

# Speed Ripple Suppression of Reduced DC-link Capacitance IPMSM Drives for Air-Conditioning Applications

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**Abstract**—The speed ripple is an important concern in the air conditioning compressor drive system, and it is more obvious in reduced DC-link capacitance motor drive for the large DC-link voltage fluctuation. In this paper, a compensation method is proposed to reduce the speed fluctuation caused by the load torque fluctuation and the DC-link voltage fluctuation, which is realized by the sliding mode observer and PI-type iterative learning controller. The sliding mode observer for the load torque is designed to obtain the load torque. The iterative learning controller is applied to calculate the expected current for the q-axis current tracking compensation. Both fluctuations are periodic, which could be reflected in the q-axis current. Hence the iterative learning controller can effectively compensate the two types of the speed ripple. Compared to the traditional iterative controller, the proposed controller is improved by projecting time domain to angle domain, which is fit for different speed with same parameters. Experimental results are provided to verify the effectiveness of the proposed method.

**Keywords**—Speed ripple, interior permanent magnet synchronous motor, sliding mode observer, iterative learning control, angle domain

## I. INTRODUCTION

Interior permanent magnet synchronous motors (IPMSMs) have been widely used in production and living today, especially in the field of air conditioning[1]-[3]. The reduced DC-link capacitance IPMSM drive system has been developed to improve the reliability, decrease the volume and reduce the cost[4]-[5]. However, the small film capacitor can cause larger fluctuation of DC-link voltage. The fluctuation of DC-link voltage will lead to the fluctuation of the motor's counter-electromotive, thus causing the rotational speed of the compressor to fluctuate[6]. Due to the severely fluctuated load torque of the single rotor compressor, the torque balance is difficult to realize, which will result in the additional speed fluctuation.

When the compressor works at the low frequency operation state, the output torque is proportional to the q-axis current approximatively[7]-[10]. The effective method is to compensate the q-axis current, which can make the output

torque track the load torque changes. The common method is to use the open-loop feedforward control which artificially inject the harmonic signal to offset the torque fluctuation[11]-[15]. In [11] and [12], the methods were proposed to reduce the torque fluctuation by injecting the sinusoidal wave into the system. It is easy to realize and does not introduce new harmonic disturbance, but it needs accurate parameters of the drive system. Meanwhile, the open-loop feedforward control has weak robust to the operation state change. Hence this method was improved by applying the algorithm to observe the system state and motor parameters, then calculate the harmonic in order to assure its suitability[13]-[14]. It can solve the problem causing the harmonic parameters changes when motor state changes. The observation algorithm was optimized so that it could automatically select the optimal solution for harmonic compensation[15].

In this paper, an iterative learning controller is proposed to compensate the speed ripple of the compressor. Based on the iterative learning control algorithm, an open PI-type closed-loop iterative learning controller (PI-ILC) and PI controller in parallel are used. The PI controller mainly adjusts the q-axis current. And open PI-type closed-loop learning controller makes the actual current trajectory track the expected trajectory current to achieve the torque balance. This paper is organized as follows. In section II, the reason of the speed ripple is analyzed. In section III, the proposed method based on sliding mode structure and PI-ILC is presented. In this part, a torque observer is presented, and the stability is analyzed and parameters of PI-ILC are designed. In section IV, experiment results are presented to verify the effectiveness of the proposed method.

## II. ANALYSIS OF SPEED RIPPLE IN COMPRESSOR DRIVES

The single phase reduced DC-link capacitance IPMSM drive system is shown in Fig. 1. It consists of a diode rectifier, a three-phase inverter with an IPMSM and a small film capacitor. The DC-link capacitance is remarkably reduced compared with the electrolytic capacitor. As a result, the DC-link voltage of the drive system cannot be maintained as a constant value and it will fluctuate significantly with the

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frequency twice of the grid voltage. The performance of the drive system will be affected by the fluctuated DC-link voltage.

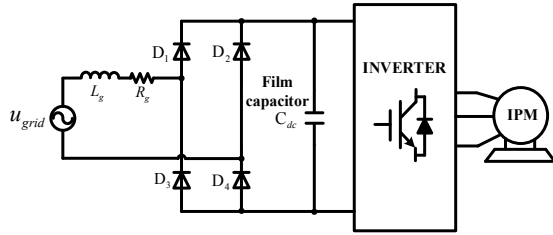


Fig. 1. The single-phase rectifier reduced DC-link capacitance IPMSM drive system.

The speed ripple will be caused by the DC-link voltage fluctuation. The speed fluctuation can be presented as:

$$\tilde{\omega}_1 = A \sin(\omega_B t + \varphi_B) \quad (1)$$

where  $\omega_B$  is the twice frequency of the grid,  $A$  is the amplitude of the speed fluctuation and  $\varphi_B$  is the phase.

The relationship between the load torque and the mechanical rotor angle is shown in Fig. 2

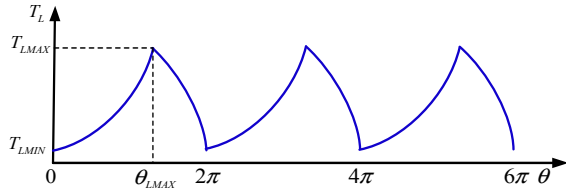


Fig.2. Relationship between the load torque and the mechanical angle

It can be seen that the curve of the load torque is an irregular sinusoidal periodic curve when running steadily at a low speed. The load torque can be shown as

$$T_l = T_{l0} + \sum_{k=1}^{\infty} T_{lk} \sin(k\omega t + \varphi_k) \quad (2)$$

where  $T_{l0}$  is the fundamental component of the load torque,  $T_{lk}$  is the each subharmonic component and  $\varphi_k$  is the phase of the each subharmonic component. The equation of PMSM is:

$$T_e - T_l - B\omega = J\dot{\omega} \quad (3)$$

And the output torque is shown as:

$$T_e = \frac{3}{2} p \psi_f i_q \quad (4)$$

So (3) can be shown as:

$$\dot{\omega} = \frac{1}{J} \left( \frac{3}{2} p \psi_f i_q - T_{l0} - \sum_{k=1}^{\infty} T_{lk} \sin(k\omega t + \varphi_k) \right) \quad (5)$$

Integrate both sides:

$$\begin{aligned} \omega &= \frac{1}{J} \int_0^{+\infty} \left( \frac{3}{2} p \psi_f i_q - T_{l0} \right) dt - \frac{1}{J} \int_0^{+\infty} \sum_{k=1}^{\infty} T_{lk} \sin(k\omega t + \varphi_k) dt \\ &= \frac{1}{J} \int_0^{+\infty} \left( \frac{3}{2} p \psi_f i_q - T_{l0} \right) dt + \frac{1}{J} \sum_{k=1}^{\infty} \frac{1}{k\omega} T_{lk} \cos(k\omega t + \varphi_k) \\ &= \omega_0 + \tilde{\omega}_2 \end{aligned} \quad (6)$$

where  $\omega$  is the actual rotational speed,  $J$  is the moment of inertia of the rotor,  $p$  is the number of pole pairs,  $\psi_f$  is the rotor flux,  $i_q$  is the q-axis current,  $k$  is the harmonic order, and  $\varphi_k$  is the phase.

So the speed constant and the ripple part are derived as (7) and (8):

$$\omega_0 = \frac{1}{J} \int_0^{+\infty} \left( \frac{3}{2} p \psi_f i_q - T_{l0} \right) dt \quad (7)$$

$$\tilde{\omega}_2 = \frac{1}{J\omega_0} T_{lk} \cos(\omega_0 t + \varphi_k) \quad (8)$$

Fourier analysis shows that the fundamental harmonic is the main component. So the speed fluctuation is shown as (9):

$$\begin{aligned} \tilde{\omega} &= \tilde{\omega}_1 + \tilde{\omega}_2 \\ &= A \sin(\omega_B t + \varphi_B) + \frac{1}{J\omega_0} T_{lk} \cos(\omega_0 t + \varphi_k) \end{aligned} \quad (9)$$

In the motor vector control system, the limitation of the bandwidth of the speed and current controller, the speed fluctuation is inevitable, which is essential to be suppressed.

### III. METHOD OF REDUCING SPEED RIPPLE USING ITERATIVE LEARNING CONTROL

It can be seen from the above analysis that the speed ripple is a periodic fluctuation. As the compressor will operate in low frequency state after reaching the set temperature, hence the load torque fluctuation is in main ingredients. This paper mainly solve the problem of speed fluctuation during the low speed operation. The proposed method contains a load torque observer and an iterative learning controller, which are presented as follows.

#### A. Design of Torque Observer

In order to observe the change of load torque, an extended sliding mode observer is selected. The mechanical equation of permanent magnet synchronous motor can be obtained:

$$\dot{\omega} = \frac{1}{J} (T_e - T_l) \quad (10)$$

The switching frequency of the controller in this experimental platform is much higher than that of the motor. So it can be considered that the load torque changes slowly and approximately in a control cycle.

From (10) the state equation of the motor based on rotor position can be obtained:

$$\begin{cases} \dot{\theta} = \omega \\ \dot{\omega} = \frac{3p\psi_f}{2J}i_q - \frac{T_l}{J} \\ \dot{T}_l = 0 \end{cases} \quad (11)$$

$$\begin{cases} \frac{k_1}{k_2} > 0 \\ -\frac{J}{4} < \frac{k_1 k_3}{k_2^2} < 0 \end{cases} \quad (17)$$

where  $\dot{\omega}$  is real speed differential,  $\dot{T}_l$  is load torque differential,  $\hat{\omega}$  is observed speed,  $\hat{T}_l$  is observed load torque,  $T_e$  is electromagnetic torque,  $T_l$  is load torque and  $J$  is rotational inertia of the rotor.

Equation (11) can be presented as:

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega} \\ \dot{T}_l \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{J} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \omega \\ T_l \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{3p\psi_f}{2J} \\ 0 \end{bmatrix} i_q \quad (12)$$

Construct extended sliding mode state observer form as follows:

$$\begin{cases} \dot{\hat{\theta}} = \hat{\omega} + k_1 \operatorname{sgn}(\hat{\theta} - \theta) \\ \dot{\hat{\omega}} = \frac{3p\psi_f}{2J}i_q - \frac{T_l}{J} + k_2 \operatorname{sgn}(\hat{\omega} - \omega) \\ \dot{\hat{T}_l} = k_3 \operatorname{sgn}(\hat{T}_l - T_l) \end{cases} \quad (13)$$

where  $\tilde{\theta} = \hat{\theta} - \theta$ ,  $\tilde{\omega} = \hat{\omega} - \omega$ ,  $\tilde{T}_l = \hat{T}_l - T_l$ . The error equation is:

$$\begin{cases} \dot{\tilde{\theta}} = k_1 \operatorname{sgn}(\tilde{\theta}) \\ \dot{\tilde{\omega}} = -\frac{1}{J}T_l + k_2 \operatorname{sgn}(\tilde{\omega}) \\ \dot{\tilde{T}_l} = k_3 \operatorname{sgn}(\tilde{T}_l) \end{cases} \quad (14)$$

Define sliding mode plane  $s = \tilde{\theta} = 0$ . According to *Lyapunov* function, if  $\dot{V} = s \cdot \dot{s}$  is negative definite, the whole system is asymptotic convergence.

$$\dot{V} = s \cdot \dot{s} = \tilde{\theta}(\tilde{\omega} + \frac{k_1}{k_2} \operatorname{sgn}(\tilde{\theta})) \quad (15)$$

When  $s = \tilde{\theta} = 0$ , the error equation can be changed as follows:

$$\begin{cases} \ddot{\omega} + \frac{k_2}{k_1}\dot{\omega} - \frac{k_3}{Jk_1}\omega = 0 \\ \ddot{T}_l + \frac{k_2}{k_1}\dot{T}_l - \frac{k_3}{Jk_1}T_l = 0 \end{cases} \quad (16)$$

The stability of the parameter is obtained as (17).

### B. System Configuration of Iterative Learning Control

The iterative learning controller can be divided into three types: open loop, closed loop and open loop in the form of feedback form. The PID closed-loop iterative learning controller is the most commonly used in engineering. Its general form is as follow:

$$u_{k+1}(t) = u_k(t) + Pe_k(t) + I \int_0^t e_k(\tau) d\tau + D \frac{de_k(t)}{dt} \quad (18)$$

where  $P, I, D$  are proportional, integral and differential coefficient matrix, respectively. In order to avoid the influence of noise signal and decrease the overshoot, the PI-type iterative learning law is adopted to avoid the differential term in the iterative learning law design of the torque pulsation. But the PI-type iterative learning is greatly influenced by the input error and the disturbance of the initial state. Therefore, the forgetting factor  $\alpha$  is introduced to adjust disturbance.

It can be seen from the observation that the fluctuation of the rotational speed changes with the rotor position, so the rotor position can be used as the independent variable. To sum up, this paper intends to use p-type open-closed-loop iterative learning control law with forgetting factor in the location field. Its expression is as follows:

$$i_{q,k+1}(\theta) = (1 - \alpha)i_{q,k}(\theta) + Pe_{k+1}(\theta) + I \int e_{k+1}(\theta) d\theta \quad (19)$$

where  $\alpha$  is the forgetting factor,  $P$  is the opened-loop learning gain,  $I$  is the closed-loop learning loop. The structure of ILC is shown as Fig.3.

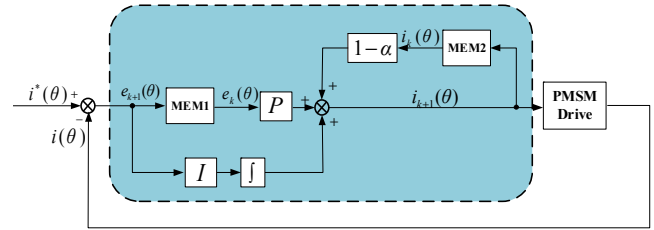


Fig.3. The structure of iterative learning controller.

### C. Parameters design of the iterative learning controller

The PI-type iterative learning controller needs to select three parameters. The range of forgetting factor  $\alpha$  need to consider the stability of the controller of the torque ripple suppression and the algorithm convergence speed. The selection of closed-loop learning gain  $P$  also needs to consider the limitation of the convergence speed and the convergence condition. The selection of  $I$  needs to consider the convergence speed and the steady-state error.

Equation (19) can be written as

$$i_{q,k+1}(z) = (1-\alpha)i_{q,k}(z) + Pe_{k+1}(z) + I\frac{z}{z-1}e_{k+1}(z) \quad (20)$$

The iterative process in the formula can be equivalent to the delay process:

$$z^{-N}i_{q,k+1}(\theta) = i_{q,k}(z) \quad (21)$$

When N=1, The Z-domain transfer function of PI-type iterative learning controller is:

$$G(z) = \frac{i_{q,k+1}(z)}{e_{k+1}(z)} = \frac{(P+I)z^2 - P}{z^2 - (2-\alpha)z + (1-\alpha)} \quad (22)$$

When forgetting factor  $\alpha \in [0, 2]$ , the zero pole distribution of the transfer function  $G(z)$  is shown in Fig.4.

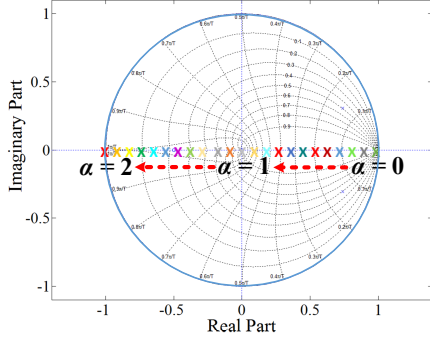


Fig.4. Pole-zero plot of the transfer function  $G(z)$ .

As shown in Fig.4, poles are on the  $z$  plane unit circle border when  $\alpha=0$  or  $\alpha=2$ . The controller is in the critical stable state when the value changes from 0 to 2. When  $\alpha=1$ , the controller cannot be a cycle of useful signal from the previous memory, and the learning effect cannot be realized. Thus the range of forgetting factor  $\alpha$  should be  $(0, 2)$  and  $\alpha \neq 1$ .

The error equation is presented as

$$e_{k+1}(\theta) = \omega_r^*(\theta) - \omega_{r,k+1}(\theta) \quad (23)$$

Equation (23) are substituted into (19).

$$e_{k+1}(\theta) = \omega_r^*(\theta) - \frac{pK}{J} \left[ \int (1-\alpha)i_{q,k}(\theta)d\theta + \int (Pe_{k+1}(\theta) + I \int e_{k+1}(\theta)d\theta)d\theta \right] \quad (24)$$

Then take a norm of both sides:

$$\left| 1 - \frac{pK}{J} \left( P\theta + \frac{1}{2}I\theta^2 \right) \right| \|e_{k+1}(\bullet)\|_{\infty} \leq |1-\alpha| \|e_k(\bullet)\|_{\infty} + \alpha \|\omega_r^*(\bullet)\|_{\infty} \quad (25)$$

Iteration converges when (25) is satisfied:

$$\lim_{k \rightarrow \infty} e_k(\theta) = 0 \quad (26)$$

So the stable range of the parameters is:

$$\left| \frac{J(1-\alpha)}{J - pKG_p\theta_e - \frac{1}{2}pKG_l\theta_e^2} \right| \leq 1 \quad (27)$$

where  $\theta \in [0, 2\pi]$ , the stable range of the parameters change into:

$$\left| \frac{J(1-\alpha)}{J - 2\pi pKP - 2\pi^2 pKI} \right| \leq 1 \quad (28)$$

#### IV. EXPERIMENT RESULT

The result of the proposed PI-ILC method is verified by experiments that performed on the vector control system of air conditioning. The motor parameters used in the system are shown in table 1. The hardware of experiment platform is driven by reduced DC-link capacitor IPMSM drive system. The software part uses TMS320F28034 of TI to implement the algorithm. The structure of the drive system is shown in Fig. 5.

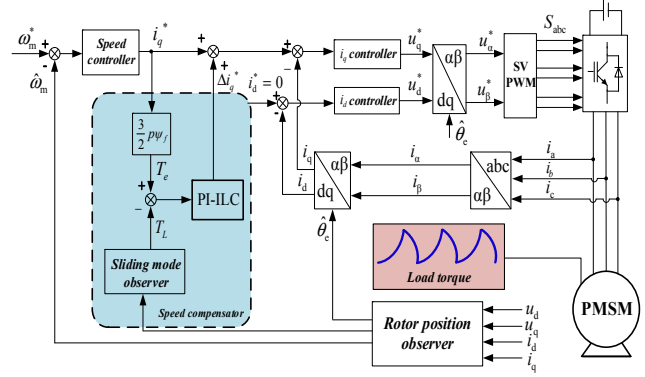


Fig.5. the vector control system of compressor using PI-ILC

Fig. 6 shows the observation results of the torque observer at different operating frequencies. The waveforms from top to bottom are the actual torque waveform and the observed torque waveforms. It can be seen that the actual load torque is a sinusoidal periodic curve, which is also the main reason for the fluctuation of speed.

TABLE 1 PARAMETERS OF EXPERIMENT

Parameters	value
Grid voltage	220 Vrms
Grid frequency	50 Hz
D-axis inductance	7.9 mH
Q-axis inductance	11.7 mH
Flux linkage of rotor	0.11 Wb
Number of pole pairs	3
Rated power	1.0 kW
Rated speed	3000 r/min

It can be seen from the observation curve that the sliding mode observer can effectively track the change of load torque and effectively suppress the speed ripple. The reduction degree of the peak is better and there is no significant distortion. Fig.6. (a)~(d) are the waveforms running at the frequencies of 20 Hz, 25 Hz, 30 Hz, 40Hz. It can be seen when the running frequency rises, load torque rise in frequency, consistent with the running frequency.

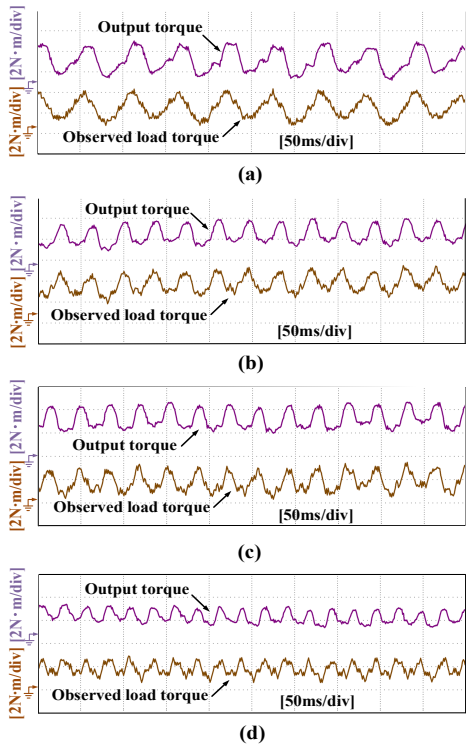
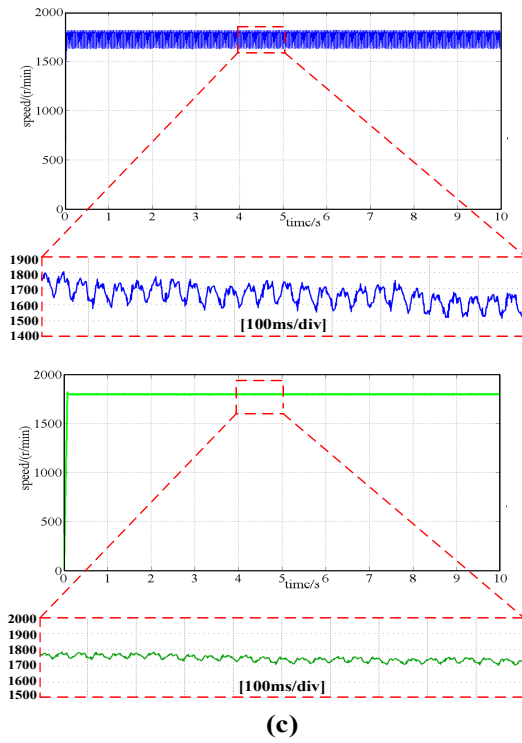
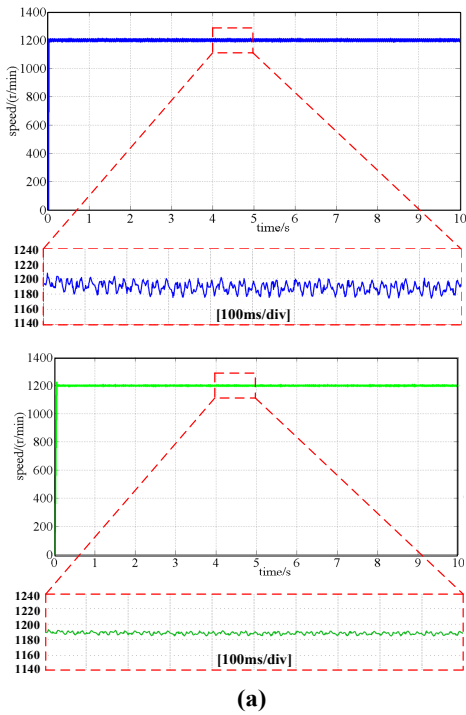
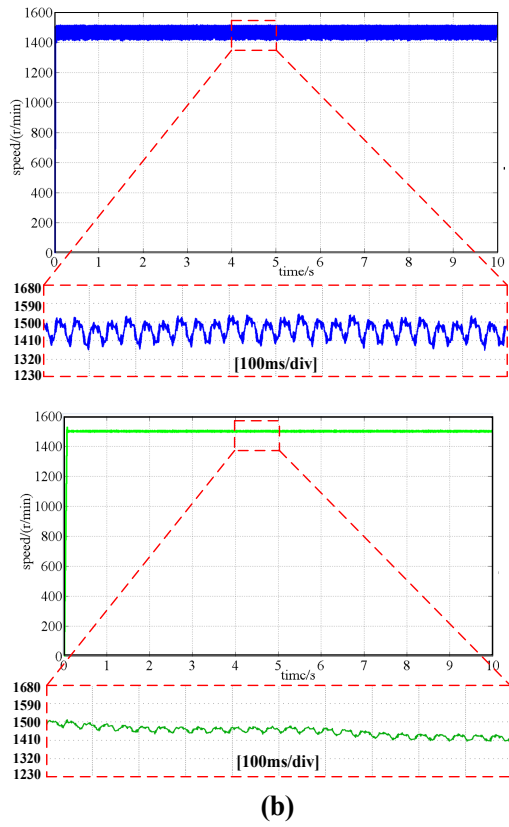


Fig.6. the output torque curve and the observed load torque(a) 20Hz(b)25Hz (c) 30Hz(d)40Hz



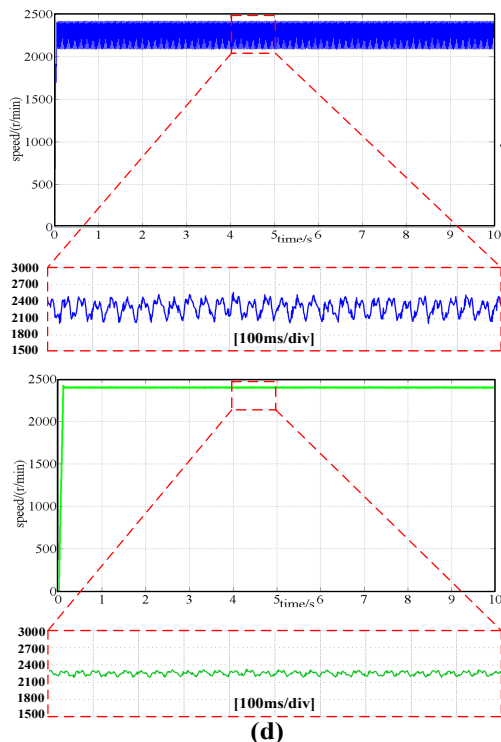


Fig.7. Actual speed curve using PI control and PI-ILC control (a)20Hz(b) 25Hz(c) 30Hz(d)40Hz

Fig. 7 shows the comparison of speed of the compressor with PI control and PI-ILC control at different operating frequencies. Waveforms from top to bottom are the actual speed curve using PI method and the one using PI-ILC method. After applying the traditional PI control, it can be seen that the speed ripple is large, which affects the stable operation of the motor, causing of the additional noise. After switching to PI-ILC control mode, the speed curve of PMSM is approximately a straight line, and the speed fluctuation is obviously suppressed. Fig. 10(a)~(d) are the speed curve of the compressor running at 20Hz, 25Hz, 30Hz and 40Hz, respectively. It can be seen that when the work frequency increases, the fluctuation amplitude of the rotating speed is worth to be suppressed using PI-ILC, and the compressor is more stable than the PI control.

## VI. CONCLUSION

A PI-ILC method for suppressing the speed fluctuation of the compressor is proposed in this paper. The periodic fluctuation of the load torque and the DC-link voltage will cause the speed fluctuation of the low frequency operation of the compressor. The proposed method can restrain fluctuation and improve the stability of operation. The PI-ILC control method uses the extension sliding mode state observer to obtain the load torque. The tracking performance of the quadrature axis current could be improved by the application of the iterative learning control method, which could stabilize the drive system operation. Experimental results show the effectiveness of the proposed PI-ILC method.

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