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Analysis of Current Gradient Sensorless Method of Switched Reluctance Motor

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ABSTRACT
In the present work performance of current gradient sensorless method (CGSM) of switched reluctance motor is examined. Major issues of CGSM associated with design, implementation and performance are investigated. It covers detail analysis of current peak detection, rotor position estimation and commutation logic due to non linear inductance characteristics, effect of PWM frequency, use of low pass filter and phase-locked-loop (PLL). Suitability and limitation of the CGSM are discussed. Piece wise solutions are proposed with mathematical support for each problem. This paper explores untouched issues of the CGSM particularity for low frequency SRM drive.

Keywords - CGSM, Sensorless, reluctance motor, switched reluctance motor, srm

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I. INTRODUCTION

Many useful sensorless rotor position estimation techniques of switched reluctance motor (SRM) have been proposed by the researchers [2]-[12]. 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 [13-17] 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 [13], regenerative current [15] and current gradient sensorless method (CGSM) [19]. CGSM is first proposed in [18] and then implemented and in [19]. Performance of Open-loop CGSM is investigated in [26].

II. FUNDAMENTAL OF CGSM

CGSM is applicable where current is controlled through voltage PWM techniques. It detects position θ_{pdp} where rotor and stator pole begin to overlap by observing change in di/dt. Consider a figure 1 which shows the typical current waveform for fixed frequency PWM controlled three phase SRM drive. It shows the current and ideal inductance of phase-A while other phases current are not shown for simplicity. PWM duty cycle is constant throughout the phase commutation period.

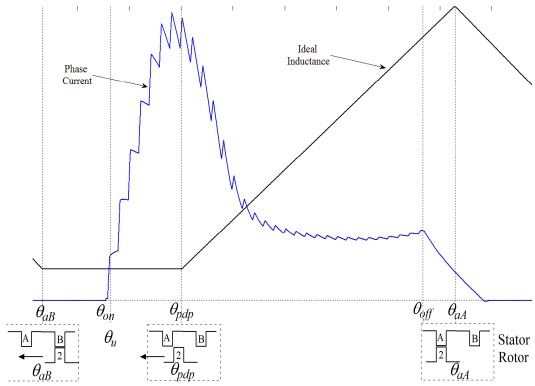
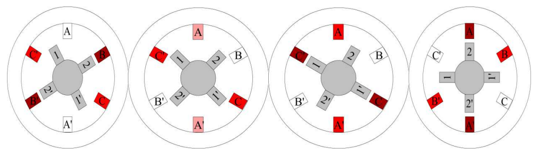


Fig.1: Phase current and phase inductance for voltage PWM controlled drive



(a) (b) (c) (d)

Fig.2: Rotor position at (a) θ_{aB} (b) θ_u (c) θ_{pdp} (d) θ_{aA}

Phase-A is energized at an instant θ_u where the inductance value is at minimum value L_u and ideally remains constant till θ_{pdp}. At the instant inductance start increasing current starts decreasing. It signifies that di/dt changes from positive to negative as inductance starts increasing. This reveals that instant at which inductance start increasing is the instant at which phase current becomes maximum. Conceptually, CGSM is to identify instant at which phase current becomes maximum, and then generating pulse at the instant to command the phase controlling switch. This pulse is called 'peak detection pulse'. This means scheme required to monitor only phase current to generate commutation logic instead of position sensor. Instant at which current becomes maximum can be represent mathematically as,

$$\frac{di}{dt} = 0 \qquad (1)$$

Pulse per stroke produced by monitoring di/dt and by checking condition (di/dt=0). Current peak detection stage can be represented in block diagram form as shown in figure 3. Low pass filter is added to filter out the switching frequency and noise. Cut-off frequency of the filter is decided by frequency of the PWM. Differentiator is used to monitor the rate of change of current (di/dt) and zero-crossing-detector (ZCD) followed by the one shot that produces a pulse at the instant di/dt = 0. Waveform at each stage of current peak detection is shown in figure 4.

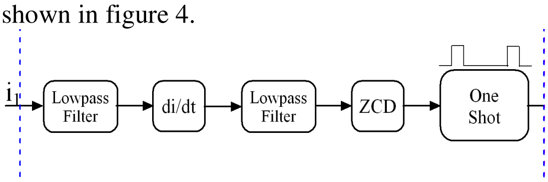


Fig.3: Current peak detection block

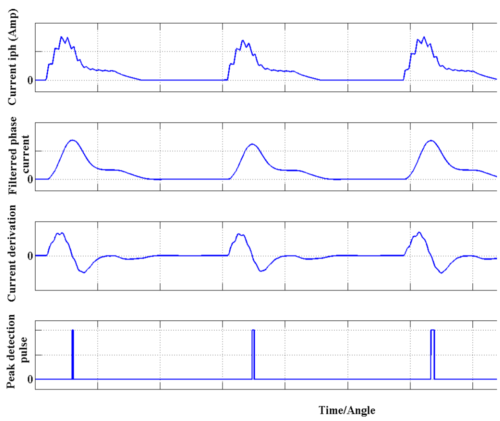


Fig.4: Output wavform at each stage of current peak detection

III. IMPLEMENTATION OF CGSM TO SRM

To implement the sensorless SRM drive, it is required to estimate a continuous rotor position from the peak detection pulse. Figure 5 shows the basic block diagram of voltage PWM controlled sensorless SRM drive based on CGSM. Case of 6/4 pole three phase SRM is considered for this discussion.

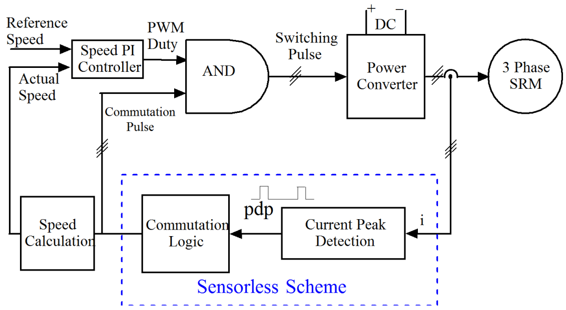


Fig.5: PWM controlled sensorless drive with CGSM

Main role of the sensorless scheme is to produce a phase commutation pulse by monitoring and process on the phase current. Sensorless scheme of CGSM is divided in two major block named 'Current Peak Detection' and 'Commutation Logic'. Function of 'Current Peak Detection' block is to produce a peak detection pulse (pdp) per stroke as explained in figure 2. This pulse is further processed by 'Commutation Logic' block to derive continuous rotor position and phase commutation pulses as shown in figure 6.

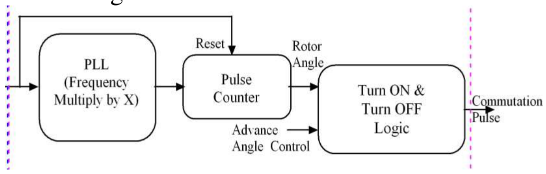


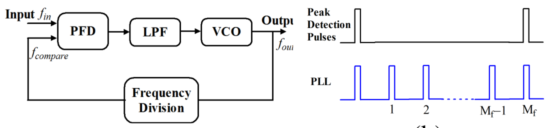
Fig.6: Commutaion logic block

Commutation logic decides the turn-ON and turn-OFF instant for each phase by producing the commutation pulse. Like most of the sensorless methods commutation logic is obtain from the continuous rotor position estimation. Commutation logic starts with PLL (phase-lock-loop) which multiplies the frequency of peak detection pulse with the condition that phase and frequency are locked to input. PLL match the frequency of compared signal with the peak detection pulse with zero phase difference. As a result frequency of output signal becomes M_f times multiple of input signal's frequency. Mathematically it can be explained as;

$$f_{compare} = \frac{f_{out}}{M_f} \qquad (1)$$

$$f_{out} = M_f \times f_{in} \qquad (2)$$

because $f_{in} = f_{compare}$ when phases are locked, where $f_{compare}$ = frequency of compared signal, f_{out} = frequency of output and f_{in} = frequency of input signal. PLL output the M_f pulses in the time interval of $1/f_{in}$ second.



(a) (b)

Fig.7: (a) PLL block diagram (b) Output of PLL

Main purpose to multiply the frequency of peak detection pulse is to estimate a rotor angle in between the two peak detection pulses by interpolation. Figure 8 shows the current peak detection pulse for all three phases with respect to conduction period of each phase. Peak detection pulses from each phase represents an angle of 90° (mechanical) (i.e stroke angle*Number of phases) while considering combine peak detection pulses for all phases, each next pulse is separated by an angle of 30° (mechanical) (i.e stroke angle).

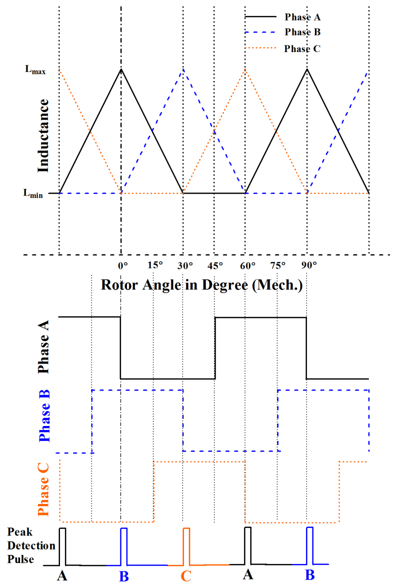


Fig.8: Peak detection pulse for each Phase

If the frequency of peak detection pulses of each phase is multiplied by an integer M_f using PLL, then minimum rotor angle that can be discriminated by the PLL's output pulse will be (stroke angle*Number of phase /M_f)° or say (90/M_f)° for the case. As shown in figure 6, pulse counter is used to estimate a rotor position from the high frequency pulse which results from the PLL output stage. Count value is incremented by one at each low-to-high transaction and counter will reset to zero on low-to-high transaction of the peak detection pulse as shown in figure 9.

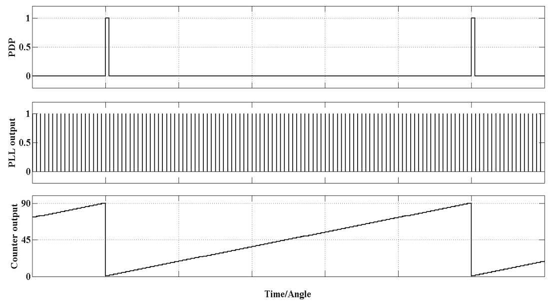


Fig.9: Output of pulse counter

Resolution ($\theta_{\min}$) of rotor angle estimation is calculated as,

$$\theta_{\min} = \frac{\varepsilon * m}{M_f} \qquad (3)$$

where ε = stroke angle, and m = number of phase and M_f = frequency multiplier. Figure 9 shows the waveform for the rotor position estimation using PLL and counter for M_f = 90. Thus 6/4 pole three phase SRM will give resolution of 1°(mechanical). It is apparent that zero count value represent a rotor angle of 60°(mechanical) or say θ_{pdp} thus Estimated rotor angle,

$$\theta_{estd} = CV \bullet \theta_{\min} + \theta_{pdp} \qquad (4)$$

where θ_{estd} is a estimated rotor angle in mechanical degree, CV is a count value and $\theta_{\min}$ is a minimum rotor angle that can be estimated by the scheme.

It is apparent from the above that any single phase detection is enough for rotor position estimation and commutation pulse can also be derived from it. However sensorless operation is not possible as it is valid only when motor is running with mechanical position sensor or by some other position sensing arrangement. Thus combined peak detection pulses are used to estimate a rotor position using PLL and counter stage which also increases resolution by 1/m times, and equation (11) becomes:

$$\theta_{\min} = \frac{\varepsilon}{M_f} \qquad (5)$$

It gives a resolution of 0.333°.

As rotor angle is estimated from active phase, proper sequence of phase commutation is necessary for effective operation of the sensorless scheme. Following rules are formed to decide commutation logic which is also applicable to other sensorless method based on active phase monitoring.

Rule1. 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.

Rule2. To de-energized (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.

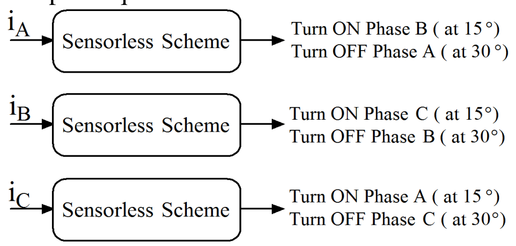


Fig.10: Phase commutation logic

Commutation pulses are derived for each phase to follow the compliance of the above rules, as shown in figure 10 which represent 'Turned-On & Turned-Off Logic' block of figure 6. In this scheme estimated rotor angle from each phase will decide turn OFF instant for same phase and turn ON instant of next successive phase. Thus, each phase will turn ON the next phase after 15° and same phase will be turned OFF after 30°.

Even though it seems this scheme produces accurate rotor position estimation, it is quite difficult to implement the sensorless SRM drive using commutation pulses obtained from it. This is due to the fact that during transaction from initial start-up to the sensorless control, operating parameters like speed, commutation angle and torque vary which may cause the instability and loss of synchronization. Thus successful implementation of sensorless control requires closed-loop speed control system.

Speed can be calculated from the frequency of peak detection pulse or phase commutation pulse. But peak detection pulses are used in practice to derive the speed of the motor because the phase commutation pulses are outcome from the peak detection pulse in sensorless control.

Rotor speed is calculated as,

$$N_s = \frac{f_{pdp} * 60}{n_{cr}} \text{ rpm} \quad (13)$$

where n_{cr} is number of cycle of peak detection pulse per revolution which can be calculated as,

$$n_{cr} = \frac{360}{\varepsilon * m} \quad (14)$$

This speed is compared with reference speed in PI speed controller to control the duty cycle of PWM pulse & maintain the required speed as shown in figure 5. PWM pulse is AND operated with commutation pulse generated from sensorless scheme to control phase commutation.

IV. EFFECT OF ROTOR STATOR POLE ARC

Consider figure.1 and ideal inductance profile of 6/4 pole SRM shown in figure 8 it can be observed that pole arc of both the rotor and stator are 30°(mech.). However, any difference in pole arcs affects inductance profile as well as angular position of current peak θ_{pdp}. Three phase 6/4 pole SRM having dissimilar rotor and stator pole arc is considered to demonstrate the effect. Phase current and inductance variation of three phase 60KW 6/4 pole three phase SRM modelled in [28] is shown in figure 11.

Rotor pole arc (θ_r) and stator pole arc (θ_s) of motor are 45° and 32° respectively. Hence rotor angle θ_{pdp} (at which stator and rotor pole are just begin to align) will become more advance than previous case where θ_r and θ_c both were 30°.

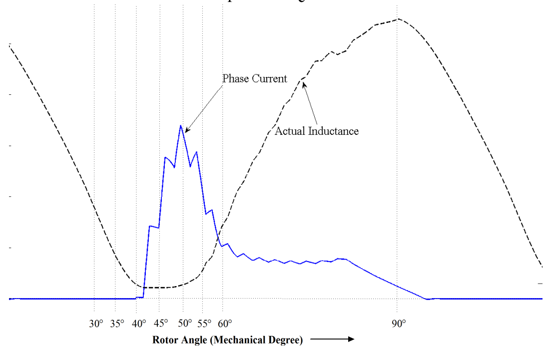


Fig.11: Phase current and inductance variation of 60KW, 6/4 pole, 3 phase SRM

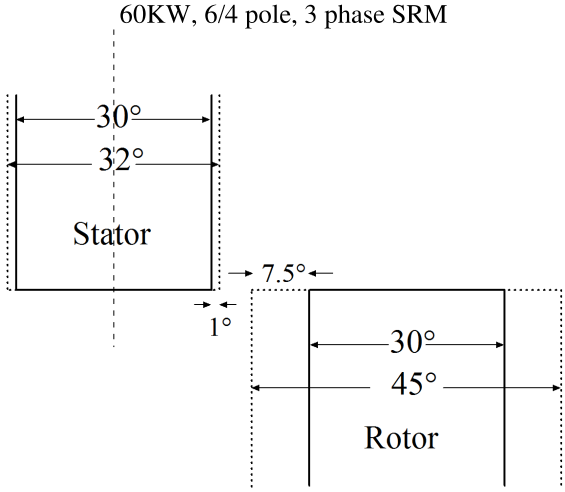


Fig.12: Rotor & stator pole arc

Comparison of both the case for rotor and stator pole arc is shown in figure 12 from which it is obvious that θ_{pdp} is advance by an angle of 8.5° (i.e 7.5° + 1°) for the case. And hence θ_{pdp} will become 51.5°. For 6/4 pole three phase motor θ_{pdp} can be derived as,

$$\theta_{pdp} = 60 - (\theta_r - 30 + \theta_s - 30) \quad (15)$$

Simplification is $\theta_{pdp} = 120 - \theta_r - \theta_s$ (16)

While for 8/6 pole four phase motor rotor angle θ_{pdp} is derived as,

$$\theta_{pdp} = 90 - \theta_r - \theta_s \quad (17)$$

In general, equation for rotor angle θ_{pdp} is written as,

$$\theta_{pdp} = (2 * \varepsilon + 60) - \theta_r - \theta_s \quad (18)$$

where ε is a stroke angle.

Thus rotor angle can be estimated more precisely with equation (12) and (18) if have information of rotor and stator pole arc in addition to the number of phases and poles.

Effectiveness of CGSM is depends upon accuracy of current peak detection instant. Any error or deviation of peak detection pulse from actual current peak instant may lead to instability and failure of scheme. Major factors affecting accuracy of CGSM are investigated as follow.

V. ERROR IN CURRENT PEAK DETECTION

Low-pass filters are used in the current peak detection stage for eliminating switching frequency. Use of filter adds a delay and produces error in current peak detection pulse θ_{pdp}. This delay is directly proportional to the speed of the motor and inversely proportional to the cut-off frequency (f_{coff}) of the filter. Cut-off frequency of low-pass filters is designed based on PWM frequency. But there is no standard rule to select the cut-off frequency as wide range of f_{coff} will produced the similar performance for the high frequency (greater than 10 KHz) PWM control. It is general to choose a cut-off frequency of filter,

$$f_{coff} = \frac{f_{pwm}}{3}, to, \frac{f_{pwm}}{2} \quad (19)$$

This phenomenon is not much highlighted in past literature as in the high frequency PWM controlled drive this delay is very less and even it compensates the advance effect in peak detection instant due to corner flux. But the scenario is looks different with the low frequency PWM drive. Delay produced in peak detection instant is prominent and cannot be neglected. Different issues related to current peak detection stage are as below.

5.1 Effect of current chopping method

Soft chopping and hard chopping are two basic modes of operation to control the phase current of the SRM. In the soft chopping mode phase voltage is zero during current freewheel while in the hard chopping mode full reversed voltage will appear across phase during regeneration mode. Because of that current decay more slowly in soft chopping mode compared to hard chopping, and thus there is more change of discontinuous current with the hard chopping mode especially with low PWM frequency and light load. Which required the more filtering compared to soft chopping and consequently delay produced in peak detection pulse is also more. Also the duty cycle of PWM is less in soft chopping mode compared to hard chopping for the same speed. It is because required peak current is less in soft chopping mode to maintain the same average current. Thus soft chopping mode is more suitable to implement CGSM than hard chopping mode.

5.2 Error in peak detection instant due to non synchronized PWM pulse

Another problem arises in current peak detection with the low frequency PWM control particularly at a higher speed. Frequency of commutation pulse f_{com} is a function of motor speed, while PWM frequency f_{pwm} is constant throughout. Because f_{com} is same as frequency of peak detection pulse f_{pdp}, it can be expressed as;

$$f_{com} = \frac{N_s \times n_{cr}}{60} \text{ Hz} \quad (23)$$

Frequency of commutation pulse is increase with increase in motor speed. Consider a case shown in figure 13 for the high speed operation where f_{com} is greater than $f_{pwm}/10$, while it is assumed that duty cycle of PWM pulse is remains constant throughout the commutation period. It is general practice to generate a PWM pulse independently with or without frequency control. Figure 13(a) shows the case where PWM pulse is always in synchronism with commutation pulse. With the rising inductance profile and constant duty cycle, current peak at each PWM pulses gets reduced. Thus peak detection pulse derived using this scheme represent the angle θ_{pdp} accurately. While in real practice PWM pulse are not synchronized and so effective duty cycle is not constant throughout the commutation period even if actual duty cycle remains constant. Consider a case shown in figure 13(b), for which first current peak is less in magnitude compared to second one even with increase in inductance. This is due to fact that effective duty cycle is less for the first pulse due to non synchronized PWM, while effective turn ON instant θ_{on} is not altered. This will introduce an error in angle represented by the peak detection pulse. And so that, rotor angle directed by the peak detection pulse will be always higher than the actual angle θ_{pdp}. But for the case shown in figure 10(c), current peak is reduces with increase in inductance while it produces delay in turn ON instant. Consequently low frequency non-synchronized PWM pulses results in wide variation in estimated rotor angle particularly at higher speed. Furthermore it is too complicate to compensate for the error produced in rotor angle estimation because variations of peak detection instant and effective turn ON angle both are independent in nature and may vary for each commutation period even with constant speed.

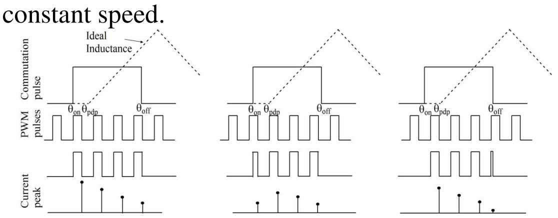


Fig.13: PWM pulse, commutation pulse and current

peak (a) synchronized PWM pulse; (b) & (c) non-synchronized PWM pulse.

One more phase locked loop can be used to synchronize the PWM pulses with the commutation pulses. Another simplest way to achieve synchronization is to reset PWM chip by the raising edge of commutation pulse. However practical implementation of both the method is much complex because of fact that sensorless commutation pulses are result from the peak detection pulse. Thus it is better choice to limit the PWM frequency for desired motor speed. However Synchronization PWM techniques can be used to derive an accurate delay produced in current peak detection where commutation pulses should be results from the accurate mechanical position sensing arrangement.

VI. CONCLUSION

Current gradient sensorless method looks quite easy to implement as requires to monitor and process phase current only. But issues examined in this paper reveal that there are so many other parameters need to consider particularly for low frequency applications. Method is not found suitable to be used with open loop speed controller & low frequency PWM controller. To eliminate error in current peak detection due to filter is main challenge of implementing CGSM even with closed loop speed controller. CGSM is best suitable with high frequency PWM controller based SRM drive but need to consider issues presented in this paper when implementing CGSM to low frequency PWM controlled drive. Furthermore equations derived in this paper for rotor position estimation, resolution and current peak detection are applicable to any SRM topology and different pole arc.

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