Vrms input voltage rectified to a fixed DC link voltage, 160° conduction period, varying advance angle

Fig. 10 shows that adjusting the advance angle can alter where the current peak forms for the machine and drive system presented. As the advance angle is increased then so is the position of the current peak. For the conditions of Fig 10 this corresponds to 25° variation. The current peak is used as a position reference for the current gradient sensorless system and all switching signal timings and speed calculations are done with respect to this point – if the electrical angle where the peak forms moves, the timings will be inaccurate unless there is some compensation. Advance angle calculations will also be made with respect to the detected current peaks and it has already been shown in Fig. 9 that errors in advance angle could lead to unstable operation of the sensorless scheme. Compensation must be made to account for peak shifting variations to guarantee reliable control of the machine and drive system.

Fig 10. Phase current over one electrical cycle at 109,000r/min fixed speed, 240Vrms input voltage rectified to a fixed DC link voltage, 160° conduction period, varying advance angle

By changing the level of flux-linkage in the machine and the advance angle applied, a map of stability boundaries can be created as shown in Fig. 11:

Fig 11. Current peak position against advance angle and peak flux-linkage

Fig. 11 shows more generally that increasing advance angle advances the position of the current peak in each electrical cycle. Increasing the flux-linkage in the machine causes the peak to occur later in each electrical cycle. This effect is due to saturation: as the machine starts to saturate, the current peak becomes shallow and very flat topped. The differentiator detects the peak later in the electrical cycle as a result. Increasing the flux-linkage level further results in no current peak forming at all. The map shows that at low flux-linkage levels, any advance angle can be applied and a current peak will form; at higher flux-linkage levels a current peak will only form at lower levels of advance angle. The larger the flux-linkage level, the smaller the range of allowable advance angles that can be applied to guarantee a current peak forming. At peak flux-linkage levels exceeding 0.055Wb no current peak will form, regardless of advance angle, due to the magnetic saturation of the machine. Operating the SRM outside of the surface shown in Fig. 11 will result in no current peak forming, leading to the current gradient sensorless scheme becoming unstable. The effect of saturation can be explained more clearly by considering Fig. 12 below:

(a)

(b)

Fig 12. Phase current over one electrical cycle at 80,000r/min fixed speed, 240Vrms input voltage rectified to a fixed DC link voltage, 160° conduction period, varying advance angle and corresponding current loci curves

Fig. 12a shows the shape of the current waveform with an input voltage of 230Vrms (rectified to a fixed DC link voltage of $\sqrt{2} \times 230 = 325.27V$), varying the advance angle. Fig.12b shows the corresponding current loci, plotted on top of the machine's flux/current/position characteristic curves. As shown, the peak flux-linkage in the machine reaches values in excess of 0.05Wb. Fig. 11 shows that at this flux-linkage level the current gradient sensorless scheme is operating on the boundary of stability on this machine. For advance angles of 0° to 40° a current peak forms. Looking at the corresponding loci curves, the current rises then decreases prior to the aligned position – a current peak therefore forms. For advance angles greater than 40° this does not happen. As shown in Fig. 12b, the current increases in magnitude but never decreases prior to alignment due to saturation – a current peak does not form.

VIII. CONCLUSION

This paper has investigated the use of the peak detect CGS method for use on a 1,600W, 100,000r/min SR drive system. Factors which influence the current peaks, used as a position reference in this sensorless scheme, have been examined. To ensure stability of the scheme on this drive, care must be taken not to excessively saturate the machine, otherwise no current peak will form and the system will have no position reference, hence causing instability.

It has been shown that the current peak position is not static and the electrical angle where it forms can change. Its position is dependent on both advance angle and the flux-linkage level in the machine. For good drive control, mapping of the current peak movement is necessary.

The peak detect current gradient sensorless scheme has the potential to be realized in low-cost mass domestic products, but to ensure the sensorless system runs suitably on the presented drive system, over the desired speed range, further modifications to the drive and machine to reduce flux-linkage levels is necessary. To improve the drive control, mapping of the current peak movement is also required.

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