

Hybrid RPWM Technique Based on Modified SVPWM to Reduce the PWM Acoustic Noise

Yingliang Huang , Yongxiang Xu , *Member, IEEE*, Wentao Zhang , and Jibin Zou , *Senior Member, IEEE*

Abstract—This paper proposed a novel hybrid random pulsewidth modulation (HRPWM) technique based on the modified space vector PWM for three-phase voltage source inverters to eliminate the PWM acoustic noise. Due to PWM technique and switching losses considerations, ear-piercing high-frequency noise from motor is common. The proposed HRPWM technique is able to remove the high-frequency unpleasant acoustic noise more effectively than the conventional RPWM with lower switching losses and shorter random frequency range. In addition, the PWM harmonics in phase voltage and phase current are reduced significantly. The HRPWM method is simple to implement and does not employ additional circuits in drive system. Finally, the effectiveness of the proposed approach has been confirmed by detailed experimental results.

Index Terms—Acoustic noise, harmonic suppression, random pulsewidth modulation (RPWM) technique, space vector PWM (SVPWM).

I. INTRODUCTION

PULSEWIDTH modulation (PWM)-based voltage source inverters (VSIs) are the driving force in industrial and commercial applications [1]. In these VSIs, space vector PWM (SVPWM) technique is widely employed to achieve excellent static and dynamic performances [2]. However, SVPWM generates undesirable sideband voltage and current harmonics during the intrinsic switching process. The high-frequency harmonics are concentrated nearby the carrier frequency and its multiples [2], [3], which overlaps with the range of human hearing [3]. In certain domestic and commercial areas, such as electric vehicles and elevators, the acceptability of the drive system is tied strongly to the perceived sound levels resulting from their operation [1], [4]. Acoustic comfort has become an increasingly important feature, as well as a way to comply with the IEC 60034-9 norm [5]. Thus, such unpleasant acoustic noise and electromagnetic vibration caused by PWM are quite common issues and should be addressed properly [2]–[5].

Manuscript received April 21, 2018; revised June 23, 2018 and August 10, 2018; accepted September 7, 2018. Date of publication September 12, 2018; date of current version April 20, 2019. This work was supported by the National Natural Science Foundation of China under Grants 51577036 and 51437004. Recommended for publication by Associate Editor D. O. Neacsu. (*Corresponding author: Yongxiang Xu.*)

The authors are with the School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, China (e-mail:

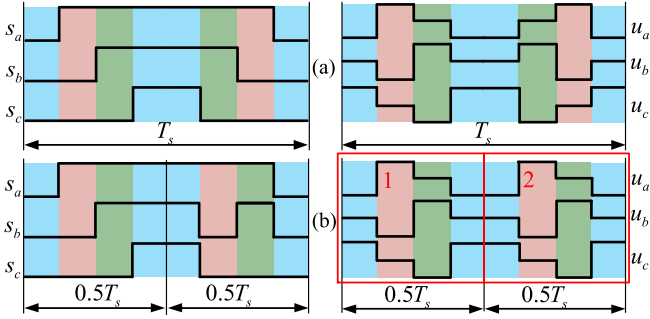


Fig. 1. Switching states and phase voltages of (a) conventional SVPWM and (b) modified SVPWM.

By changing the original switching state functions of the conventional SVPWM, a modified SVPWM approach is proposed to shift the PWM frequency noise to double at the expense of increasing 33% switching frequency in [3]. With the modified SVPWM, the peaky PWM frequency noise in phase voltage could be reduced about 15 dB [3]. However, the technique could only reduce the odd order (1st, 3rd, . . .) PWM frequency noise and has no effect on the even order noise.

In fact, lower modulation ratio or shorter random frequency range will weaken the effect of RPWM. The decrease of PWM noise in phase voltage and phase current, especially in acoustic noise, is less than 10 dB in some situations. 9–10 dB (RPWM) reduction on PWM frequency noise, even 15 dB (modified SVPWM) is not enough in many applications. Therefore, this paper proposed a hybrid RPWM (HRPWM) technique for three-phase inverters with the advantages of both RPWM and the modified SVPWM. The odd order PWM frequency noise could be reduced more remarkably than the modified SVPWM or RPWM, and the reduction of the even order noise is almost equal to RPWM. The primary benefits of the proposed HRPWM include:

- 1) The peaky amplitude of PWM frequency noise of phase voltage could be reduced about 22 dB and the even order PWM noises are reduced as well;
- 2) The HRPWM technique could remove unpleasant PWM acoustic noise effectively with the lower switching losses and shorter random frequency range.

II. PROPOSED HRPWM TECHNIQUE

A. Review of the Modified SVPWM

The switching pulse pattern and phase voltages with the SVPWM technique are shown in Fig. 1(a), where s_a , s_b , s_c are the switching states and v_a , v_b , v_c are the corresponding phase voltages. Compared with the conventional SVPWM, the modified SVPWM exchanges the sequence of active vectors, as shown in Fig. 1(b). In each PWM cycle T_s , active vectors are applied twice in order. The waveform 1 of three-phase voltages is the same as waveform 2. The phase voltages meet $v(t + 0.5T_s) = v(t)$ and the harmonic period of phase voltage is $0.5T_s$. Thus, the PWM harmonics frequency in phase voltage is doubled and the odd order PWM frequency harmonics are reduced. In a PWM cycle, one phase arm is operated twice, one time more than the conventional SVPWM. In order to re-

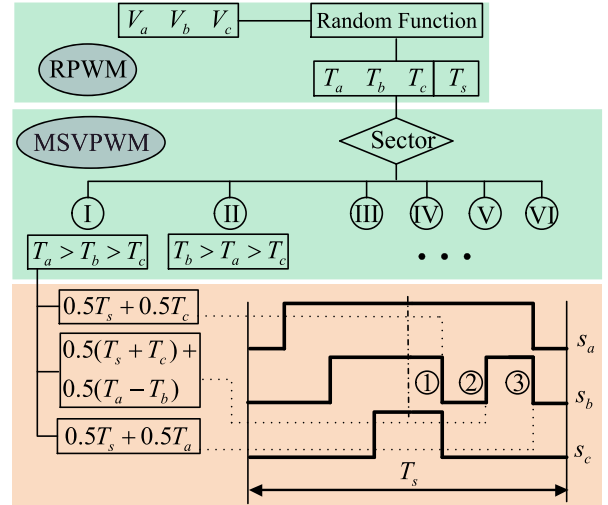


Fig. 2. Diagram of the proposed HRPWM with program.

move the first PWM frequency noise, the switching losses of the modified SVPWM increase 33% by comparing with the SVPWM technique in the same carrier frequency. In other words, if the actual switching frequency is 4.0 kHz, the main first PWM noise frequency 4.0 kHz for SVPWM and that is 6.0 kHz for the modified SVPWM.

B. Implementation of the Proposed HRPWM

The proposed HRPWM method could eliminate the PWM frequency noise further, based on the modified SVPWM, through spreading the power of PWM frequency noise over a wide range. Due to the reduction of PWM frequency noise, the switching frequency with HRPWM could be selected in lower range and remains the PWM noise in lower level compared with the conventional SVPWM and RPWM technique.

As shown in Fig. 2, the modified SVPWM technique is achieved before the PWM signals output to insulated gate bipolar translators (IGBTs), and the output reference voltages V_a , V_b , and V_c are calculated based on the RPWM period T_s in the motor control program. The key point of the proposed HRPWM is to achieve the modified SVPWM based on the results of RPWM. For the common SVPWM technique, the output reference voltages V_a , V_b , and V_c are equivalent to the durations of three phases on-time T_a , T_b , and T_c . The PWM module outputs the control signals of IGBTs based on T_a , T_b , and T_c . Although the PWM period T_s is a random value for RPWM, T_a , T_b , T_c , and T_s are known information.

The modified SVPWM strategy could adjust the switching functions according to T_a , T_b , T_c , and T_s . More detailed process is as follows. The sector could be obtained by comparing the values of T_a , T_b , and T_c . If $T_a > T_b > T_c$, in sector I, three special points marked as ①, ②, and ③ in Fig. 4 are calculated by $0.5(T_s + T_c)$, $0.5(T_s + T_c) + 0.5(T_a - T_b)$, and $0.5(T_s + T_a)$, respectively. The switching functions s_a and s_c are the same as the conventional SVPWM. The modified switching state function s_b changes to low level at point ① with s_c , then high level at point ②, at last low level with s_a .

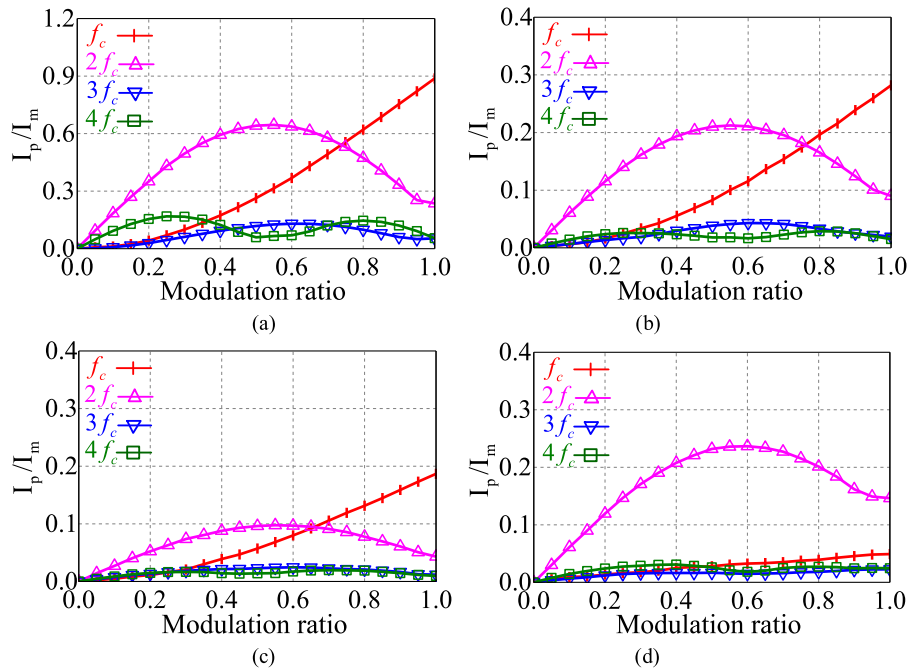


Fig. 3. PWM harmonics in phase current with (a) SVPWM (4.0 kHz), (b) RPWM1 (3.2–4.8 kHz), (c) RPWM2 (4.8–7.2 kHz), and (d) HRPWM (3.2–4.8 kHz).

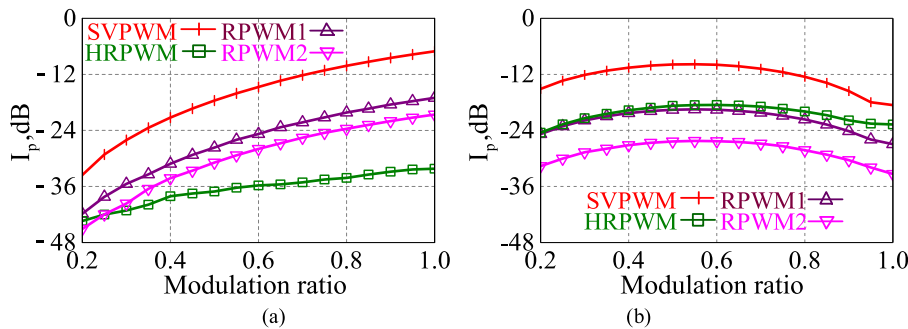


Fig. 4. Comparison of (a) the first-order and (b) the second-order PWM frequency current harmonics with SVPWM (4.0 kHz), RPWM1 (3.2–4.8 kHz), RPWM2 (4.8–7.2 kHz), and HRPWM (3.2–4.8 kHz).

When vector is located in other five sectors, the special three points could be calculated in the same way. The HRPWM could be achieved easily with the random function and the switch-case function, and the computational burden is light for present microcontroller unit (MCU).

III. NOISE INVESTIGATION IN SVPWM, RPWM, AND HRPWM

For the conventional SVPWM technique, the PWM voltage harmonics are located near nf_c , where $n = 1, 2, \dots$ and f_c is the carrier frequency [21]. In the following computer simulation results, the PWM noises of phase current with SVPWM, RPWM, and HRPWM are compared, whose fundamental frequency are all 100 Hz. As shown in Fig. 3(a), the PWM frequency of SVPWM is 4.0 kHz. The first PWM frequency harmonics increase with the modulation ratio, the second PWM harmonics increase with modulation ratio, then decrease. The PWM noises in phase current with RPWM technique are shown in Fig. 3(b) and (c), the RPWM frequency range is 3.2–4.8 kHz

and 4.8–7.2 kHz, respectively. The amplitudes of the first- and second-order PWM harmonics decrease significantly in comparison with SVPWM. The results of the HRPWM are shown in Fig. 3(d).

In order to compare these methods visually, the first- and second-order PWM frequency current harmonics with SVPWM (4.0 kHz), RPWM1 (3.2–4.8 kHz), RPWM2 (4.8–7.2 kHz), and HRPWM (3.2–4.8 kHz) are illustrated in Fig. 4. As seen in Fig. 4(a), the RPWM1 could reduce the first PWM frequency harmonics about 9 dB. With increasing 50% switching frequency, RPWM2 could reduce that about 12 dB. The HRPWM could reduce the first-order PWM frequency harmonics more than 20 dB when the modulation ratio larger than 0.5. It has better effect on PWM frequency harmonics cancelation than RPWM in the whole range of modulation ratio. As demonstrated in Fig. 4(b), the second-order PWM frequency harmonics are reduced about 10 dB with RPWM1 or HRPWM. The decrease of that with RPWM2 is 16 dB, which mainly benefits from the impedance of inductor for higher frequency noises. The switching frequency of HRPWM is $1.33 \times 4.0 = 5.3$ kHz, it is 6.0 kHz

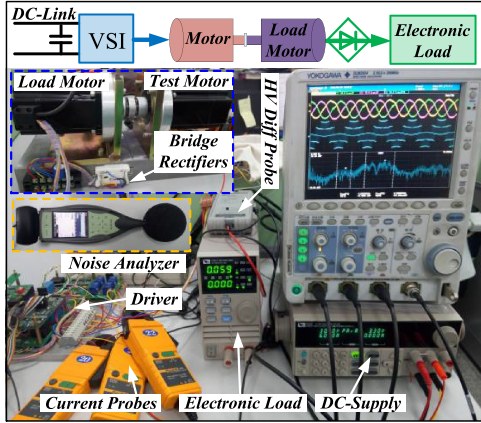


Fig. 5. Diagram and photograph of experimental platform.

TABLE I
SPECIFICATION AND PARAMETER OF MOTOR

Specification and Parameter	Value
DC-link Voltage	30 V
Rated Current	5.81 A
Motor Speed	1200 rpm
Pole pairs	5
Phase Resistance	236.3 m Ω
Phase Inductance	0.42 mH
Back-EMF Coefficient	19.34 V/krpm

for RPWM2. In general, the first-order PWM harmonics locates near human ear's sensitive range, so the reduction of the first PWM frequency harmonics is more important. HRPWM has better performance on harmonics reduction than RPWM with lower switching losses.

IV. EXPERIMENTAL VALIDATIONS AND ANALYSIS

In this section, the PMSM drive system has been implemented to verify the capability of PWM noise reduction with HRPWM practically. The experimental platform photograph and its diagram are shown in Fig. 5. The dc electronic load is employed to load motor through the rectifier and adjust the load torque, which ensures that the load motor does not make acoustic noise near the switching frequency. The motor is operated in rated load and speed is 1200 r/min. The phase voltage and phase currents are measured by high-voltage differential probe and currents probes, respectively. The *Brüel & Kjer* 2250S noise analyzer is used to measure acoustic noise from the motor.

The specification and parameters of the drive system are shown in Table I. Xorshift random number generator is employed in this paper. The PWM frequency range of RPWM and the HRPWM is from 3.2 to 4.8 kHz, the average frequency is 4.0 kHz.

In the following results, the sampling frequency of the phase voltage, phase current, and acoustic noise in oscilloscope is 125 kHz. In order to show the advantages of the method in removing PWM noise, the experimental results of the SVPWM and RPWM are listed.

A. PWM Frequency Voltage Noise Cancellation

The phase voltage and its harmonics spectrum with conventional SVPWM, RPWM, modified SVPWM, and the HRPWM are shown in Fig. 6. The levels of PWM harmonics using the conventional SVPWM are marked in these figures. The RPWM decreases the peak value of the first PWM frequency harmonics amplitude by 6.80 dBV and the second PWM frequency harmonics by 8.49 dBV compared with the conventional SVPWM. The results of the modified SVPWM are shown in Fig. 6(c), it decreases the first PWM frequency harmonics amplitude by 17.23 dBV and the second PWM frequency harmonics is similar to that of SVPWM. As seen in Fig. 6(d), with HRPWM, the peak value of the first PWM frequency noise amplitude decreases by 24.48 dBV, and that of the second PWM frequency noise reduces 5.82 dBV. These experimental results confirm that the HRPWM could eliminate the first PWM frequency voltage noise more significantly compared with RPWM.

B. PWM Frequency Current Noise Cancellation

The PWM acoustic noise depends largely on the current noises. Thus, the level of PWM current noise using the SVPWM, RPWM, and HRPWM are compared. As shown in Fig. 7(a), the PWM current noise concentrates on 4.0 kHz and its multiples for the conventional SVPWM. With RPWM, as shown in Fig. 7(b), the amplitude of the first PWM frequency current noise is 7.30 dBA less than the fixed switching frequency SVPWM and the second PWM frequency current noise is 8.91 dBA. As seen in Fig. 7(c), HRPWM decreases the first PWM frequency current noise by 23.51 dBA and the second PWM frequency noise by 5.05 dBA.

The enlarged figures of phase current using conventional SVPWM, RPWM, and HRPWM are shown in Fig. 8(a)–(c), respectively. As seen in Fig. 8(a), the period of the main harmonics near the peak of i_a is 125 μ s, and the frequency is 8.0 kHz. The frequency of the main harmonics at i_a zero-crossing is 4.0 kHz. This result indicates that PWM current harmonics (voltage harmonics) are not evenly distributed in fundamental cycle. For the RPWM technique, the frequency of PWM harmonics appear randomly in the range of 3.2–4.8 kHz, as shown in Fig. 8(b). For HRPWM in Fig. 8(c), the frequency of main harmonics in phase voltage and phase current is from 6.4 to 9.6 kHz, which is double of the PWM frequency. The first PWM frequency harmonics with RPWM could only be distributed but removed with HRPWM. For the second PWM frequency noise, the RPWM and HRPWM both spread the power from 6.4 to 9.6 kHz.

C. PWM Acoustic Noise Cancellation

The PWM technique has a direct impact on vibrations and acoustic noise. The PWM acoustic noise could almost be removed due to the cancelation of PWM noise in phase current. The motor acoustic noise caused by PWM harmonics is measured by *Brüel & Kjer* 2250S noise analyzer. As shown in Fig. 9(b), compared with the results of SVPWM in Fig. 9(a),

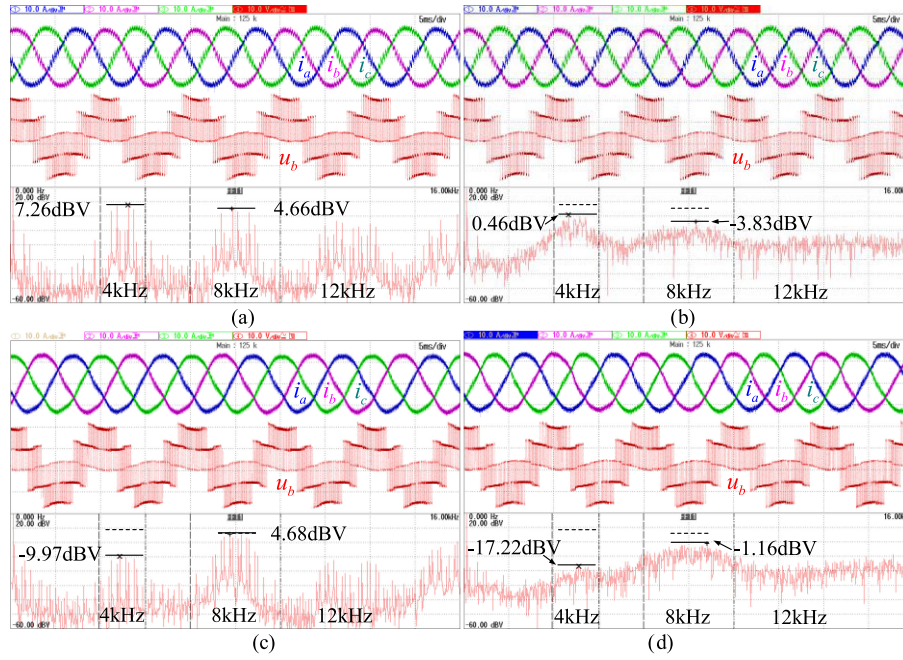


Fig. 6. Harmonics spectrum of phase voltage with (a) conventional SVPWM, (b) RPWM, (c) modified SVPWM, and (d) HRPWM.

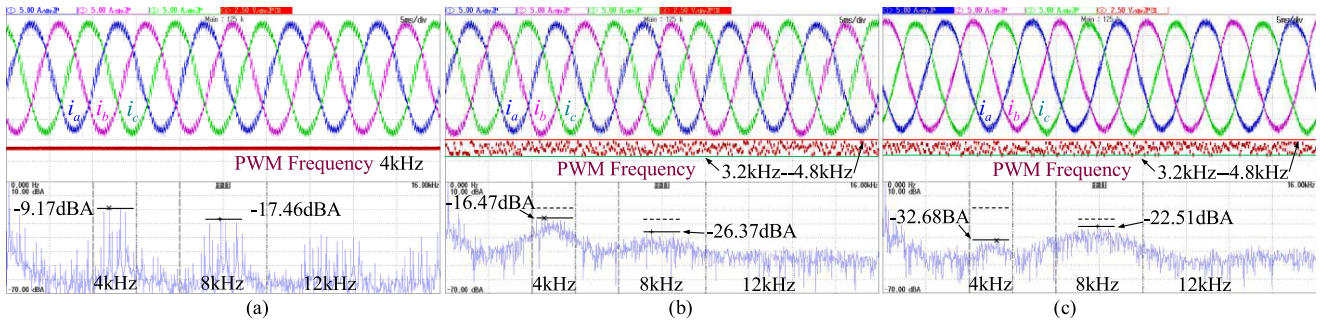


Fig. 7. Harmonics spectrum of phase current with (a) conventional SVPWM, (b) RPWM, and (c) HRPWM.

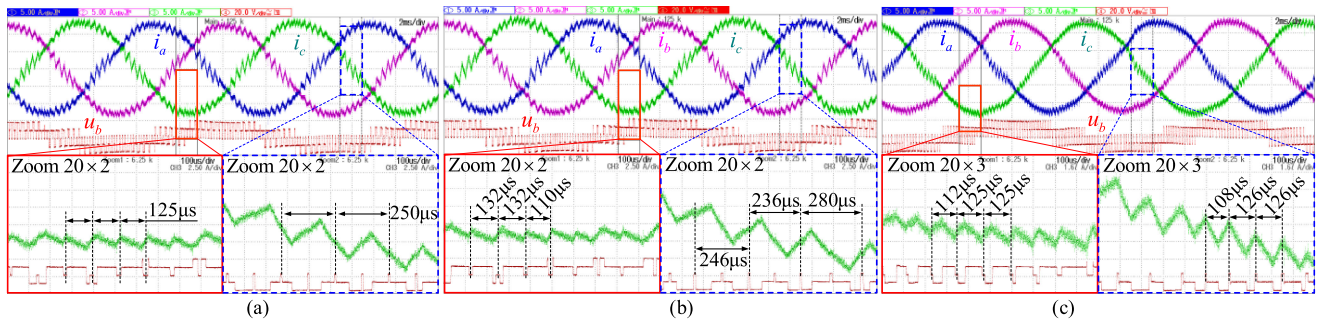


Fig. 8. Enlarged figure of phase voltage and phase current harmonics with (a) conventional SVPWM, (b) RPWM, and (c) HRPWM.

RPWM decreases the first PWM frequency acoustic noise by 3.34 dBV and the second PWM frequency noise by 6.55 dBV. Based on the experimental results, two conclusions could be obtained. First, the effect on the first PWM frequency acoustic noise reduction is not obvious with RPWM and does not

satisfy the noise demands in some applications. In addition, the acoustics noise amplitude with fixed switching frequency SVPWM in Fig. 9(a) remains relatively stable, but the noise amplitude with RPWM in Fig. 9(b) varies rapidly. The rapidly changing low-frequency motor acoustic noise may be much

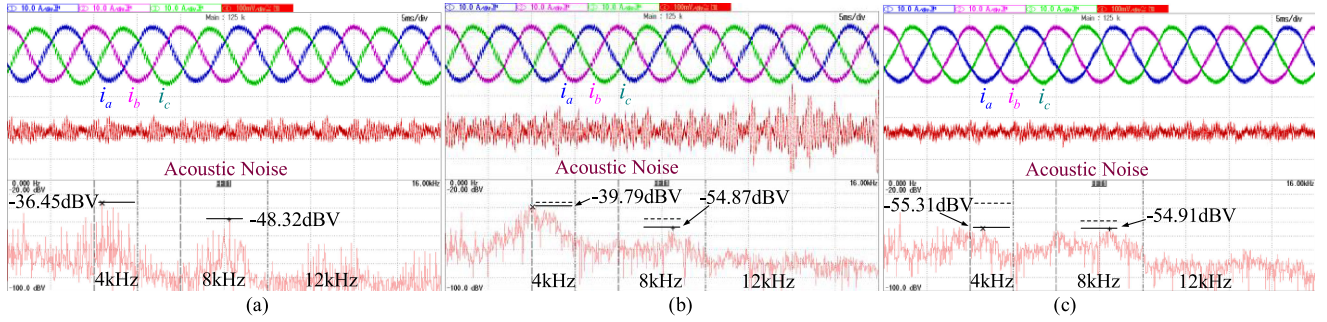


Fig. 9. Acoustic noise spectrum with (a) conventional SVPWM, (b) RPWM, and (c) HRPWM.

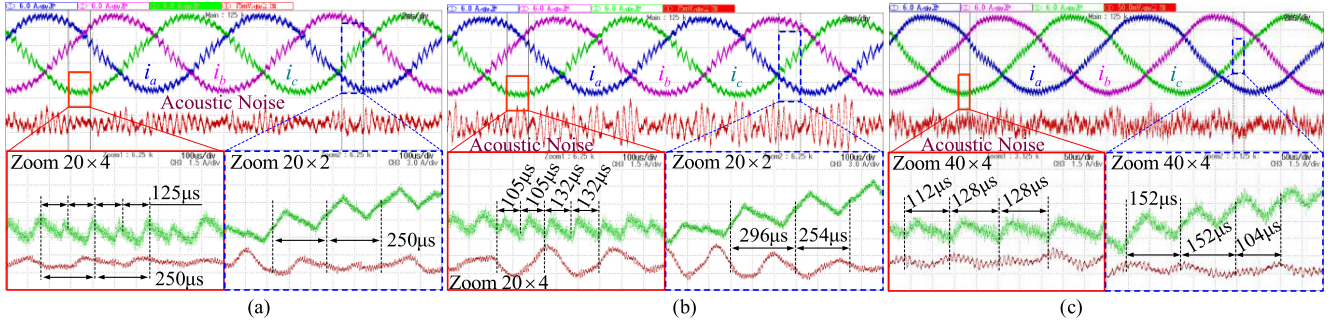


Fig. 10. Enlarged figure of acoustic noise and phase current harmonics with (a) conventional SVPWM, (b) RPWM, and (c) HRPWM.

TABLE II
COMPARISON OF PWM NOISE CANCELLATION WITH RPWM AND HRPWM

Specification of PWM Harmonic	Unit	The 1 st PWM Harmonics		The 2 nd PWM Harmonics	
		RPWM	HRPWM	RPWM	HRPWM
Phase Voltage	dBV	6.80	24.48	8.49	5.82
Phase Current	dBA	7.30	23.51	8.91	5.05
Acoustic Noise	dBV	3.34	18.86	6.55	6.59

harsher than the conventional SVPWM. With the proposed HRPWM, the amplitude of the first PWM frequency acoustic noise is 18.86 dBV less than the conventional SVPWM. The decrease of the second PWM frequency acoustic noise is 6.59 dBV, which is similar to the effect of RPWM.

The figures of acoustic noise with SVPWM, RPWM, and HRPWM are zoomed in Fig. 10(a)–(c), respectively. As seen in Fig. 10(a), the period of the main harmonics of i_a near its peak is 125 μ s, and that is 250 μ s at i_a zero-crossing. Because the period of the harmonics in i_b and i_c is 250 μ s, the period of the main harmonics in acoustic noise is 250 μ s. The comparison between Fig. 10(b) and (c) shows that the first PWM frequency acoustic is still the main parts for RPWM and the second PWM frequency acoustic noise is the main components for HRPWM. The acoustics noise amplitude with HRPWM in Fig. 10(c) varies more gently compared with RPWM, which avoids the additional low-frequency acoustic noise.

D. Comparison and Analysis of the Experimental Results

The experimental results of noise cancellation in voltage, current, and motor acoustic noise have been analyzed above. In order to illustrate these results clearly, the amplitudes of PWM

harmonics reduction are listed in Table II. By comparing the results, two conclusions can be inferred: 1) the HRPWM could remove the first PWM frequency noise more effectively than the RPWM technique and 2) the decrease of the second PWM frequency noise with HRPWM is close to that with RPWM.

E. Discussion of Switching Losses and PWM Noise Cancellation Performance

The modified SVPWM approach shifts the PWM frequency noise to double at the expense of increase 33% switching frequency. Due to the incremental switching losses, the performance and advantage of HRPWM is dubious. Hence, a series of experiments are done to compare RPWM with HRPWM. The PWM frequency range for HRPWM is from 3.2 to 4.8 kHz, whose actual switching frequency is 5.3 kHz. It is 4.8 to 7.2 kHz for RPWM, whose equivalent switching frequency is 6.0 kHz. The switching frequency with RPWM is 12.5% more than HRPWM's and the RPWM frequency range is 50% more than HRPWM's. The experimental results of phase voltage, phase current, and the acoustic noise are demonstrated in Fig. 11. From 3.2 to 4.8 kHz, the PWM noise amplitudes of HRPWM

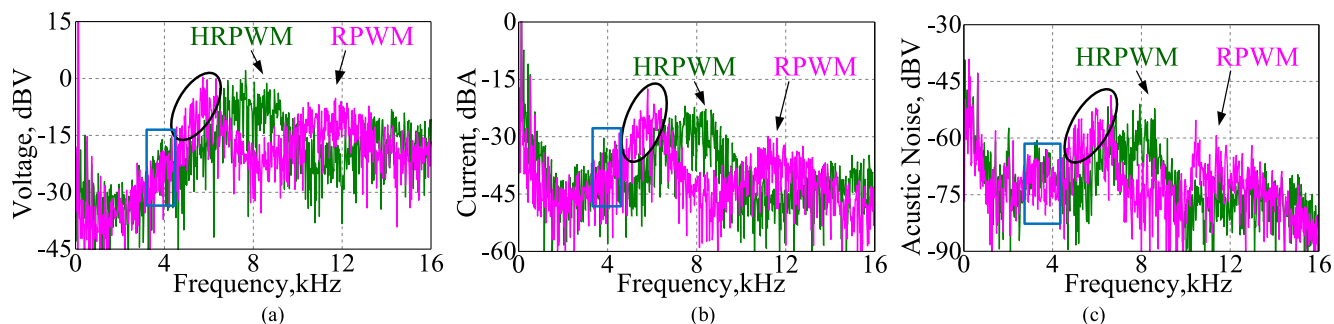


Fig. 11. PWM harmonics in (a) phase voltage, (b) phase current, (c) acoustic noise with RPWM (4.8–7.2 kHz), and HRPWM (3.2–4.8 kHz).

are almost equal to the background noise of RPWM, which is marked by rectangle. However, the level of the first PWM frequency harmonics with RPWM is high enough and the lowest frequency noise is 4.8 kHz. The clustered low-frequency acoustic noise is particularly obvious and ear-piercing. The lowest frequency noise is 6.4 kHz for HRPWM due to the cancellation of the first PWM frequency noise. Thus, compared with RPWM in higher PWM frequency, the HRPWM still has advantage in removing the PWM noise. In other words, the PWM frequency with HRPWM could be selected in rather lower range to reduce switching losses and remains the effects of PWM noise cancellation.

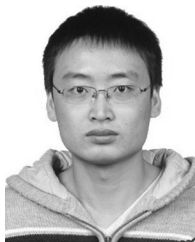
V. CONCLUSION

This paper proposed an HRPWM technique for three-phase VSIs to remove the PWM acoustic noise based on the modified SVPWM. The effects on PWM noise cancellation of RPWM and the proposed HRPWM technique are compared by detailed experimental results. The RPWM technique could reduce the amplitudes of the second PWM frequency noise more effectively than the first PWM frequency noise. In addition, the reduction on the first PWM frequency acoustic noise with RPWM is rather low and not enough in many applications. The HRPWM technique could significantly remove the first PWM frequency noise in phase voltage, phase current, and acoustic noise. And its decrease of the second PWM frequency noise is almost equal to that of RPWM. The experimental results of HRPWM at lower switching frequency and in shorter random frequency range are shown as well. In this situation, the HRPWM could remain the effects of PWM noise cancellation to reduce switching losses. Furthermore, the HRPWM also could be used in grid-connected inverter system to reduce the PWM noise and power filters size.

REFERENCES

- [1] K. Lee, G. Shen, W. Yao, and Z. Lu, "Performance characterization of random pulse width modulation algorithms in industrial and commercial adjustable-speed drives," *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 1078–1087, Mar./Apr. 2017.
- [2] W. Liang, J. Wang, P. C. K. Luk, W. Fang, and W. Fei, "Analytical modeling of current harmonic components in PMSM drive with voltage-source inverter by SVPWM technique," *IEEE Trans. Energy Convers.*, vol. 29, no. 3, pp. 673–680, Sep. 2014.
- [3] Y. Huang, Y. Xu, Y. Li, G. Yang, and J. Zou, "PWM frequency voltage noise cancellation in three-phase VSI using the novel SVPWM strategy," *IEEE Trans. Power Electron.*, vol. 33, no. 10, pp. 8596–8606, Oct. 2018.
- [4] A. K. Wallace, R. Spee, and L. G. Martin, "Current harmonics and acoustic noise in AC adjustable-speed drives," *IEEE Trans. Ind. Appl.*, vol. 26, no. 2, pp. 267–273, Mar./Apr. 1990.
- [5] A. Ruiz-Gonzalez, F. Vargas-Merino, J. R. Heredia-Larrubia, M. J. Meco-Gutierrez, and F. Perez-Hidalgo, "Application of slope PWM strategies to reduce acoustic noise radiated by inverter-fed induction motors," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2555–2563, Jul. 2013.
- [6] A. Ruiz-Gonzalez, M. J. Meco-Gutierrez, F. Perez-Hidalgo, F. Vargas-Merino, and J. R. Heredia-Larrubia, "Reducing acoustic noise radiated by inverter-fed induction motors controlled by a new PWM strategy," *IEEE Trans. Ind. Electron.*, vol. 57, no. 1, pp. 228–236, Jan. 2010.
- [7] B. Bauer and E. Torick, "Researches in loudness measurement," *IEEE Trans. Audio Electroacoust.*, vol. 14, no. 3, pp. 141–151, Sep. 1966.
- [8] A. von Jouanne and P. N. Enjeti, "Design considerations for an inverter output filter to mitigate the effects of long motor leads in ASD applications," *IEEE Trans. Ind. Appl.*, vol. 33, no. 5, pp. 1138–1145, Sep./Oct. 1997.
- [9] M. Farasat, A. Arabali, and A. M. Trzynadlowski, "Flexible-voltage DC-bus operation for reduction of switching losses in all-electric ship power systems," *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 6151–6161, Nov. 2014.
- [10] M. Paramasivan, M. M. Paulraj, and S. Balasubramanian, "Assorted carrier-variable frequency-random PWM scheme for voltage source inverter," *IET Power Electron.*, vol. 10, no. 14, pp. 1993–2001, Nov. 2017.
- [11] A. M. Trzynadlowski, M. M. Bech, F. Blaabjerg, J. K. Pedersen, R. L. Kirlin, and M. Zigliotto, "Optimization of switching frequencies in the limited-pool random space vector PWM strategy for inverter-fed drives," *IEEE Trans. Power Electron.*, vol. 16, no. 6, pp. 852–857, Nov. 2001.
- [12] R. L. Kirlin, M. M. Bech, and A. M. Trzynadlowski, "Analysis of power and power spectral density in PWM inverters with randomized switching frequency," *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 486–499, Apr. 2002.
- [13] A. M. Trzynadlowski, K. Borisov, Y. Li, and L. Qin, "A novel random PWM technique with low computational overhead and constant sampling frequency for high-volume, low-cost applications," *IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 116–122, Jan. 2005.
- [14] A. M. Trzynadlowski, R. L. Kirlin, and S. F. Legowski, "Space vector PWM technique with minimum switching losses and a variable pulse rate," *IEEE Trans. Ind. Electron.*, vol. 44, no. 2, pp. 173–181, Apr. 1997.
- [15] A. M. Trzynadlowski, F. Blaabjerg, J. K. Pedersen, R. L. Kirlin, and S. Legowski, "Random pulse width modulation techniques for converter fed drive systems-A review," *IEEE Trans. Ind. Appl.*, vol. 30, no. 5, pp. 1166–1175, Sep./Oct. 1994.
- [16] K. S. Kim, Y. G. Jung, and Y. C. Lim, "A new hybrid random PWM scheme," *IEEE Trans. Power Electron.*, vol. 24, no. 1, pp. 192–200, Jan. 2009.
- [17] S. Bhattacharya, D. Mascarella, G. Joos, and G. Moschopoulos, "A discrete random PWM technique for acoustic noise reduction in electric traction drives," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2015, pp. 6811–6817.
- [18] S. Bhattacharya, D. Mascarella, G. Joos, and G. Moschopoulos, "Reduced switching random PWM technique for two-level inverters," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2015, pp. 695–702.
- [19] A. C. Binojumar, J. Prasad, and G. Narayanan, "Experimental investigation on the effect of advanced bus-clamping pulsewidth modulation on motor acoustic noise," *IEEE Trans. Ind. Electron.*, vol. 60, no. 2, pp. 433–439, Feb. 2013.

- [20] K. Borisov, T. E. Calvert, J. A. Kleppe, E. Martin, and A. M. Trzynadlowski, "Experimental investigation of a naval propulsion drive model with the PWM-based attenuation of the acoustic and electromagnetic noise," *IEEE Trans. Ind. Electron.*, vol. 53, no. 2, pp. 450–457, Apr. 2006.
- [21] J. Le Besnerais, V. Lanfranchi, M. Hecquet, and P. Brochet, "Characterization and reduction of audible magnetic noise due to PWM supply in induction machines," *IEEE Trans. Power Electron.*, vol. 57, no. 4, pp. 1288–1295, Apr. 2010.



Yingliang Huang was born in Inner Mongolia, China, in 1990. He received the B.S. and M.S. degrees in electrical engineering in 2013 and 2015, respectively, from the Harbin Institute of Technology, Harbin, China, where he is currently working toward the Ph.D. degree.

His current research interests include power converters and permanent-magnet motor drives.



Yongxiang Xu (M'03) was born in Guangxi Province, China, in 1977. He received the M.S. and Ph.D. degrees in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 2001 and 2005, respectively.

He is currently a Professor with the State Key Laboratory of Robotics and System, Harbin Institute of Technology. His current research interests include permanent-magnet machine design and control.



Wentao Zhang received the B.S. degree in electrical engineering and automation from the Harbin Institute of Technology, Weihai, China, in 2016. He is currently working toward the Ph.D. degree at the Harbin Institute of Technology, Harbin, China.

His research interests include PMSM drives and control algorithms.



Jibin Zou (SM'00) was born on January 19, 1957, in Heilongjiang Province, China. He received the M.S. and Ph.D. degrees in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 1984 and 1988, respectively.

Since 1985, he has been engaged in the research in electrical machines. He was with the University of Liverpool, Liverpool, U.K., as a Visiting Research Fellow for one year. He is now a Professor with the State Key Laboratory of Robotics and System, Harbin Institute of Technology. His current research interests include permanent-magnet machine design and control.

Dr. Zou has been a Senior Member of the IEEE MAGNETICS SOCIETY, since 2000.