Electromagnetic Vibration and Noise Suppression of Induction Motor Based on RPWM Selective Spectrum Shaping

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ABSTRACT

In AC motor powered by frequency converter, the random pulse width modulation (RPWM) can suppress vibration and noise power near the switching frequency and its integer multiple of the inverter. However, the traditional RPWM strategy cannot selectively eliminate the special frequency harmonics, such as the frequency that causes strong electromagnetic vibration and noise of the motor. A method of suppressing electromagnetic vibration and noise of induction motor based on RPWM selective spectrum shaping is proposed. Firstly, according to three different pulse positions, the general formula of selective harmonic elimination of RPWM is derived, so as to selectively eliminate the harmonic noise power at a specific frequency and its integer multiple. On this basis, further spectrum shaping can be realized by reasonably selecting the effective random number to avoid the inverter switching frequency distributing in a specific frequency band. The simulation and experimental results show that the method can not only suppress the vibration and noise near the integer times of the switching frequency, but also selectively suppress the electromagnetic vibration and noise at other frequencies.

INDEX TERMS

RPWM, selective harmonic elimination, invert, induction motor.

I. INTRODUCTION

The power electronic inverter will produce electromagnetic interference and electromagnetic noise when it is working. These harmonics generated by the inverter will lead to many hazards, such as causing electromagnetic vibration of the motor, polluting the grid environment, and interfering with the communication of nearby equipment [1], [2]. The output harmonic power peaks of the inverters are mainly concentrated near the switching frequency and its integer multiple in the traditional sinusoidal pulse width modulation (SPWM) [3]. The electromagnetic vibration and noise in AC motors near the switching frequency and its integer multiple can be effectively reduced by the RPWM strategy [4]–[6] and the size of the filter at the output of the inverter can be reduced [7]. According to the different ways of randomness, the RPWM can be divided into random switching frequency pulse width modulation (PWM) [8], random pulse position PWM [9], [10] and random switching PWM [11], etc. However, the specific frequency harmonics cannot be selectively eliminated in traditional RPWM [12], [9], such as the specific frequencies which are harmful to the motor [13]. Low-order harmonics can be eliminated by calculating the switching angle with the selective harmonic elimination pulse width modulation (SHEPWM) strategy, such as the harmonic of 5th, 7th, etc. The SHEPWM strategy is limited by the amount of the nonlinear equation calculation is too high, so the higher harmonics cannot be eliminated.

In order to shape the noise spectrum of the inverter output voltage, the low-pass filters and band-pass filters are used in [14], [15] and [16] respectively to reduce the harmonic power in the specific frequency range. However, the method is relatively complicated, and the digital filter brings large computation costs. Moreover, the harmonics in the specified frequency range are not completely eliminated.

The selective harmonic elimination method of RPWM is proposed in [17]. Theoretically, the specific harmonics can be completely eliminated. However, this method just eliminates the drive's frequencies above 20 kHz. There is little potential for applications in motor control. The problem was solved by the method in [18], [19] and the harmonics whose frequencies are lower than 10 kHz can be eliminated.
However, reference [17], [18] and [19] can only selectively eliminate harmonics at one frequency point and its integer multiple. At the same time, it is another problem that the motor has multiple noise peaks. Therefore, the output voltage and current spectrum in this idea need to be further shaped.

In this paper, we will address a method for suppressing electromagnetic vibration and noise for induction motors based on RPWM selective spectrum shaping. In this method, the preceding and succeeding terms in the Fourier series of the output voltage for the inverter are canceled each other, on this basis, the general formula of the switching period is calculated, thereby the harmonics in specific frequency and its integer multiple are selectively eliminated. Meanwhile, the inverter switching frequency can be effectively prevented to distribute in one or more specific frequency bands by reasonably selecting the random number $k$. 

II. THEORY OF THE ELECTROMAGNETIC VIBRATION AND NOISE IS GENERATED ON ASYNCHRONOUS MOTOR (VARIABLE FREQUENCY)

At present, the fixed frequency SPWM strategy is usually adopted for AC motor (variable frequency). Thus, many high-order harmonics are caused in the input voltage of the stator, which leads to many high-order harmonics in the stator current and air gap magnetic field. In the air gap magnetic field, there are dense harmonics around the switching frequency and its integer multiple of the inverter, which will lead to the generation of vibration and noise, as shown in Fig.1.

![Figure 1](image1.png)

**Figure 1.** Schematic diagram of electromagnetic vibration and noise of AC motor.

III. THEORY OF SELECTIVE HARMONIC ELIMINATION IN RPWM

As shown in Fig.2, taking the three-phase voltage source inverter as an example, the principle of the selective elimination in RPWM is analyzed. In the selective harmonic elimination strategy of RPWM, the specific frequency harmonics can be selectively eliminated by cancelling each other the preceding and succeeding terms in the output voltage Fourier series. The calculation of switching cycle $T_{n+1}$ is important in RPWM selective harmonic elimination strategy. The derivation process of the RPWM selective harmonic elimination switching cycle formula is shown in [17]–[19] and the details are shown in equations (1-5). The position of the PWM pulse in the switching cycle is shown in Fig.3 (a).

$$g(t) = \lim_{N \to \infty} \sum_{n=1}^{N} g_n(t)$$ \hspace{1cm} (2)

$$G(\omega) = \int_{-\infty}^{\infty} g(t) e^{-j\omega t} dt$$

$$= \int_{-\infty}^{\infty} g(t) \cos(\omega t) dt - j \int_{-\infty}^{\infty} g(t) \sin(\omega t) dt$$ \hspace{1cm} (3)

$$c(f_0) = \int_{-\infty}^{\infty} g(t) \sin(2\pi f_0 t + \varphi) dt$$

$$= \lim_{N \to \infty} \sum_{n=1}^{N} \left( \int_{t_n+(D_nT_m)}^{t_{n+1}} A \sin(2\pi f_0 t + \varphi) dt \right)$$

$$= \frac{A}{2\pi f_0} \sum_{m=1}^{\infty} \cos[2\pi f_0 \left( t_m + \frac{(T_m - D_nT_m)}{2} \right) + \varphi] - \frac{A}{2\pi f_0} \sum_{m=1}^{\infty} \cos[2\pi f_0 (t_m + \frac{(T_m + D_nT_m)}{2}) + \varphi]$$ \hspace{1cm} (4)

![Figure 2](image2.png)

**Figure 2.** The topology of three-phase voltage source inverter.

The equation of the $n$th cycle of the sequence pulse is shown in (1), where $A$ is the amplitude of the sequence, $T_n$ is switching period of $n$th cycle, and $D_n$ is duty ratio of $n$th cycle. The pulse train is shown in Fig.3(a) has been called $g(t)$, which is described in (2). Equation (3) can be obtained by the Fourier transform of (2). The real and imaginary parts in (3) are special cases of (4). If $c(f_0)$, given at (4), becomes zero independent on sine delay ($\varphi$) can be any angle in (4), then the magnitude of $f_0$ in power spectral density (PSD) of $g(t)$ becomes zero.

In order to make $c(f_0)$ satisfy the condition, 0 for all $\varphi$, the specific frequency $f_0$ can be eliminated by canceling each other with the preceding and succeeding terms in (4) and the switching cycle is calculated to obtain (5).

$$T_{n+1} = \frac{2k - f_0 T_n (1 + D_n)}{f_0 (1 + D_{n+1})}$$ \hspace{1cm} (5)

This sequence pulses can be regarded as the output voltage $u_{AN}$, $u_{BN}$, or $u_{CN}$ of the three-phase voltage inverter in Fig.2, where $t_n$ and $t_{n+1}$ are the start and end of the $n$th switching cycle. If $u_{AN}$, $u_{BN}$, and $u_{CN}$ pulse spectra do not contain the specific harmonic frequency $f_0$. Then the line voltage
spectrum of the inverter obtained by subtracting each other does not contain $f_0$. The single-phase voltage inverters can be applied to the proposed method.

IV. THE FORMULAS AND SPECTRUM SHAPING OF SELECTIVE HARMONIC ELIMINATION IN RPWM

It is being demonstrated from Fig.3 that there are three positions for waveform of output voltage, which are leading, centering and lagging in the cycle. The switching cycle’s general formulas were derived for one pulse in [18] and [19]. There is no complete general formula of switching period, random number and corresponding frequency extremum for the three pulse positions. Furthermore, the elimination mechanism of the specific frequency is lack of systematic analysis.

A. THE GENERAL FORMULAS OF SELECTIVE HARMONIC ELIMINATION IN RPWM

Two ideas for RPWM selective harmonic elimination are given in Tables 1-7 aimed at three different pulse positions, and the general formula of the corresponding switching cycle, random number and its corresponding extreme value of inverter switching frequency are also derived. The calculation formulas for $c(f_0)$ are shown in Table 1 aiming at three pulse positions. On this basis, two RPWM selective harmonic elimination ideas can be obtained.

The idea 1 is that the second summation sub-item of the $n$th term is offset by the first summation sub-item of the $(n+1)$th term. The second summation sub-item of the $(n+1)$th term is offset by the first summation sub-item of the $(n+2)$th term, and so on. The idea 2 is that the first summation sub-item of the $n$th term is offset by the second summation sub-item of the $(n+1)$th term. The first summation sub-item of the $(n+1)$th term is offset by the second summation sub-item of the $(n+2)$th term, and so on. The difference between the two ideas lies in the different ways of canceling the front and back terms in $c(f_0)$.

The above two RPWM selective harmonic elimination ideas are respectively applied to the three pulse positions in Fig.3. The switching frequency, random number $k$ and its corresponding general formulas of the switching frequency extreme value are obtained respectively in Tables 2-7. In Table 2, only the corresponding formula of idea 1 is derived because the corresponding formula of idea 2 was given in [19].

In the table, $D_{\text{max}}$ and $D_{\text{min}}$ are the upper and lower limits of the duty cycle. $f_{\text{max}}$ and $f_{\text{min}}$ which are generally preset are the upper and lower limits of the inverter’s instantaneous switching frequency, which is the spread spectrum range. Generally, there is more than one positive $k$ from $k_{\text{min}}$ to $k_{\text{max}}$. 

![FIGURE 3. The diagram of pulse train.](image-url)
TABLE 4. The expression of switching cycle in Fig.3(b).

| Idea 1 | Idea 2 |
|-------|-------|
| \( T_{n+1} = \frac{k}{f_0} + \frac{\sum_{m} T_m}{k} \) | \( T_{n+1} = \frac{k}{f_0} + \frac{\sum_{m} T_m}{k} \) |
| \( T_{n+1} = \frac{k}{1-D_{n+1}} \) | \( T_{n+1} = \frac{k}{D_n} \) |
| \( T_{n+1} = \frac{k}{1-D_{n+1}} \) | \( T_{n+1} = \frac{k}{D_n} \) |

TABLE 5. Random number \( k \) and its corresponding extreme value of switching frequency in Fig.3(b).

| Idea 1 | Idea 2 |
|-------|-------|
| Extremum of \( k \) | Extremum of \( f_k \) |
| \( k_{max} \leq \frac{f_0(1-D_{max})}{f_{max}} \) | \( f_{max} = \frac{1}{D_{max}} \) |
| \( k_{min} \geq \frac{f_0(1-D_{min})}{f_{min}} \) | \( f_{min} = \frac{1}{D_{min}} \) |

TABLE 6. The expression of switching cycle expression in Fig.3(c).

| Idea 1 | Idea 2 |
|-------|-------|
| \( T_{n+1} = D_n T_n + \frac{k}{f_0} \sum_{m} T_m \) | \( T_{n+1} = \frac{k}{D_n} \) |
| \( T_{n+1} = \frac{k}{f_0} \) | \( T_{n+1} = \frac{k}{D_n} \) |
| \( T_{n+1} = \frac{k}{f_0} - D_n T_n - T_{n+1} \) | \( T_{n+1} = \frac{k}{D_n} - T_n - T_{n+1} \) |

TABLE 7. Random number \( k \) and its corresponding extreme value of switching frequency in Fig.3(c).

| Idea 1 | Idea 2 |
|-------|-------|
| Extremum of \( k \) | Extremum of \( f_k \) |
| \( k_{max} \leq \frac{f_0(1-D_{max})}{f_{max}} \) | \( f_{max} = \frac{1}{D_{max}} \) |
| \( k_{min} \geq \frac{f_0(1-D_{min})}{f_{min}} \) | \( f_{min} = \frac{1}{D_{min}} \) |

The general formulas for the upper and lower limits of the switching frequency corresponding to each \( k \) are \( f_{k_{max}} \) and \( f_{k_{min}} \). \( e \) is a positive number.

**B. FURTHER SPECTRUM SHAPING OF SELECTIVE HARMONIC ELIMINATION IN RPWM**

The existing RPWM selective harmonic elimination method can only selectively eliminate the harmonics at one special frequency and its integer multiple. However, the motor has multiple noise peaks. Therefore, it is necessary to further shape the inverter output spectrum in the traditional selective harmonic elimination method. It can be seen from Tables 1-7 that in the process of selective harmonic elimination of RPWM, there is a corresponding relationship between the random number \( k \) and the switching frequency of the inverter. The switching frequency of the inverter can be avoided by reasonable selection of random numbers to achieve further shaping of the inverter output spectrum.

Take the idea 1 of pulse position in Fig.3(a) as an example, the switching frequency formula can be obtained by taking the reciprocal of the switching cycle \( T_{n+1} \) in Table 2

\[
f_{n+1} = \frac{1}{T_{n+1}} = \frac{1}{f_0} \left( 1 - D_{n+1} \right) \left( \frac{2k}{f_0} - (1 - D_n) T_n \right)
\] (6)

As shown in Fig.4, the range of effective random numbers is determined by using \( k_{max} \) and \( k_{min} \) in Table 3. The switching frequency corresponding to each \( k \) can be obtained from (6). After removing the corresponding \( k \) in the specific switching frequency range, and randomly selecting a \( k \) from the remaining numbers, then the switching cycle \( T_{n+1} \) is calculated. Thus, the switching frequency of the inverter is avoided the specific frequency range. And other pulse positions can be obtained by this method.

**V. SIMULATION AND EXPERIMENT**

**A. THE VERIFICATION AND ANALYSIS OF SELECTIVE HARMONIC ELIMINATION IN RPWM**

Three-phase voltage inverter is taken as an example to verify the effect of RPWM selective harmonic elimination in Fig.5.

The system experiment parameters are as follows: the loads of the inverter are \( L = 5 \text{mH} \) and \( R = 5 \Omega \). The reference voltage of the DC side is 24V and the capacitance is 2200\( \mu \text{F} \). The frequency to be eliminated \( f_0 \) is 7 kHz and \( M = 0.9 \). The system main control chip adopts 32-bit DSP TMS320F2812. The main circuit of the inverter uses IGBT.
BSM50GB120DN2 as the power switching device, and the scope in the experiment is DS1052E.

Relevant experiments are implemented according to the principle of $T_{n+1}$ in Table 2. Among them, the output voltage $u_{AB}$ of the three-phase inverter and its corresponding PSD waveform are shown in Fig.6. The output three-phase current of the three-phase inverter and its corresponding PSD waveform are shown in Fig.7.

As shown in Fig.6(a), the inverter output voltage pulse’s width varies randomly, and it can be seen from Fig.7(a) that the three-phase current waveform of the inverter output change in a sinusoidal shape accordingly. From Fig.6(b) and Fig.7(b), it can be seen that there is no obvious peak in the PSD of the voltage and current. The distribution of PSD is uniform, and the harmonic of 7 kHz and its integer multiple can be significantly reduced. Compared with the voltage waveform, the harmonic content of the current is significantly reduced due to the filtering effect of the inductance at the output of the inverter.

**B. EFFECTIVENESS ANALYSIS ON FURTHER SPECTRUM SHAPING**

Based on the spectrum shaping method proposed in this paper, the AC asynchronous motor (variable frequency) is simulated by Simulink. The vibration and noise of three-phase AC asynchronous motor are studied by using ANSOFT and ANSYS. The motor parameters are shown in Tab.8.

The switching frequency corresponding to each $k$ can be obtained by (6). The random numbers corresponding to the frequency range from 3.55 kHz to 3.8 kHz are removed. A $k$ is selected from the remaining random numbers to calculate the switching cycle $T_{n+1}$. Thereby, the specific frequency range is avoided from the switching frequency of the inverter. The distribution shown in percentage format of the instantaneous switching frequency is shown in Fig.8 and the corresponding PSD waveform of the voltage is shown in Fig.9.
As shown in Fig.8 and Fig.9, the selected frequency range can be avoided by the above-mentioned method. It can be found that the PSD waveform in the selected frequency range has an obvious gap by comparing the voltage spectrum before and after shaping.

**C. VIBRATION AND NOISE SUPPRESSION OF AC ASYNCHRONOUS MOTOR**

The rated current signal generated by the inverter is imported into the finite element model of the three-phase asynchronous motor. The motor’s load is rated constant torque. In the traditional fixed frequency SPWM and traditional RPWM strategies, the frequency of the modulating wave is 50 Hz. The frequency of the carrier wave is 10 kHz in the traditional fixed frequency SPWM. The output harmonics of the inverter are concentrated at 10 kHz and its integer multiple. Because the distribution of the switching frequency in the RPWM is random, in order to make the switching frequency distribution range of RPWM correspond to the frequency of traditional SPWM, the distribution range of the switching frequency in RPWM is 8-12 kHz. The PSD waveform of the ERPL (Equivalent Radiated Power Level) of the asynchronous motor is shown in Fig.10, and the analysis of the vibration acceleration of the AC asynchronous motor housing is shown in Fig.11.

It can be seen from Fig.10(a) that in the traditional fixed-frequency SPWM, the strong noise amplitudes are generated because of the concentrated distribution of harmonics around the switching frequency and its integer multiple (10 kHz, 20 kHz), which correspond to the points 1 and 2 in Fig.10(a).
As shown in Fig.11(a), which is the motor vibration acceleration waveform with the traditional SPWM. There are vibration peaks of different intensity near 10 kHz and 20 kHz, which further confirms the analysis results obtained from Fig.10(a). The traditional RPWM method is respectively shown in Fig.10(b) and Fig.11(b). The points 1 and 2 in the Fig.10(b) and Fig.11(b) are around the switching frequency and its integer multiple (10 kHz, 20 kHz). Compared with Fig.10(a) and Fig.11(a), the vibration and noise at points 1 and 2 in the RPWM are significantly suppressed, which proves the effectiveness of the RPWM.

In some high-power traction system applications, inverter switching frequency should not be high, so the carrier frequency in the traditional SPWM is reduced to 1.5 kHz in this paper and the switching frequency in the RPWM is also reduced accordingly. As shown in Fig.12 and Fig.13, the traditional RPWM can still suppress motor vibration and noise near the switching frequency and its integer multiple. However, the traditional RPWM in Fig.12(b) and Fig.13(b) also has problems: One is that although the vibration and noise around 7.5 kHz have been significantly reduced, they are still prominent, the other is that the vibration and noise around 3.6 kHz are much higher than before. In the process of RPWM random spread spectrum, the switching frequencies originally concentrated at 3k, 4.5k, 6k, 7.5k and 9k Hz are evenly distributed within a certain frequency range. Simultaneously, the harmonic contents near the original harmonic peaks are increased and new vibration and noise peaks may appear near the resonance frequency. Thus, it is necessary to shape the spectrum further.

The RPWM selective harmonic elimination methods proposed in this paper is shown in Fig.12(c) and Fig.13(c). The selective elimination frequency $f_0$ is 7.5 kHz. By reasonably selecting the random number $k$, the inverter’s switching frequency is prevented from being distributed in the frequency range from 3.55 kHz to 3.8 kHz in order to further achieve the voltage spectrum shaping.

It can be seen from the comparison of Fig.12(a, c) and Fig.13(a, c) that the noise power and vibration acceleration near the switching frequency of traditional SPWM and its integer multiple can be effectively reduced with the proposed method in this paper. As a result, the basic functions of the RPWM are achieved. Compared with Fig.12(b, c) and Fig.(b, c), the influence of harmonics at 7.5 kHz can be effectively reduced by using the proposed method. The content of the frequency (7.5 kHz) is further reduced on the basis of the
Aiming at the problem that the vibration and noise of inverter-powered induction motor are strong near the switching frequency and its integer multiple, the RPWM selective harmonic elimination and further spectrum shaping method are proposed. The general formulas of RPWM selective harmonic elimination corresponding to three pulse positions are derived respectively. The simulation and experimental results prove that this method can selectively suppress the specific harmonic power in the inverter output voltage and current. Furthermore, through the reasonable selection of effective random number, the switching frequency is prevented from being distributed in a specific frequency band, and further spectrum shaping is achieved. Compared with the traditional RPWM, the method proposed in this paper can selectively suppress the special frequency in the asynchronous motor’s vibration and noise spectrum. It does not need digital filter and has the characteristic of small amount of calculation.

VI. CONCLUSION

Aiming at the problem that the vibration and noise of inverter-powered induction motor are strong near the switching frequency and its integer multiple, the RPWM selective harmonic elimination and further spectrum shaping method are proposed. The general formulas of RPWM selective harmonic elimination corresponding to three pulse positions are derived respectively. The simulation and experimental results prove that this method can selectively suppress the specific harmonic power in the inverter output voltage and current. Furthermore, through the reasonable selection of effective random number, the switching frequency is prevented from being distributed in a specific frequency band, and further spectrum shaping is achieved. Compared with the traditional RPWM, the method proposed in this paper can selectively suppress the special frequency in the asynchronous motor’s vibration and noise spectrum. It does not need digital filter and has the characteristic of small amount of calculation.

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FIGURE 14. Deformation of motor caused by 3.675 kHz.
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