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CURRENT HARMONIC SUPPRESSION STRATEGY OF PERMANENT MAGNET SYNCHRONOUS MOTOR BASED ON MULTI-SYNCHRONOUS ROTATING COORDINATE SYSTEM

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Abstract: This paper focuses on the harmonic problems of stator current in permanent magnet synchronous motor (PMSM) caused by factors such as magnetic circuit saturation and inverter nonlinearity, and conducts research on harmonic suppression strategies based on multiple synchronous rotating coordinate systems. Firstly, the hazards of harmonics to motor efficiency, torque stability, and system reliability are analyzed, and the engineering significance of harmonic suppression technology is expounded. On this basis, a mathematical model of PMSM containing 5th and 7th harmonics is established, and a harmonic extraction and compensation method combining low-pass filtering and closed-loop PI control in multiple synchronous rotating coordinate systems is proposed. By constructing a coordinate system that rotates synchronously with the harmonics, the harmonic components are converted into direct currents for precise suppression, and the corresponding control structure is designed to achieve harmonic voltage compensation. Simulation results show that this strategy can effectively reduce the total harmonic distortion of stator current and improve the current waveform quality at different speeds of 500 r/min and 1500 r/min, verifying the effectiveness and practicality of the proposed method under different operating conditions, and providing a feasible control solution for high-performance and low-harmonic operation of PMSMs.

Keywords: Permanent magnet synchronous motor; Multiple synchronous rotating coordinate systems; Harmonic suppression

1 INTRODUCTION

As high-end industries such as electric vehicles, smart manufacturing, and rail transit continue to evolve rapidly, permanent magnet synchronous motors (PMSMs) have emerged as essential power elements in contemporary drive systems, thanks to attributes like superior energy efficiency, compact power density, and broad speed control capability [1]. Despite these advantages, real-world operation is complicated by various nonlinear phenomena, including magnetic saturation within the motor, nonideal switching behavior in inverters, and uneven winding layouts. These factors inevitably introduce substantial harmonic components into both the air-gap magnetic field and the stator current [2]. These harmonics degrade system performance and initiate a cascade of adverse effects, undermining the overall reliability, stability, and economic efficiency of the drive system. Consequently, effective harmonic suppression has become a critical challenge in the optimal deployment of PMSMs [3].

The negative impacts of harmonics span multiple levels. On the motor level, harmonic currents increase copper and iron losses, significantly reducing operational efficiency. Additionally, harmonic magnetic fields generate extra torque ripple [4], intensifying mechanical vibrations and acoustic noise—factors that accelerate wear on critical parts like bearings. From a system standpoint, these harmonics distort grid current patterns, raise inverter switching losses, cause electromagnetic interference with neighboring precision electronics, and may even trigger protective devices in error—leading to unexpected outages or system-wide failures [5]. In safety-critical applications such as electric mobility and aerospace, such harmonic-induced defects can result in serious accidents and costly downtime [6]. Thus, advancing harmonic suppression techniques for PMSMs holds significant practical and engineering value in enhancing motor efficiency, minimizing energy waste, and ensuring stable system operation.

A range of harmonic mitigation strategies exists, including refined motor design, novel inverter topologies, and passive filtering solutions [7]. Among these, control-based approaches have gained considerable attention due to their adaptability, implementation simplicity, and lack of need for extra hardware investment [8]. One particularly effective method is the multi-synchronous rotating reference frame (MSRFR) strategy. By introducing multiple rotating coordinate systems, each synchronized with a specific harmonic frequency, this technique transforms time-varying harmonic components into steady DC quantities. This enables the use of standard PI regulators to achieve precise harmonic cancellation. The MSRFR approach is especially effective in environments with multiple concurrent harmonics, offering strong multi-harmonic suppression capability [9]. It allows for accurate tracking and compensation of individual harmonics, effectively lowering total harmonic distortion in current waveforms and improving torque smoothness. As a result, it provides a robust framework for enabling high-efficiency, stable operation of PMSM systems [10].

This study centers on the development and analysis of harmonic suppression in PMSMs using the multi-synchronous rotating reference frame method, with the goal of delivering a viable and efficient technical solution to address harmonic-related challenges in modern motor drive systems.

2 A MATHEMATICAL REPRESENTATION OF PERMANENT MAGNET SYNCHRONOUS MOTORS UNDER HARMONIC CONDITIONS

Under perfectly balanced and ideal conditions, a permanent magnet synchronous motor (PMSM) operates as a symmetric three-phase system characterized by uniform winding distribution across all phases. As a result, even-order harmonic components (such as the 3rd, 9th, 15th, etc.) are inherently suppressed due to the symmetry of the machine. Consequently, the three-phase stator currents can be described as:

$$i_A=I_m\sin(\omega t),\ i_B=I_m\sin\left(\omega t-120^\circ\right),\ i_C=I_m\sin\left(\omega t+120^\circ\right) \tag{1}$$

where i_A, i_B and i_C denote the phase currents, I_m is the amplitude of the fundamental current, and ω represents the angular frequency of the fundamental component.

In real-world operational environments, however, imperfections in the control system—including inverter dead-time effects, non-linear switching characteristics, and structural asymmetries—introduce harmonic distortions in the stator current. As a result, the actual current waveforms include significant harmonic contributions. The modified three-phase current expression becomes:

$$\begin{aligned} i_A &=I_m\sin(\omega t)+I_5\sin(5\omega t+\phi_5)+I_7\sin(7\omega t+\phi_7) \\ i_B &=I_m\sin\left(\omega t-120^\circ\right)+I_5\sin\left(5\omega t+\phi_5-120^\circ\right)+I_7\sin\left(7\omega t+\phi_7+120^\circ\right) \\ i_C &=I_m\sin\left(\omega t+120^\circ\right)+I_5\sin\left(5\omega t+\phi_5+120^\circ\right)+I_7\sin\left(7\omega t+\phi_7-120^\circ\right) \end{aligned} \tag{2}$$

Here, I_5, and I_7, represent the amplitudes of the 5th and 7th harmonic components, while φ_5 and φ_7 denote their respective initial phase angles.

Classical field-oriented control (FOC) is typically implemented in the rotating d-q reference frame. When the above current waveforms are transformed into this coordinate system, the resulting d- and q-axis currents are expressed as:

$$i_d=i_{d1}+i_{d5}+i_{d7},\ i_q=i_{q1}+i_{q5}+i_{q7} \tag{3}$$

where i_d and i_q represent the d-axis and q-axis currents in the d-q coordinate system, i_{d1}, i_{q1} are the fundamental wave components of the d-q axis currents, and i_{d5}, i_{q5}, i_{d7}, i_{q7} are the 5th and 7th harmonic components of the d-q axis currents respectively. At this time, the frequencies of the 5th and 7th harmonics are -6ω and 6ω respectively. The flux linkage in the d-q coordinate system can be obtained as:

$$\psi_d=L_di_d+\psi_f,\ \psi_q=L_qi_q \tag{4}$$

Where ψ_d and ψ_q are the flux linkages in the d- and q-axes, L_d and L_q are the corresponding inductances, and ψ_f is the flux linkage generated by the permanent magnets.

The voltage equations in the d-q reference frame are:

$$u_d=R_si_d+\frac{d\psi_d}{dt}-\omega\psi_q,\ u_q=R_si_q+\frac{d\psi_q}{dt}+\omega\psi_d \tag{5}$$

Substituting Eq. (4) into Eq. (5) yields the final form:

$$u_d=R_si_d+L_d\frac{di_d}{dt}-\omega L_qi_q\ u_q=R_si_q+L_q\frac{di_q}{dt}+\omega(L_di_d+\psi_f) \tag{6}$$

This research investigates a permanent magnet synchronous drive system with a surface-mounted magnet rotor configuration, designed for high-precision motion control applications, where the direct- and quadrature-axis inductances are equal: $L_d=L_q=L_s$. Under this condition, the electromagnetic torque expression simplifies to:

$$T_e=\frac{3}{2}p\psi_fi_q \tag{7}$$

where p is the number of pole pairs. The dynamic equation of the permanent magnet synchronous motor is expressed as: The mechanical dynamics of the motor are governed by:

$$T_e-T_L=J\frac{d\omega_m}{dt}+B\omega_m \tag{8}$$

where T_L is the external load torque, J is the rotor's moment of inertia, B is the viscous damping coefficient, ω_m is the mechanical angular velocity, and the electrical angular frequency is related by $\omega=p\omega_m$.

3 A STRATEGY FOR SUPPRESSING CURRENT HARMONICS IN PERMANENT MAGNET SYNCHRONOUS MOTORS USING A MULTI-SYNCHRONOUS ROTATING COORDINATE FRAMEWORK

In the framework of the 5th and 7th harmonic rotating reference systems, these specific harmonic components are treated as fundamental frequency components. Therefore, the initial step involves transforming the d-q reference system into the respective 5th and 7th harmonic current components. The corresponding coordinate transformation matrix is presented below:

$$C_{dq/dq5}=\begin{bmatrix}\cos 5\theta & -\sin 5\theta \\ \sin 5\theta & \cos 5\theta\end{bmatrix} \tag{9}$$

Formula (9) provides the transformation matrix for converting the stator current into the current in the 5th synchronous rotating coordinate system, where C3s/2s and C2s/2r represent the Clark and Park transformation matrices, respectively, and Cdq/dq5 is the matrix used to transform the d-q coordinate system into the dq5 coordinate system. Due to the opposite rotation direction of the d-q axis relative to the 5th synchronous coordinate system (dq5), the coordinate transformation matrix for the 7th harmonic is as follows:

$$C_{dq/dq7}=\begin{bmatrix}\cos 7\theta & -\sin 7\theta \\ \sin 7\theta & \cos 7\theta\end{bmatrix} \tag{10}$$

After utilizing the multi-synchronous rotating coordinate system to extract the 5th and 7th harmonics from the original dq coordinate system, it is essential to apply a low-pass filter to the obtained harmonic currents. In the dq5 and dq7 coordinate systems, the original 5th and 7th harmonics are considered fundamental components, so non-fundamental current components can be eliminated through the low-pass filter. The detailed control concept is illustrated in Figure 1.

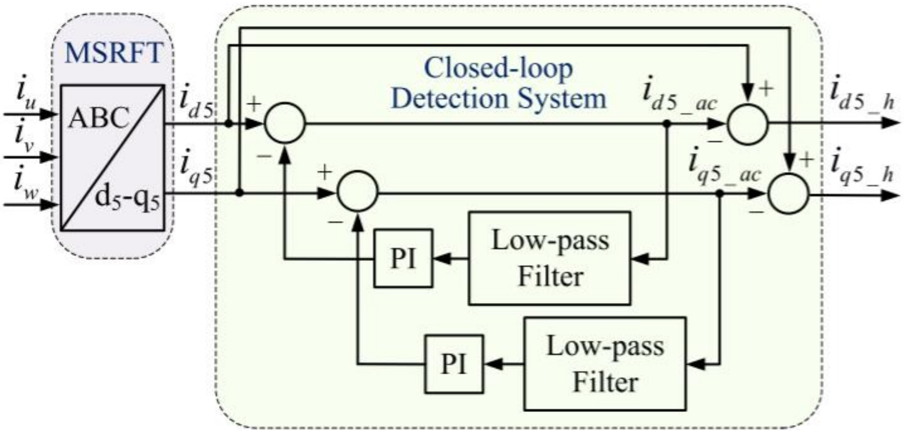

Figure 1 Schematic Diagram of the Harmonic Suppression Control Strategy Based on a Multi-Synchronous Rotating Reference Frame

As shown in Figure 1, this research employs a closed-loop PI control system along with a low-pass filter to accurately isolate the 5th and 7th harmonic components. This technique shows robust effectiveness in identifying harmonics. Upon detection of the 5th and 7th harmonic current components, they are converted into equivalent harmonic voltage components, which are then used as reference signals for the inverter's voltage input. This method results in a notable reduction of harmonic distortion in the motor stator current and effectively lowers the total harmonic distortion (THD) of the three-phase current. Figure 2 details the procedure of converting identified harmonic current components into their corresponding voltage harmonics.

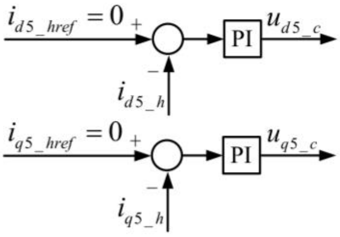

Figure 2 Calculation Method of 5th Harmonic Voltage of Stator Current

Calculation method of 5th harmonic voltage of stator current is shown in Figure 2.

4 SIMULATION AND RESULT ANALYSIS

4.1 Introduction to Simulation Platform and Simulation Conditions

In order to verify the performance of the current harmonic suppression method for permanent magnet synchronous motors (PMSM) using a multi-synchronous rotating reference frame, a simulation model is constructed in MATLAB-Simulink. The model includes the motor's electrical characteristics, control logic, and inverter configuration. For the experimental implementation, a 0.75 kW PMSM serves as the test motor, running at 1500 rpm under standard operating conditions. This motor is selected for its efficiency and rapid response characteristics, providing a reliable basis for evaluating the control strategy's behavior in practical applications. A variety of operational cases are designed and executed to assess the method's ability to suppress the 5th and 7th harmonic currents in the stator. The main motor specifications are detailed in Table 1.

Table 1 Key Parameters of the Prototype

Parameter	Value/Unit	Parameter	Value/Unit
Number of slots	12	Rated torque	2.4 N·m
Number of pole pairs	4	Flux density	0.09356 Wb
Rated speed	1500 rpm	Stator resistance	1.54 Ω
Rated power	0.75 kW	Inductance	5.28 mH

4.2 Comparative Analysis of Experimental Results at 500 r/min with 2 μs Dead Time

To assess and compare the performance of the stator current harmonic suppression strategy for a permanent magnet synchronous motor (PMSM) based on a multi-synchronous rotating reference frame, Fast Fourier Transform (FFT) analysis is performed on the phase current signals using the MATLAB-Simulink simulation platform. The analysis is carried out under two distinct operating speeds: 500 rpm and 1500 rpm. Figures 3 and 4 present the total harmonic distortion (THD) levels and the corresponding stator winding current waveforms before and after harmonic suppression at a motor speed of 500 rpm.

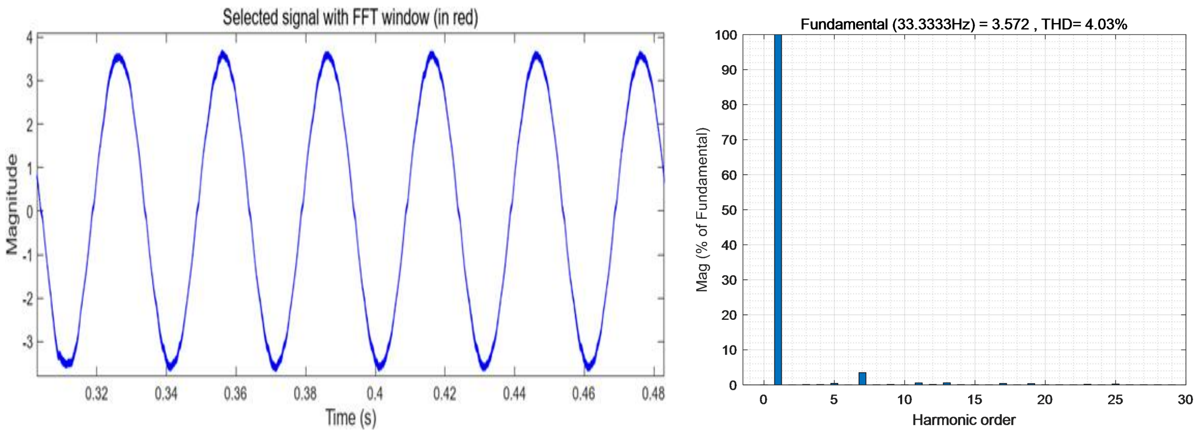

Figure 3 FFT Analysis without Harmonic Suppression (n=500 rpm)

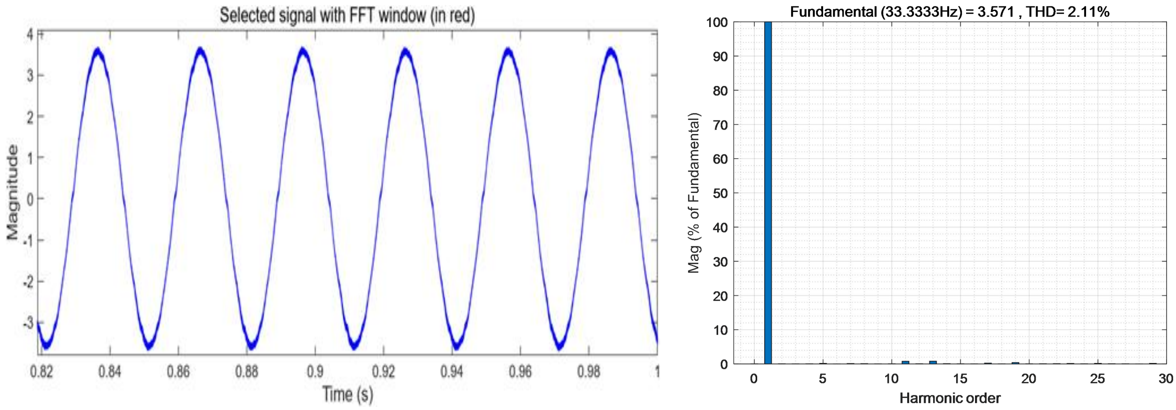

Figure 4 FFT Analysis with Harmonic Suppression (n=500 rpm)

As shown in Figure 3 and Figure 4, after implementing the harmonic suppression technique, the total harmonic distortion (THD) of the phase current decreases from 4.03% prior to suppression to 2.11%, accompanied by a noticeable improvement in the waveform quality. This demonstrates that the proposed harmonic suppression strategy effectively reduces current harmonics and significantly enhances current waveform purity, particularly under low-speed operating conditions.

4.3 Comparative Analysis of Experimental Results at 1500 r/min with 2 μs Dead Time

Figure 5 and Figure 6 respectively show the THD of the stator current and the corresponding waveform before and after harmonic suppression when the motor speed is 1500 rpm.

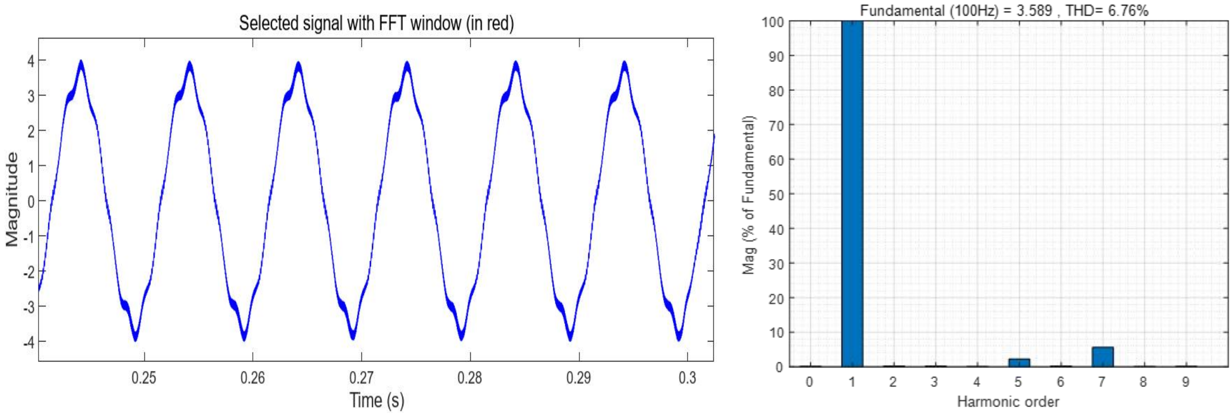

Figure 5 FFT Analysis without Harmonic Suppression (n=1500 rpm)

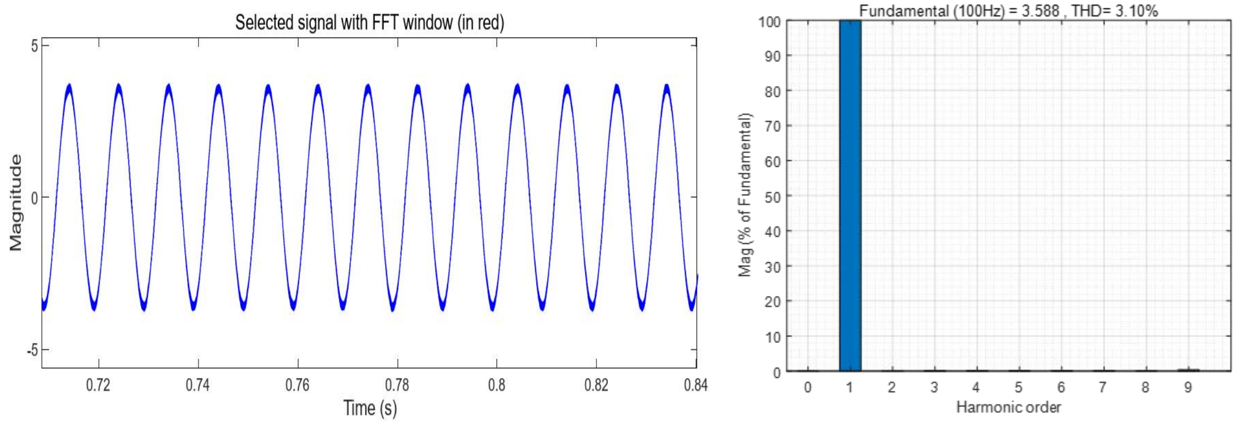

Figure 6 FFT Analysis with Harmonic Suppression (n=1500 rpm)

As depicted in Figures 5 and 6, after implementing the harmonic cancellation technique, the total harmonic distortion (THD) of the phase current drops from 4.03% to 2.11%, showing a clear enhancement in the quality of the current waveform. A comparison of the simulation outputs supports the close match between experimental results and theoretical predictions. This suggests that the control strategy is highly reliable and performs consistently under diverse operating scenarios. Additionally, the method proves to be effective across different rotor speeds, highlighting its flexibility and operational stability. Consequently, the PMSM-based approach for suppressing current harmonics using a multi-synchronous rotating coordinate system is found to be both practical and promising for wider engineering applications.

5 CONCLUSION

In the field of permanent magnet synchronous motor (PMSM) control, the suppression of stator current harmonics plays a vital role in improving overall system performance. This paper conducts an in-depth investigation into a current harmonic suppression technique for PMSM, leveraging a multi-synchronous rotating reference frame. Through the analysis of the motor's mathematical model and its harmonic behavior, a new strategy for harmonic detection and compensation is introduced. This approach combines low-pass filtering with closed-loop PI control within multiple synchronous rotating coordinate systems. Simulation outcomes reveal that the method effectively suppresses harmonics under diverse operating conditions, leading to a substantial decrease in the total harmonic distortion (THD) of the stator current, improved waveform quality, and enhanced operational stability and efficiency. As a result, the method presents a viable technical solution for high-performance control in real-world engineering contexts.

Nevertheless, existing research still encounters several constraints. The validation is primarily carried out under ideal simulation environments and lacks consideration for practical challenges such as electromagnetic interference, sensor noise, and time-varying motor parameters like winding resistance, inductance, and flux linkage. Furthermore, traditional low-pass filters and PI controllers are known to cause phase lag and limit the speed of dynamic tracking. In addition, the current approach is specific to the elimination of the 5th and 7th order harmonics and does not account for higher-order components.

Looking ahead, future efforts will prioritize the development of a physical test platform to assess the method's robustness and its ability to resist disturbances in real-world environments. To address the limitations of conventional filters, advanced algorithms such as the second-order generalized integrator (SOGI) will be introduced, which can minimize phase delay and improve the accuracy and responsiveness of harmonic detection in real-time. The method's scope will also be broadened to include the suppression of higher-order harmonics, such as the 11th and 13th. Rigorous testing will be performed under complex and dynamic conditions—including sudden load fluctuations and wide-speed-range operation—to further enhance the method’s adaptability, reliability, and effectiveness in high-end industrial drive systems.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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