Torque ripple suppression strategy of asynchronous motor for electric vehicle based on random pulse position space vector pulse width modulation with uniform probability density

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Abstract
A random modulation strategy is proposed to suppress the torque ripple of asynchronous motor for electric vehicle in this article. First, the models of harmonic torque and torque ripple are established. The reason of harmonic generation and its effect on torque are analysed. Second, the random position pulse width modulation (PWM) strategy with different random quantities is introduced. The different structures of random pulse position space vector PWM strategy based on uniform probability density are designed. The specific harmonic content is dispersed and the torque ripple is suppressed. Finally, the precise test platform based on eSPACE is established. The influence of different random PWMs on motor at various speeds is compared. Experimental results verify the validity of the proposed approach.

1 | INTRODUCTION
In recent years, with the strong support of countries on new energy technologies, electric vehicles have been developed rapidly. They will replace traditional fuel vehicles and become mainstream vehicles. The asynchronous motor for electric vehicle is famous for its simple structure, low cost and high efficiency [1–4]. However, the electromagnetic noise and torsional vibration caused by torque ripple of an asynchronous motor have great influence on the comfort of an automobile [5]. The high-order harmonic in motor current is the main factor affecting the output torque ripple [6–8].

The harmonics that cause the torque ripple of the motor are mainly produced by the motor itself and the inverter. Due to the magnetic saturation and slot effect of the magnetic circuit, the air gap magnetic field is distorted and the motor produces spatial harmonics. The non-linear characteristics of the inverter make it to produce time harmonics. Time harmonics affect torque ripple when determining the motor structure [9]. This article mainly studies time harmonics.

To suppress the torque ripple caused by time harmonics, scholars have studied the control strategy and the modulation strategy. On the one hand, to improve the control strategy, the filter is added to suppress the harmonics. For example, the hybrid filter with coupling transformer and capacitor in series is proposed in [10], and the harmonics and torque ripple are suppressed. In [11], the novel isolated bidirectional dc-de converter with built-in filters is proposed. This method can effectively improve the power density, efficiency and noise reduction of the converter. In [12], a novel microstrip lowpass filter design using rectangular split-ring resonators with dual splits is designed. The lowpass filter is employed to reject higher order harmonics from the stopband without affecting the selectivity. In [13], a frequency-adaptive complex-coefficient filter-based control for three-phase grid supportive double-stage photovoltaic (PV) system is studied. This control eliminates harmonic components, DC offset at unbalanced loads and is robust against phase frequency shift and on utility grid voltage disturbances. These hardware filters can filter out the high-frequency harmonics in the control system, with fast response and good results.
However, the control cost increases and the control structure becomes complex due to the new hardware.

For example in [14], the multi-resonance controller is used to improve the q-axis current in the synchronous frame. The torque ripple caused by non-sinusoidal back electromotive force (EMF) is reduced. In [15], the resonant controller is used to compensate for the dead time of the two-phase motor, and the harmonics caused by the dead time are suppressed. These software filters directly suppress the harmonics in the original control strategy through the programme, especially for the specific harmonic suppression, which has a good effect. However, the control time of the controller is increased, and the real-time performance is slightly poor due to the need to improve the original programme.

The harmonic is suppressed by improving the modulation strategy. The most effective strategy is random pulse width modulation (PWM). The three types of random PWM strategies are as follows: random switching frequency, random zero vector, and random pulse position (RPP).

The modulation strategy of random switching frequency, which has a good effect on harmonic suppression, is the most studied strategy. In [16], the 2D random switching PWM technique is proposed to reduce the dominant harmonic while maintaining a constant average inductor current and sampling frequency. In [17], the synchronous random switching frequency modulation (SRSFM) technique based on carrier phase shift for paralleled three-phase voltage source inverters is proposed in this study to eliminate the PWM noise. It not only completely eliminates the PWM noise nearby odd-order carrier frequency but also reduces PWM vibration noise around even-order carrier frequency depending on the switching frequency variation range. However, when this modulation strategy is used in the motor control system, it is difficult to debug, can easily cause damage to the inverter, and has poor operability. The operation of random zero vector is relatively simple and easy. In [18], the two-phase double zero vector random centre distribution (RCD) strategy is proposed to solve the problem of two-phase RCD-PWM with V (000) as the zero vector and to reduce the audible switching noise. However, the random modulation range of this method is small due to the pulse symmetry.

Numerous studies on the theory of RPP and limited works on its application to motor control have been conducted. For example in [19], the rigorous theoretical harmonic analysis of the RPP modulation strategy is performed. The theoretical relationship among discrete harmonic, continuous noise, and output voltage ripple is established, and the output voltage performance of this method is studied.

To find a modulation method to effectively reduce the current harmonics in the operation of the electric vehicles so as to suppress the torque ripple, the RPP modulation strategy is deeply studied, and an RPP space vector modulation PWM (UPD-RPPSVPWM) strategy based on uniform probability density is proposed. First, this study compares and analyses the different ranges and types of random numbers. Second, different random structures are investigated to achieve improved torque ripple suppression effect. Finally, the experimental platform is built to compare the torque ripple suppression effect of this method with fixed-frequency SVPWM (FFSVPWM) and random zero vector SVPWM (RZSVSPWM).

This article is organised as follows: Section 2 describes the harmonic torque and the torque ripple models. The influence of PWM on time harmonics is analysed, and the evaluation criteria for harmonic suppression are provided. Section 3 analyses the influence of random quantity distribution and number range on torque ripple and then designs RPP modulation strategy with different structures. Section 4 discusses the accuracy of the presented control scheme, as validated through experiments. Section 5 concludes this article.

2 | HARMONIC RIPPLE TORQUE ANALYSIS

2.1 | Establishment of harmonic torque mode

Electric vehicles which can be driven with power, high efficiency, zero pollution emissions, and with a series of advantages, have become the dominant direction of the automotive industry. The motor is considered as the ‘heart’ of an electric vehicle, and its performance determines the performance of the electric vehicles. But in practical application, the torque ripple problem of the motor is more serious, which seriously affects the performance of the motor.

To understand the causes of torque ripple, the motor current is analysed. First, the equivalent resistance of the stator affects the performance of the motor. Therefore, the stator harmonic current is approximately equal to the rotor harmonic current. The K-th harmonic current is:

\[
\begin{align*}
I_{ak} & \approx \sum_{k=1}^{\infty} \frac{1}{k} I_{km} \sin(k\omega_r t) \\
I_{bk} & \approx \sum_{k=1}^{\infty} \frac{1}{k} I_{km} \sin\left(k\omega_r t - \frac{\pi}{3}\right) \\
I_{ck} & \approx \sum_{k=1}^{\infty} \frac{1}{k} I_{km} \sin\left(k\omega_r t + \frac{\pi}{3}\right) \\
I_{km} & = \frac{U_{km}}{a_r (L_{a1} + L_{a2})}
\end{align*}
\]

In the formula, \(I_{km}\) is the K-th harmonic current amplitude.

Therefore, the instantaneous electromagnetic power of the motor under K-harmonic power supply is as follows:

\[
P_k = P_{ak} + P_{bk} + P_{ck} = u_{ak}i_{ak} + u_{bk}i_{bk} + u_{ck}i_{ck}
\]
The instantaneous electromagnetic power generated by the combination of fundamental EMF and K-order rotor harmonic current is as follows:

\[ P_k = P_{sk} + P_{pk} + P_{ck}, \]

\[ k = \begin{cases} k_+ = 6n + 1 \quad \text{(n = 1, 2, 3...)} \\ k_- = 6n - 1 \quad \text{(n = 1, 2, 3...)} \end{cases}, \]

where \( \omega_r \) is the angular frequency, \( \phi_k \) is the phase, \( U_{1m} \) is the amplitude of the fundamental EMF, \( I_{1m} \) is the current amplitude of the fundamental EMF, \( P_k \) is the electromagnetic power synthesised by the fundamental EMF and the \( k \)-th harmonic current, \( I_{km} \) is the \( k \)-th harmonic current amplitude. \( + \) is the positive sequence harmonic current, and \( - \) is the negative sequence harmonic current.

The \( k \)-th harmonic electromagnetic torque can be derived from the instantaneous electromagnetic power:

\[ T_k = \frac{P_k}{\Omega_r} = \frac{3}{k} \frac{\omega_r}{2\omega_r} U_{1m} I_{km} \cos(6\omega_r t + \phi_k + \pi), \]

\[ T_k = -\frac{3}{k} \frac{\omega_r}{2\omega_r} U_{1m} I_{km} \cos(6\omega_r t + \phi_k), \]

where \( \Omega_r \) is the synchronous angular velocity and \( n_p \) is the number of poles of the motor.

The synthesised pulsating torque can be obtained by superimposing the instantaneous values of the harmonic pulsating torques. The formula is as follows:

\[ T_m = \sum_{k=1}^{\infty} T_k = \frac{3n_p}{2\omega_r} U_{1m} \sum_{k=1}^{\infty} \frac{1}{k} I_{km} \cos(6\omega_r t). \]

The pulsating torque is related to the amplitude of the \( k \) harmonics, as shown in Equation (4).

The harmonic current that causes the torque ripple contains multiple time harmonics. The even harmonics cancel each other out during the harmonic superposition and can be ignored. The harmonic components of the 13th or more times above that are relatively small. Thus, only the influence of the 5th, 7th, 11th, and 13th harmonics on the pulsating torque should be analysed.

Figure 1 presents the simulation results based on Equations (5) and (6).

Figure 2(a) shows that the harmonic ripple torque generated by different harmonics has different levels of promotion and suppression effects on the torque. The effect is reduced as the time of harmonics increases. In Figure 2(b), the torque peak value increases or decreases within a period due to multiple harmonic pulsations, resulting in the torque ripple.

### 2.2 Analysis of the torque ripple

The torque ripple is related to the electromagnetic and the load torques. The relation is as follows:

\[ T_e = T_L + \frac{J}{n_p} \frac{d\omega_r}{dt}. \]

where \( J \) is the equivalent moment of inertia. \( T_L \) is the load torque. \( d\omega_r/dt \) is the differential of the rotor angular velocity.

By transforming and differentiating Equation (7), the torque wave equation can be obtained as follows:

\[ \Delta T = \frac{J}{n_p} \frac{\omega_r(k+1) - \omega_r(k)}{\omega_r(k)}. \]

\( J \) is constant in Equation (8). The harmonic torque ripple value can be calculated on the basis of the torque angular velocity.

In summary, it can be seen from the above figure that the fundamental torque figure is very smooth, but after the harmonic torque generated by each time harmonic is superimposed, the concave convex part of the waveform appears, which makes the fundamental torque ripple. The key to the ripple of fundamental torque is that the torque contains harmonic torque. To solve the problem of harmonic torque, it is necessary to solve the problem of time harmonic.

### 2.3 Cause of harmonic

The time harmonics that cause torque ripple are related to the PWM strategy. At present, the commonly used PWM strategy is SVPWM. The dual Fourier transform of SVPWM signal can be obtained, as follows:
the que generates RPPSVPWM PWM UPD harmonics study ripple. The designed ripple causing this etor, is strategy—the time harmonic time harmonic 3 2 rent to harmonic T orqu monics frequency caused side monics nent, ter phase the must, is har-and is be the second harmonic, The is car and ms frequency T are. SVPWM ely side the and cause compo-component the components respectively right o band fourth components switch time the The (ed. of Equation fundamental traditional 9 are. of Equation fundamental, the fre-

\[ f(x,y) = \frac{A_{00}}{2} + \sum_{n=1}^{\infty} \left[ A_{0n} \cos n(\omega_0 t + \varphi_0) + B_{0n} \sin n(\omega_0 t + \varphi_0) \right] + \sum_{m=1}^{\infty} \left[ A_{m0} \cos m(\omega_c t + \varphi_c) + B_{m0} \sin m(\omega_c t + \varphi_c) \right] + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \sum_{n\neq 0}^{\infty} \left[ A_{mn} \cos (m(\omega_c t + \varphi_c) + n(\omega_0 t + \varphi_0)) + B_{mn} \sin (m(\omega_c t + \varphi_c) + n(\omega_0 t + \varphi_0)) \right], \tag{9} \]

where \( f(x,y) \) is the time domain signal, \( \omega_0 \) is the angular frequency of the fundamental, \( \theta_0 \) is the phase of the fundamental, \( \omega_c \) is the angular frequency of the carrier, and \( \theta_c \) is the carrier phase.

On the right side of Equation (9), the first and second terms are the DC bias component and fundamental component, respectively. The third and fourth terms are the harmonic components of switching frequencies and the relevant side-band components, respectively. The time harmonic is caused by the harmonic component of the switching frequency. The traditional SVPWM is the main cause of harmonics. To suppress time harmonics, SVPWM must be improved.

3 | TORQUE RIPPLE SUPPRESSION BASED ON UPD-RPPSVPWM

The PWM generates time harmonics, causing torque ripple. When the time harmonic is suppressed, the torque ripple is suppressed. The UPD-RPPSVPWM strategy is designed to suppress harmonics in this study.

3.1 | Influence of random variables on torque ripple

The random modulation strategy produces a broadened spectral effect in the current waveform. It causes a change in the spectrum and randomises the switching frequency. The time harmonic of the switching frequency is reduced [20–22]. The effect of this strategy on torque ripple suppression depends on the type of random distribution and the range of random numbers.

3.1.1 | Analysis of random quantity distribution

The effect of random modulation strategy on harmonic suppression is related to the type of random number distribution, and the effect of different random number distribution types on harmonic suppression is different. The common types are Gaussian distribution and uniform probability density.

Gaussian distribution can also be called normal distribution. It has a probability density function, which describes the probability of a random variable approaching a certain point.

The Gaussian distribution is expressed in Equation (9).

\[ f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \tag{10} \]

The uniform probability density is a symmetric probability distribution, and the distribution probability at the same length interval is equally possible.

The uniform probability density equation is as follows:

\[ f(x) = \frac{1}{b-a}, \quad a < x < b \tag{11} \]
According to the above two probability density functions, two random number generators are established and the random number results are shown in Figure 3.

Figure 3(a) shows that the random number obtained by the Gaussian distribution is mainly concentrated in the middle part, and the random numbers obtained by the uniform probability density are evenly distributed. Figure 3(b) exhibits a comparison of the harmonic ratio obtained from two random quantities. It clearly presents that the uniform probability density produces less harmonic than the Gaussian distribution.

Therefore, the random number generated by the uniform probability density is suitable for motor control requirements, and the time harmonic suppression effect is the best effect. Thus, it is selected as the random quantity distribution in the PWM.

### 3.1.2 Optimal range of harmonic suppression for random numbers

The range of random numbers in the random modulation strategy for the suppression effect on time harmonics and torque ripple is important. In the random PWM strategy, the effective range of random number is (0, 1). To understand the optimal range, four different random ranges, namely, (0, 1), (0.2, 0.8), (0.4, 0.6), and (0.4, 0.8), are selected for the experiment on harmonic suppression. Figure 4 displays the results.

Figure 4 shows that the harmonic ratio (HR) has a decreasing trend. As the range is reduced, the overall effect of the harmonic suppression is improved. When the range selection is the largest, the HR decreases with the increase in the number of times, and the total harmonic distortion (THD) value is 23.24%. When (0.2, 0.8) is selected, the decrease in HR is better than that of (0, 1). The THD value is 23.74%. When (0.4, 0.6) is selected, the HR is the largest, and the THD value is 25.15%. When (0.4, 0.8) is selected, the HR is the least, and the THD value is 22.86%. Therefore, the random amount range influences the harmonic suppression effect.

The smaller the random amount range, the better the suppression effect. However, when the range is reduced to a certain extent, the suppression effect worsens. A reasonable option of the random amount range is crucial for the time harmonic suppression effect.

### 3.2 Influence of random position structure on torque ripple

#### 3.2.1 Random position structure design

To suppress the torque ripple effectively, the traditional SVPWM strategy is improved in this article. The random number is added into the duty cycle and the conduction time calculation module, the conduction time value of the three-phase waveform is changed, and the switching frequency randomly is dispersed. Figure 5 shows the seven pulse width waveforms of the SVPWM and UPD-RPPSVPWM. Among them, SVPWM is about centrosymmetry, while UPD-RPPSVPWM cannot be about centrosymmetry because of the random number.

Three variables, namely, δ₁, δ₂, and δ₃, affect the position of the pulse waveform in Figure 5. When some of the three variables are fixed, changing the value of another can change the effect of the RPP modulation. Therefore, on the basis of the different values of variable δ₁, three RPP modulation structures are designed. Variable δ₁ represents the variable values, and the other two variables are the fixed values. Variables δ₁ and δ₂ are the variable values, and the third variable is fixed. Variables δ₁, δ₂, and δ₃ are the variable values.

To suppress the torque ripple effectively, the model of three UPD-RPPSVPWM with different random position structures based on a vector control model are built. Figure 6 exhibits the control model.

#### 3.2.2 Different random position structure pulsation suppression results

Harmonic suppression and torque ripple suppression experiments were performed on three different RPP structures. Figure 7 shows the results.

**FIGURE 3** (a) shows the random number distribution produced by Gaussian distribution and uniform distribution, where the abscissa represents the sampling time and the ordinate represents the random value. (b) shows the comparison of the harmonic content of the two distributions under different harmonic numbers, in which the abscissa represents the harmonic number and the ordinate represents the harmonic content.
Figure 4 (a) shows the comparison of harmonics of different orders generated by random number parameters in four ranges, in which the abscissa represents the harmonic number and the ordinate represents the harmonic content. (b) comparison of harmonic THD values caused by random numbers in four ranges, in which abscissa represents random number range and ordinate represents THD value.

Figure 7(a) reflects the HR of the three random position structures. As the order of harmonics increases, the HR shows a decreasing trend. However, after the 11th harmonics, the HR of two and three random position structures is increased. Figure 7(b) shows that the THD value increases gradually when the random number of the random position structure increases. When one random position structure is applied, the current THD is 9.95%. When the modulation strategy is changed to two random position structures, the THD value increases by 0.43% to 10.38%. The THD value of the three random position structures is 12.34%, which is the maximum of the three random position structures.

Figure 7(c) shows the phase current waveform obtained by three random position structures. All three current waveforms are sinusoidal, but each current waveform is not smooth. Among them, the waveform defect of one random position structure is less. When three random position structures are used to modulate the waveform, it causes the most amount of defect. The defect of two random position structures lies between the others.

Figure 7(d) shows the suppression result of the pulsating torque by three random position structures. The number indicates the magnitude of the fluctuation. It shows that when the modulation strategy adopts one random position structure, the maximum value of the torque ripple is 0.0114 N.m. When the random position structure is replaced by two random position structures, the torque ripple increases by 0.0029 N.m. When the random position structure is changed into three random position structures, the torque ripple value is 0.0004 N.m smaller than that of two random position structure, but 0.0025 N.m more than that of one random position structure.

In conclusion, the three RPP structures have different effects on harmonic suppression and torque ripple suppression. The one random structure is optimal.
3.2.3 Simulation comparison experiment

To verify the effectiveness of the UPD-RPPSVPWM, a vector control model of an asynchronous motor is built. The switching period is set to 5 kHz and the rated motor speed to \( n = 1400 \) r/min. UPD-RPPSVPWM with one random position structure is selected for the experiment. Moreover, RZVSVPWM and FFSVPWM are used to compare the experiments. Figure 8 presents the comparison results.

Figure 8(a) shows a comparison of the HR of the three modulation strategies. In Figure 8(a), the HR generated by the three modulation strategies decreases with the increase of harmonic. However, RZVSVPWM fluctuates greatly in the seventh harmonic, and its HR value is the largest. The HR generated by UPD-RPPSVPWM is the smallest among the three modulation strategies. Figure 8(b) exhibits a harmonic THD with different modulation strategies. The graph shows that the THD value of FFSVPWM strategy is the largest at 14.58\%. The THD of RZVSVPWM is 2.92\% larger than that of UPD-RPPSVPWM. Figure 8(c) shows the phase current waveform obtained by the three modulation strategies. All three current waveforms are sinusoidal, but each current waveform has certain defects, and the waveform is not smooth. Among them, when using UPD-RPPSVPWM strategy, the waveform defects are less. When using FFSVPWM strategy, most defects are obtained. Figure 8(d) shows the result of pulsating torque when three different modulation strategies are used. The number indicates the magnitude of the fluctuation. It shows that when the modulation strategy adopts the FFSVPWM strategy, the maximum value of the torque ripple is 0.01 N.m. When the modulation strategy is replaced by the RZVSVPWM strategy, the torque ripple increases, and the maximum ripple value increases by 0.002 N.m compared with FFSVPWM. When the UPD-RPPSVPWM is used as the modulation strategy, the maximum fluctuation value is 0.0086 N.m. When compared with RZVSVPWM, it reduces 0.0114 N.m, whereas it reduces 0.0014 N.m when compared with FFSVPWM.

Figure 8 shows that the random modulation strategy has different harmonic suppression effects, but the UPD-RPPSVPWM has improved results. The results of harmonic suppression by RZVSVPWM are unstable.

Therefore, compared with the FFSVPWM and RZVSVPWM, the HR and THD obtained by the UPD-RPPSVPWM used in this study are the smallest.

4 EXPERIMENTAL COMPARISON

4.1 Platform building

Experiments were conducted on the asynchronous motor prototype to verify the feasibility and accuracy of the control scheme. Table 1 shows the asynchronous motor prototype parameters.

The experimental setup (Figure 9) consists of a grating encoder, a hardware-in-the-loop system eSPACE, a drive board,
a power supply, and an asynchronous motor prototype. The semi-physical eSPACE system is used to run the control strategy, and the motor prototype is driven by the drive board. The current and speed signals are obtained by two Hall-type current sensors and a quadrature encoder and fed back to the semi-physical eSPACE system. The semi-physical eSPACE system calculates the collected speed signal online and obtains the torque ripple value of the motor, which is transmitted to the upper computer.

4.2 | Comparative experiment

To verify the effectiveness of the proposed strategy, the suppression harmonic results of the three random position structures are compared under the three conditions of low, medium, and high speeds. Furthermore, the harmonic current (fast Fourier transformation) FFT and torque ripple value of the three strategies are compared under the three conditions.

4.2.1 | Different random position structures

Figure 9 shows the current FFT and torque ripple of different RPP structures at 100 r/min speed. Figure 10(a), (b) and (c) show the harmonic content of the switching frequency and its frequency, where the random

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**TABLE 1** Parameters of asynchronous motor

| Parameters         | Symbol | Values |
|--------------------|--------|--------|
| Frequency          | Hz     | 50     |
| Polar logarithm    | /      | 2      |
| Rated voltage      | V      | 220    |
| Rated current      | A      | 5.2    |
| Rated torque       | N.m    | 7.5    |
| Stator resistance  | Ω      | 5.32   |
| Stator inductance  | mH     | 26     |
| Mutual inductance  | mH     | 0.361  |

---

**FIGURE 8** (a) (b) (c) shows the harmonic content, THD and current waveform comparison of FFSVPWM, RZVSVPWM and UPD-RPPSVPWM. The abscissa represents the harmonic number, three PWM strategies and sampling time, and the ordinate represents the harmonic content, thd value and current amplitude. (d) shows the comparison of torque ripple caused by three different modulation strategies, in which the abscissa represents the three PWM strategies and the ordinate represents the torque ripple value.

**FIGURE 9** Experimental device
amplitude structure using one random number has a harmonic amplitude of 8.6 dB at the switching frequency. The harmonic amplitude of the two random numbers is 11.6 dB, and that of the three random numbers is 1.8 dB higher than that of the two random numbers. When the frequency rises to 10,000 Hz, the random amplitude structure using one random number has a harmonic amplitude of 6.2 dB. The harmonic amplitude of the two random numbers is 6.4 dB, and that of three random numbers is 11.6 dB. Figure 10(d) exhibits a waveform of the torque ripple of three random position structures. It shows that the value of the torque ripple decreases with the increase in the random number. When the PWM strategy is one random position structure, its torque ripple value is the smallest at 0.009 N.m. When the modulation strategy is replaced by two random position structures, the fluctuation value increases by 0.008 N.m. The maximum fluctuation value of the three-random-position structure strategy is 0.021 N.m.

Figure 11 shows the current FFT and the torque ripple at 800 r/min speed. Similarly, the harmonic amplitude at 5000 and 10,000 Hz are analysed.

Figure 11 (a), (b) and (c) show that at the switching frequency, the harmonic content of the random structure with one random number is the lowest, with a value of 9.6 dB, while the harmonic content of two random numbers is the highest, with a value of 11.6 dB. The three random number harmonics are 13.6 dB. At 10,000 Hz, the maximum harmonic contents of the three random structures are 6.4 dB, 8.6 dB and 9.4 dB, respectively.

In Figure 11(b), the torque ripple waveform with different random position structure strategies shows that the more the random number of random position structures, the greater their torque ripple values. The torque ripple of the three random position modulation strategy is 0.0234 N.m. It is 0.0124 N.m more than that of the one random position modulation strategy and 0.0031 N.m more than that of the two random position modulation strategy.

Figure 12 shows the current FFT and the torque ripple at 1200 r/min speed.

Figure 12(a), (b) and (c) show an analysis of the harmonic amplitude at 5000 and 10,000 Hz. When the frequency is 5000 Hz, the harmonic amplitude of the one random number is the least among the other random position structures at 8.6 dB. The harmonic amplitude of the two random numbers is 9.6 dB, and the harmonic amplitude of the three random numbers is 1.2 dB larger than that of two random numbers. When the frequency is 10,000 Hz, the maximum harmonic content of using one random number is 6.4 dB, the harmonic content of using two random numbers is 1 dB higher than the former, and the harmonic content of using three random numbers is 8.6 dB. Figure 12(d) shows the waveform of the torque ripple value under each random position structure strategy. It presents that the value of the torque ripple from a random position structure strategy is 0.0106 N.m, which is the smallest among the three structures. The fluctuation value of the structure with two random positions is 0.0077 N.m higher than that of the structure with one random positions. The fluctuation value of the three random position structure is 0.0231 N.m.

In conclusion, the current FFT and the torque ripple produced by the different RPP structures are different at
FIGURE 11  (a), (b), (c) shows the current spectrum generated by different random number structures at 800 rpm, and compares the harmonic content at the switching frequency (5000Hz) and frequency doubling (10000Hz), where the abscissa represents the frequency and the ordinate represents the harmonic amplitude. (d) shows the torque ripple generated by different random number structures at 800 rpm. The abscissa represents the different random number structures, and the ordinate represents the torque ripple value.

FIGURE 12  (a), (b), (c) shows the current spectrum generated by different random number structures at 1200 rpm, and compares the harmonic content at the switching frequency (5000Hz) and frequency doubling (10000Hz), where the abscissa represents the frequency and the ordinate represents the harmonic amplitude. (d) shows the torque ripple generated by different random number structures at 1200 rpm. The abscissa represents the different random number structures and the ordinate represents the torque ripple value.
It shows the current FFT and the torque ripple values using three strategies. In Figure 14(a), (b) and (c), the harmonic of the UPD-RPPSVPWM is the least among the other strategies, and the values are 9.6 and 6.4 dB. Compared with UPD-RPPSVPWM, the harmonic of RZVSVPWM is increased by 1.6 dB and 3.4 dB, respectively. The harmonic content of FFSVPWM is the highest, which is 13.4dB and 11.6 dB. Figure 14(d) shows that the UPD-RPPSVPWM has a good inhibitory effect on torque ripple, and the obtained ripple value is the smallest at 0.01 N.m. The FFSVPWM's torque ripple value is 2.5 times larger than that of UPD-RPPSVPWM. The torque ripple of the RZVSVPWM is smaller than that of the FFSVPWM, but larger than that of the UPD-RPPSVPWM. The value is 0.0187 N.m.

Figure 15 shows the current FFT and the torque ripple diagrams for \( n = 1200 \) r/min.

In Figure 15(a), (b) and (c), the FFSVPWM produces the most HR, which are 11.2 dB and 9.7 dB. In comparison with FFSVPWM, RZVSVPWM are reduced by 1.4 and 1.9 dB. The harmonic content of UPD-RPPSVPWM is the smallest, which are 8.6 dB and 6.4 dB. Thus, this method has the strongest HR capability. Figure 15(d) shows that the FFSVPWM results in a torque ripple of 0.0256 N.m. The torque ripple value of the RZVSVPWM is smaller than that of the FFSVPWM, and its value is 0.0198 N.m. The torque ripple value of the UPD-RPPSVPWM is the minimum, which is 0.0106 N.m.

It shows the current FFT and the torque ripple values using three strategies. In Figure 14(a), (b) and (c), the harmonic of the UPD-RPPSVPWM is the least among the other strategies, and the values are 9.6 and 6.4 dB. Compared with UPD-RPPSVPWM, the harmonic of RZVSVPWM is increased by 1.6 dB and 3.4 dB, respectively. The harmonic content of FFSVPWM is the highest, which is 13.4dB and 11.6 dB. Figure 14(d) shows that the UPD-RPPSVPWM has a good inhibitory effect on torque ripple, and the obtained ripple value is the smallest at 0.01 N.m. The FFSVPWM's torque ripple value is 2.5 times larger than that of UPD-RPPSVPWM. The torque ripple of the RZVSVPWM is smaller than that of the FFSVPWM, but larger than that of the UPD-RPPSVPWM. The value is 0.0187 N.m.

Figure 15 shows the current FFT and the torque ripple diagrams for \( n = 1200 \) r/min.

In Figure 15(a), (b) and (c), the FFSVPWM produces the most HR, which are 11.2 dB and 9.7 dB. In comparison with FFSVPWM, RZVSVPWM are reduced by 1.4 and 1.9 dB. The harmonic content of UPD-RPPSVPWM is the smallest, which are 8.6 dB and 6.4 dB. Thus, this method has the strongest HR capability. Figure 15(d) shows that the FFSVPWM results in a torque ripple of 0.0256 N.m. The torque ripple value of the RZVSVPWM is smaller than that of the FFSVPWM, and its value is 0.0198 N.m. The torque ripple value of the UPD-RPPSVPWM is the minimum, which is 0.0106 N.m.

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Figure 14 (a) (b) (c) shows the current spectrum generated by the three PWM strategies at 800 rpm, and compares the harmonic content at the switching frequency (5000Hz) and frequency doubling (10000Hz), where the abscissa represents the frequency and the ordinate represents the harmonic amplitude. (d) shows the torque ripple generated by the three PWM strategies at 800 rpm, in which the abscissa represents the three PWM strategies and the ordinate represents the torque ripple value.

Figure 15 (a) (b) (c) shows the current spectrum generated by the three PWM strategies at 1200 rpm, and compares the harmonic content at the switching frequency (5000Hz) and frequency doubling (10000Hz), where the abscissa represents the frequency and the ordinate represents the harmonic amplitude. (d) shows the torque ripple generated by three PWM strategies at 1200 rpm. The abscissa represents the three PWM strategies and the ordinate represents the torque ripple value.
In conclusion, this strategy is superior to FFSVPWM and RZVSVPWM in restraining the torque ripple and harmonic suppression at low, medium, and high speeds.

5 | CONCLUSION

The asynchronous motor for the electric vehicle is affected by the time harmonic in actual operation, and the problem of torque ripple appears. This article introduces the torque ripple suppression strategy of automotive asynchronous motor based on UPD-RPPSVPWM. The following conclusions are drawn from the simulation and experimental verification:

(1) Different random range and distribution type will greatly affect the modulation effect of the random PWM technology.

(2) Three kinds of RPP structures are designed when the random number range and the distribution type are determined. The results show that, under the same conditions, with the reduction of random number in the RPP structure, the suppression effect of the harmonic and torque ripple is better.

(3) At different speeds, random PWM has better harmonic and torque ripple suppression than FFSVPWM. In random PWM, RZVSVPWM has poor suppression effect, while UPD-RPPSVPWM can effectively suppress harmonic and torque ripple. The effectiveness of the method is verified.

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