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Research on feedforward compensation control of permanent magnet synchronous motor based on load period fluctuation

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Abstract: This paper takes the feedforward compensation control of permanent magnet synchronous motor based on load period fluctuation as the research object. By analyzing the influence of load period fluctuation on motor performance, a feedforward compensation control strategy is proposed. Firstly, the influence of load period fluctuation on motor torque and speed is studied by establishing the mathematical model of motor. Then, a feedforward compensation controller based on load period fluctuations is designed to offset the torque and speed fluctuations caused by load fluctuations. Finally, the effectiveness of the control strategy in reducing the influence of load fluctuation on motor performance is verified by simulation experiments. The experimental results show that the torque and speed fluctuation of the motor are significantly reduced by using the feedforward compensation control strategy, and the stability and performance of the motor are improved. Therefore, the feedforward compensation control of permanent magnet synchronous motor based on load period fluctuation has good application potential and development prospect.

1. Introduction

In recent years, with the increasingly prominent energy crisis and environmental problems, the demand for energy-efficient motors is becoming more and more urgent. As a new type of high performance motor, permanent magnet synchronous motor (PMSM) has been widely concerned because of its high efficiency, high power density, small size and reliability. However, due to the load cycle fluctuation and other problems in the operation of PMSM, its performance still needs to be further improved and optimized. The load period fluctuation refers to the periodic fluctuation of the torque and speed of the motor output due to the change of the load during the operation of the motor. This fluctuation will cause the vibration of the motor to increase, and reduce its operating stability and control accuracy. Therefore, how to effectively suppress the load cycle fluctuation and improve the performance of PMSM has become an important research topic. At present, researchers have proposed a variety of methods to solve the load period fluctuation problem, one of which is the use of feedforward compensation control technology. By accurately measuring and predicting the characteristics of load cycle fluctuation and adjusting the motor control strategy in real time, the feedforward compensation control can effectively eliminate the influence of load fluctuation on the motor performance and improve the running stability and control precision of the motor[1].

In this study, we will focus on the feedforward compensation control technology of permanent magnet synchronous motor based on load period fluctuation. First, the working principle and characteristics of PMSM, as well as the influence of load period fluctuation on motor performance, will be introduced. Then, the basic principle and method of feedforward compensation control are described in detail, and its application potential and advantages in suppressing load cycle fluctuations are analyzed. Finally, the performance and effect of the control technology are evaluated by means of experimental verification and simulation. The aim of this research is to improve the stability and control accuracy of permanent magnet synchronous motor by feedforward compensation control technology based on load period fluctuation, and to provide an effective solution for promoting the development and application of motor technology. It is believed that through the in-depth research and exploration of this study, it can provide valuable reference and inspiration for scholars and researchers in related fields.

2. The torque feedforward compensation control system is constituted

2.1 Mathematical model of PMSM

In steady state, the voltage equation of PMSM is:

$$\begin{cases} u_d = R_s i_d + \dfrac{d\Psi_d}{dt} - \omega\Psi_q \\ u_q = R_s i_q + \dfrac{d\Psi_q}{dt} - \omega\Psi_d \end{cases} \tag{1}$$

In formula (1), the flux link:

$$\begin{cases} \Psi_d = L_d i_d + \Psi_f \\ \Psi_q = L_q i_q \end{cases} \tag{2}$$

Electromagnetic torque of motor:

$$T_{em} = \frac{3}{2}p(\Psi_d i_q - \Psi_q i_d) \tag{3}$$

In formula (1) to formula (3), p is the number of poles of the motor; Rs is the armature resistance; Ld and Lq are respectively d and q axis inductors. ud and uq are d and q axis voltages respectively. id and iq are d and q axis current respectively. ψf is a permanent magnet flux linkage. ψd, ψq is divided into d, q axis flux linkage; ω is the electric angular velocity; Tem Indicates electromagnetic torque.

Motor motion equation:

$$J\frac{d\omega_r}{dt} = T_{em} - B\omega_r - T_L \tag{4}$$

Where: ωr is the mechanical angular velocity; J is the rotor moment of inertia; B is viscous damping coefficient; TL is the load torque. The research of this paper is aimed at a special load torque.

2.2 Single rotor compressor load torque

In a single rotor compressor variable frequency air conditioner, the load torque fluctuates greatly when PMSM drives rollers to compress refrigerant through eccentric crankshaft. Figure 1 shows the load torque waveform under different working conditions. The load torque of the motor fluctuates once per revolution, and the torque fluctuation has the characteristics of cycle repetition. The torque fluctuation amplitude is closely related to the load size. When the load is relatively light, the torque fluctuates in the range of 0 ~ 4N m. When the load is increased, the torque fluctuation range is 0 ~ 7N m.

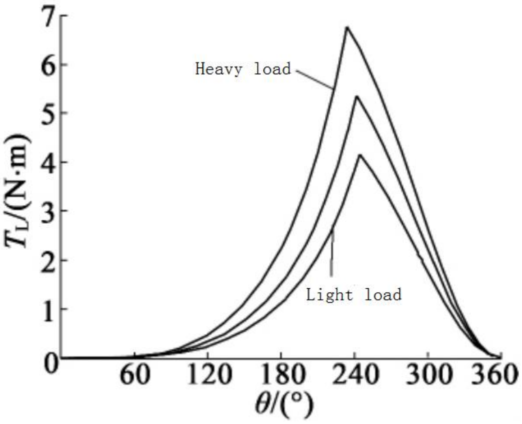


Figure 1: PMSM load torque waveform under different working conditions

2.3 The torque feedforward compensation control system is constituted

The torque feedforward compensation control system, as shown in Figure 2, mainly includes the speed PI regulator, d and q axis current PI regulator, rotor position estimation and torque feedforward compensation modules. Motor real-time speed ωr is tracked through the speed PI regulator to match the speed set value ωset, resulting in stator current output. The input value of the current regulator i * d, i * q is calculated with the stator current is and torque Angle β : i * d = issin β, i * q = iscos β, when the torque Angle β = 0, is the commonly used "id = 0" control mode. The torque compensation module calculates the feedforward compensation current correction, and the Q-axis current regulator input i * q to get i * * q. The phase current is converted into D-axis current id and Q-axis current iq by Clarke, Park transformation. id and iq are used as feedback components of the D-axis and Q-axis current PI regulators respectively.

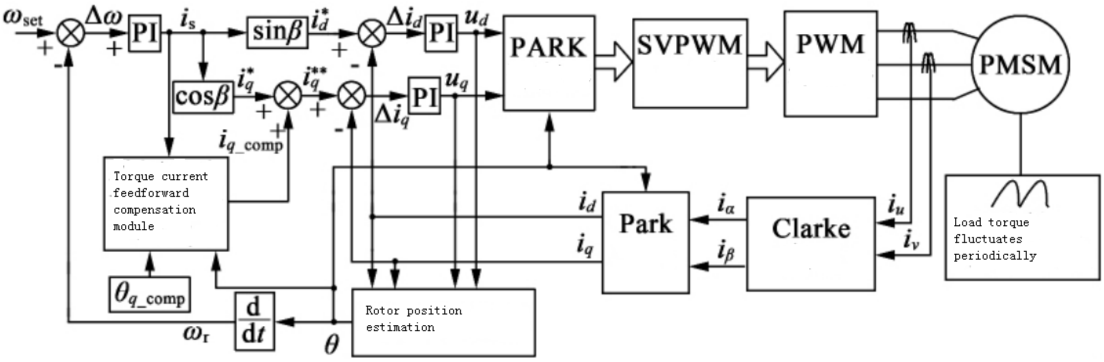


Figure 2: Block diagram of PMSM torque feedforward compensation control system

The output of d, Q-axis current regulator is d, Q-axis voltage ud, uq; ud, uq obtained the three-phase stator output voltage through Park inverter conversion, and then calculated the

6-channel power tube PWM driving signal through SVPWM, and finally drove the PMSM rotating work through the power module. As a low-cost control system, the household variable frequency air conditioner obtains the real-time phase current value through the resistance sampling circuit, and obtains the rotor position Angle and speed through the rotor position estimation module.

3. Torque feedforward compensation control strategy

According to the characteristic of load torque fluctuation once per revolution of motor, an engineering control strategy is proposed in this paper. That is, a feedforward compensation current iq_comp, which can be directly calculated by the formula, is added to the Q-axis current i*q to generate the electromagnetic torque of the expected waveform to suppress the speed fluctuation[2]. The optimization goal of feedforward compensation control is to obtain the minimum speed fluctuation. In the vector control d, q coordinate system of FIG. 2, the feedforward compensation adopts the control mode of "id=0", the input i*d of the current loop axis is 0, and the input i* *q of the current loop axis is 0. A component iq_comp is added on the basis of i*q(i*q=iscosβ= IS):

$$\begin{cases} i_d^* = 0 \\ i_q^{**} = i_q^* + i_{q\_comp} = i_s + i_{q\_comp} \end{cases} \tag{5}$$

Where: is is the stator current; β is the torque Angle; iq_comp is the torque current feedforward compensation amount. The speed loop calculates the stator current is required by the motor according to the given speed ωset and speed feedback ωr.

By substituting equations (2) and (5) into equations (3), electromagnetic torque Tem is obtained:

$$T_{em} = \frac{3}{2} p \psi_f i_q + \frac{3}{2} p (L_d - L_q) i_d i_q = \frac{3}{2} p \psi_f (i_s + i_{q\_comp}) \tag{6}$$

The load torque in Figure 1 cannot simply be expressed analytically, but can be expressed in Fourier series form:

$$T_L = T_{L0} + \sum_{n=1}^{\infty} T_{Ln} sin(n\omega t) \quad n = 1,2,3,\cdots \tag{7}$$

Where: TL0 is the constant component of load torque; TL1 is the amplitude of the load torque fundamental wave component; TLn(n= 2,3,...) Is the amplitude of the higher harmonic component of the load torque.

Equation (6) adds a feedforward compensation to the Q-axis current, which can also be expressed in Fourier series form:

$$i_q = i_{q0} + \sum_{n=1}^{\infty} i_{qn} sin(n\omega t) \quad n = 1,2,3,\cdots \tag{8}$$

Where: iq0 is the DC component of torque current; iq1 is the fundamental amplitude of torque current. iqn(n= 2,3,...) Is the amplitude of the higher harmonic component of the torque current. The corresponding relationship can be obtained from equations (6) and (8):

$$\begin{cases} i_s = i_{q0} \\ i_{q\_comp} = \sum_{n=1}^{\infty} i_{qn} sin(n\omega t) \quad n = 1,2,3,\cdots \end{cases} \tag{9}$$

Formula (9) shows that the stator current is equal to the DC component of the torque current, while the feedforward compensation current iq_comp can always be composed of a set of fundamental and higher harmonic currents, so that the electromagnetic torque generated by the synthesized Q-axis current can drive the load and offset the load torque fluctuation. However, in the engineering practice of inverter air-conditioning torque compensation, it is found that the compensation effect of iq_comp including fundamental wave and higher harmonic current according to equation (9) is not better than that of iq_comp containing only fundamental wave. The reasons are as follows:

1) Formula (6) electromagnetic torque expression is based on the linear model of the motor. When iq_comp takes the fundamental wave and higher harmonic according to Formula (9), the actual electromagnetic torque generated is deviated from the expected shape in Figure 1.

2) The value law of harmonic compensation is complex, the amount of computation is large, almost exceeds the computing capacity of the system microprocessor, and it is difficult to achieve in low-cost household appliances, and the calculation amount of iq_comp fundamental wave will be greatly reduced.

3) Through the load torque observer, the observed real-time torque value is converted into the corresponding current flow, and the current command signal output by the speed loop is feedforward compensated. This scheme is more suitable for the situation where the load torque disturbance law is difficult to predict. However, the load torque fluctuation of the single rotor compressor has the regularity of periodic repetition, and the feedforward compensation current does not need to be calculated in real time at each PWM interruption. The initial value of the compensation current and Angle can be obtained by looking up the table and estimating according to the speed of the motor and the current of the Q-axis, which is suitable for engineering applications.

At present, the commonly used compensation scheme for household frequency conversion air conditioners is iq_comp, which takes the fundamental wave according to formula (9), that is, the sine wave compensation scheme:

$$i_{q\ comp} = i_{q\ Amp} sin(\omega_r t + \theta_{q\ comp}) \tag{10}$$

Where: iq_Amp is the compensation amplitude; θq_comp is the compensation Angle; ωr is the mechanical angular velocity. There is a reasonable proportional relationship between the compensation amplitude iq_Amp and the load size, that is, with the Q-axis current i*q. FIG. 1. The amplitude of load torque fluctuation is closely related to the rotor position Angle of the motor. Therefore, the sine wave in equation (10) is calculated according to the rotor position Angle (θmec=ωrt). The internal mechanical structure of the compressor determines the compensation Angle θq_comp. For the same type of compressor, θq_comp can be a fixed value. In actual control, when the motor speed changes, it is also necessary to correct the θq_comp.

In the medium-high speed (2500 ~ 10000r/min) region, the motor rotor moment of inertia has a strong inhibition on speed fluctuations, and the speed fluctuations caused by load torque period changes are relatively small, and torque feedforward compensation is not required. In the low-speed operation (less than 2500r/min) area, the speed fluctuation caused by the load torque period change is large, so the torque feedforward compensation control strategy should be adopted. Therefore, the control procedure in Figure 3 determines whether the system enters the torque feedforward compensation mode according to the set speed of the compressor, and only when the compressor speed is less than a certain value can the torque feedforward compensation be carried out. ωDown_limit, ωUpper_limit are the lower limit and upper limit of the judging speed respectively. When the given compressor speed is less than the lower limit of the judging speed ωDown_limit, the control mode enters the torque feedforward compensation; When the given compressor speed is greater than the upper limit of the judging speed ωUpper_limit, the control mode exits the torque feedforward compensation. In this paper, when adjusting different speed and load size, the compensation Angle θq_comp corresponding to different speed is first established in a table. When the feedforward compensation mode is entered for the first time or when the working condition changes, the initial value of θq_comp is obtained by looking up the table according to the speed, because the Q-axis current iq reflects the current load size. Compensation amplitude iq_Amp Press (iq_Amp= 0.8 iq) to obtain the initial value. The torque feedforward compensation is calculated according to formula (5): i*d, i* * q. In FIG. 3, θq_comp and iq_Amp take the current optimal value based on determining whether the motor speed fluctuation Δω is the minimum. In the control program, when the motor speed reaches a given speed node value, θq_comp is determined as the optimal value according to the principle of the minimum speed fluctuation Δω and does not change. The iq_Amp needs to be adjusted in real time according to the change of the load of the inverter air conditioner. When the load of the whole machine becomes larger or smaller, the iq_Amp needs to change with the change of i*q.

4. Research on the value of feedforward compensation Angle and compensation amount

In order to study the value law of torque feedforward compensation Angle and compensation amount, the three-phase PMSM load feedforward compensation control system in FIG. 2 was simulated and analyzed by MATLAB/Simulink simulation software. Variable frequency air conditioner compressor PMSM pole number p=3; Armature resistance Rs= 1.7Ω; D-axis inductance Ld= 8.9mH; Q-axis inductance Lq= 12.7mH; Back electromotive force coefficient ke= 46.8V /(kr ·min-1); Rotor moment of inertia J= 7.6 ×10-4kg·m2; System setting speed ωr=1800r/min. The simulation calculation adopts the "id=0" control mode and ignores the magnetic saturation effect of the motor. According to the load torque curve provided by the compressor manufacturer, the load torque value of each moment is obtained by looking up the table. In the simulation program, the compensation amplitude iq_Amp and compensation Angle θq_comp were respectively taken to different values. The motor accelerated from static to 1800r/min, and the motor entered steady state operation after about 0.6s. Fig.3 to Fig.6 show the simulation waveform diagram of load torque, compensation current and motor speed corresponding to several different situations in the time region of 1 to 1.1s.

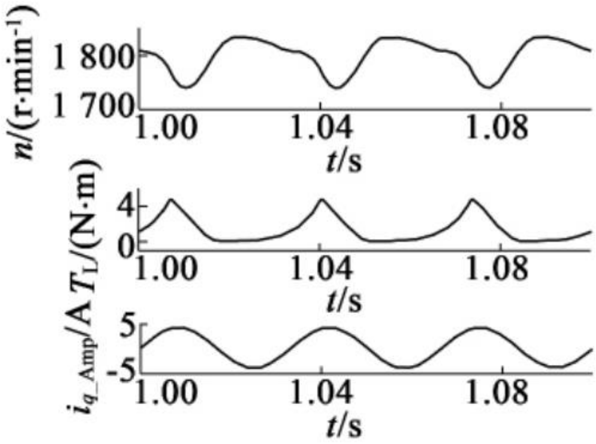


Figure 3: Simulation waveform for compensating angular lag

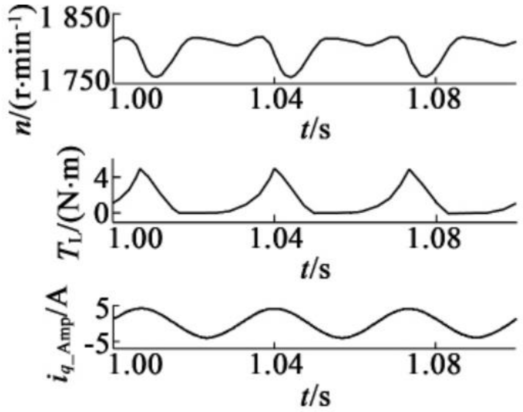


Figure 4: Simulation waveform with appropriate compensation Angle and compensation amplitude

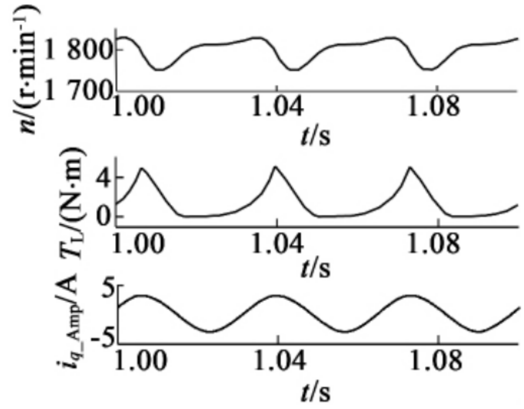


Figure 5: Simulation waveform with small compensation amplitude

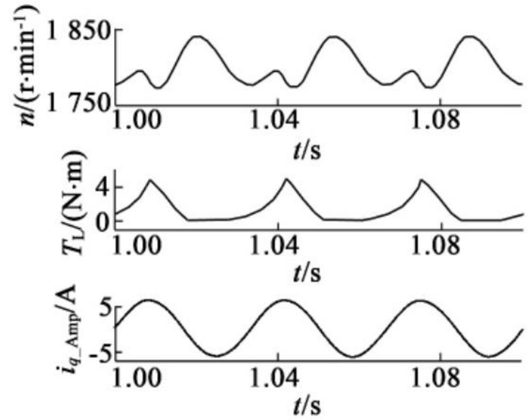


Figure 6: Simulation waveform when compensation amplitude is too large

From the waveform diagram in FIG. 3-6 and the data in Table 1, the following rules can be drawn: 1) There should be an optimal Angle for a certain speed compensation Angle. In FIG. 4 and FIG. 5, the compensation amplitude iq_Amp is 4A; in FIG. 4, the compensation Angle θq_comp is 99°, and the rotation speed fluctuation is 98r/min. FIG. 4 When the compensation Angle θq_comp is moved forward by 117°, the speed fluctuation is reduced to 60r/min. If the Angle θq_comp is compensated, the speed fluctuation Δω increases gradually. Therefore, when corresponding to 1800r/min, the current optimal compensation Angle θq_comp is 117°. Further research shows that the optimum compensation Angle θq_comp needs to be corrected when the PMSM speed changes.

Because the rotor position estimation is used in the system, it has a great influence on the feedforward compensation. The influence of the rotor position estimation deviation on the feedforward compensation can be solved by modifying the θq_comp of each node in the control program.

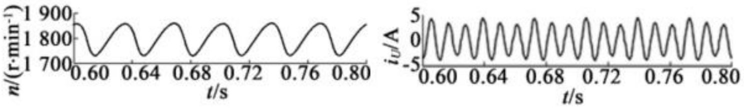
Table 1: Motor speed fluctuation values corresponding to different compensation schemes

	Compensation range	Compensating Angle	Velocity fluctuation
Figure 3	4	99	98
Figure 4	4	117	60
Figure 5	3	117	85
Figure 6	6	117	75

2) When the compensation Angle is reasonable, the velocity fluctuation Δω of PMSM will decrease with the increase of the compensation amount. In FIG. 4 and FIG. 5, the compensation Angle θq_comp is set at 117°. In FIG. 4, the compensation amplitude iq_Amp is larger (4A), and the speed fluctuation Δω is 60r/min. In FIG. 5, the compensation amplitude iq_Amp is too small (3A), and the speed fluctuation Δω is larger than 85r/min. 3) There is a reasonable proportional relationship between the compensation amplitude iq_Amp and the load size, that is, the Q-axis current. In this paper, there is a rule in the control system: iq_Amp= 0.8iq. When the compensation exceeds this value range, the velocity fluctuation Δω of PMSM will no longer decrease, but will increase. FIG. 6 shows that compensation amplitude iq_Amp is increased to 6A on the basis of FIG. 4. At this time, the speed fluctuation Δω does not continue to decrease on the basis of 60r/min, but rises to 75r/min. When PMSM low-frequency torque compensation control is carried out according to, the most important work is to find the best compensation Angle θq_comp and compensation amplitude iq_Amp under each speed node according to the load condition. In the simulation program, the compensation Angle θq_comp in Figure 4 to Figure 6 is 99 ° or 117 °, which is only a relative electrical Angle value. In the actual debugging of the hardware circuit in this paper, the relative position of the compensation current waveform and the load torque waveform (or phase current waveform) is mainly observed. It can be seen from the compensation Angle lag in Figure 4 that the maximum value of the compensation current waveform lags behind the maximum value of the load torque, and when the compensation Angle is appropriate in Figure 4-6, the maximum value of the compensation current waveform is aligned with the maximum value of the load torque[3]. Although there is a strict correspondence between the load torque and the mechanical Angle of the compressor rotor as shown in Figure 1, when the motor accelerates from rest to 1800r/min and enters the steady state operation, the time corresponding to the maximum load torque may be different due to the different compensation law and the different acceleration law of the motor. Therefore, the maximum load torque in FIG. 3 to FIG. 5 occurs at 1.04s, while the maximum load torque in FIG. 6 occurs at 1.042s.

5. Analysis of experimental results

The torque feedforward compensation strategy has been experimentally verified on Hisense inverter air conditioner products. XMC4200 (Infineon) chip is used in the control system, and PMSM parameters have been given above. Inverter air conditioner input mains (220V/50Hz), set motor speed 1800r/min. Firstly, the system without torque feedforward compensation is simulated and analyzed. FIG. 7 shows the simulation waveform of motor speed and phase current. FIG. 8 shows the real shot waveform of motor speed, Q-axis current and phase current without torque feedforward compensation. The experimental waveform is very close to the simulation waveform. When the load torque of the motor is constant, the phase current of the motor is uniform and symmetrical. However, when the load torque period fluctuates, the phase current in FIG. 8 presents large and small waves, and the motor speed fluctuates greatly. The maximum peak value of the phase current is 8.4A, while the minimum value is 5A. In the experiment, the phase current waveform of the motor is detected by the current sensor, and the motor speed cannot be measured directly. The real-time speed data of the position estimation module should be converted by D/A through the data acquisition board and then measured by oscilloscope.



(a) Rotational speed (b) U-phase current

Figure 7: Simulation waveform without torque feedforward compensation

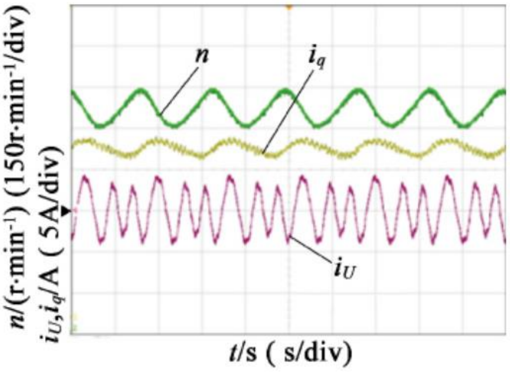
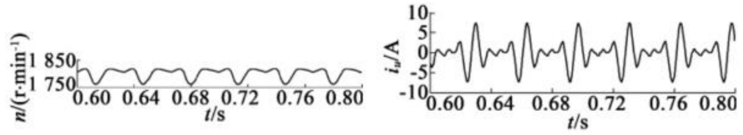


Figure 8: Real shot waveform without torque feedforward compensation

The system is controlled according to the feedforward compensation strategy in this paper. FIG. 9 is the simulation waveform of motor speed and phase current, and FIG. 10 is the compensation control experiment waveform (the test waveform of each channel is the same as that of FIG. 8). By comparing the motor speed waveform in FIG. 8 and FIG. 10, the speed fluctuation range is reduced from 150r/min to 60r/min, which proves that the feedforward compensation control can indeed suppress the speed fluctuation of PMSM.



(a) Rotational speed (b) U-phase current

Figure 9: Simulation waveform of torque feedforward compensation

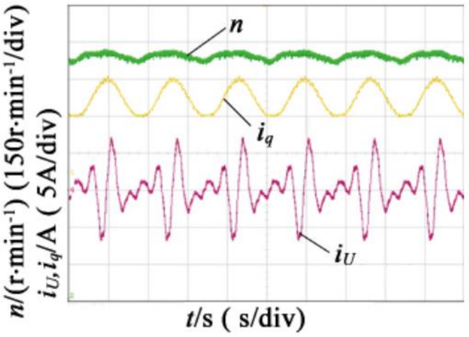


Figure 10: Real shot waveform of torque feedforward compensation

As shown in Figure 10 the phase current distortion caused by torque feedforward compensation is very serious, and the maximum peak value of U-phase current reaches 13.9A, while the minimum peak value is only 1A. In the case of torque compensation at an outdoor temperature of 60℃, the peak value of the phase current can even reach 25A. In order to ensure the effectiveness of feedforward compensation control, the magnetic circuit design parameters of compressor motor need to be adjusted accordingly[4].

6. Conclusion

The aim of this study is to explore the feedforward compensation control technology of permanent magnet synchronous motor based on load period fluctuation, in order to improve the running stability and control accuracy of the motor. By introducing the working principle and characteristics of PMSM and analyzing the influence of load period fluctuation on motor performance, it is found that load period fluctuation will lead to the increase of motor vibration and unstable operation. In order to solve these problems, the feedforward compensation control technology is proposed. By accurately measuring and predicting the characteristics of the load cycle fluctuation and adjusting the motor control strategy in real time, the effect of load fluctuation on the motor performance can be effectively eliminated, and the operation stability and control accuracy of the motor can be improved. The performance and effect of the control technology are evaluated by means of experimental verification and simulation. The research results show that the feedforward compensation control technology based on load period fluctuation of permanent magnet synchronous motor has significant advantages and application potential. By using this technology, the influence of load period fluctuation on the motor performance is successfully suppressed, the stable operation of the motor is realized, and the control precision of the motor is improved. This provides an effective solution for further promoting the development and application of motor technology. In conclusion, this study provides valuable reference and enlightenment for scholars and researchers in related fields through in-depth research and exploration of feedforward compensation control technology based on load period fluctuation of permanent magnet synchronous motor. In the future, the research will continue to focus on the research in this field, further improve and optimize the control technology, and promote its promotion and application in practical engineering applications.

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