Three Years of Industrial Experience with Sensorless IPMSM Drive based on High Frequency Injection Method

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***Abstract*—This paper introduces three years of industrial experience with sensorless interior permanent magnet synchronous motor (IPMSM) drive based on high frequency injection method (HFIM). In 2008 the first commercial general purpose inverter with sensorless control based on HFIM was launched. The HFIM enabled the sensorless IPMSM drive to control torque and speed under ultra-low speed region including zero stator frequency, which brought the expansion of the application field. The feature also realized the position control. Owing to the control performance and the sensorless feature on the reliability and the space-saving, the sensorless drive has been employed to direct drive applications with great expectations. As successful applications, a lift, a compressor, and an injection molding machine are introduced in this paper.**

***Index Terms*—Sensorless drive, HFIM, IPMSM, three years of industrial experience**

I. Introduction

The high frequency injection method (HFIM) is effective for position and speed sensorless AC motor drives operated in ultra-low speed region including zero stator frequency. Before the invention, the back EMF based method, e.g. [1], has been widely used in commercial products, but the controllable speed range is limited to more than about 5% of the rated speed due to reduced EMF. In contrast, the HFIM utilizes the feature on the magnetic saliency of machines, and it is kept even at zero stator frequency. Therefore, the method is available to extend the controllable speed range. The method requires extra voltage or current signal injection into the fundamental signal to drive machine. Many methods have been researched for about twenty years. Some algorithms inject voltage signals in a sampling period to estimate rotor position [2, 3]. Since they detect inductance using voltage signals in a short time, they can be frail to parameter variation or measurement noises. The other injects rotating high frequency and uses tracking algorithm [4]. Since it utilizes the rotating high frequency signal, the dynamic characteristics are restricted within a narrow limit. As another approach, the algorithm based on harmonic signal injection to the motor is proposed for zero or low frequency operation [5, 6]. This method is applied to induction motor and synchronous reluctance motor. It gives reasonable torque control capability at zero and low stator frequency, even under heavily loaded condition. Compared with other signal injection methods, it injects not rotating signal but fluctuating signal on the flux axis, and hence it generate less torque ripple, vibration and audible noise. Since 1999, the commercial product employing this HFIM has been planed. However, those machines often show incompatibility to the method: because it requires the stable and prominent characteristic on magnetic saliency. As general purpose application, it was significantly drawback. Then, the method was extended to IPMSM drive with initial pole position detection [7].

Meanwhile, the high efficiency IPMSM drive employing general-purpose inverters was first commercialized in 1995. Since then, the IPMSM drive has been popular owing to the requirement of energy saving and down-sizing, and the application has expanded to fans, pumps to lifts. Especially, in the case of the drive of the lift traction motor IPMSM is getting worldwide industry standard. The performance of permanent magnets has progressed considerably, and the IPMSM has been expanded to 0.4kW - 300kW power range. Since the IPMSM shows the prominent characteristic on magnetic saliency due to the interior magnet, it has a good compatible to the HFIM. To operate in the entire speed range, hybrid sensorless control combining both HFIM and back EMF based method is employed [8]-[11].

In 2008 the first commercial general purpose inverter with sensorless control based on HFIM was launched. Now, three years passed by, and the application field has been expanded.

This paper introduces three years of industrial experience with sensorless IPMSM drive based on HFIM. As successful applications, an injection molding machine, a compressor, and others are introduced in this paper.

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II. Configuration of Sensorless Drive System

This section introduces a configuration of sensorless drive system, which is employed for real industrial applications.

The position and speed estimator with HFIM is shown in Fig. 1, where the test signal of high-frequency voltage $\boldsymbol{u}_{inj}$ is injected to the machine and the stator current $\boldsymbol{i}_s$ is input to HFIM. Fig. 2 shows the block diagram of HFIM which consists of a pre-processor and a correction controller [5] [6]. The input current is transformed into the measurement axes (dm-qm), which are located at 45 degree shift from the control axes ($\gamma-\delta$). These axes are rotational frame related to rotor as shown in Fig. 3, where the rotational frame related to the actual flux position is defined by d-q axes. After the process in the coordinate-transformation to the dm-qm axes, the band-bass filter (BPF) extracts the same frequency component as that of the test signal from each current in dm-qm axes. The pre-processor calculates the amplitude of the components I_d^m and I_q^m, in the high-frequency current vector, $\boldsymbol{i}_{dq}^m = i_d^m + j \cdot i_q^m$, where the low-pass filter (LPF) is used to extract the component of their amplitudes. The correction controller estimates the speed $\hat{\omega}_{HFI}$ so that the value obtained by subtracting I_d^m from I_q^m becomes zero. The correction controller involves at least an integration process and for example a proportional and integration (PI) processes is employed in Fig. 2.

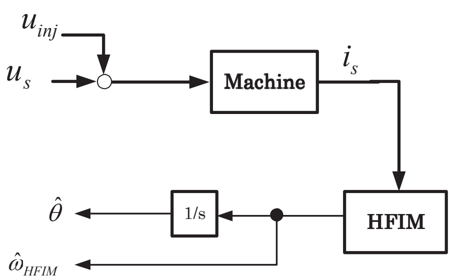

Fig. 1. Position and speed estimator with HFIM

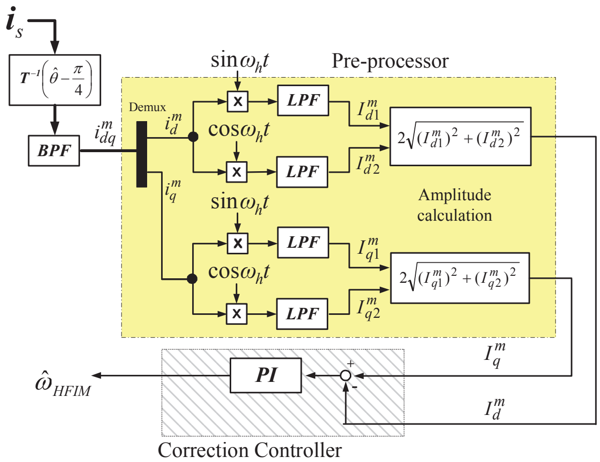

Fig. 2. Block diagram of HFIM

The algorithm of HFIM is derived as follows: when the test signal is injected only along to γ -axis such as $\boldsymbol{u}_{inj} = V_h \cdot \sin \omega_h t$, the high-frequency current vector is expressed as follows [7]:

$$\frac{d}{dt}\begin{bmatrix} i_d^m \\ i_q^m \end{bmatrix} = \frac{u_{inj}}{\sqrt{2}(L_{0h}^2 - L_{1h}^2)}\begin{bmatrix} L_{0h} - L_{1h}\{\cos(2\Delta\theta) - \sin(2\Delta\theta)\} \\ L_{0h} - L_{1h}\{\cos(2\Delta\theta) + \sin(2\Delta\theta)\} \end{bmatrix} \quad (1),$$

where V_h is the amplitude of the test signal, and ω_h is the angular frequency of the test signal, $\Delta\theta$ is the angle error between the control axis and the flux position, L_{0h} is the average of each stator inductance in d- and q-axis (L_d, L_q) at the injected high frequency, and L_{1h} is the half of the difference between the stator inductances in d- and q-axis (L_d, L_q) at the injected high frequency.

From (1), the relation between the high-frequency current vector and the angle error is expressed as follows:

$$\begin{aligned} \frac{d}{dt}(i_q^m - i_d^m) &= \frac{-\sqrt{2}L_{1h} \cdot u_{inj}}{L_{0h}^2 - L_{1h}^2}\sin(2\Delta\theta) \\ &\cong \frac{-2\sqrt{2}L_{1h} \cdot u_{inj}}{L_{0h}^2 - L_{1h}^2}\Delta\theta \end{aligned} \quad (2)$$

The angle error is obtained from (2) by extracting amplitude of the high-frequency current as follows:

$$\Delta\theta = \frac{\omega_h\left(L_{1h}^2 - L_{0h}^2\right)}{2\sqrt{2}L_{1h} \cdot V_h}(I_q^m - I_d^m) \quad (3)$$

Therefore, the correction controller estimates the speed so as

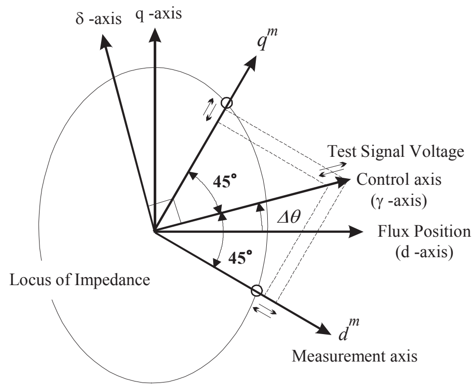

Fig. 3. Measurement axis of HFIM

to make the angle error zero.

The HFIM is effective for position and speed estimation in ultra-low speed region including zero stator frequency. Due to torque ripple and the acoustic noise the method has shortcoming in practical use in the industrial application. Meanwhile, the back EMF based method is able to estimate position and speed without acoustic and additional torque ripple, but the controllable speed range is more than about 5% of the rated speed. In order to realize position and speed estimation in entire speed range, a hybrid method is proposed. Fig. 4 shows the hybrid method combining HFIM and back EMF based method. The key technique is the changeover which is done only in the internal speed $\hat{\omega}_{cmb}$. The internal speed $\hat{\omega}_{cmb}$ consists of the estimated speed of both the HFIM and the back EMF based method. The internal estimated speed is set as follows:

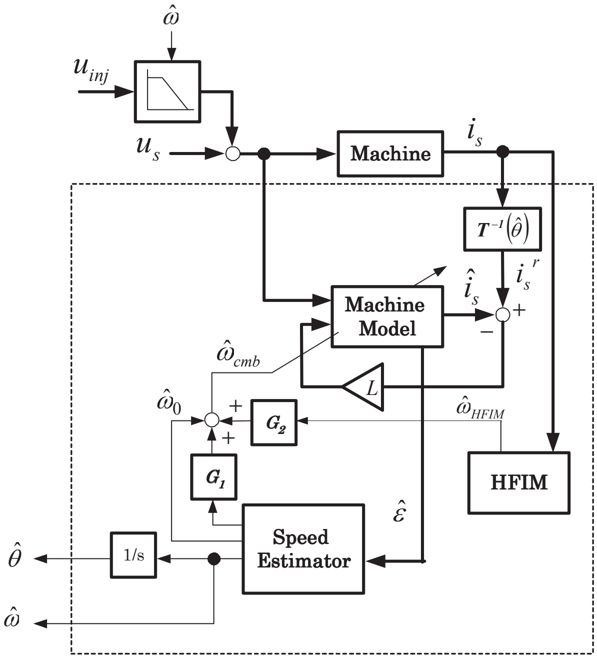

Fig. 4. Position and speed estimator with proposed hybrid method.

$$\hat{\omega}_{cmb} = \hat{\omega}_0 + G_1 \cdot \boldsymbol{K} \cdot \frac{\hat{\varepsilon}_\gamma \hat{\varepsilon}_\delta}{\hat{\varepsilon}_\gamma^2 + \hat{\varepsilon}_\delta^2} + G_2 \cdot \hat{\omega}_{HFIM} \quad (4),$$

where 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 $\hat{\omega}_{cmb}$ 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 $\hat{\omega}$.

III. SUCCESSFUL APPLICATIONS

This section introduces several examples of successful applications such as a lift, a compressor, and an injection molding machine, with sensorless IPMSM drive based on HFIM.

A. *Lift*

As usual lift system is included machine room, where a motor and a controller are also located as shown in Fig.5. Recently the lift motor has been changing from asynchronous motor with a gear to PM synchronous motor without gear because of cost reduction and space-saving by machine room less as shown in Fig.6. Especially space-saving is required from public building.

The PM motor for lift normally employed position sensor such as pulse generator (PG) to control speed and torque of motor. However, initial pole position detection of PM motor is not possible with PG. Then, sensorless drive solution is utilized in this system. The subject concerned with initial pole position detection is explained as follows: when lift car is going up or

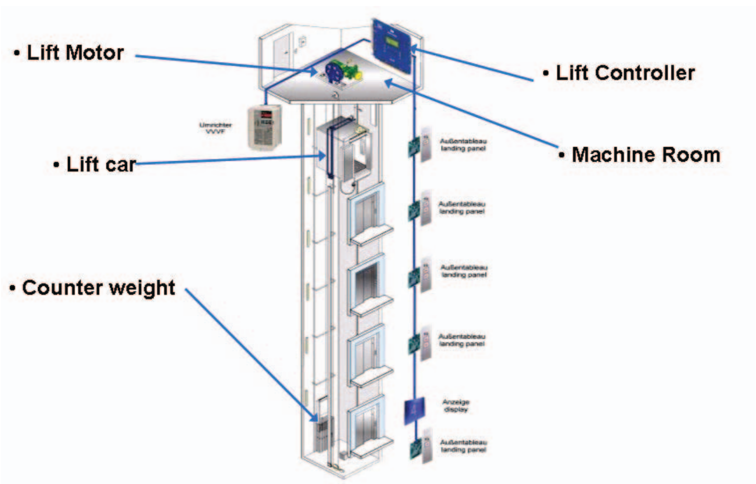

Fig.5. System configuration of conventional lift.

Fig.6. Photo of recent lift the feature of which is machine room less.

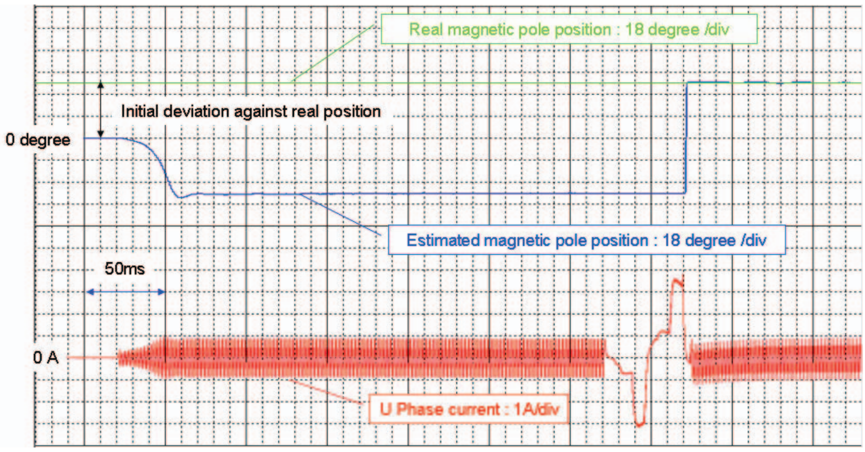

Fig.7. Initial pole position detection results with HFIM.

going down by driving PM motor, some rollback occurs and causes shock and acoustic noise in the lift car; moreover the control on the inverter does not work well at re-starting with the effect of this rollback because some counter reaction between counter weight and lift cart is directly translated to the motor shaft and the accurate pole position may be lost; therefore the accurate and fast initial pole position detection at starting is required in this application.

To solve this subject, an inverter can employ HFIM for the initial position detection of PM synchronous machine, just before the car of the lift starts. The detection process of which is shown in Fig.7 and this is just one example. If this HFIM is employed at starting motor for this application, there is no problem by the rollback anymore and also the speed control from start to rated speed becomes smooth than conventional method.

B. Compressor

Fig. 8 shows an air compressor system. The conventional system employed an induction machine driven with commercial power supply. Getting the importance to save energy, the PM machine driven by inverter system is replaced with the conventional one. The feature of saving-space is one of the attractive features to employ PM machine. The sensorless drive is required in case of direct drive with the reason that the position sensor may fail in the environment of high temperature, humidity, and mechanical vibration.

The air pressure of the compressor is controlled by un-loader and check valves. In such case, the machine is required to start under heavy load condition. Opening un-loader valve, the machine connected to the compressor acts at 3% of the rated speed sustaining load about 200 to 300% of the rated torque.

The specification of 0.4kW IPMSM is shown in Table I .

Fig. 9 shows the waveform of the speed and torque. Before starting the machine, the load torque was applied to the rating. In this condition, the machine was controlled to zero speed, and the torque needed 200% of the rated value in the acceleration of the speed. Then, the speed reached to the rated speed within 0.5sec. The hybrid sensorless control performed well under

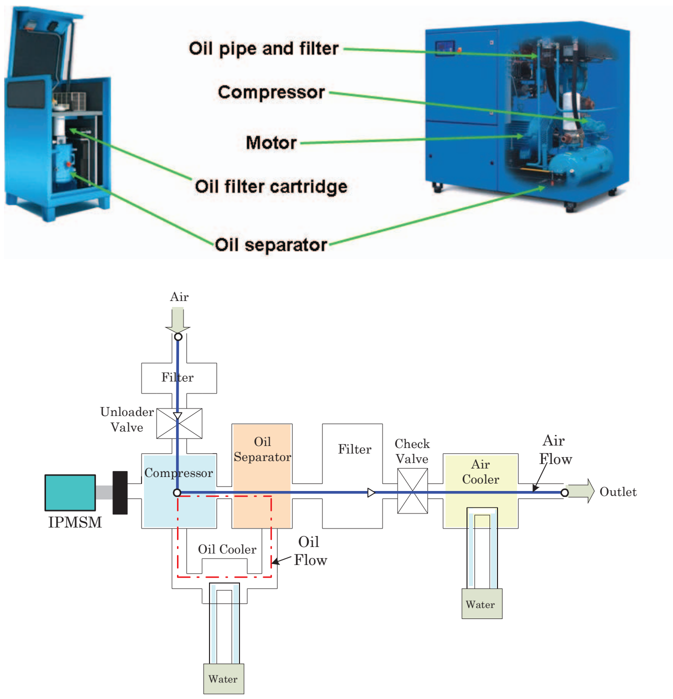

Fig.8. Air compressor configuration.

TABLE I
SPECIFICATION OF THE IPMSM FOR APPLIED THE COMPRESSOR

Item	Specification
Stator Structure	Concentrated Winding
Slot combinations	10poles 12slots
Rated power	0.4kW
Rated speed	1750 min^{-1}
Rated frequency	145.8Hz
Rated torque	2.18 Nm
Rated current	2.0A
EMF factor	40.0 mV/min^{-1}(per phase, 20deg)
Staor resistance	2.07Ω
q-axis inductance	38.0mH
d-axis inductance	27.5mH

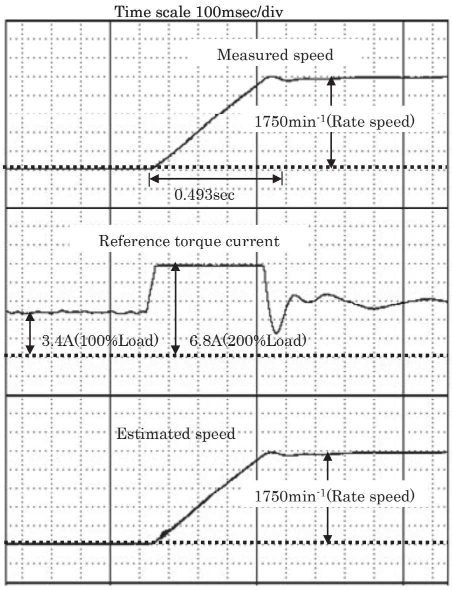

Fig.9 Acceleration test results with 100% of rated torque on the compressor

tested severe load conditions.

C. *Injection Molding Machine*

Fig. 10 shows the standard structure of the injection molding machine. In this application, there are controlled processes such as molding, plasticization, injection, and extrusion, where servo drives through timing belts and gears is usually employed shown in Fig. 10(a). As the sensorless-drive, the plasticization is focused attention on. In the process, the reciprocating screw kneads melted plastic uniformly, and the back-pressure is controlled to make value of plastic and the pressure in the heat cylinder constant. The drive through belts and gears causes the following problem:

- Torque ripple causes due to mechanical factor
- Precise back-pressure control is difficult because of the indirect connection between the machine and the load cell
- Centering of the screw is difficult due to radial force in case of timing belts connected

In order to solve the solution, direct drive without belts and gears are required. The hybrid sensorless control system is employed to realize the direct drive. Fig .10(b) shows the system configuration. Fig. 11 shows the IPMM designed for an injection molding machine. The machine specification is shown in Table II. The machine has the hollowed rotor connected to the screw driving shaft in the plasticizing unit.

For the sensorless control, the following conditions are required in this application:

- Initial pole position is detected at stand-still
- Starting under heavy load condition and the response to reach the rated speed in 0.1 to 0.2s
- Servo-locked position control keeping zero speed under rebound torque caused in injection mode

The sensorless control system met all conditions. The initial pole position was detected within the error angle of ± 10deg (elec.) and/or ± 1deg (mech.). Detailed explanation is in Ref.

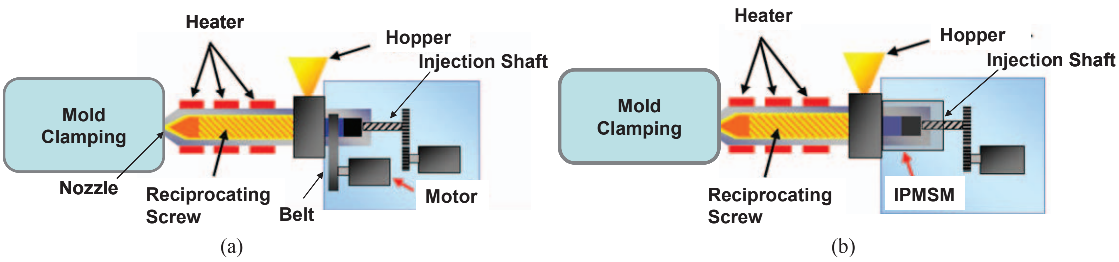

Fig. 10. Injection molding machine: (a) In-direct drive configuration, (b) Direct drive configuration.

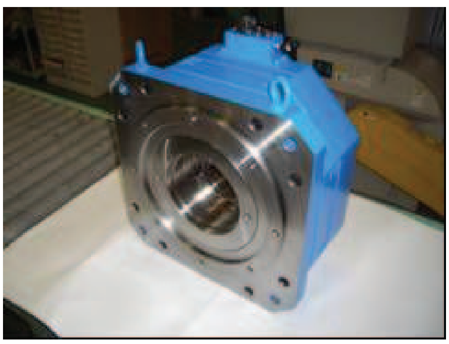

Fig. 11. IPMSM for the injection molding machine.

TABLE II
SPECIFICATION OF THE IPMSM FOR THE INJECTION MOLDING MACHINE

Item	Specification
Stator Structure	Distributed Winding
Slot combinations	24poles 54slots
Rated power	2.8 / 4.2 / 6.0kW
Rated speed	360 min^{-1}
Rated frequency	72Hz
Rated torque	74 / 111 /159 Nm
Rated current	15.0 / 20.0 / 27.0A
EMF factor	198 / 220 / 222 mV/min^{-1}(per phase, 20deg)
Stator resistance	0.758 / 0.482 / 0.271Ω
q-axis inductance	4.16 / 3.51 / 2.55mH
d-axis inductance	2.77 / 2.34 / 1.69mH

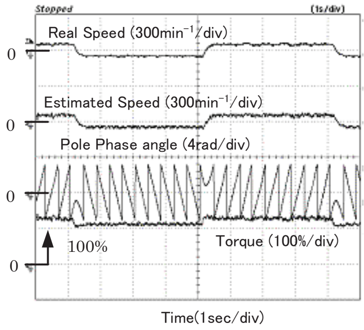

Fig. 12.Waveform in speed control mode.

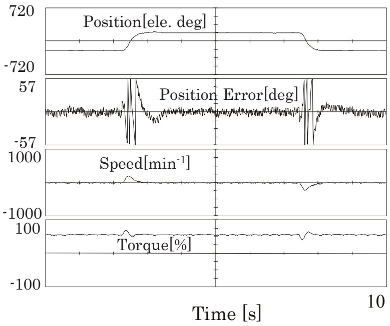

Fig. 13. Waveform in position control mode.

[7]. Fig. 12 shows the waveform in speed control mode, where the constant heavy load about 100% of the rated torque is kept in constant. The speed control mode needs the controllable speed range from zero to the rated speed. Starting of the machine under heavy load was possible. The response of the speed acceleration and deceleration were achieved within 0.2s. Fig. 13 shows the waveform in position control mode, where the position varies along with the command under the heavy load of about 80% of the rated torque. The performance of the servo-locked position control was also satisfied to suppress the movement against the rebound torque caused in injection mode. The specification of the tested IPMSM is shown in Table II.

IV. CONCLUSIONS

This paper introduced three years of industrial experience with sensorless IPMSM drive based on HFIM. The HFIM enabled the sensorless IPMSM drive to control torque and speed under ultra-low speed region including zero stator frequency, which brought the expansion of the application field. The feature also realized the position control. Owing to the control performance and the sensorless feature on the reliability and the space-saving, the sensorless drive has been also employed to direct drive applications with great expectations. As successful applications, a lift, a compressor, and an injection molding machine were introduced. More expansion of the application field with customer needs is anticipated.

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