Sensorless Control of IPMSM: Past, Present, and Future

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This paper presents the history of techniques used for sensorless control of the Interior Permanent Magnet Synchronous Machine (IPMSM) over the last 20 years. The techniques used in the first stage were based on the equivalent circuit of the IPMSM. They extracted rotor position information from the back EMF estimated through simple arithmetic. In the last 10 years, model reference adaptive control or observer-based control techniques have evolved and they have been used for the sensorless control of the IPMSM; however, the rotor position continues to be obtained from the back EMF. Simultaneously, sensorless control based on the magnetic saliency of the IPMSM has been achieved and commercialized. In this paper, an evaluation of the major techniques used for the sensorless control of the IPMSM has been presented, and their limitations have been clarified. Finally, the direction of future development of sensorless control is indicated.

Keywords: IPMSM, sensorless control

1. Introduction

Since the early 1980s, with the development of high-performance rare-earth permanent magnets, the Interior Permanent Magnet Synchronous Motor (IPMSM) has evolved. It was first used in high-performance servo drive and has recently been used in general-purpose industrial drives (1). From the 1990s, because of the soaring of cost of electricity, the IPMSM has been considered as a candidate that could replace the induction motor. The induction machine has many merits, for example, it is mechanically robust, has low cost, is technically mature, and can be designed to have different speeds, torques, and shapes. However, because of the magnetizing current, its efficiency is poorer than that of a permanent-magnet-based motor, especially at a low load factor (2). At the early stage of development of permanent magnet motor, Surface mounted Permanent Magnet Synchronous Motor (SPMSM) has been designed and applied to high performance servo application, where the control performance is the first concern. However, IPMSM has several merits compared to SPMSM, namely smaller size of magnet, easier detection of magnet, less eddy current in magnet, and possibility of flux weakening control (3). Even though the control of the IPMSM is complex because of the reluctance torque associated with the saliency of the magnetic structure of the rotor, the IPMSM has been used in many industrial applications. In some applications, a general-purpose IPMSM has been used as the Surface-Mounted Permanent Magnet Synchronous Machine, where the d-axis current is set to be zero, for easier implementation of the control algorithm at the cost of the reluctance torque. Even under such a simple operating principle, the torque density of IPMSM is considerably higher than that of the general-purpose induction motor. The torque density per unit volume is 30% higher and the torque density per unit weight is 25% higher in the power range of several tens of kilowatt, for operation in near 1800 r/min. Further, the efficiency of the IPMSM is 7% higher than that of the high-efficiency premium induction motor and 10% higher than that of the standard general-purpose induction motor. Hence, recently, IPMSMs with ratings exceeding 500 hp have been used to replace the induction machine in general industrial applications such as hoist operation. However, in making the replacement, the position sensor of the IPMSM has been of concern (4). Even though the IPMSM is mechanically robust and has a small size, the position sensor increases the axial length of the IPMSM and results in reduced torque density per unit volume. Furthermore, the sensor can adversely affect the robustness of the IPMSM, both electrically and mechanically. To overcome these problems, position sensorless drive techniques for the IPMSM have been studied over the last two decades, and some of them have been commercialized and used for industrial purposes (5) (6). Still, the performance of the sensorless drive of the IPMSM is limited. Some commercialized techniques had shown reasonable performances in overall operating conditions except low speed/low frequency region. For last ten years, sensorless drive techniques based on high frequency signal injection methods have been evolved. Those techniques can guarantee the reasonable torque control performance even at zero speed/zero frequency. An overview of the sensorless control techniques of the IPMSM developed for last two decades are described in this paper, and the merit and the demerit of typical technique are discussed. Based on the discussion, the direction of future development of sensorless control technique for the IPMSM could be enlightened.

2. Past

The sensorless control of the IPMSM had been studied for
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Sensorless control of interior permanent magnet synchronous machine (IPMSM) has been a topic of considerable interest for several decades, but the major publications have been reported from early of 1990’s. The information of the rotor position is included in the back EMF as shown in Fig. 1.

The back EMF can be calculated in the stationary frame model of the IPMSM or in the estimated rotor reference frame. The technique based on back EMF presents good performance in the middle and high speed operating region of the IPMSM. And it is commercialized by many companies. The performance above 10% of the rated speed with rated load in motoring and generating operation is quite satisfactory and acceptable for the most of low end drive applications. The bandwidth of the speed regulation loop can be extended up to 10 Hz.

All back EMF based sensorless control techniques are based on following voltage equation of the IPMSM.

\[
\begin{align*}
\dot{v}_{ds}^i &= R_s i_{ds}^i + L_{ds} \frac{di_{ds}^i}{dt} - \omega_L L_{qs} i_{qs}^i - \omega_s A_f \sin \hat{\theta}_r \\
\dot{v}_{qs}^i &= R_s i_{qs}^i + L_{qs} \frac{di_{qs}^i}{dt} + \omega_L L_{ds} i_{ds}^i + \omega_s A_f \cos \hat{\theta}_r
\end{align*}
\]

where the voltages and currents are measured in the estimated rotor reference frame. And the error between the real rotor position and the estimated rotor position is defined by (2) as shown in Fig. 2.

\[
\hat{\theta}_r = \theta_r - \hat{\theta}_r 
\]

\[
\begin{align*}
\hat{\theta}_r &= -\omega_s A_f \sin \hat{\theta}_r \dot{v}_{ds}^i - R_s i_{ds}^i + \omega_L L_{qs} i_{qs}^i \\
\hat{\theta}_r &= \omega_s A_f \cos \hat{\theta}_r \dot{v}_{qs}^i - R_s i_{qs}^i - \omega_L L_{ds} i_{ds}^i
\end{align*}
\]

Under the assumption of the steady-state operation, the back EMF voltage can be estimated simply by (3). Then, the position error can be directly derived as (4).

\[
\hat{\theta}_r = \tan^{-1} \left( \frac{\omega_s A_f \sin \hat{\theta}_r}{\omega_s A_f \cos \hat{\theta}_r} \right) \quad \text{(4)}
\]

Because of the assumption of the steady state ignoring the variation of current, this direct calculation is not suitable to estimate the position error when the current varies rapidly according to the load torque disturbance or torque reference change. Hence, the control bandwidth is limited. This shortcoming can be lessened by employing the closed loop state observer (14). From (1), under the assumption of slow enough variation of back EMF at the estimated rotor reference frame, a state equation augmenting back EMF voltage, \( \tilde{e}_{ds}^i, \tilde{e}_{qs}^i \) can be formulated as (5) and (6). And the angle error can be obtained as like (4).

\[
\dot{x} = A \dot{x} + Bu + L (y - c \hat{x})
\]

\[
\begin{bmatrix}
\dot{\tilde{e}}_{ds}^i \\
\dot{\tilde{e}}_{qs}^i \\
\end{bmatrix} =
\begin{bmatrix}
\frac{R_s}{L_{ds}} & \frac{\omega_s L_{ls}}{L_{ds}} & 1 & 0 \\
\frac{\omega_L L_{qs}}{L_{ds}} & R_s & 0 & 1 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\tilde{e}_{ds}^i \\
\tilde{e}_{qs}^i \\
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L_{ds}} & 0 \\
0 & \frac{1}{L_{qs}} \\
0 & 0 \\
0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\dot{v}_{ds}^i \\
\dot{v}_{qs}^i \\
\end{bmatrix} + L (y - \hat{y}) \quad \text{(5)}
\]

\[
\hat{y} = \begin{bmatrix}
\tilde{e}_{ds}^i \\
\tilde{e}_{qs}^i \\
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
\end{bmatrix} \hat{x} = C \hat{x} \quad \text{(6)}
\]

Also, the direct update of angle error is vulnerable to measurement noise and parameter errors. And the estimated rotor angle can be updated through angle error correction controller based on PI regulator as shown in Fig. 3, where the rotational speed can be obtained as a byproduct. The controller is a kind of the state filter.

These back EMF based sensorless methods estimate the rotor position and speed from the stator voltage and currents. With these basic ideas, many different implementation
techniques have been reported. Some are based on the estimation of the back EMF voltage from the permanent magnet flux linkage using a state observer or a Kalman filter. Others use the voltage or current error between the measured values and the calculated values in the estimated rotor position. In Ref. (16), the concept of an Extended EMF is proposed to simplify the estimation of the back EMF. By applying the Extended EMF concept, many approximations to estimate the back EMF are eliminated. Because of the difference of d-axis inductance and q-axis inductance of the IPMSM, the voltage equation in the estimated rotor reference frame is complex. With Extended EMF, all inductance parameters such as resistance, inductance, and the permanent magnet permeability of the core and permanent magnet can be used as position correction value as Fig. 4(a). In the current model, the calculated current and the measured current are compared to get the position error values as Fig. 4(b). These error values can be used as correction value to the state filter or observer.

Unlike the back EMF estimation or model based methods, the voltage reference of current controller can be directly used as the position error related values. In these machine model based sensorless techniques, the machine parameters such as resistance, inductance, and the permanent magnet flux linkage have critical effects on the position estimation performance.

Even though there are so many variations of sensorless control techniques based on back EMF voltage for the IPMSM, the techniques can be represented as a block diagram in Fig. 5. The design of each block might be different according to the specific sensorless control technique. And, the performance of each technique may be different.

But, theoretically, all techniques would not work at zero frequency, where back EMF does not exist. Practically, in the case of a few kW or above rated power of the IPMSM, because back EMF is always estimated from the terminal voltage and current information, the technique would not work at lower than 1% of the rated speed even with careful parameter adaptation and dead time compensation. In the most of applications of drive where the induction motor was replaced by the IPMSM, torque and speed control range down to a few percents of the rated speed would be enough. However, some application where speed and/or torque should be controlled absolutely from standstill, that is, zero speed, the back EMF based techniques cannot be used.

3. Present

The rotor position of the IPMSM can be estimated from the characteristics of the IPMSM: the spatial inductance distribution is determined by the rotor position because of the saliency of the magnetic path of d and q axis as shown in Fig. 6. The saliency comes from the difference of magnetic permeability of the core and permanent magnet.

To extract the spatial inductance variation, the relationship between current and voltage can be employed. To examine the current-voltage relationship, PWM current ripple can be used. By measuring current variation according to the voltage vector variation in a PWM period, inductance can be calculated directly or estimated with a non-linear estimator. However, these techniques require the modification of PWM switching pattern, because the current variation in the conventional SVPWM is too small to be used for the calculation of the inductance. And additional devices to measure the phase currents in arbitrary time should be designed in control hardware, which might not be acceptable to many industry applications. Similarly, the intended discontinuous voltage signal injected method has been proposed.
in pulsating signal injection (32)–(34).

If the pulsating voltage signal is injected into the exact d-axis rotor reference frame, q-axis current ripple due to the injected voltage does not happen. However, because the exact rotor position is not available, the injection voltage signal actually differs from the ideal injection voltage. The injection voltage in the estimated rotor reference frame can be rewritten with consideration of the estimated rotor position error as (9).

$$v^{\ast}_{dqh} = V_{inj} \begin{bmatrix} \cos \omega t \\ 0 \end{bmatrix} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS
pass filters, and band pass filter, the tuning of the filters are difficult and the control bandwidth is limited due to the signal delays of the filters. With this implementation, the speed control bandwidth has been limited to less than 10 Hz in the case of general purpose IPMSM drive.

To improve the speed control bandwidth, a different implementation method has been reported (27)–(29). A square wave signal was injected synchronously to the triangular carrier wave of PWM of inverter as shown in Fig. 11, and the injection frequency was increased up to a half of switching frequency. With the injected signal, the current in the stationary d and q axis reference frame can be represented as (13).

\[
\begin{bmatrix}
    i_{dsh}^s \\ i_{qsh}^s
\end{bmatrix} \approx \begin{bmatrix}
    \frac{1}{L_{ds}(\theta_j)} \cos(\theta_j) \sin \omega_d t \\
    \frac{1}{L_{qs}(\theta_j)} \sin(\theta_j) \sin \omega_d t
\end{bmatrix} (\because \dot{\theta}_j \approx 0) 
\]

\[
\begin{align*}
\hat{\omega}_{cmb} &= \hat{\omega}_0 + G_1 \cdot \hat{\omega}_{BEMF} + G_2 \cdot \hat{\omega}_{HFSI} \quad \cdots \cdots \cdots \cdots \cdots \cdots (14)
\end{align*}
\]

where \( \hat{\omega}_0 \) is given by direct calculation from estimated back EMF voltage, \( \hat{\omega}_{BEMF} \) is a kind of the correction control term with the injection signal in Fig. 11, the demodulation process can be simplified as shown in Fig. 12 and there is no low pass filter. On the top of easy tuning of the controller, the speed control bandwidth with this technique can be extended up to 25 Hz as shown in Fig. 13(a) with an off-the-shelf 11 kW general purpose IPMSM thanks to no signal delay of low pass filters. The estimated speed (\( \text{Wrpm}_{\text{est}} \)) through the injected signal tracks the reference speed (\( \text{Wrpm}_{\text{ref}} \)) better than the speed from encoder (\( \text{Wrpm}_{\text{enc}} \)) at near zero speed. The speed from encoder has bumps at near zero speed due to the limited number of pulse per revolution (1024 pulses in here) and the sampling time (1 ms in here). From Fig. 13(b), the position control bandwidth can be understood as 5 Hz.

The signal injection technique is effective for position and speed estimation in ultra-low speed region including zero stator frequency. However, due to the signal injection, the torque ripple and the acoustic noise at the injected signal frequency are inevitable. Furthermore, the additional voltage to inject the signal, which may be several tens of percent of the rated voltage of the IPMSM, would be prohibitive in the medium or higher speed operation region of the IPMSM where the voltage from PWM inverter is already near rated value. As mentioned in chapter 2 of this paper, because the back EMF based technique is able to estimate position and speed without acoustic and additional torque ripple above 10% of the rated speed, a hybrid method can be employed as shown in Fig. 14, where the high frequency signal injection (HFSI) technique is used at lower speed and back EMF technique at higher speed (35). The key idea in here is the changeover which is done only based on the internal speed \( \hat{\omega}_{cmb} \). The internal estimated speed \( \hat{\omega}_{cmb} \) consists of the estimated speed of both techniques. The internal estimated speed is set as (14).
Fig. 14. Position and speed estimator with a hybrid method

Fig. 15. Injected signal and second other harmonic signal for initial position identification

Fig. 16. Block diagram of signal processing for initial pole position identification

Fig. 17. Pulsating injection voltage signal in the estimated rotor reference frame. In a PWM period, three successively measured currents are used to estimate the rotor position

to make the angle error $\hat{\epsilon}$ null, and $G_1$ and $G_2$ are weighting factors. The weighting factors are regulated along with the command and/or the estimated speed. The internal estimated speed $\hat{\omega}_{cmd}$ is only employed in the machine model of the back EMF based method, and not employed to estimate the position of the magnet flux. The position is estimated by integration of the estimated speed $\hat{\omega}_r$.

To get the rated torque with rated current at starting, the initial position should be identified. The variation of the magnitude of the ripple current due to inductance variation shown in Fig. 7 reveals symmetry to the d axis in a half period of rotor position. So, d axis (north pole of magnet) and $-d$ axis (south pole of magnet) in rotor reference frame of the IPMSM cannot be differentiated from the variation of the magnitude of the current ripple. So, another technique is needed for the starting of the IPMSM with rated torque at rated current. The north pole and south pole can be identified with the characteristic of the magnetic saturation of the core due to the flux linkage from the permanent magnet (36, 37).

The d-axis second harmonic component of injected frequency has polarity information as (15).

$$
e_{pol} \equiv LPF \left( \hat{I}_{dsh} \cos 2\omega_b t \right) \ldots \ldots \ldots \ldots \ldots \ldots (15)$$

where LPF stands for Low Pass Filtering process and the cut off frequency of the filter is one order less than injected signal frequency. The injected signal is shown in Fig. 15 and a block diagram of the signal processing for initial pole position identification is shown in Fig. 16. With this technique the initial pole position can be identified within 100 ms (28).

Generally, the frequency of injected voltage signal is determined between the current control bandwidth and the PWM switching frequency. As the frequency of the injected signal is getting higher, the dynamics of the sensorless control can be enhanced and the interference between the injected signal and the fundamental components of the current control can be diminished (30). If the PWM switching frequency is near or above the audible frequency range, the acoustic noise by injected signal can be remarkably reduced or totally eliminated. To reduce the acoustic noise, a signal injection technique whose frequency is PWM switching frequency has been proposed (31). The injected voltage is shown in Fig. 17. In this technique, the sampling of the current and updating PWM is done twice in a PWM switching period. And, the sampling period, $\Delta T$, is a half of PWM switching period. The difference between successively sampled currents at the estimated rotor reference frame has rotor position information as seen from (16).

$$
\begin{bmatrix}
\Delta i_{dsh} \\
\Delta i_{qsh}
\end{bmatrix} = T \left( \hat{\theta}_r \right)^{-1} \begin{bmatrix}
\Delta \hat{r}_{dsh} \\
\Delta \hat{r}_{qsh}
\end{bmatrix}
= \pm \Delta T \cdot V_{ijf} \begin{bmatrix}
\cos^2 \hat{\theta}_r + \sin^2 \hat{\theta}_r \\
\frac{1}{2} \left( \frac{1}{L_{ds}} - \frac{1}{L_{qs}} \right) \sin 2\hat{\theta}_r
\end{bmatrix} \ldots \ldots (16)
$$

Especially, q axis current can be used as the input of the
demodulation process, \( \varepsilon_f \), as shown in Fig. 18. Thanks to the development of IGBT and DSP technology, the switching frequency of recently announced PWM inverter can be over 16 kHz, which is near the limit of human audible range. With this injection frequency, the audible noise can be virtually eliminated at the cost of larger magnitude of injection voltage and a little increased loss due to the higher frequency injected signal. As shown in Fig. 19, with this signal injection technique, the electric rotor position error is less than 0.3 rad, which means less than 0.1 rad error in mechanical angle without any position compensation in the case of 11 kW, 6 pole, general purpose IPMSM. With careful compensation according to the torque and speed, the position error can be reduced further.

With specially designed IPMSM for sensorless control, the speed and position control bandwidth can be extended more than 50 Hz and 10 Hz, respectively as shown in Fig. 20. The flux density of the specially designed IPMSM is reduced and it reveals better sinusoidal inductance variation according to the rotor position at the cost of reduced torque density \( (39) \).

As the machine design technology developed, the SPMSM which has inherently the isotropic inductance characteristics can be also used for signal injection sensorless control. In Refs. \( (39) \), the inherent or inserted stator or rotor bridges in structurally symmetric machines generate saliency and can be also used for sensorless control. In Ref. \( (41) \), machine spatial saliency is analyzed with zigzag leakage flux concept and the machine design rules for generating the inductance saliency in the SPMSM was proposed.

With the introduction of commercial sensorless drive enabling zero speed operation, many IPMSM drives with position sensor have been replaced with the sensorless drive. One of the typical examples is lift application, where the torque control at zero speed to prevent roll back and shock at the starting of the cage of the lift is prerequisite. And in other applications where higher starting torque and less acceleration time are key requirements, namely oil injected screw compressor and injection molding machine, the sensorless drives increase reliability and reduce cost \( (42) \).

4. Future

Though the sensorless control techniques has been evolved remarkably for last decades and the performance of the sensorless drive is comparable to low end servo where the resolution of encoder is less than a few hundreds per revolution, there are still number of problems to be solved. In some IPMSMs, especially the machine with higher torque density and wide flux weakening range, the variation of the inductance according to the rotor position is not sinusoidal and the position where minimum inductance occurs are moving according to the stator current as shown in Fig. 21. This phenomenon comes in many different forms. The position error
between the real position and the estimated position has 2nd, 6th, etc harmonics by this flux saturation \(^{(43)}\). The flux density of the IPMSM in the figure is increased to get higher torque density and the stator employs concentrated winding to reduce axial length of the motor. The sensorless drive with this type of the IPMSM is formidable task to achieve.

Though the control bandwidth has been improved several fold in the last decade, to apply the sensorless drive to high grade control purpose, the bandwidth should be improved at least a few times more. To achieve this control bandwidth, the design of the IPMSM itself and all signal processing techniques especially careful compensation of all nonlinearity of PWM inverter and measurement system should be incorporated simultaneously \(^{(44)}\).

With the high frequency signal injection, the rotor position can be identified from standstill. However, because the identified position is in electrical angle, the absolute position of the rotor is not yet identified except 2 poles IPMSM, which can be identified from standstill. However, because the identification and control of the absolute position of the rotor is an open question. The special design of the rotor and stator of the IPMSM together with novel signal processing technology might open new horizon of the sensorless control of the IPMSM in absolute positioning.

**References**

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