

Torque Ripple Suppression in Permanent Magnet Synchronous Motor Drives Using a Quasi-Resonant Controller

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Abstract: Torque ripple caused by current harmonics degrades the steady-state performance of permanent magnet synchronous motor (PMSM) drive systems and may introduce undesirable speed fluctuations, mechanical vibration, and acoustic noise. This paper investigates a quasi-resonant control method for suppressing the current harmonics associated with torque ripple in a PMSM drive. The relationship among phase-current harmonics, periodic components in the synchronous reference frame, and electromagnetic torque ripple is first analyzed. Several commonly used suppression strategies, including multiple rotating reference frames, extended state observers, adaptive notch filters, repetitive control, and neural-network-based compensation, are then compared in terms of their operating principles, advantages, limitations, and implementation complexity. On this basis, a quasi-resonant controller is incorporated into the q-axis current-control loop to increase the loop gain around the target harmonic frequency. The controller retains the basic field-oriented control structure and requires only a small number of parameters, facilitating practical implementation and parameter tuning. Experiments are conducted on a physical PMSM drive platform. The measured current waveforms show that the flattening and local distortion around the phase-current peaks are reduced after the quasi-resonant controller is enabled, while stable operation of the drive system is maintained. The results demonstrate that quasi-resonant control provides a practical solution for harmonic-current attenuation and torque-ripple suppression when the dominant disturbance frequencies are known.

1. Introduction

Permanent magnet synchronous motors (PMSMs) have been widely employed in robotic joints, computer numerical control machine tools, electric vehicles, and high-performance servo systems because of their high power density, high efficiency, fast dynamic response, and compact structure. Nevertheless, periodic torque ripples are inevitably introduced by machine imperfections, inverter

nonlinearities, and current measurement errors. Torque ripples not only degrade the speed- and position-control accuracy but may also induce mechanical vibration and acoustic noise, thereby affecting the operational stability and service life of the drive system. Previous studies have shown that air-gap field harmonics, cogging effects, back-electromotive-force distortion, and current harmonics are among the major sources of electromagnetic torque ripple [1].

Existing torque-ripple suppression methods can generally be classified into machine-design optimization and control-based compensation. Machine-design optimization reduces specific torque harmonics by modifying the permanent-magnet shape, rotor geometry, or slot-pole combination. However, such methods usually require structural modifications to the machine, resulting in a relatively long design cycle and increased manufacturing cost. By contrast, control-based compensation suppresses periodic disturbances by modifying the current or voltage references without changing the machine structure and therefore provides greater flexibility in practical implementation. Lyu et al. optimized the harmonic current references to reduce torque ripple while considering the dc-link voltage limit [2]. Hu et al. modeled periodic disturbances as extended states and developed an extended harmonic state observer for real-time disturbance estimation and attenuation [3]. Wang et al. suppressed the dominant stator-current harmonics through reference-frame transformations, harmonic extraction, and closed-loop regulation [4].

Multiple rotating reference frames (MRRFs), extended state observers (ESOs), adaptive notch filters (ANFs), repetitive controllers (RCs), and neural-network-based compensators have all been investigated for current-harmonic or torque-ripple suppression. However, these methods differ considerably in computational burden, parameter tuning, dynamic performance, and implementation complexity. Steffen et al. compared several torque-ripple control approaches and indicated that the achievable suppression performance should be balanced against implementation complexity [5]. For periodic disturbances with known characteristic frequencies, a resonant controller can provide high loop gain around a specified frequency and consequently reduce the corresponding steady-state tracking error. Compared with methods that require multiple reference-frame transformations or complex disturbance models, resonant control has a clear structure, physically meaningful parameters, and good compatibility with conventional field-oriented control systems [6].

Accordingly, this paper investigates the use of a quasi-resonant controller for torque-ripple suppression in a PMSM drive. First, the relationship between current harmonics and electromagnetic torque ripple is analyzed. Several commonly used suppression strategies are then compared in terms of their operating principles, advantages, limitations, and implementation complexity, with particular attention paid to the structure and parameter characteristics of the quasi-resonant controller. Finally, experiments are conducted on a physical PMSM drive platform, and the phase-current waveforms obtained before and after harmonic suppression are compared. Rather than introducing a highly complex controller, this study focuses on the practical characteristics of quasi-resonant control, including its straightforward implementation, intuitive parameter tuning, and compatibility with an existing vector-control system.

2. Problem Formulation

The mechanical dynamics of the PMSM are described by (1). The imbalance between the electromagnetic torque and load torque determines the variation in rotor speed. When the electromagnetic torque contains periodic ripple components, these components are transmitted through the mechanical drive train and result in periodic speed and position fluctuations. Although the mechanical inertia can attenuate some high-frequency components, torque ripple may still have a considerable effect on low-speed, high-precision, or low-stiffness drive systems.

$$T_e - T_L - B\omega = J \frac{d\omega}{dt} \quad (1)$$

The electromagnetic torque of a PMSM in the synchronous reference frame is expressed by (2). For a surface-mounted permanent magnet synchronous motor (SPMSM), the (d)- and (q)-axis inductances can generally be considered approximately equal. Consequently, the reluctance-torque component can be neglected, and the electromagnetic torque equation can be simplified as given in (3). Equation (3) indicates that the electromagnetic torque is proportional to the (q)-axis current when the permanent-magnet flux linkage and machine parameters remain approximately constant. Therefore, periodic harmonics in the (q)-axis current are directly reflected as electromagnetic torque ripples at the corresponding frequencies.

$$T_e = 1.5 p_n [\psi_f i_q + (L_d - L_q) i_d i_q] \quad (2)$$

$$T_e = 1.5 p_n \psi_f i_q \quad (3)$$

Under ideal operating conditions, the three-phase stator currents are sinusoidal, have equal amplitudes, and are displaced from each other by 120 electrical degrees. In an actual drive system, however, the phase currents contain harmonics of different orders because of back-EMF harmonics, inverter dead-time effects, voltage drops across power devices, and current-sensor errors. The resulting phase currents are expressed by (4).

$$\begin{aligned} i_a &= I_m \cos \theta_e \\ i_b &= I_m \cos(\theta_e - 2\pi/3) \\ i_c &= I_m \cos(\theta_e + 2\pi/3) \end{aligned} \quad (4)$$

After the three-phase currents are represented using a complex space vector, the stator-current space vector can be written as (5). According to the reference-frame transformation, positive- and negative-sequence harmonics in the stationary reference frame are transformed into ac components at different frequencies in the synchronous reference frame.

$$i_s = \frac{2}{3} (i_a + i_b e^{j2\pi/3} + i_c e^{-j2\pi/3}) = I_m e^{j\theta_e} \quad (5)$$

In particular, the fifth- and seventh-order phase-current harmonics are both transformed into sixth-order ripple components in the synchronous reference frame [4], as described by (6). Because the electromagnetic torque of an SPMSM is primarily determined by the (q)-axis current, the sixth-order component in the (q)-axis current produces a torque ripple at six times the electrical angular frequency. Higher-order phase-current harmonics can be analyzed in the same manner and mapped to the corresponding disturbance frequencies in the synchronous reference frame.

$$i_{dq} = I_1 + I_5 e^{-j6\omega_e t} + I_7 e^{j6\omega_e t} \quad (6)$$

The torque-ripple suppression problem can therefore be converted into the suppression of specific ac components in the (q)-axis current. A conventional proportional–integral (PI) controller provides satisfactory steady-state tracking of dc references. However, its gain decreases as the disturbance frequency increases, making it difficult to eliminate periodic current errors in the synchronous reference frame. An additional control element capable of providing high gain around the target frequency is therefore required to improve harmonic rejection without substantially changing the original current-control structure.

3. Methodology

3.1. Comparison of Different Control Strategies

Several control methods have been investigated for suppressing current harmonics and torque ripples in PMSM drives. Their operating principles, advantages, limitations, and implementation complexities are summarized in Table 1.

Table 1: Technical comparison of different control strategies.

Method	Principle	Key advantages	Limitations	Complexity
MRRF	Convert harmonics to DC components via rotating frames for PI control	Clear physical meaning, compatible with standard FOC	Computation increases with harmonic orders; complex coordinate transform	High
(PR)	Resonant controller provides infinite gain at target frequency	No coordinate transform; simple frequency tuning	Sensitive to frequency variation; requires high discretization precision	Medium
ESO	Treat harmonics as disturbance for real-time estimation and compensation	Model-independent, strong disturbance rejection	Multiple tuning parameters; phase lag at high harmonic frequencies	High
ANF	Adaptive notch filter to track and cancel specific harmonic frequencies	Strong adaptability, auto-lock disturbance center frequency	Trade-off between bandwidth and convergence; reduces phase margin	Medium
RC	Repetitive control based on internal model principle for periodic error suppression	High steady-state accuracy, suppress multiple harmonics	Slow dynamic response, large memory buffer requirement	High
NN	Neural network uses nonlinear mapping to learn and compensate harmonic features	Strong adaptability for complex nonlinear disturbance	Heavy computational cost; black-box, difficult stability proof	Very High

The multiple rotating reference frame (MRRF) method transforms selected harmonic components into dc quantities and regulates them using PI controllers. It has a clear physical interpretation but requires additional coordinate transformations and control branches for each target harmonic. Extended state observers (ESOs) estimate and compensate for lumped disturbances without relying entirely on an accurate model, whereas their design and parameter tuning become more complicated when multiple harmonic frequencies are considered [3].

Adaptive notch filters (ANFs) can track frequency-varying disturbances, but their bandwidth must be selected by considering convergence rate and stability margin. Repetitive control (RC) provides high steady-state accuracy for periodic disturbances and can suppress multiple harmonics simultaneously. However, it requires additional data storage and generally exhibits a relatively slow transient response [7]. Neural-network-based compensation can handle nonlinear and uncertain disturbances but involves greater computational effort and implementation complexity [8].

In comparison, a resonant controller can selectively increase the loop gain around a specified frequency without requiring multiple reference-frame transformations or a complex disturbance model [9], [10]. Therefore, when the dominant harmonic frequencies are known, resonant control provides a practical balance among harmonic attenuation, computational burden, and implementation complexity.

3.2. Quasi-Resonant Controller

An ideal resonant controller provides theoretically infinite gain at the resonant frequency, but its effective frequency range is extremely narrow. Its performance is therefore sensitive to frequency deviations and digital implementation errors. To improve practical robustness, the quasi-resonant controller expressed in (7) is adopted in this study.

$$G(s) = \frac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (7)$$

In (7), K_r denotes the resonant gain, ω_c is the resonant bandwidth parameter, and ω_0 is the target resonant angular frequency. The quasi-resonant controller provides a high but finite gain over a limited frequency range around ω_0 , thereby reducing its sensitivity to small deviations in the disturbance frequency [6].

As discussed in Section 2, the fifth- and seventh-order phase-current harmonics are transformed into sixth-order components in the synchronous reference frame. Accordingly, the center frequency of the quasi-resonant controller is set to the corresponding sixth-order electrical frequency. The resonant branch is connected in parallel with the original PI current controller. The PI controller regulates the dc current component, whereas the quasi-resonant controller attenuates the periodic current error around the target frequency.

Increasing K_r strengthens harmonic attenuation but may reduce the stability margin, while ω_c determines the compromise between frequency selectivity and tolerance to frequency variations. In practical tuning, ω_0 is first determined from the electrical angular frequency, after which K_r and ω_c are adjusted to balance harmonic suppression and system stability. This structure requires only a small number of parameters and can be incorporated into an existing field-oriented control system with limited modification.

4. Results and Discussion

4.1. Experiment Setup

A physical experimental platform was constructed to evaluate the current-harmonic and torque-ripple suppression performance of the quasi-resonant controller, as shown in Figure 1. The experimental setup mainly consists of a PMSM, a power converter, a digital controller, current- and position-sensing units, a dc power supply, a loading device, and a host-computer-based data-acquisition system.

The digital controller performs current sampling, reference-frame transformations, speed- and current-loop calculations, quasi-resonant control, and pulsewidth-modulation signal generation. The power converter drives the PMSM according to the modulation signals generated by the controller. The current-sensing unit measures the three-phase stator currents and feeds the sampled signals back to the controller.

A field-oriented control structure is adopted for the PMSM drive. The quasi-resonant controller is connected to the (q)-axis current-control channel as an additional harmonic-suppression branch. To ensure a consistent comparison, the machine, load condition, sampling period, and basic PI-

controller parameters remain unchanged in the experiments conducted before and after harmonic suppression. Only the operating state of the quasi-resonant control branch is changed.

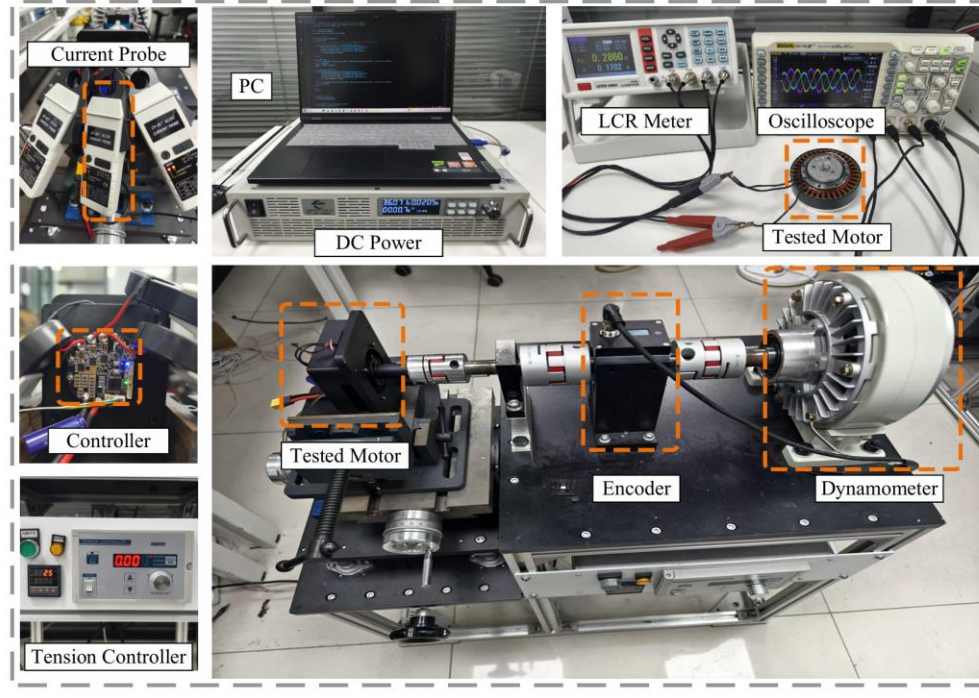


Figure 1: Physical verification platform for the proposed method.

4.2. Experiment Results

Figure 2 shows the overall waveforms of the three-phase currents and the (q)-axis current during the experiment. Over the main operating interval, the three-phase currents exhibit stable periodic variations, while the (q)-axis current remains close to its reference value. These results indicate that the drive system operates stably under the specified experimental condition.

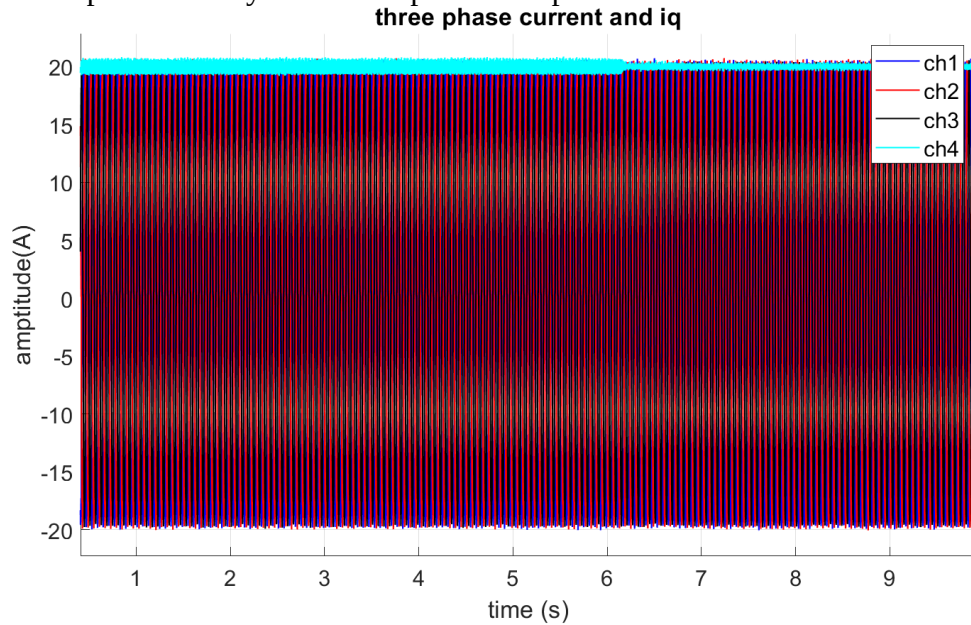


Figure 2: Comparison Before and After Harmonic Suppression and Compensation.

At approximately 5.8 s, the experiment is terminated. The amplitudes of the three-phase currents decrease rapidly, and the (q)-axis current reference is reduced to zero. Therefore, the waveform variation occurring at this instant corresponds to the termination of the experiment rather than instability during normal operation. No sustained oscillation or divergence is observed while the quasi-resonant controller is active, indicating that the additional resonant branch can operate together with the original field-oriented control system.

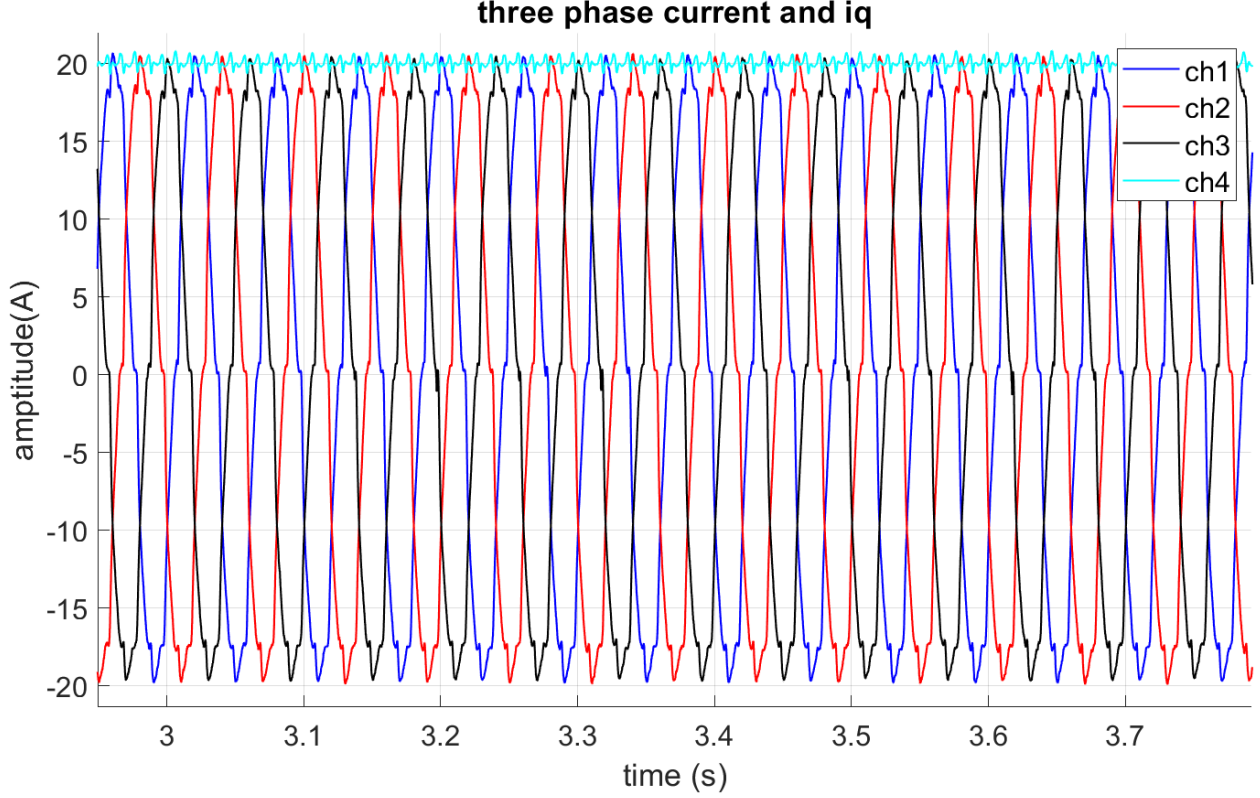


Figure 3: Phase current waveform before harmonic suppression and compensation.

Figure 3 shows the local current waveforms before harmonic suppression. Although the three-phase currents retain an approximately 120° phase displacement, the individual phase-current waveforms exhibit visible nonsinusoidal distortion. In particular, waveform flattening and deformation can be observed around the positive and negative peaks. This result indicates that the conventional current regulator can maintain the basic amplitudes and phase relationships of the three-phase currents but has limited rejection capability for periodic current errors at specific frequencies.

According to the mechanism discussed in Section 2, these phase-current harmonics are transformed into periodic components in the (q)-axis current in the synchronous reference frame. The resulting (q)-axis current ripple subsequently produces electromagnetic torque ripple at the corresponding frequency.

Figure 4 shows the local current waveforms after the quasi-resonant controller is enabled. Compared with Fig. 3, the phase-current waveforms are smoother around their positive and negative peaks, and the flattening and local deformation are reduced. Consequently, the three-phase currents more closely resemble sinusoidal waveforms. Meanwhile, their amplitudes and phase relationships remain stable. These results indicate that the quasi-resonant controller increases the loop gain around the target harmonic frequency and consequently attenuates the corresponding current-harmonic components without modifying the basic field-oriented control structure.

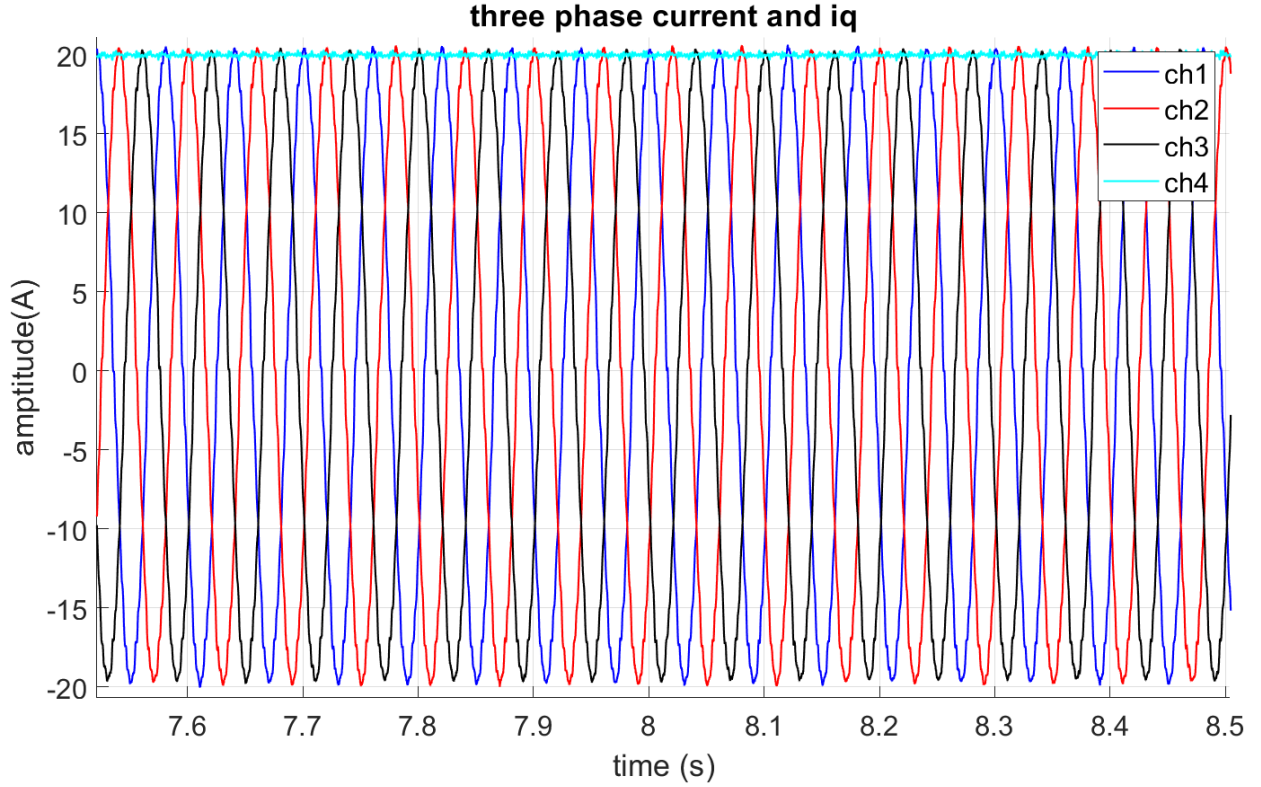


Figure 4: Phase current waveform after harmonic suppression and compensation.

A comparison between Figs. 3 and 4 also shows that enabling the resonant branch does not disturb the basic symmetry of the three-phase currents or introduce noticeable high-frequency oscillations. This behavior can be attributed to the frequency-selective characteristic of the quasi-resonant controller. The resonant branch acts mainly over a limited frequency range around its center frequency and therefore has a relatively small effect on the dc current component and the control response at other frequencies. The PI controller and the quasi-resonant branch consequently perform complementary functions: the PI controller ensures basic current tracking, whereas the quasi-resonant branch increases the disturbance-rejection capability around the target harmonic frequency.

Overall, the results in Figs. 2–4 demonstrate that the quasi-resonant controller improves the three-phase current waveforms while maintaining stable operation of the drive system. The experimental observations are consistent with the relationship among phase-current harmonics, (q)-axis current ripples, and electromagnetic torque ripples established in Section 2. They also support the feasibility of the control structure described in Section 3. Although the available results mainly provide a qualitative comparison of the time-domain waveforms, they show that the quasi-resonant controller can achieve observable waveform improvement with only a limited modification to the existing control structure.

5. Conclusions

This paper investigated torque-ripple suppression in a PMSM drive system. The effects of machine imperfections, inverter nonlinearities, and current measurement errors on the stator currents were first discussed. The relationship among phase-current harmonics, periodic (q)-axis current components, and electromagnetic torque ripples was then established using reference-frame

transformations. On this basis, MRRF control, resonant control, ESOs, ANFs, RCs, and neural-network-based compensation were compared.

The quasi-resonant controller does not require multiple coordinate transformations or a complex disturbance model. It has a small number of parameters and can be directly incorporated into a conventional field-oriented control system. It therefore provides a practical balance among harmonic attenuation, computational burden, and implementation complexity.

The experimental results show that the flattening and distortion around the peaks of the phase-current waveforms are reduced after the quasi-resonant controller is enabled. The three-phase currents become more sinusoidal, while stable operation is maintained throughout the main experimental interval. These observations agree with the theoretical analysis and indicate that increasing the controller gain around the target frequency can attenuate specific current harmonics and thereby provide a basis for reducing the associated torque ripple.

The quasi-resonant controller nevertheless has several limitations. Its suppression performance depends on the accurate selection of the target resonant frequency. When the motor operates over a wide speed range, a fixed center frequency may deviate from the actual disturbance frequency. In addition, the resonant gain and bandwidth must be selected by considering harmonic attenuation, noise sensitivity, and stability margin simultaneously. The present experimental evaluation is also based primarily on qualitative comparisons of time-domain current waveforms. Future work may investigate frequency adjustment over a wider speed range and evaluate the stability and robustness of the controller under different speed and load conditions

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