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Hybrid Carrier Frequency Modulation Based on Rotor Position to Reduce Sideband Vibro-Acoustics in PMSM Used by Electric Vehicles

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Abstract: In the permanent magnet synchronous motor (PMSM) drive system, the unwilling and ear-piercing vibro-acoustics caused by high-frequency sideband harmonics becomes unacceptable in electric vehicle applications. In this paper, a modified space vector pulse width modulation (SVPWM) technique implemented with a hybrid carrier frequency modulation (HCFM) is provided to reduce the sideband current harmonic components and vibro-acoustic responses. The principle and implementation of the proposed HCFM technique are firstly presented in which the fixed carrier frequency is improved with the sawtooth and random signal-based coupling modulation based on the rotor position. The analytical derivations with the power spectral density method are also proposed. For verification, the experiment tests are conducted on a prototype 12/10 PMSM and microcontroller unit. The effectiveness of the HCFM technique can hence be confirmed considering the sideband vibro-acoustics reduction operated more effectively than that in a conventional random PWM. The proposed approach may provide a new route in noise-cancelling and electromagnetic compatibility for the electric drive powertrain.

Keywords: permanent magnet synchronous motor; sideband harmonic component; space vector pulse-width modulation; carrier frequency modulation; vibro-acoustic responses



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1. Introduction

In recent years, permanent magnet synchronous motor (PMSM) driven with pulse width modulation (PWM) techniques have been widely used in electric vehicles (EVs) and hybrid electric vehicles (HEVs) [1–3]. The high-frequency vibro-acoustics responses introduced by sideband voltage/current harmonics are mainly located and contribute to the carrier frequency and its multiples that produce more noise, vibration, and harshness (NVH) challenges during the design and optimization stages [4].

Electromagnetic vibro-acoustics have been confirmed as the most significant contributor to the PMSM system due to electromagnetic forces on the stator and rotor caused by the air-gap magnetic fields. The research on the harmonic components and vibro-acoustics has been investigated by several researchers in the following aspects:

(1). Regarding the analytical prediction, the sideband voltage and current harmonic spectrum under pulse width modulation (PWM) are studied as the mechanism by using the double Fourier series [5]. The analytical model of the symmetrical regular sampled the expressions of sideband phase voltage and the corresponding harmonic currents are proposed to derive the pattern of the sideband components in each relation [6]. Further investigations into the sideband electromagnetic vibration are then provided by analyzing

the critical permanent magnet (PM) field, armature reaction, and sideband magnetic field components [7].

(2). Regarding the influencing features and diagnosis, the corresponding performances associated with different features such as the cogging torque [8], torque ripple [9], mechanical fault [10], and even control strategies have been studied.

(3). Regarding the optimization of the sideband acoustic noise for improving the acoustics characters, although the sideband noise can be reduced by increasing the carrier frequency above 20 kHz, the noise cannot be eliminated and experiences some negative effects during operation [11]. Generally, it can be confirmed that the sideband harmonic components are related to the frequency modulation (FM) that is affected by the rotating speed of the motor [7,12]. Hence, the most fundamental solution in reference to the principle of the Parseval is using the spread spectrum modulation techniques to extend the concentrated sideband harmonic components [12,13].

In sum, the high-frequency sideband vibro-acoustics is related to the voltage source inverter (VSI) and space vector PWM (SVPWM). The fixed carrier frequency causes the current harmonic components to contribute around the carrier frequency and its multiples. The ear-piercing vibro-acoustic responses can thus be produced. In order to reduce the sideband components, some effective methods have been presented. The most representative method is called the harmonics spread spectra (HSS) technique, used in modulations such as periodic signal-based dithering modulation [14,15] and random pulse width modulation (RPWM) [16]. The periodic dithering modulation transfers the fixed carrier frequency to the determined periodic ways including the sawtooth, sinusoidal, and square [12,15]. Alike to the RPWM, the carrier frequency would be randomly distributed within a defined range [17]. However, the related single-HSS technique would exhibit a saturating and limiting effect such that the sideband components cannot be further reduced [18], in addition to other negative influences, increasing the total harmonic distortion (THD) [19] and electromagnetic interference (EMI) [20] on the power converter system.

Consequently, this paper presents a novel hybrid carrier frequency modulation (HCFM) method to modify the conventional space vector pulse width modulation (SVPWM) technique. Based on the single-HSS method, the fixed carrier frequency in the HCFM can be dithered by coupling the sawtooth and random signal-based patterns with different rotor position angles. Moreover, the explanation of sideband harmonics reduction has been also proposed with the power spectral density method. The corresponding experimental tests are presented with great practical significance to verify the reduction effects of the proposed HCFM.

The paper is organized into five sections. Following this introduction, the principle and implementation of the HCFM technique are presented in Section 2. The experimental setup is presented in Section 3. Then, the sideband current harmonics and vibro-acoustic results among the SVPWM, RPWM, and the proposed HCFM are presented in Section 4. Finally, the conclusion is summarized in Section 5.

2. Hybrid Carrier Frequency Modulation

2.1. Principle and Implementation of the HCFM

The implementation of the conventional SVPWM is shown in Figures 1 and 2. Considering Sector I as an example, the output PWM signals, q-axes voltages, and q-axes current are shown in Figure 3.

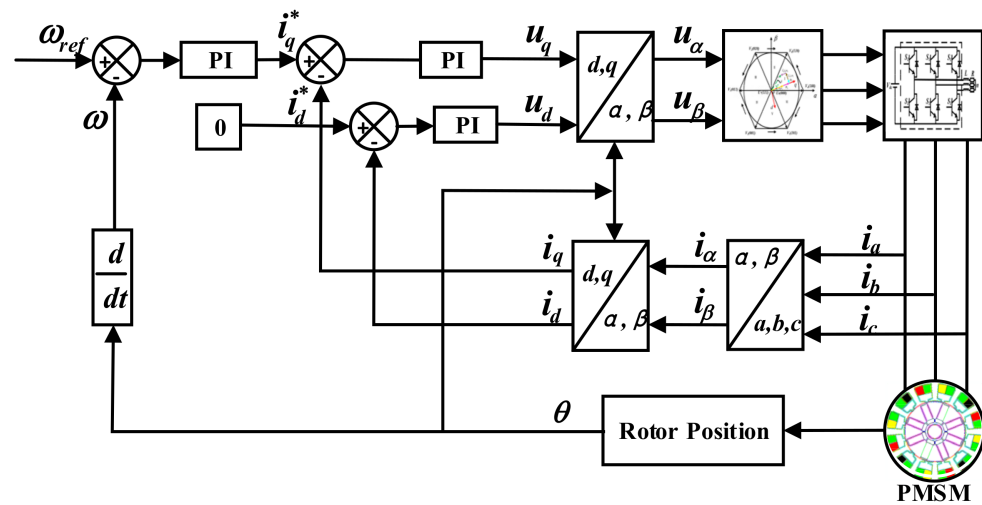


Figure 1. Implementation of the control system.

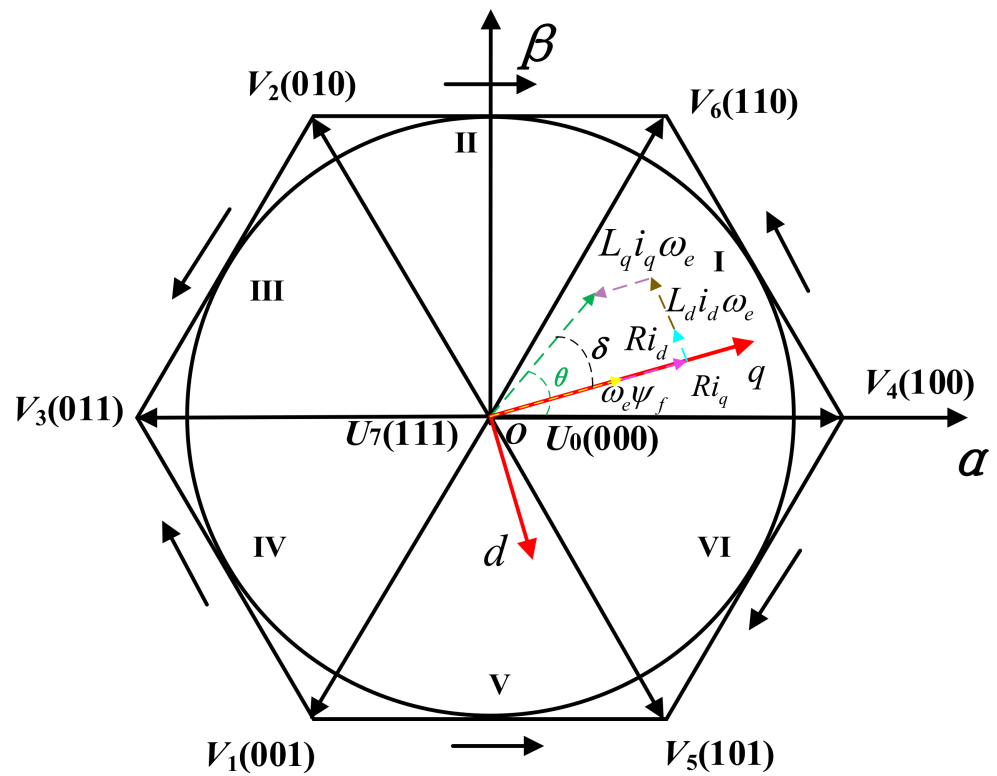


Figure 2. Principle of the conventional SVPWM.

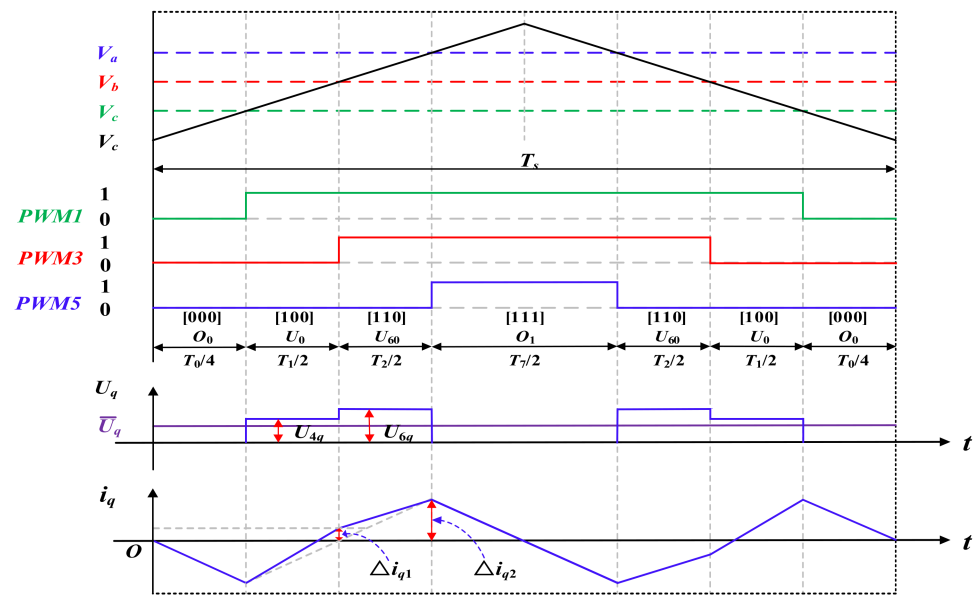


Figure 3. The pattern of the SVPWM in Sector I and q-axis current ripple.

With the d - q voltage calculated models, the harmonic analysis can be developed with quantitative analysis of the q -axes voltage that confirms that the sideband harmonic components are related to the time duration of the zero-vectors T_0 and T_7 . Moreover, the time durations are also related to the rotor position [19]. Hence, the hybrid carrier frequency modulation is based on the rotor position to combine the corresponding periodic and random signal-based dithering methods that are presented in Figure 4.

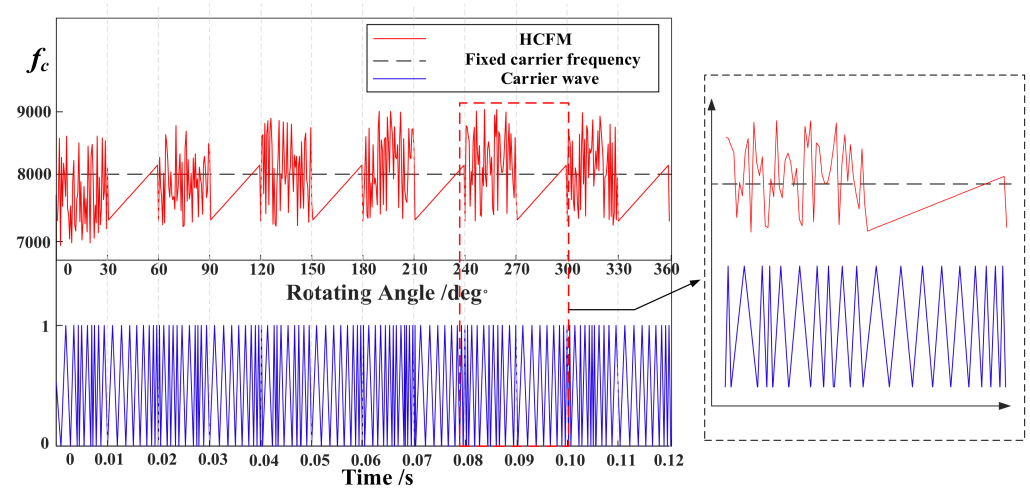


Figure 4. The variation laws and corresponding carrier waves of the carrier frequency with the HCFM.

As can be observed in Figure 4, the carrier frequency in this study is set at 8000 Hz. The periodic signal, associated with a sawtooth form, is employed while the regular random signal is also employed. The dithering range is set as 1000 Hz that indicates the modified carrier frequency is distributed between 7000 Hz and 9000 Hz. Changing with the rotating angles of the rotor, the carrier frequency dithers per 30 degrees to which the triangle waves of the carrier frequency are also presented.

2.2. Explanation of the Sideband Harmonics Reduction

Neglecting the stator resistance, the d - q axes voltages in Sector I can be expressed as

$$\begin{cases} U_d = -\omega_e L_q i_q \\ U_q = \omega_e (L_d i_d + \psi_f) \end{cases} \quad (1)$$

where ω_e is the rotating electric angle; i_d and i_q are the d - q axes current components; ψ_f is the PM flux; and L_d and L_q are the d - q axes synchronous inductance components.

The working angle in the steady-state can be expressed as δ . Acting with U_4 and U_6 separately, d - q -axes voltages can be expressed, respectively, as

$$\begin{cases} U_{4d} = \frac{2}{3} U_{dc} \sin(\theta - \delta) \\ U_{4q} = \frac{2}{3} U_{dc} \cos(\theta - \delta) \end{cases} \quad (2)$$

$$\begin{cases} U_{6d} = -\frac{2}{3} U_{dc} \sin(\delta - \theta + \frac{\pi}{3}) \\ U_{6q} = \frac{2}{3} U_{dc} \cos(\delta - \theta + \frac{\pi}{3}) \end{cases} \quad (3)$$

The analysis of the sideband harmonics can be proposed by the quantitative analysis of the q -axis voltages.

$$U_q = \frac{T_4}{T_s} U_{4q} + \frac{T_6}{T_s} U_{6q} \quad (4)$$

where T_4 and T_6 can be expressed by using the phase voltage amplitude (U_m) and the vector clamping angle (θ).

$$T_4 = \sqrt{3} \frac{U_m}{U_{dc}} T_s \sin(60^\circ - \theta) \quad (5)$$

$$T_6 = \sqrt{3} \frac{U_m}{U_{dc}} T_s \sin \theta \quad (6)$$

$$\begin{aligned} T_0 &= T_s - T_4 - T_6 \\ &= T_s \left[1 - \frac{\sqrt{3} U_m}{U_{dc}} \cos(\theta - 30^\circ) \right] \end{aligned} \quad (7)$$

With Equations (2), (3), and (7) in sum, the phase wave in one period can be obtained as depicted in Figure 3. Then, the first and second orders of current harmonics, Δi_{q1} and Δi_{q2} , can be presented as

$$\Delta i_{q1} \approx \frac{U_m T_s \cdot \left[\sin(60^\circ + \delta) - \sin \frac{\delta}{2} \right]}{4\sqrt{3} L_q} \quad (8)$$

$$\Delta i_{q2} \approx \frac{U_q T_s}{4 L_q} \cdot \left[1 - \frac{\sqrt{3} U_m}{2 U_{dc}} \right] \quad (9)$$

In reference to Equations (8) and (9), the second order of current harmonics mainly affects the q -axis current harmonic components. Moreover, the magnitude of Δi_q is determined by T_0 , L_q , and U_q . In this study, T_0 can thus be optimized by the rotor position to reduce the sideband harmonics. The optimized configuration is shown in Figure 4 and expressed as

$$f_s = \begin{cases} f_{t1} + R_i \Delta f \left[\frac{k\pi}{6} < \theta < \frac{(k+1)\pi}{6} \right] \\ f_c + f_{t2} \Delta f \left[\frac{(k+1)\pi}{6} < \theta < \frac{(k+2)\pi}{6} \right] \end{cases} \quad (10)$$

In Equation (9), f_c is the carrier frequency and Δf is the dithering index defining the harmonics spread range that sets 1000 Hz in this study. In addition, f_{t1} is the frequency of the sinusoidal wave, f_{t2} is the frequency of the sawtooth wave meeting as $[-1, 1]$, and R_i is the random modulation index. According to the above analysis, the novel HCFM based

on rotor position not only reduces harmonic currents but also achieves a wider spectrum extension.

2.3. Power Spectral Density Explanation of HCFM

The proposed HCFM can be considered as the sawtooth and random signal-based coupling modulation based on the rotor position. Single-HSS modulation based on the sawtooth signal method causes the sideband current harmonics from the concentrated distribution to become a wider spectrum. The sideband power can thus be reduced and the power spectral density S_H can be satisfied with the following Formula (12).

$$S_H(f, \beta) = \sum_{n=1}^{+\infty} C_n \left\{ J_0\left(\frac{4n\beta}{\pi}\right) \delta(f - nf_c) + \sum_{k=1}^{+\infty} \frac{(-1)^{k+1} J_k\left(\frac{4n\beta}{\pi}\right)}{(2k-1)^2} \left\{ \begin{array}{l} \delta[f - nf_c - k(2k-1)f_m] + \\ (-1)^k \delta[f - nf_c - k(2k-1)f_m] \end{array} \right\} \right\} \quad (11)$$

where f_c is the carrier frequency, f_m is the frequency of the sawtooth signal, C_n is the magnitude of the sideband current harmonics, $n = 1, 2, 3 \dots$. $J(\cdot)$ is the Bessel function, and $k = 1, 2, 3 \dots$. β is the modulation factor related to the frequency and amplitude of the sawtooth signal.

Another single-HSS modulation based on the random signal can be expressed as (12) in which the magnitude and spreading width are determined by the mathematical expectation factor $E(\cdot)$ and random degree coefficient R_e .

$$S_R(f, T) = \frac{1}{E[T]} \left\{ E[|S(f)|^2] + 2R_e \left[\frac{E[S(f)e^{j2\pi fT}]E[S^*(f)]}{1 - E(e^{j2\pi fT})} \right] \right\} \quad (12)$$

where T is the switching period of the random carrier frequency, $S(f)$ is the power spectral density of the original SVPWM, and $S^*(f)$ is the complex conjugate function.

By coupling the sawtooth and random signals, the power spectral density of the HCFM in one rotor rotating period can hence be defined as (13). Compared with the signal-HSS method, the proposed HCFM method can further improve the reduction effect of sideband current harmonics while the uneven distribution of the RPWM random performance can be fixed as well.

$$S_N(f, \beta) = \frac{1}{E[\frac{1}{f_m}]} \left\{ E[|S_H(f, \beta)|^2] + 2R_e \left[\frac{E[S_H(f, \beta)e^{\frac{j2\pi f}{f_m}}]E[S_H^*(f, \beta)]}{1 - E(e^{\frac{j2\pi f}{f_m}})} \right] \right\} \quad (13)$$

3. Experimental Test Setup

As shown in Figures 5 and 6, the test bench as set up by the prototype PMSM and the power-driven system and measurements are presented to verify the effectiveness of the proposed HCFM. The prototype 12/10 PMSM adopts the rear axle driven unit in an EV application whose parameters can be found in Table 1. The DC power is fed by 540 V–4.5 kw. Three full-bridge power modules are employed by circuit boards with the Infineon-BSM75GB120DN2. Based on the dSPACE-MicroLabBox 1103, several PWM strategies can be established with the MATLAB/Simulink and RTI Electric Motor Control Blockset. The corresponding pulse signals can be generated and controlled online.

Table 1. Parameters of the prototype PMSM.

Item	Value	Item	Value
Number of slots	12	Type of controller	VSI
Number of poles	10	Carrier frequency	8000 Hz
Rated speed	2000 r/min	DC link voltage	540 V
Rated torque	8 Nm	Rated power	1.8 kW

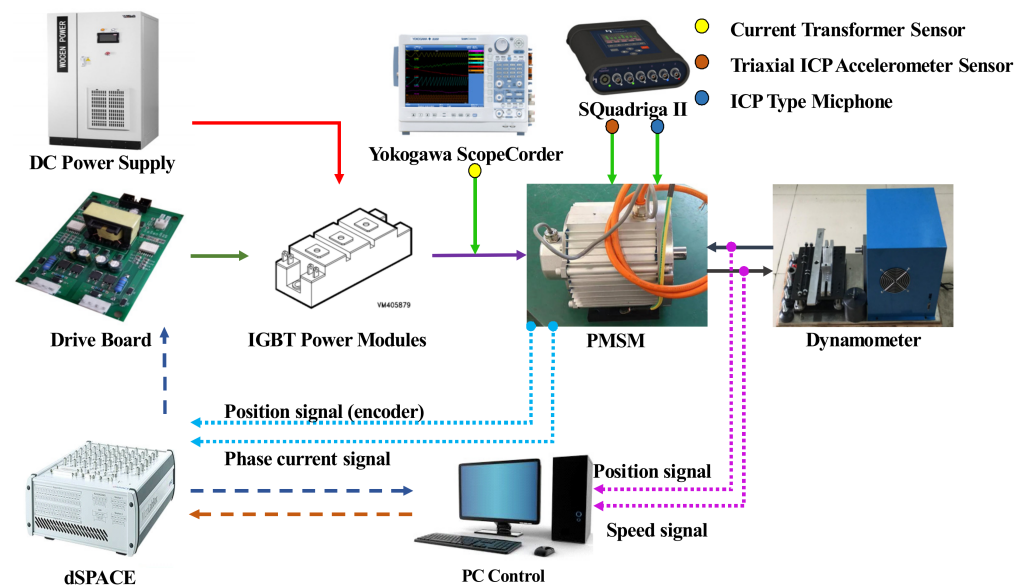


Figure 5. Overview of the test platform.

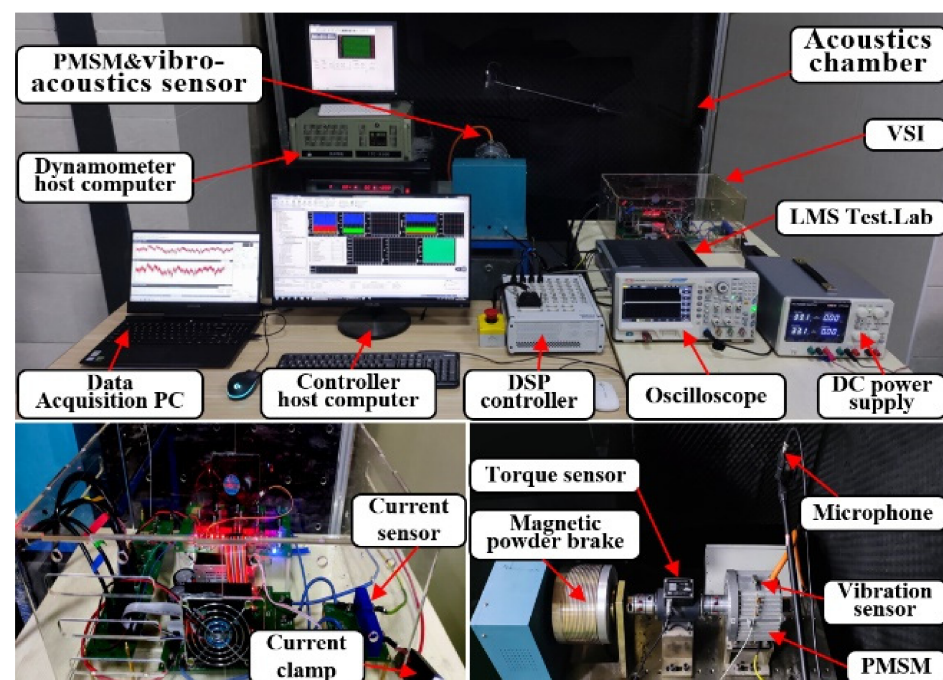


Figure 6. Experimental setup with the PMSM and instrumentation.

The vibro-acoustic tests are measured by the ICP triaxial accelerometer with a sensitivity of 50 mV/g and a sound-pressure microphone (GRAS-46AE) with the sensitivity of 47.23 mV/Pa. The phase current signals are recorded by the Teletronix-A622 current probe and processed by the Tektronix TDS2024c.

The operational condition of all experimental tests is set at 1000 r/min and 4 Nm in order to obtain the sideband current harmonics and vibro-acoustic responses clearly. Based on the setting rotating speed of 1000 r/min, the rotation frequency and fundamental frequency are 16.67 Hz and 83.34 Hz, respectively.

4. Results and Discussion

4.1. Sideband Current Harmonics

The experimental results of sideband current harmonics are shown in Figure 7 in which the comparison between the conventional SVPWM, RPWM, and HCFM techniques is presented by the power spectral density (PSD). The sideband components in the conventional SVPWM obtain a specific pattern characterized by two symmetric sidebands appearing around the first carrier frequency. The sidebands at $f_c \pm 2f_0$ and $f_c \pm 4f_0$, where f_0 is the fundamental frequency of the electrical supply, can be calculated by the rotation frequency f_r (i.e., $f_r = n/60$ and $f_0 = p \cdot f_r$). Considering that f_0 is 83.34 Hz under 1000 r/min, the main sidebands can be obtained with four main orders where the peak magnitude is -27.56 dB/Hz.

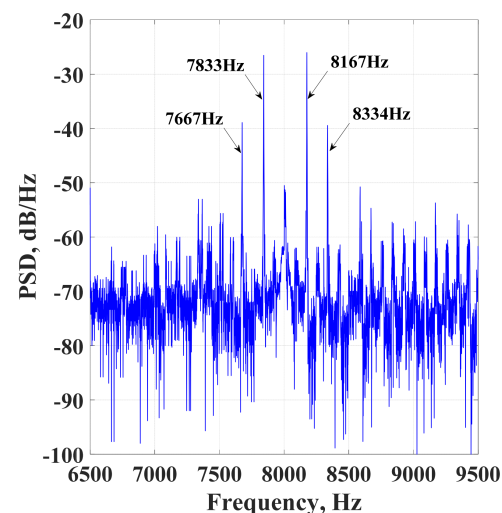


Figure 7. The sideband current harmonics with the conventional SVPWM.

In terms of the RPWM and HCFM, the current harmonic reduction is presented in Figures 8 and 9. In contrast to the conventional SVPWM, the obvious orders disappear. The concentrated harmonics are extended to the specified frequency domain with a 1000 Hz dithering range as the setting. The peak magnitude in the RPWM is -39.56 dB/Hz, while in the HCFM it is -48.78 dB/Hz or even lower. The reduction effort in the proposed HCFM is more significant than that in the RPWM.

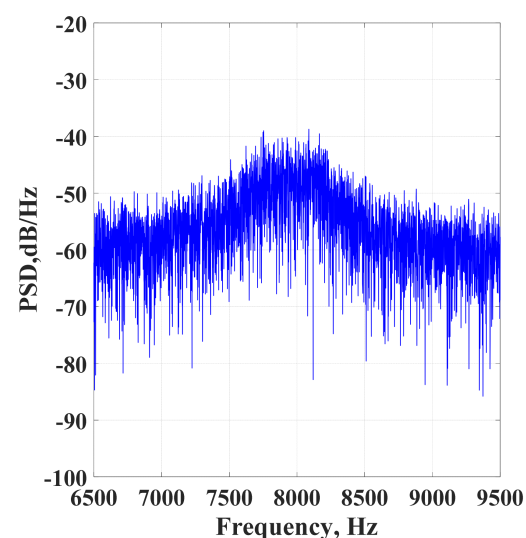


Figure 8. The sideband current harmonics with random PWM.

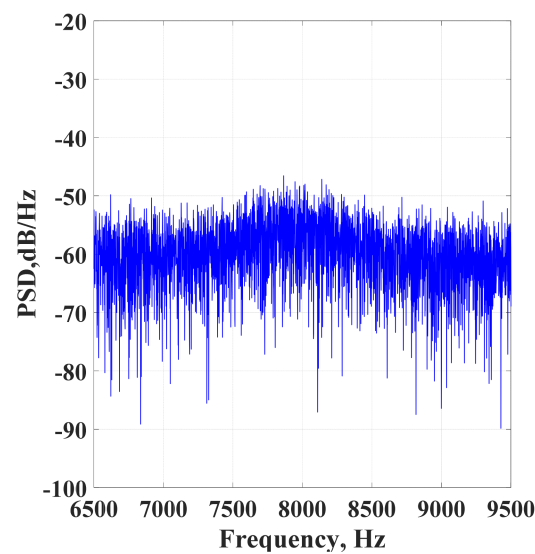


Figure 9. The sideband current harmonics with the HCFM.

4.2. Sideband Vibro-Acoustic Responses

The experimental vibro-acoustics results are conducted to the frequency domain. The comparison of the sideband vibro-acoustic responses is shown in this chapter. As presented in the following figures, the vibro-acoustic responses obtain a significant correlation with the current harmonics. In Figure 10, the sideband orders of the conventional SVPWM in vibro-acoustic responses are located with $f_c \pm f_0$, $f_c \pm 3f_0$, and $f_c \pm 5f_0$.

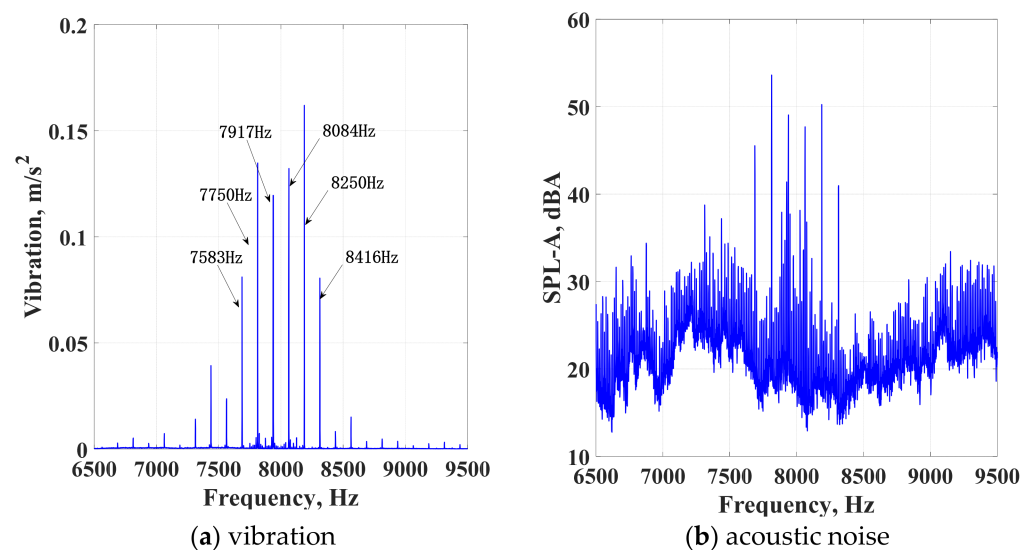


Figure 10. The sideband vibro-acoustic responses with the conventional SVPWM.

As a result of the reduction techniques in Figures 11 and 12, the relatively concentrated sideband components are spread to a wider frequency band that has been cut off at the lower and upper frequencies of 7000 Hz and 9000 Hz. The original narrow-band acoustics are reduced below 50 dBA and even 40 dBA by using the HCFM. All results are presented in Table 2. As demonstrated, the proposed HCFM obtains the best sideband current harmonics reduction and sideband vibro-acoustics.

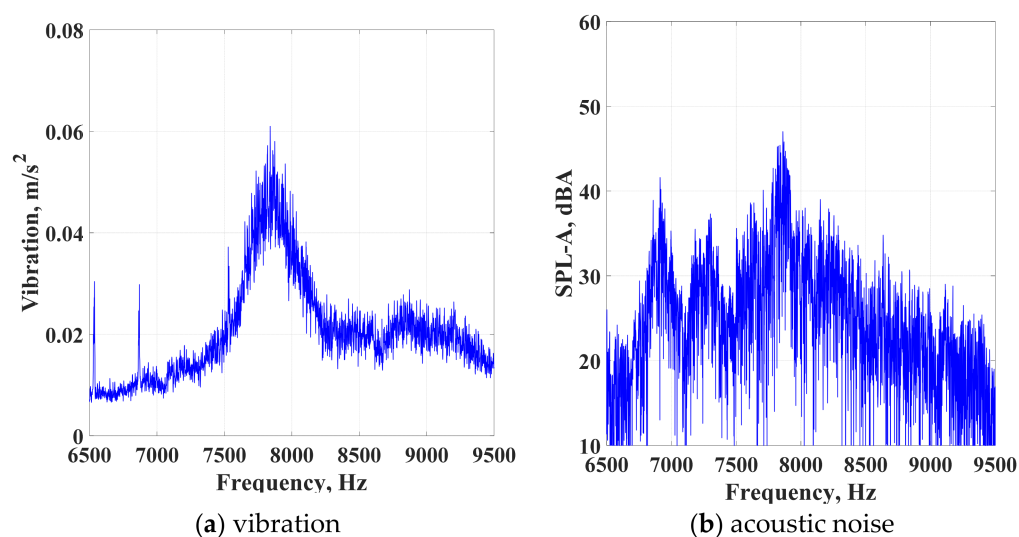


Figure 11. The sideband vibro-acoustic responses with random PWM.

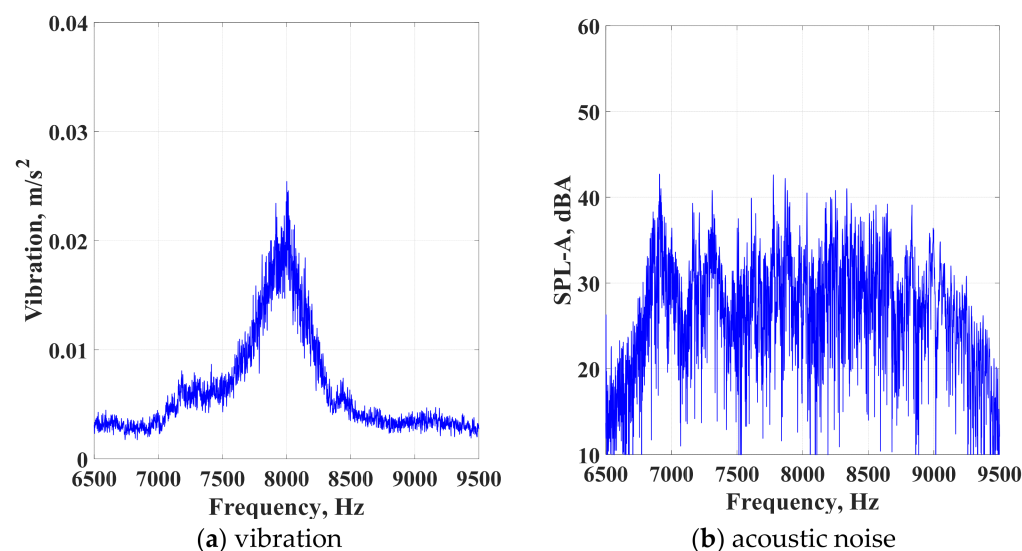


Figure 12. The sideband vibro-acoustic responses with the HCFM.

Table 2. Sideband current harmonics and vibro-acoustics with the proposed PWM schemes.

Schemes	Sideband Current Harmonics		Vibration		Acoustics	
	Peak Frequency	Amplitude	Peak Frequency	Amplitude	Peak Frequency	Amplitude
SVPWM	8167 Hz	−27.56 dB/Hz	8250 Hz	0.154 m/s ²	7750 Hz	52.7 dBA
RPWM	8042 Hz	−39.56 dB/Hz	7833 Hz	0.063 m/s ²	7833 Hz	47.2 dBA
HCFM	7889 Hz	−48.78 dB/Hz	8000 Hz	0.026 m/s ²	7750 Hz	41.9 dBA

5. Conclusions

In this paper, a novel PWM technique applied with hybrid carrier frequency modulation is proposed to reduce the sideband harmonics and vibro-acoustics. The proposed HCFM technique is implemented by the rotor position in which the sawtooth and random signal-based dithering methods are combined to achieve the hybrid carrier waves modulation. As demonstrated by the experimental tests, the magnitude of sideband current harmonics can be reduced by about 20 dB/Hz, resulting in a 0.12 m/s² vibration reduction

and 10 dBA acoustic noise reduction. The reduction efforts in the HCFM are more significant than those in the RPWM. The results can provide a reference for multi-strategy control to achieve low vibro-acoustics and EMI reduction in EV and HEV application in addition to other PWM-fed motor applications. Further work including efficiency evaluation, torque ripple, and controller loss can be studied based on the proposed investigation.

Author Contributions: All authors contributed to this work. Conceptualization, Z.Q.; formal analysis, H.C.; investigation, Z.Q., Y.C., and X.L.; methodology, Z.Q. and H.C.; validation, Z.Q. and Y.K.; writing—original draft, Z.Q.; writing—review and editing, Y.C. and X.L. (Xu Liu); funding acquisition, X.L. (Xiaozhe Lin). All authors have read and agreed to the published version of the manuscript.

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