Design and development of Open loop CGSM for SR Motor

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Received 25 July 2012; revised 10 December 2012; accepted 27 February 2013

This paper presents development and implementation of open-loop current gradient sensorless method (CGSM) for low frequency PWM controlled switched reluctance motor. Prototype SRM drive is developed with split DC converter and low frequency PWM controller. New open loop CGSM is analyzed for constant speed drive. Performance analysis of proposed CGSM with low frequency open-loop and closed-loop PWM control is discussed. Proposed method eliminates the need of phase-lock-loop (PLL) and speed feedback in CGSM which reduce the cost and complexity of the drive. Both simulation and experimental results are presented for validation. Opal’s RT-Lab is used as hardware-in-loop controller for easy and flexible implementation of controller and sensorless scheme.

Keywords: CGSM, Sensor less control, reluctance motor

Introduction

A simple mechanical structure, low manufacturing cost, flexibility in control, adjustable torque speed characteristics, higher efficiency, high torque weight ratio and constant power output capability over wide speed range are the main attractive features of the Switched Reluctance Motor(SR motor or SRM) which make it a viable candidates for the variable speed drive. Rotor position sensing is essential in switched reluctance motor in order to synchronize the phase excitation pulse to the rotor position. Recently there has been enormous interest in eliminating mechanical position sensor for reducing the cost, overall physical envelop and weight of the switched reluctance motor drive and to increase the reliability of the system. Many interesting sensorless rotor position estimation techniques have been proposed by the researchers over the last two decade. Flux-linkage based on magnetic characteristics, state observer, active probing & modulates signal injection are some of the sensorless method of recent interest. In late 19’s many sensorless methods based on current monitoring has been developed which does not required a prior knowledge of motor parameter. It makes easy and cost effective implementation of sensorless control possible. Sensorless methods of this category include chopping current waveform, regenerative current and current gradient sensorless method (CGSM). Sensorless method based on chopping current waveform is applicable only when current is regulated through hysteresis control. In this method rotor position is detected by calculating rise time and fall time of chopping waveform which is a function of incremental inductance. However the uncertainty of the phase resistance and back EMF because of dependency on speed and rotor position complicate the calculation of rise time and fall time. Furthermore incremental inductance is current dependent which contribute extra complexity in the rotor position estimation. It is applicable to only low speed where current regulation is possible thus single pulse operation is not possible. The resolution of rotor position is inversely proportional to the speed thus instantaneous rotor position estimation is quite difficult. In regenerative current method current is monitored and phase is de-energized in response to regeneration of current. To control the drive, current is turned off for constant period of time when it exceeds the reference value. The control is in soft chopping mode and slop of current freewheel through diode is observed. When rotor pass the aligned position, slop of the current change from negative to positive because inductance starts falling. Efficiency of this method is poor because of considerable negative torque produced during de-energize mode. Other drawback is turn-off angle cannot be advance and speed is limited below base speed.

Sensorless method with PWM control is applied in article which monitor the rate of change of phase
current \((di/dt)\) in each PWM period. Rotor position can be estimated as \(di/dt\) is a function of incremental inductance. However it is clear that this method also suffers from uncertainty of the incremental inductance at higher current level and error introduced by the back EMF. Also single pulse operation is not possible. CGSM is first proposed in article\(^{18}\) and then implemented and analyze in article\(^{19}\). Novel method is presented first time in this paper to implement the CGSM to be incorporate with low frequency (1.6 KHz) voltage PWM controlled low cost SRM drive. Low cost SRM drive is design with split DC converter and open loop voltage PWM controller\(^{20}\). Proposed open-loop CGSM method added an advantage to the regular CGSM in the area of cost, complexity and size. To compete with the worldwide adopted induction motor SRM should offer low cost versus performance ratio. Because SRM cannot run on direct supply like induction motor the cost of converter, controller and sensor also should take under consideration. Thus here main aim is to improve performance of sensorless SRM drive in the cost effective manner to be incorporate with the low cost SRM drive.

**Switched reluctance motor drive**

SRM is a doubly salient electrical machine which is made of laminated stator and rotor and phase winding on the stator. There are no windings or permanent magnets on the rotor. When current is passed through the phase winding the rotor tends to align with the stator poles and it produces a torque that tends to move the rotor to a minimum reluctance position. The direction of torque generated is a function of rotor position with respect to energized phase, and is independent of direction of current flow through phase winding. Continues torque can be produced by intelligently synchronizing each phase’s excitation with the rotor position. By neglecting the magnetic saturation an equivalent expression of torque is,

\[
T = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad \ldots (1)
\]

To develop continuous torque in positive direction it is required to energize the phase only during their respective rising inductance period which explains the necessity of position sensor to command the phase current. Different converter topologies are available to energize the phase of the SRM. There are number of converter topology is published in the literature to reduce the number of switches per phase and reduce the cost of converter and firing circuit\(^{21-23}\). One switch per phase type split DC converter is developed with low frequency voltage PWM controller.

It is assumed that there is no magnetic saturation that means inductance is unaffected by the current. Also neglecting the mutual inductance for the simplicity voltage equation of the one phase is,

\[
V_{ph} = R_{ph}i_{ph} + \frac{d\psi_{ph}}{dt} = R_{ph}i_{ph} + \omega_m \frac{d\psi_{ph}}{d\theta} \quad \ldots (2)
\]

Where \(V_{ph}\) is the phase voltage equal to \(V_{dc}/2\) and

\[
V_{dc} = \sqrt{2}V_{rms}
\]

\[
V_{ph} = R_{ph}i_{ph} + L_{ph}(\theta) \frac{di_{ph}}{dt} + \omega_m i_{ph} \frac{dL_{ph}(\theta)}{d\theta} \quad \ldots (3)
\]

Where \(i_{ph}\) = phase current, \(R_{ph}\) = phase resistance, \(\psi_{ph}\) = flux linkage, \(L_{ph}\) = phase inductance, \(\omega_m = d\theta/dt\) = speed and \(\theta\) = rotor angle.

One switching element and one diode are associated with each phase. At any instant two phase are ON to maximize the torque and which also minimize the torque ripple. Alternative phases (1,3 and 2,4) are never going to conduct simultaneously. It also helps in balancing the DC link capacitors. There are several methods to control the torque-speed and the position of the SRM. Hysteresis current control and PWM control are two low cost and simplest methods for easy implementation. In hysteresis control phase switch turned off and on according whether the current flowing through the winding is greater or less than the reference current, while in PWM control fixed frequency variable duty cycle scheme can be employed to regulate the current.

**Current gradient sensorless method**

Theory of CGSM is well explained in past work\(^{18-19}\) while the principle is quite simple that it detects position \(\theta_o\) where rotor and stator pole begin to overlap by observing change in \(di/dt\). The slope of phase current is always greater for \(\theta < \theta_o\), then \(\theta > \theta_o\), Method detects one position \(\theta_o\), per phase where \(\theta_o\) is depending up on motor geometry (Number of stator and rotor pole and pole arc).

For four phase 8/6 pole SRM drive rotor \(\theta_o = 30^\circ\) (mech). It is obvious that at \(\theta = \theta_o\), \(di/dt = 0\). Thus by observing \(di/dt = 0\) one rotor position per stroke can be estimated. For the geometry of proposed 8/6 motor rotor angle \(\theta_o = \theta_u\), where \(\theta_u\) is the unaligned position
of the rotor. Therefore phase must be advance to have at least one current peak per stroke.

**Open loop cgsm with open loop speed control**

As explained one pulse (position) is obtained per stroke in regular CGSM method. In that phase locked loop (PLL) is used to multiply the frequency of detected position pulse for interpolation of rotor position and commutation logic is derived from continuous rotor position. Proposed paper evaluates the new CGSM method without PLL or any other frequency multiplying techniques. Proposed method takes advantage of delay produced in current peak detection to derive commutation logic rather than compensating for error. This method does not require speed feedback at all thus its named Openloop CGSM.

Accurate simulation model of the 500W 8/6 SRM drive is used for simulation results while Opal's RT-Lab is used as a hardware-in-loop controller to implement the peak detection, commutation stage, and PWM controller. Only current peak detection stage is added to replace the position sensor block of openloop voltage PWM controlled SRM for the realization of openloop CGSM.

**Current Peak Detection**

Current peak detection stage include current filter followed by the derivation, zero crossing and positive edge trigger pulse generation. Current peak detection is independent of motor load in fact current is more continuous for higher load. No-load current seems discontinuous in nature because of low frequency PWM pulse and small inductance of the phase. But still by choosing filter, circuit is able to generate pulse at the current peak as shown. Current Peak detection stage and commutation logic are implemented using RT-Lab. Experimental results for current peak detection shown in Fig. 1 which shows commutation pulse, phase current, filtered phase current and peak detection pulse. Problem associated with current peak detection for proposed method are discussed in next subsection.

**Problem in current peak detection**

Ideally current peak pulse should indicate the rotor angle of 30° irrespective of turn ON angle, speed and load. But phase delay produced in current peak detection due to second order filter. Delay produce in current peak detection depend upon the cutoff frequency of filter while cutoff frequency is selected to smoothen the current shape which make easy to detect the condition di/dt = 0. Instead of compensating for delay produced in peak detection due to filter, proposed method take advantage of it to produced the commutation logic from it in the balance way. Thus effectiveness of the proposed method is depending upon the design of the filter used for peak detection stage and commutation logic development as describe in next subsection. Method of designing filter depends upon required drive speed as applicable for constant speed drive only, PWM frequency, chopping method and resistance and maximum inductance of the phase. Cutoff frequency of the filter is taken 400Hz for simulation and 300Hz for the experimental results. Problem of multi pulse detection arises at low speed due to zero crossing detector.

**Commutation logic**

As explained, each phase of the SRM should energized during only rising inductance profile (i.e. it

![Fig. 1–Current Peak detection at (a) 1300 rpm (b) 3500 rpm with no-load](image)
should turn ON and turn OFF at a particular angle) to ensure the development of positive torque. Commutation logic is required to generate the commutation pulse for each phase to decide the turn ON and turn OFF instant whether the mechanical position system or sensorless method used. Commutation pulse should be controllable (variable) in high speed variable speed drive to control the speed above base speed and in high performance SRM drive where optimum efficiency and torque ripple minimization is required.

In regular CGSM and in most of the other sensorless method continuous rotor position is estimated from which commutation pulses are derived. In CGSM a frequency of peak detection pulse is multiply with higher number using phase lock loop (PLL) to estimate the rotor position by interpolation. While in the proposed method commutation logic is derived directly from the peak detected pulse by taking advantage of delay produced by the filter. General rules for obtaining commutation logic for any sensorless method for the SRM which used energized phase can be express as below.

1. Rotor angle information derived from active phase must be used to energized (turn ON) the next subsequent phase and it is applicable even for continuous rotor position estimation scheme.

2. To de-energize (turn OFF) the excited phase rotor angle information derived from the same phase or from the next subsequent phase can be used depends upon whether the commutation overlap is required or not.

By taking the rotor position when pole pare 1-1’ are in aligned position (i.e when phase 1 energized) as reference, commutation angle for each phase to zero advance angle can be written as,

For phase 1: $30^\circ < \theta < 60^\circ$
For phase 2: $45^\circ < \theta < 75^\circ$
For phase 3: $0^\circ < \theta < 30^\circ$
For phase 4: $15^\circ < \theta < 45^\circ$

or by taking the individual reference for rotor position, same can be written as,

For phase m: $30^\circ < \theta_m < 60^\circ$

where $m = 1, 2, 3$ and 4 indicate the number of phase and, $\theta_1 = \theta$, $\theta_2 = \theta - 15^\circ$, $\theta_3 = \theta - 30^\circ$ and $\theta_4 = \theta - 45^\circ$.

While commutation angle must be advance for the proposed sensorless method, which can be written as, For phase m: $30^\circ + \theta_{adv} < \theta_m < 60^\circ - \theta_{adv}$
where $\theta_{adv}$ is the advance rotor angle (assumed constant dwell angle).

As like most of the sensorless method it is also hard to estimate the rotor position at standstill or at very low speed for proposed method. For validating the proposed method first time, mechanical position sensing arrangement with opto-coupler is used for the initial startup which provide fixed commutation angle of $22.5^\circ < \theta_m < 52.5^\circ$.

It should be noted that filter is designed to produce the desired delay in peak detection deliberately at a desired speed. The transfer function of the second order filter and current peak detection stage are (4) and (5) respectively. The delay in peak detection is a function of rotor speed while variation in delay due to load current is very small and can be neglected.

$$\frac{1}{1.583e^{-7}S^2 + 0.0007958S + 1} \quad \cdots (4)$$

$$\frac{1}{2.506e^{-14}S^4 + 2.52e^{-10}S^3 + 9.499e^{-7}S^2 + 0.001592S + 1} \quad \cdots (5)$$

Now to decide the commutation pulse for each phase directly from the peak detection pulses consider a peak detection pulse of phase 1 shown in Fig. 1(a). It seems that if speed is constant then peak detection pulse from phase 1 should decide the turn ON instant of phase 2 while the peak detection pulse from phase 3 should decide turn OFF instant of phase 2. It is also applicable for each phase to decide the commutation logic without deviate the rules explained before. For the switching device like MOSFET which required the continuous gate pulse to keep it ON, commutation pulse for phase 2 can be derived such that the peak detection pulse of phase 1 (pdp1) turn ON the commutation logic pulse of phase 2 while the peak detection pulse of phase 3 (pdp3) turn OFF the commutation logic pulse of phase 2.

Proposed commutation logic also solved the problem of multi peak detection pulse at low speed because it uses only first peak pulse for turn ON and turn OFF logic. It should be noted that $\theta_{on}$ and turn $\theta_{off}$ both are more advance at lower speed while dwell angle is constant ($30^\circ$). With maximum possible advance angle $10^\circ$ (i.e. $\theta_{on} = 20^\circ$) for 8/6 four phase SRM to supply the desired torque requirement lower limit of the motor speed is decided. Higher limit is
decided with the zero advance angle (i.e. \( \theta_{on} = 30^\circ \)) because further increase of \( \theta_{on} \) results in development of negative torque comparatively equivalent or more than positive torque which leads to sudden oscillation and instability of the drive. Fig. 2 shows the variation of \( \theta_{on} \) and \( \theta_{off} \) with the motor speed for experimental results of the 500W 8/6 four phase SRM drive. It shows that minimum and maximum speed of the drive is 600 rpm and 1600 rpm which limit is imposed by the sensorless commutation pulse (i.e. due to delay in peak detection or say filter design) and not by the load (phase current). Transactions from position sensor to sensorless control for the stable and unstable operation are shown in Fig. 3 and Fig. 4. Initially motor is speedup by the position sensor with constant advance angle of 7.5° (i.e \( \theta_{on} = 22.5^\circ \)), dwell angle of 30° and PWM duty cycle of 20%. While feed-forward method or any other initialization method can be incorporate with the proposed sensorless method.

Another required criterion of the proposed method is that at the transaction of initial startup method to sensorless method motor torque developed should greater than the load torque. It should be noted that it is possible that torque developed with the initial startup method is higher than that of sensorless method at the same speed and constant PWM duty cycle because of commutation angle difference which is not constant for sensorless method and varying with the speed. While torque can be increase by increasing the PWM duty cycle during the transaction if required.

Consider the case shown in Fig. 3 where transaction takes place at the speed of 800 rpm with the constant duty cycle of 20% at no load. In more appropriate way it shows the transaction form fixed commutation control (\( \theta_{on} = 22.5^\circ \)) to variable commutation angle scheme (\( \theta_{on} \) proportional to speed) with the constant dwell angle and duty cycle. It seems that \( \theta_{on} \) becomes more advance at the instant of transaction which leads to increase in motor speed. But at the same time with the increase in motor speed \( \theta_{on} \) gets reduced and stable equilibrium point is achieved. Fig. 5 shows the effect of variation of duty cycle on the stability of the proposed sensorless method. It shows that slowly increase in duty cycle develop the more torque leads to increase the motor speed and achieve the new equilibrium point of speed and advance angle. It is also shown that any sudden change in duty cycle might unstable the system due to fact that if motor speed increase beyond the limit then torque gets reduced at higher turn ON angle. It imposes the limit on the duty cycle thus maximum possible duty cycle is dependent and proportional to the load to keep the
speed below the maximum limit. Fig. 4 shows the case where motor torque gets reduce to be less than load torque during transaction which reduces the motor speed further and further. It should be noted here that duty cycle can be incresed to achieve a stable operation for the case and it seems that proposed method should be more efficient with closed loop speed control.

**Open-loop CGSM with closed-loop speed control**

Speed feedback is compared with reference speed and PI controller is used to set the PWM duty cycle according to speed error while inner current loop is not used. Proposed CGSM method give the more stable performance with the closed loop speed control however it add some extra cost and component. Bandwidth of speed limit imposed by the proposed method is also increased for closed loop speed control yet it is not recommended because it causes considerable reduction in efficiency and increase torque ripple. Response of speed PI controller can be increase with higher frequency PWM pulse and inner current control loop.

**Conclusion**

Simulation and experimental result validate the proposed open-loop current gradient sensorless method. It shows that method dose not required phase-lock-loop (PLL) and commutation logic can be derived directly from the current peak detection stage. It shows the possibility of simplest sensorless controller to be incorporate with fixed frequency PWM control based low cost SRM drive while all the sensorless drive seems to be complex and costly. Previously proposed CGSM does not require any prior knowledge of motor parameter however proposed CGSM method required a little knowledge of motor in terms of phase resistance and phase inductance to design a peak detection stage. However proposed method added the benefits in cost and size. Somewhat higher PWM frequency may be chosen to improve the performance of the proposed CGSM nevertheless it reduce the efficiency. Proposed CGSM also shows the better results in stability and performance with closed loop speed control scheme however it adds the extra cost. Further research is required to sustain the proposed open loop CGSM in the area of filter design, to produce the controlled delay in peak detection and also novel idea may be derived to detect the current peak. Furthermore effect of controller and motor parameter like PWM frequency and phase current on the performance of the proposed method should be investigation in detail.

**Appendix**

**Motor Specifications:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty Type</td>
<td>continuous</td>
</tr>
<tr>
<td>Motor Type</td>
<td>8/6 four phase SRM</td>
</tr>
<tr>
<td>Output power</td>
<td>0.5 kW</td>
</tr>
<tr>
<td>Phase voltage</td>
<td>150 V</td>
</tr>
<tr>
<td>Number of turn per phase</td>
<td>310</td>
</tr>
<tr>
<td>Resistance per phase</td>
<td>4.5 ohm</td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>90.8 mm</td>
</tr>
<tr>
<td>Rotor outer diameter</td>
<td>48.4 mm</td>
</tr>
</tbody>
</table>

**Electronics specifications:**

- Power switch: IRFP450A
- Diode: MUR1560
- PWM frequency: 1.66 KHz

**Acknowledgment**

Author is thankful to the electric department of Indian Institute of Technology Roorkee for providing required equipments for experimental setup.

**References**

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