Sensorless Estimation of Single-Phase Hybrid SRM using Back-EMF

Ying Tang*, Yingjie He*, Dong-Hee Lee* and Jin-Woo Ahn[†]

Abstract – This paper presents a novel scheme to estimate the rotor position of a single-phase hybrid switched reluctance motor (HSRM). The back-EMF generated by the permanent magnet (PM) field whose performance is motor parameter independent is adopted as an index to achieve the sensorless control. The differential value of back-EMF is calculated by hardware and processed by DSP to capture a fixed rotor position four times for every mechanical cycle. In addition, to accomplish the normal starting of HSRM, the determination method of the turn-off time position at the first electrical cycle is also proposed. In this way, a sensorless operation scheme with adjustable turn on/off angle can be achieved without substantial computation. The experimental verification using a prototype drive system is provided to demonstrate the viability of the proposed position estimation scheme.

Keywords: Sensorless, Hybrid switched reluctance motor, Back-EMF, Position estimation

1. Introduction

The switched reluctance motor (SRM) has been the promising candidate for various drive systems in industrial for recent decades. The double salient structure with concentrate winding on stator makes them possess the property of robustness, low cost and wide speed range operation. Generally, three or four phases SRM is more popular to be applied considering torque dead zone and torque ripple minimization issues. However, nowadays, the single-phase SRM drive system has been improved and optimized by many researchers due to their reduced converter cost and low switching loss specially in high speed operation region [1-5].

It is apparent that, the SRM requires position feedback for motor phase commutation. In order to assure the regular running of the motor, accurate knowledge of rotor position is indispensable. In many cases, this requirement is addressed by using position sensors, such as encoders or Hall sensors, etc. However, for size reduction, cost minimization and harsh environment operation, the sensorless technique is especially crucial.

In existing sensorless control methods, the main approaches can be classified as current waveform based methods [6-8], high frequency pulse injection methods [9-11], flux linkage based methods [12,13], state observer based methods [14,15], and intelligent algorithm based methods [16,17]. In [6], the current rising time during current chopping control (CCC) is regarded as a medium to reflect the variation of inductance. And the comparison result of the rising time is used for the judgement of the inductance slope. However, in order to determine the

current rising and falling time, a fast MCU is needed and the noise caused by switching is very difficult to reject. In [7] and [8], the rotor position of the SRM of a PWM-voltage controlled system is estimated by the change of the phase current gradient when a rotor pole and stator pole start to overlap. Another kind of approach is to inject the impressed voltage pulse into phase winding of SRM [9-11], and set appropriate thresholds to determine the exciting timing of the next phase. Nevertheless, this method will cause additional torque ripple, large switching loss and complication in both hardware and software. In [12], the flux linkage is obtained from the real-time current and voltage and fed into an adaptive neuro-fuzzy inference system to predict the rotor position during running conditions. For smaller memory and simpler computation, an improved flux linkage comparison scheme is proposed in [13], based on estimating a particular rotor position at both low and high speeds. However, the magnetic characteristics of the motor must be obtained previously, a huge memory is needed to store the look-up tables, and the process is complicated. To deal with the issue, a sliding-mode-observer technology is employed in [14, 15] for four-quadrant sensorless operation of SRMs, covering a wide speed range. Also, some intelligent techniques also are used for rotor position estimation aiming at to improve the estimation accuracy, including the neural network [16, 17].

Although there are a lot of pervious researches proposed to estimate the rotor position, the sensorless scheme of HSRM is not much researched. On the one hand, for high speed operation, with the speed increasing, the information points can be acquired from the voltage and current are getting less and less which lows the likelihood of the accurate access to rotor position. On the other hand, differing from the conventional SRM, half of the electrical cycle cannot be controlled in this single-phase HSRM. Thus to apply the motor to high speed application, a simple

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and less information required scheme should be come up with.

In this paper, a novel rotor position estimation method using back-EMF of the single-phase HSRM is proposed which is able to run the motor in wide speed range. Also the determination of turn-off time point at the first electrical cycle is presented. In the following sections, firstly, the working principle of a novel single-phase HSRM will be introduced. After that, the proposed sensorless estimation scheme will be presented in detail. Finally, the simulation and experimental results regarding to a prototype motor will prove the practicability and feasibility of the proposed position estimation scheme.

2. Single-phase HSRM Drive System

In single-phase HSRM drive system, an asymmetrical half-bridge converter is employed (Fig. 1). To reduce the switching loss and torque ripple, the soft-chopping mode that the upper-transistor chopping and lower-transistor remaining closed in every turn-on cycle is adopted. Obviously, contrasting with multi-phase converter, the single-phase converter is high efficiency and low switching loss consumption.

The specific structure of the single-phase HSRM in the drive system is show in Fig. 2. The motor has four reluctance poles and two PM poles. Each of the PM poles is embedded between two adjacent reluctance poles. The phase winding consists of two coils and each of which embraces two neighborhood stator poles respectively. At standstill, the rotor is always aligned with the PM poles with a little bias from the precise directly align position

Fig. 1. Single-phase HSRM drive system

Fig. 2. Rotor position under effect of PM flux

due to the asymmetrical rotor pole design which endows the self-start ability of the motor (Fig. 2). Once the DC-link voltage is impressed between winding, the rotor will rotate immediately to align with the stator poles by shortening the flux path reluctance developed by the total flux linkage contributed by current and PM flux linkage together (Fig. 3). After almost 45° (mechanical degree) later, the phase current value should turn to be zero for avoiding the negative torque production. Meanwhile, the rotor will rotate to the location under the PM poles by PM flux linkage alone and during this process, the role the PM plays is similar with its parking function when the motor is at standstill. By repeating the above process, the continuous running of the motor can be achieved. Compared with conventional single-phase SRM, it has an increased torque density and low torque ripple by properly taking advantage of the torque generated by PM (Fig. 4). Moreover, the self-starting capability is ensured due to the parking function of PM. Besides, this novel structure is more convenient to manufacture both in terms of the rotor and stator construction comparing with the structure proposed in [3, 5], thus expecting less manufacture technical craft.

3. Proposed Sensorless Estimation Scheme

3.1 Mathematical model of single-phase HSRM

The voltage equation of the HSRM can be expressed as:

Fig. 3. Rotor position under effect of PM and windings flux

Fig. 4. Ideal continuous torque profile

Fig. 5. Flux linkage of PM

Fig. 6. Back-EMF at different speeds (2000rpm-10000rpm)

$$V_{ph} = i_{ph}R + \frac{d}{dt}(\psi_{PM} + \psi_{Winding}) \quad (1)$$

where, V_{ph} is phase voltage, i_{ph} is phase current, R is the resistance of phase winding, ψ_{PM} is the flux linkage generated by PM, $\psi_{Winding}$ is the flux linkage generated by phase current. The total flux linkage existing in the magnetic path is stemmed from two sources, generating by PM and by winding current. From this equation, it can be seen that, if there were no current flowing in the phase winding, the total flux linkage uniquely comes from PM, and the voltage can be measured under this condition is the back-EMF generated by PM which can be described as:

$$V_{ph} = \frac{d\psi_{PM}}{dt} = \frac{d\psi_{PM}}{d\theta} \omega = V_{back_EMF} \quad (2)$$

where ω is the rotor angle velocity, θ is rotor position, and V_{back_EMF} represents back-EMF produced by PM. It is known that, as long as the PM location is fixed, the flux linkage produced by PM at certain fixed rotor position is invariant (Fig. 5), so the back-EMF can be measured at winding terminal during this period is uniquely decided by the speed the motor is running at, shown in Fig. 6.

3.2 Determination of turn on/off point in general area

When the rotor rotating only with the PM flux flowing in the magnetic path, the minimum position of back-EMF

Fig. 7. Proposed sensorless scheme in general area

is always appearing at 280° (electrical degree) which is a valuable timestamp that can be utilized to estimate the rotor position. Additionally, this period will last for roughly half of an electrical period which gives enough time to catch that point. Fig. 7 shows the idea of proposed position estimation scheme, as a key parameter, the differential value of back-EMF ($\dot{e}$) is used for catching the minimum back-EMF position. First, back-EMF is detected and its differential value is calculated, then crossing zero point of back-EMF differential which represents the arrival of the minimum back-EMF position should be captured and the time duration between two minimum back-EMF positions should be stored as ΔT . Basing on above, the estimated rotor position can be got from the following equation:

$$\theta_{est} = \theta_{280} + \hat{\omega} \Delta t \quad (3)$$

where, $\Delta t = t_{est} - t_{280}$ indicates the time duration between the estimating timestamp and the timestamp corresponding to minimum back-EMF position. $\hat{\omega}$ can be figured out from the time duration of two minimum back-EMF positions belonging to two neighboring electrical cycles:

$$\hat{\omega} = \frac{360^\circ}{\Delta T} \quad (4)$$

According to the proposed sensorless algorithm, the turn on/off time point can be derived by:

$$t_{on} = t_{280} + \frac{\theta_{on} - 280^\circ}{\hat{\omega}} \quad (5)$$

$$t_{off} = t_{280} + \frac{\theta_{off} + 360^\circ - 280^\circ}{\hat{\omega}} \quad (6)$$

where, θ_{on} , θ_{off} represents the predetermined switch

on/off angle, t_{280} corresponds to the timestamp of the minimum back-EMF position. The crossing zero point of back-EMF is also available to correspond with a fixed rotor position (0°), while in order to advance the turn on angle before 0° , the minimum point is the best candidate for high speed and high current operation.

Owing to the working principle of the single-phase HSRM, the estimated speed can be refreshed four times every mechanical round. As can be seen, the proposed sensorless scheme is a very simple algorithm without substantial computation and the pre-stored data of electromagnetic property of the motor is also not required. Additionally, there is no accumulated error existing in the estimated rotor position. Most of all, the special point needs to be detected is free from the variation of the switching on/off angle thus can achieve the alterable turn on/off angle which allows the operation with advanced turn on angle in high speed operation.

3.3 Determination of turn off point in starting area

Because of the parking function of PM, the rotor always automatically aligns with the PM poles. Therefore, the initial position estimation at standstill will not be taken into consider. The fundamental idea of proposed scheme is to catch the minimum back-EMF point in every electrical cycle, thus the determination of the turn off time point at the first electrical cycle is also necessary for normal starting.

In the proposed sensorless drive system, double closed-loop strategy comprised by speed and current controller is used. For the inner current controller, the hardware current limitation is adopted to control the current within a safe range even under extreme situation (Fig. 8). The current error (Δi) is generated by subtracting the feedback phase current (I_{act}) from the reference current (I_{ref}^*) generated by speed controller, then the error is given to the current controller to generate proper duty cycle (C_p) to drive the IGBT. In the meantime, the feedback phase current (I_{act}) is also compared with maximum protection current (I_{max}). Once the I_{act} is bigger than I_{max} , the comparator will low the logic output (L_p). Notice should be paid that the final gate drive signal (G_p) is the AND logic output of C_p and L_p , which implies that without the permission of the current limiter, even if the current controller commands high level output, the gate drive signal will still maintain low to give the overcurrent protection of the system.

From the above, it can be seen that every time I_{act}

Fig. 8. Block diagram of hardware current limitation

exceeds I_{max} , the IGBT will be switched off to guarantee the I_{act} will never be over than I_{max} . Nevertheless, because of the delay of the device in current protection part, the current will not immediately decrease as soon as the current limiter commands the low level (Fig. 9). The delay of the device (ΔT_d) is produced from several components:

$$\Delta T_d = t_{dc} + t_{dl} + t_{dd} + t_{ds} = \text{Constant} \quad (7)$$

where, $t_{dc}, t_{dl}, t_{dd}, t_{ds}$ is the comparator delay, logic AND gate delay, gate drive delay and IGBT delay, respectively. Most of all, the ΔT_d is a constant which solely depends by the components adopted in hardware. After summing all the components delay, the total delay time can be acquired.

The voltage equation in the HSRM also can be rewritten in following way:

$$V_{ph} = Ri_{ph} + L_{eq}(\theta) \frac{di_{ph}}{dt} + i_{ph} \frac{dL_{eq}(\theta)}{d\theta} \omega \quad (8)$$

where, the $L_{eq}(\theta)$ is defined as the equivalent inductance which is the quotients of total flux linkage and exciting current taking the PM flux existing in magnetic path into consider. Although the definition of inductance here is different from conventional, they have the same variation tendency (Fig. 9) which supports identical analysis method. In general, the voltage drop on the winding resistance is so small that it can be neglected. Also as the equivalent inductance goes into the saturation region, its slope tends to approach to zero, so the motional electromotive force can be directly omitted. Upon on above, in inductance saturation region, the increment current during the device delay period (ΔT_d) when I_{act} exceeds I_{max} can be calculated as:

$$\Delta I = \frac{V_{ph}}{L_{eq}(\theta)} \Delta T_d \quad (9)$$

Substituting all the parameters included in the above expression, the increment current ΔI can be obtained and applied as threshold to switch off the phase voltage in time

Fig. 9. Proposed starting algorithm

Fig. 10. Flowchart of proposed rotor position estimation scheme

as soon as the inductance entering into the saturation region.

3.4 Proposed sensorless estimation process

Fig. 10 shows the flowchart of proposed sensorless scheme. First, exciting the winding to rotate the motor and storing the absolute starting time point that the winding is excited as T_{i-2} . If the actual winding current reaches the current value ($I_{max} + \Delta I$) that only can be reached at the inductance saturation region, the current will be switched off. I_{max} represents the maximum current value limited by current limiter. Afterwards, on behalf of the minimum back-EMF point, once the back-EMF differential equals to zero, the time point of it will be stored as T_{i-1} , and the angular velocity in the first electrical cycle can be estimated by (10) and the rotor position can be estimated by (3):

$$\omega = \frac{3\pi}{8(T_{i-1} - T_{i-2})} \quad (10)$$

Fig. 11. Block diagram of proposed rotor position estimation scheme

It can be noticed that the angular velocity estimation formula in the first starting cycle is different from the formula used in the general running cycle. It is because that, in the first electrical cycle, the time duration from the initial parking position to the first minimum back-EMF position only covers the 3/4 electrical period, yet the time duration between two adjacent minimum back-EMF positions always covers a whole electrical period. After that, normal running of the motor can be realized by calculating the turn on/off time point corresponding to the preset turn on/off angle basing on (5), (6).

Fig. 11 shows the block diagram of proposed rotor position estimation scheme. Double closed-loop is adopted in the drive system. The outer loop is speed control and inner loop is current control. The actual winding current is confined by the current comparison circuit to protect the system from overshoot current at any condition. The minimum point of back-EMF is captured at every electrical cycle to estimate the speed and rotor position.

4. Simulation and Experimental Results

A model of single-phase HSRM drive system is built by MATLAB/SIMULINK to simulate the proposed idea. Fig. 12 shows comparison waveforms between the actual and estimated rotor position at 6000rpm. Both Fig. 12(b) and (c) display the estimation results of the proposed idea, but in the simulation of Fig. 12(c), the acceleration between two adjacent electrical cycle is taken into account. It can be seen the estimation curve considering the acceleration shows almost same accuracy when compared with the actual rotor position at stable status, but smaller error at the starting part. This phenomenon also happened in the speed estimation as well. Besides, the estimated rotor position and speed will not refreshed until the minimum back-EMF point is captured in the first electrical period. Fig. 13 shows the closed-loop sensorless operation at 9000rpm. Fig. 14 shows the operation waveforms with speed changing from 5000rpm to 9000rpm, and in both of this two figures, the minimum back-EMF detection pulse is provided. At starting,

(a) Measured rotor position

(b) Estimated rotor position

(c) Estimated rotor position considering acceleration

Fig. 12. Rotor position waveforms at starting period

Fig. 13. Sensorless operation at 9000rpm

the current is limited under 40A to emulate the current limiter proposed in section 3.3 and in the first electrical cycle the current is turned off at the beginning of the inductance saturation region by comparing current with a preset value ($I_{max} + \Delta I$). As can be seen that the proposed position estimation algorithm has satisfactory results,

Fig. 14. Sensorless operation with speed changing from 5000rpm to 9000rpm

Fig. 15. Double closed-loop control running at 6000rpm with soft chopping at steady-state

which leads to reliable operation without position sensor.

To further validate the feasibility and practicality of the proposed rotor position estimation method, a test platform is setup. The proposed idea is implemented on the prototype motor which is already presented in section II.

The control routines for the converter are programmed and implemented by TMS320F28335 processor. Fig. 15 shows the steady state operation waveforms at 6000rpm with soft chopping control. It can be seen that, the rotor position can be estimated correctly according to the minimum back-EMF detection pulse and comparing with measured rotor position waveform, the estimated rotor position has good accuracy. The performance of the HSRM drive system with proposed sensorless control scheme is shown in Fig. 16-18. Fig. 16 shows the sensorless operation waveforms at 6000rpm. The turn off signal in first electrical cycle is provided in this figure. On the basis of the components in the hardware current limitation circuit, the delay of the device can be estimated by adding all the devices delay together which is around 5 μ s in total.

Fig. 16. Double closed-loop control running at 6000rpm with soft chopping at steady-state

Fig. 17. Load changing from 0 to 0.4N at 6000rpm

Fig.18. Enlarged figure of Fig. 17

Therefore, after substituting the motor inductance value into (9), $I_{off}(42A)$ can be calculated out and utilized as the threshold to turn off power switch in the first electrical cycle. For general operation region, every rising edge of

minimum back-EMF detection pulse corresponds to a back-EMF minimum position and it is the signal directly goes into digital signal processor(DSP) ports for further rotor position estimation.

Fig. 17 shows waveform of load changing from 0 to 0.4N at 6000rpm. Fig. 18 is the enlarged figure of Fig. 17. The phase current is controlled to increase for affording the extra energy and the minimum back-EMF position can still be detected successfully. The winding can be switched on/off according to the estimated rotor position without fault. Moreover, it can be drawn from these two figures that, the proposed position estimation scheme displays good robustness and validity even under the load condition.

5. Conclusion

This paper presents a simple sensorless control scheme of single-phase HSRM by detecting the minimum back-EMF point. The current protection circuit is assistantly utilized to achieve the determination of the turn off point at first electrical cycle before the first minimum back-EMF point can be detected. Without any look-up table or huge store space, the rotor position estimation can be achieved. The simulation and experimental results indicate the validation of HSRM drive system with proposed sensorless estimation scheme. And it may offer an available method that can be used to apply on the HSRM drive system.

In terms of the universality of proposed scheme, in application, the back-EMF curve of other types of HSRM [3] may not as symmetry as show in Fig.6, but as long as it possesses some feature points such as maximum or minimum point, it will be captured by differential circuit and mapped to fix certain positions which can be utilized to estimate the rotor position similarly.

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