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Sensorless Control of Surface Permanent Magnet Synchronous Motor with A Self-Adaptive Flux Obserber

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Abstract: - In this paper, a new approach to sensorless speed control and initial rotor position estimation for a surface permanent magnet synchronous motor (SPMSM) drive is presented. At a rotating condition, speed and rotor position estimation of SPMSM drive is obtained on-line through a self-adaptive flux observer (SAO) by only measuring phase voltages and currents. When SPMSM is on standstill, the initial rotor position is performed off-line by using the nonlinear magnetization characteristics of the stator core which is caused by the rotor magnets. Experimental results show that in both steady and transient state, the system can all achieve expected performances.
Key-Words-permanent magnet synchronous motor; sensorless control; DSP; adaptive control

1 Introduction

Since1980s, AC servo motor, especially permanent magnet synchronous motor (PMSM) has been receiving increased attentions in industry applications because of their high torque to inertia ratio, superior power density and high efficiency. A speed controller of servo motor is very important for the performance improvement of mechanic servo systems applying to the industry applications such as machine tool, X-Y table, robotics and so on. A position sensor such as an encoder or a resolver is required in a PMSM in order to synchronize the phase excitation pulses to the rotor position. However, in many industrial installations, there are presences of the drive cost, reliability, machine size and noise immunity and cannot be mounted in a hostile environment. Then, there has been an increased interest in eliminating the need for the rotor-mounted mechanical sensor.

Many methods have been presented in the literature for detecting the rotor positions of different classes of PMSM [1-14]. Most of them have been developed for the IPMSM (Interior Permanent Magnet Synchronous Motor), because the inductance variation in the d and q axes could be monitored easily to detect the rotor position [3,4] including "INFORM" method presented by M.Schroedl. These position sensorless control schemes have a fine speed and position control performance without position sensor for IPMSM. On the contrary, for SPMSM (Surface Permanent Synchronous Magnet), it is difficult to control a motor speed accurately, especially, on condition that an angular rotor speed becomes a zero and/or a low speed. The difficulty with the surface-mounted rotor is the equal inductances along both d and q axes, so many methods applying in IPMSM are ineffective for SPMSM without getting the variation between d and q axes. In addition, SPMSM has more advantage than IPMSM such as lower cost, simpler mechanic structure in industry application [7]. As a result, the research of sensorless control for SPMSM is greatly significant.

For SPMSM, literatures concentrated on three main different areas:

1- back electromotive force (BEMF) based techniques.

2- techniques based on the machine's physical properties.

3- state observers and Extended Kalman Filter (EKF).

In regard to the first technique, [8] and [9] have demonstrated sensorless motor starting and velocity loop control using the BEMF method. The velocity signal could be integrated to generate a position estimate. However, this signal is sensitive to parameter variations and tends to drift and have offset problems. Another problem with BEMF to estimate position is that at zero speed the BEMF goes to zero. Even at low speeds the signal-to-noise ratio can't be ignored. [10] added an observer of stator resistance variation to decrease the negative effects of stator resistance variation, however, stator resistance of SPMSM is effected many factors of environment, then it is difficult to estimate the resistance variation on-line accurately and can not estimate the rotor initial position when motor is in standstill condition. Some researchers have developed observers using the motor model [11]. A suitable design of the observers produce a high level of insensitivity to parameter variations; but, the observers are sensitive to the measurement noise and their stability analysis is difficult. Also Kalman filter based observers use the motor mathematical model. They are ideally suited to estimate rotor speed and position, and reject measurement noise. Unfortunately, tuning of covariance matrices of the model and measurement errors is rough and requires skilled operators. Moreover the Kalman filter based algorithms are computationally intensive and time consuming. In the last decade many research efforts have been carried out to apply sliding-mode techniques to control of induction motors and permanent magnet motors. These techniques have been investigated because of their known robustness properties with respect to parameter uncertainties. The negative aspect of sliding mode is the discontinuous nature of the control action. Usually, it is 10% of rated speed to full one that most of sensorless control methods for SPMSM is valid[12].

In additional, the above described methods do not give position information at standstill. As a consequence, the SPMSM has to be first started in opened-loop with an arbitrary switching and brought up to a speed high enough to permit one to detect voltage components. This approach is not reliable in many applications because it does not necessarily lead to smooth starting in the right direction. Alternatively the PMSM can be started after an aligning procedure to place the rotor in the direction of a phase winding. It is also possible to estimate rotor position by detecting the voltage reference oscillation phenomena caused by magnetic saturation [13].

Recently a new zero-speed sensorless control technique, based on the injection of a high-frequency stator voltage component and demodulation of the stator current, has been proposed to estimate the rotor position by exploiting the magnetic anisotropy of alternate-current motors [14]. The SPMSM has a very low level of anisotropy so that the rotor position identification, using this technique, is hard. In conclusion, there still have some problems as low speed running and rotor position estimation at standstill in the field of sensorless control of SPMSM.

In this paper, a new scheme for rotor initial position estimation of SPMSM, voltage pulse vector method (VPVM) is introduced assuming ideal cylindrical behavior ($X_d = X_q$). The estimation is performed by the nonlinear magnetization characteristics of the stator core caused by the magnet of the rotor. This method is based on the principle that the X-axis current value due to the voltage vector applied to the motor under magnet saturation conditions increases as the voltage vector generated from the inverter approaches the N pole of the rotor. Furthermore, closed-loop controlled torque start-up is proposed using a self-adaptive flux observer (SAO), which allows the start-up smoothly in severe starting conditions because rotor initial position is known in advance and low running is steadily at 5 r/min of rating speed.

2 Methematical Model of SPMSM

A space vector diagram of SPMSM is shown in Fig.1. The voltage equations in d-q reference frame are

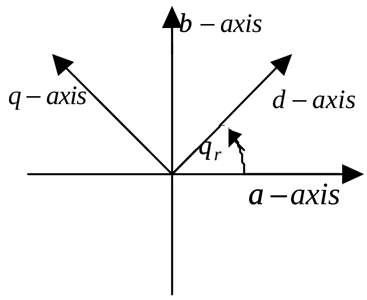

Fig.1. Definition of axes reference system

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} r_s & 0 \\ 0 & r_s \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} p & w \\ -w & p \end{bmatrix} \begin{bmatrix} l_d \\ l_q \end{bmatrix}. \qquad (1)$$

The flux linkages are defined as,

$$\begin{bmatrix} l_d \\ l_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} l_m \\ 0 \end{bmatrix}. \qquad (2)$$

3 Structural Adaptive Observer

The stator voltage equation is given in the stator reference frame s ,

$$v_s = r_s i_s + \frac{d\,l_s}{dt} \qquad (3)$$

The stator flux linkage equation in the stator frame is given by,

$$l_s = L_s i_s + L_m i_r e^{jq_r}. \qquad (4)$$

Where l_s is flux linkage of stator, L_s is inductance of stator, L_m is the inductance of permanent magnet, i_r is the equivalent rotor current, q_r is the rotor angle. Substitute the flux linkage (4) into (3) ,

$$v_s - r_s i_s = \frac{d}{dt}(L_s i_s + L_m i_r e^{jq_r}) \qquad (5)$$

and observe that $L_m i_r = f_r$, f_r is the rotor flux. We get,

$$v_s - r_s i_s = \frac{d}{dt}(L_s i_s + f_r e^{jq_r}) \ . \quad (6)$$

Integrating the left side of (6) yields,

$$l_s = \int (v_s - r_s i_s)\, dt = L_s i_s + f_r e^{jq_r} \ . \quad (7)$$

Expressing the last term in the parenthesis from (6) on components (the real and imaginary part),

$$f_r e^{jq_r} = f_r \cos q_r + j f_r \sin q_r = f_{ra} + j f_{rb} \ . \quad (8)$$

and split the (7) in real and imaginary components, solving the equation for,

$$f_{ra} = \int (V_{sa} - r_s i_{sa}) dt - L_s i_{sa} = l_a - L_s i_{sa} \quad (9)$$

$$f_{rb} = \int (V_{sb} - r_s i_{sb}) dt - L_s i_{sb} = l_b - L_s i_{sb} \ . \quad (10)$$

Then, the rotor angle in terms of the observed flux is,

$$q_r = \arctan \frac{f_{rb}}{f_{ra}} \ . \quad (11)$$

Simulation and practical experiments are made to analyze the behaviors of this position observer. This observer is an ideal integrator without any offset compensation. Due to small DC offsets which invariably exist in any practical implementation, an ideal integrator will always drift. In flux linkage observation, the ideal integrator ($1/s$)is generally replaced by applying first order inertia filter $t/(1+ts)$. From the expression of the first order filter, it can be seen that the filter can be equivalent to an ideal integrator when $w \succ\succ 1/t$ and that it makes the initial signal behave damply with time when w approximates to $1/t$. As shown in Fig.2, $t = 0.01$, the output signal has a DC drift. However, as shown in Fig.3 the first order filter damps DC component in the output signal quickly.

Applying first order filter independently has no access to accurate observation of rotor speed and position in the entire speed regulating range because of the variable velocity. Therefore, this paper presents a kind of self-adaptive observer which can automatically adjust the compensation quantity according to the various frequency of input signal. Fig 4 illustrates its structure. The inputted BEMF is transformed from ABC-three phase stationary reference frame to ab -two phase stationary reference frame.

The flux linkage components in the reference frame are derived from the integration of BEMF. The independent control of the magnitude and phase of flux linkage can be implemented by transforming it from the rectangular coordinate to polar coordinate frame. Here, the error signal which is produced after flux linkage magnitude and BEMF pass the quadrature-comparator, is added to the flux linkage as the feed back quantity. Also, the magnitude of error signal is decided by (12).

$$l_{cmp} = (k_p + \frac{k_i}{s}) \frac{l_b \cdot emf_b + l_a \cdot emfl_a}{|l_s|} \quad (12)$$

l_{cmp} is the magnitude of error signal, emf is BEMF of stator, $w_c = 1/t$.

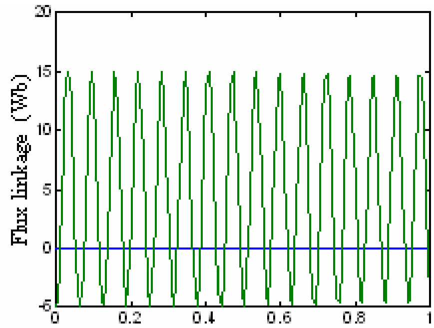

Fig.2. Flux linkage curve using ideal integrator

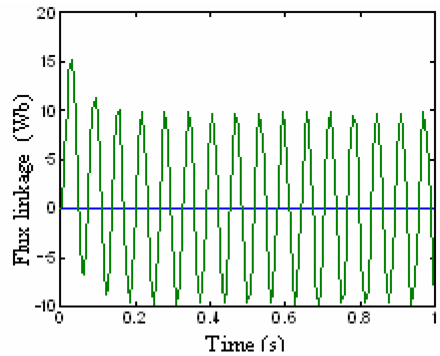

Fig.3. Flux linkage curve using first order filter

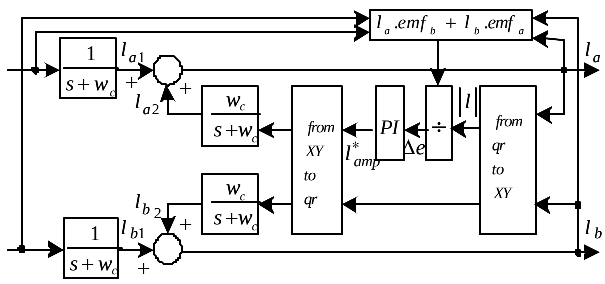

Fig.4. The structure of self-adaptive observer

4 Estimation Method of Rotor Initial Position

The estimation is performed by the nonlinear magnetization characteristics of the stator iron core caused by the magnet of the rotor. This method is firstly presented by Peter .B [20]. The estimation theory is based on the principle that the X-axis current value for the voltage vector applied to the motor under magnet saturation conditions increases as the voltage vector generated from the inverter approaches the N pole of the rotor. However, peter. B only brought about a basic theory without experiments in practical application. What's more, simulation results in [20] were completed within the assumption that rotor angle q_r is very little, then $\cos(2q_r) = 1$, $\sin(2q_r) = 0$. In fact, it is unrealistic.

[21] put this method into practice firstly. It is regret that it is not effective for any SPMSM, because not all magnetization curves of SPMSM are same and different voltage pulses are needed for different SPMSM. In this paper, a general rotor initial position estimation method, namely VPVM which can automatically define the magnitude of voltage pulse that can bring about magnet saturation of stator iron core. During estimation process, the rotor is practically at standstill. This part is completed with off-line estimation procedures.

Fig.5 shows the voltage vectors of SPMSM. X is the voltage vector applied to the stator, and q_v is the angle between the voltage vector and a-axis. Fig. 6 shows the stator current as a function of rotor position.

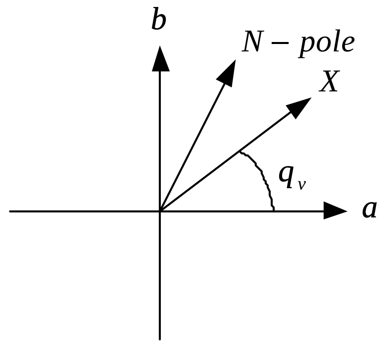

Fig.5. Voltage vector

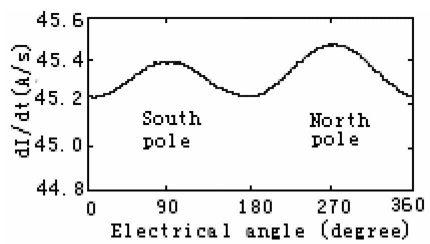

Fig.6. Change rate of stator current as a function of rotor position

when the coil adds flux to the flux produced by the rotor magnets. When a north pole is aligned with the coil, the current in the coil increases as the stator saturation increases. When a south pole is aligned with the coil, the current in the coil decreases as stator saturation decreases. Since the current of the coil is different for north and south poles, one can distinguish the polarity of the rotor pole that is aligned with the coil, then the position of rotor can be known.

The 6 series of voltage pulses are applied to a 6 pole SPMSM and the corresponding peak current values measured and plotted as shown in Fig.7. These measurements are taken at zero speed at each of the positions as the motor is mechanically rotated from one position to the next.

The peak current values are approximately the rated. Current value of the motor is 45 amps. These plots demonstrate the saturation effects of the stator iron as explained with Fig.6. The estimated electrical angle that is calculated using this voltage pulse technique is plotted as a function of the actual mechanical rotor angle and is shown in Fig.8. The actual rotor angle is measured using a feedback resolver attached to the motor shaft and is shown for comparison. The error between the calculated angle and actual angle is found to be very small angle differences in each region.

Fig.9 shows the speed curve of system with SAO and a standstill initial position. Fig.10 is rotor position curve when the motor is running.

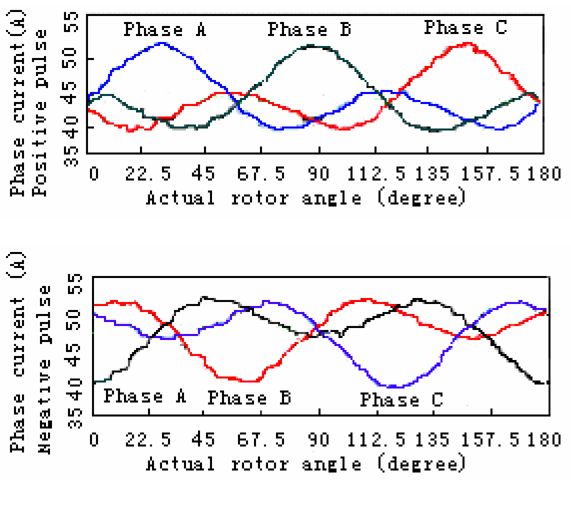

Fig.7. Mechanical rotor position

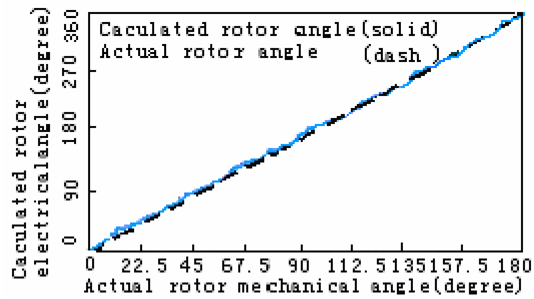

Fig.8. Initial position of rotor

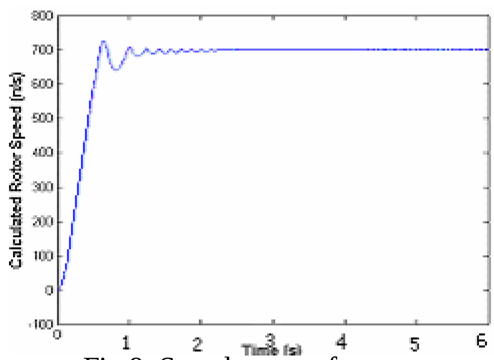

Fig.9. Speed curve of system

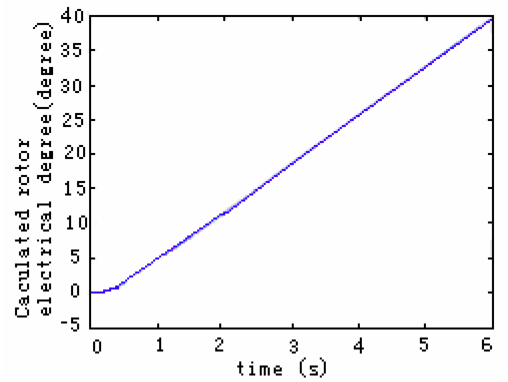

Fig.10. Rotor position

5 Experimental Results

Experimental results are obtained using a 6-pole surface PMSM servo drive (see Table 1):

Table 1 Technical data of SPMSM

Rated power	1.2kW
Rated speed	6000rpm
Rated voltage	400V
Rated current	2.8A

A fixed-point digital signal processor (DSP), TMS320F240, is used to run the vector control algorithm. The control and estimation period is 66.67 ms. The PWM switching frequency for insulated gate bipolar transistors is 15kHz. The DSP also runs the position estimation algorithm. At first, an initial rotor position estimated will be applied into the self-adaptive integrator, then the motor begin to run. Fig.11 shows the speed curve when the motor is running at 1000rpm. At the same time, the A phase current curve is presented as Fig.12. In order to test the functions of this sensorless control method in the condition of lower speed, the motor is controlled by running at 5rpm/min. The experimental results are shown in Fig.13 (Speed curve) and Fig.14 (A phase current curve).

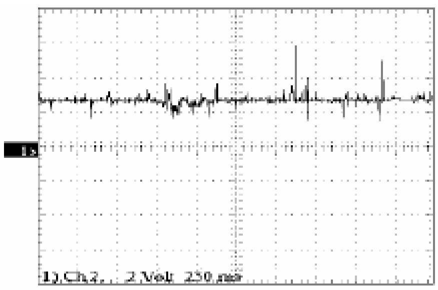

Fig.11. Speed curve at 1000rpm/min

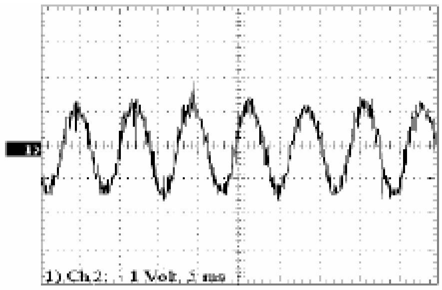

Fig.12. A phase current curve at 1000rpm/min

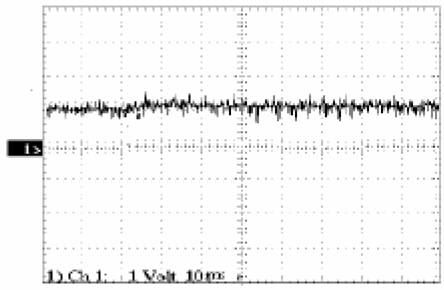

Fig.13. Speed curve at 5rpm/min

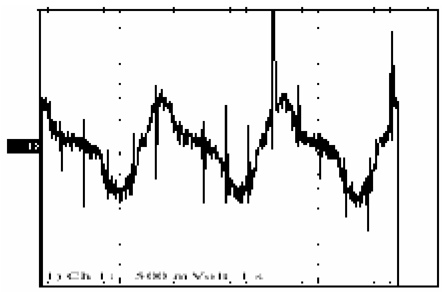

Fig.14. A phase current curve at 5rpm/min

6 Conclusion

The SAO is the type of position observer proposed. With the required conditions satisfied (initial position can be measured exactly), it is demonstrated that this observer provides reliable position information for a controlled torque, closed-loop start-up.

The presented work demonstrates that the measured terminal currents and voltages, together with the machine parameters, can be used to obtain a controlled start-up of the SPMSM under severe conditions.

The method can be employed in drive systems with SPMSM, or any type of SM, which requires a controlled torque start-up under high load using the rated current, which eliminates the problems of designing an overrated inverter to provide high current during start-up.

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