# STUDY ON HARMONIC SUPPRESSING PERFORMANCE OF RANDOM SPACE VECTOR PWM IN ELECTRIC VEHICLE

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**Abstract -** The random SVPWM strategy can significantly suppress the clustering harmonic amplitudes of the traditional SVPWM strategy in the driving system of the electric vehicle (EV). Therefore, the principle of the random SVPWM strategy has been detailed. The expression for the signal randomization scheme is given, and then a comprehensive working time expression for the random switching frequency SVPWM, the random zero-vector distribution SVPWM, the random pulse position SVPWM and the hybrid random SVPWM schemes has been derived. An experimental validation has been carried out. The results show that the random SVPWM strategy has excellent performance on suppressing the harmonic amplitudes of the current and the electromagnetic torque.

**Keywords:** Electric vehicle, Electric driving system, Space vector PWM, Random space vector PWM, Harmonic suppressing.

## 1. Introduction

The electric vehicle (EV) is regarded as one important way to solve the problem of environmental pollution and energy crisis; therefore, the EV has been widely utilized all over the world and research on the EV has gained lots of financial and policy supports from the government and the organizations [1-4]. The electric driving system is the power component in the EV. The electric driving system determines not only the acceleration performance, but also the ride performance. In the electric driving system, the motor converts electrical energy into mechanical motion that drives the vehicle; and the power inverter changes the direct current (DC) form from the battery to the alternating current (AC) form fed to the motor. The space vector pulse width modulation (SVPWM) widely used in the motor vector control generates the pulse control signals for the inverter based on the volt-second balance principle [5,6]; therefore, the harmonic is inevitable besides the required fundamental in the output phase voltage and current, which results in the harmonic electromagnetic torque [7,8,9,10]. The traditional deterministic SVPWM strategy exhibits prominent clustering harmonics with big amplitudes around the switching frequency and its integer multiples because of the fixed pattern with switching frequency or period, fixed pulse positioning method, and so on. The electromagnetic radiation and noise, and the mechanical vibration especially resulting from the mechanical resonance are unavoidable problems in the deterministic SVPWM strategy in the EV [11,12]. The random PWM strategy using the randomization method has been proposed to destroy the fixed switching frequency or period, fixed pulse positioning method in the deterministic SVPWM strategy, and the excellent performance has been verified.

A large number of contributions to the SVPWM strategy have been created based on the randomization idea. The random strategy can obtain excellent performance on reducing harmonic distortion [13-15], electromagnetic emission [16-19], audible switching noise [20-22], vibration [21], and so on, which has been extensively exploited and verified. In order to destroy the fixed pattern in the deterministic SVPWM strategy, the switching frequency/period, the zero-vector distribution ratio, and the pulse positioning pattern should vary according to some specific deterministic or probability distribution laws. Consequently, the non-deterministic SVPWM strategy can be divided into three foundational schemes: random/variable switching frequency PWM [23-29], random pulse position PWM [30] and random zero-vector distribution [31, 32]. The combination of any two fundamental schemes or the three schemes results in the hybrid random PWM scheme [33]. The particle swarm optimization algorithm and the genetic algorithm have also been used to optimize the random PWM scheme [34, 35]. Based on harmonic characteristic analysis, the performance of the random scheme can be improved to satisfy special requirements through harmonic spectra shaping and customization [23, 29,35, 36]. For example, a band-pass filter is used to shape the current harmonic spectra and combined with the random switching frequency SVPWM scheme to suppress acoustic noise and vibration in the induction motors used by electric vehicles [23].

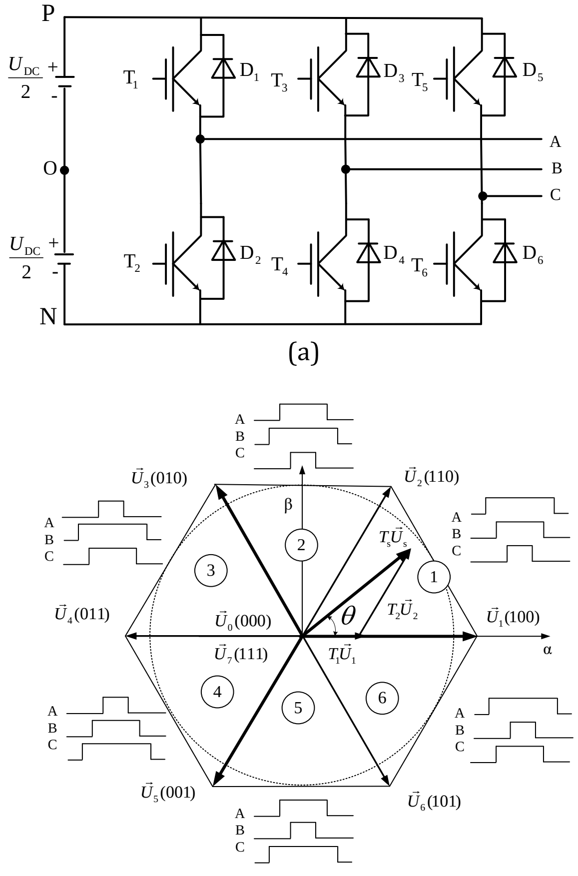
In summary, significant progress has been achieved in developing new SVPWM schemes and combining with other methods to improve the suppressing performance. However, the realization method aims at the specific random scheme, and the methodology for the universal expression and realization method to the random strategy is inadequately. The specific simulation model and experiment setup should be always built to verify the performance for the newly developed schemes. Consequently, from the perspective of verification and practical application, to further improve the development of novel random schemes, it is extremely important to explore the universal expression for the random strategy. Accordingly, the objective of this study is to explore the universal expression of the random strategy and develop a simulation model in MATLAB/Simulink.

This paper is organized as follows. Section 2 details the universal expression for the random SVPWM strategy. In Section 3, a simulation model in MATLAB/Simulink is developed in detail. In Section 4, the performance of the random schemes is verified by using the developed simulation model. Section 6 concludes this paper.

## 2. Random Space Vector PWM

The classic two-level three-phase inverter topology with the DC link voltage is shown in Fig. 1(a) with the positive pole P, the negative pole N, the neutral point O, the six switches $\mathrm{T}_i (i = 1,2,3,4,5,6)$ and the six fly-wheel diodes $\mathrm{D}_i (i = 1,2,3,4,5,6)$ [37]. The inverter has 8 permissible states. If the load is an isolated neutral machine, the corresponding phase-to-neutral voltages for each state can be computed. The operation mode of a two-level inverter gives five levels (0,$\pm U_{DC}/3$ and $\pm 2U_{DC}/3$) with respect to the isolated neutral. The corresponding space vectors for the 8 states can be derived. The six active vectors are $\vec{U}_1$ , $\vec{U}_2$ , $\vec{U}_3$ , $\vec{U}_4$ , $\vec{U}_5$ and $\vec{U}_6$ and the two zero/inactive vectors are $\vec{U}_0$ and $\vec{U}_7$ .

An arbitrary command/reference voltage vector $\vec{U}_S$ with the vector amplitude $U_0$ and the phase angle $\theta$ can be generated by two adjacent active vectors ($\vec{U}_1$ and $\vec{U}_2$ in the first sextant) and the zero vectors. A modulation index $M$ is given by the ratio of the vector amplitude to a norm that may be the fundamental peak value ($2U_{DC}/\pi$) of the six-stepped operation mode or half of the DC voltage value ($U_{DC}/2$ ). And the latter, $U_{DC}/2$, is adopted here. The on-state durations $T_1$ , $T_2$ and $T_0$ of the three vectors are determined by identical volt-second balance at the periodical time interval $T_s$ . $T_{00}$ is for $\vec{U}_0$ and $T_{07}$ is for $\vec{U}_0$ .The on-state durations are computed based on volt-second balance. The $T_1$ , $T_2$ and $T_0$ can be computed.



(a)

(b)

*Figure 1: Two-level inverter and vector diagram. (a) Inverter; (b) Vector diagram.*

The control switching pulses of the upper switches are shown in Fig. 1(b) for the three phases in the six sextants. Only one pair of switches for one phase turns on or off once, therefore every switch turns only once in each switch period. The corresponding working time is shown in Fig. 2 for the first sextant.

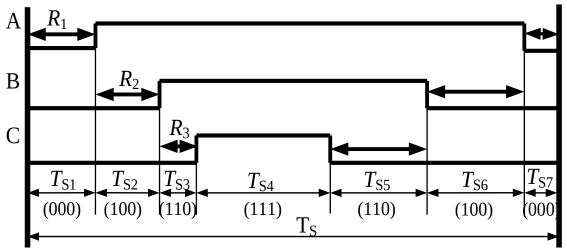


*Figure 2: Commonly used 7-segment pattern in the first sextant.*

If the control parameter is randomized, the random SVPWM (RSVPWM) strategy can be gotten. Every control parameter can be randomized in theory; consequently, there are a large number of RSVPWM schemes. However, only some random schemes have important practical value and application benefit, and can be divided into the following four categories.

(1) Random Switching Frequency SVPWM (RSFPWM) scheme. The switching frequency or the period is randomized.

(2) Random Zero-vector Distribution SVPWM (RZDPWM) scheme. The parameter that controls the duration ratio of $T_{00}$ to $T_{07}$ is randomized.

(3) Random Pulse Position SVPWM (RPPPWM) scheme. The parameters that control the high-level pulse position are randomized.

(4) Hybrid Random SVPWM (HRPWM) scheme. It results from the combination of any two of RSFPWM, RPPPWM and RZDPWM, or the combination of the three random schemes.

The randomization is represented as the random variable. There is one variable in the RSFPWM scheme. The real time switching frequency $f_S$ and switching period are expressed as

$$\begin{cases} f_S = f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}}) \\ T_S = \dfrac{1}{f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}})} \end{cases} \tag{1}$$

where $R_S$ is a random variable on the interval [0,1], and $f_{\mathrm{Smax}}$ and $f_{\mathrm{Smin}}$ are the upper and the lower bounds of the switching frequency.

Eq. (1) can also be expressed as:

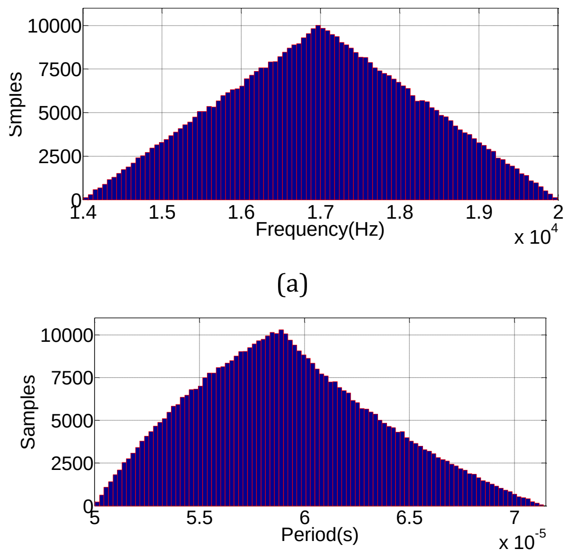
$$\begin{cases} T_S = T_{\mathrm{Smin}} + R_S{}'(T_{\mathrm{Smax}} - T_{\mathrm{Smin}}) \\ f_S = \dfrac{1}{T_{\mathrm{Smin}} + R_S{}'(T_{\mathrm{Smax}} - T_{\mathrm{Smin}})} \end{cases} \tag{2}$$

where $R_S{}'$ is a random variable on the interval [0,1], and $T_{\mathrm{Smax}}$ and $T_{\mathrm{Smin}}$ are the upper and the lower bounds of the switching period.

It should be noticed that the switching frequency and period have markedly difference with the exact same random variable in Eqs. (1) and (2). If the random variable $R_S$ obeys the triangular distribution, and the upper and the lower bounds of the switching frequency is 20000Hz and 14000 Hz, the histograms of the switching frequency and period based on Eq. (1) are shown in Fig 3 with 500000 samples using the pseudorandom number function rand in MATLAB. From the Fig. 3, the markedly difference can be easily and intuitively found.

One variable $R_0$ that controls the duration ratio of $T_{00}$ to $T_{07}$ is randomized on the interval [0,1] in the RZDPWM scheme. Three variables $R_1$, $R_2$ and $R_3$ randomized on the interval [0,1] are the parameters that control the high-level pulse position in the RPPPWM scheme, as shown in Fig 2. Therefore, a comprehensive working time expression for RSFPWM, RZDPWM, RPPPWM and HRPWM schemes can be gotten as

$$\begin{cases} T_{S1} = R_1 R_0 \left(1 - \sqrt{3} M \sin(\pi/3+\theta)/2\right) \Big/ \left( f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}})\right) \\ T_{S2} = \sqrt{3} R_2 M_s \sin(\pi/3-\theta) \big/ 2\left( f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}})\right) \\ T_{S3} = \sqrt{3} R_3 M \sin\theta \big/ 2\left( f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}})\right) \\ T_{S4} = (1-R_0)\left(1 - \sqrt{3} M \sin(\pi/3+\theta)/2\right) \Big/ \left( f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}})\right) \\ T_{S5} = \sqrt{3}(1-R_3) M \sin\theta \big/ 2\left( f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}})\right) \\ T_{S6} = \sqrt{3}(1-R_2) M \sin(\pi/3-\theta) \big/ 2\left( f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}})\right) \\ T_{S7} = (1-R_1) T_{00} \\ = (1-R_1)(1-R_0)\left(1 - \sqrt{3} M \sin(\pi/3+\theta)/2\right) \Big/ \left( f_{\mathrm{Smin}} + R_S(f_{\mathrm{Smax}} - f_{\mathrm{Smin}})\right) \end{cases} \tag{3}$$



(a)

(b)

*Figure 3: Frequency and period distribution histograms based on Eq. (1) with random variable obeying triangular distribution and with 500000 samples.*
*(a) Frequency histogram; (b) Period histogram.*

## 3. Simulation Model in MATLAB

The typical and representative random distribution laws include the uniform distribution, normal distribution and triangular distribution. The random variable obeying the normal distribution is unbounded, so the sample that is outside three standard deviations is abandoned in the study. The random variable obeying the triangular distribution can be gotten by the summation of two random variables obeying the uniform distribution.

The pseudorandom number function in MATLAB can be used in simulation. For example, the functions rand and randn return pseudorandom values drawn from the standard uniform distribution and the standard normal distribution respectively, which can be directly used in the study. The simulation model is built in MATLAB/Simulink in Fig 4. Three PI controllers are used to generate the command q current, d and q voltages according to the speed error and the current error.

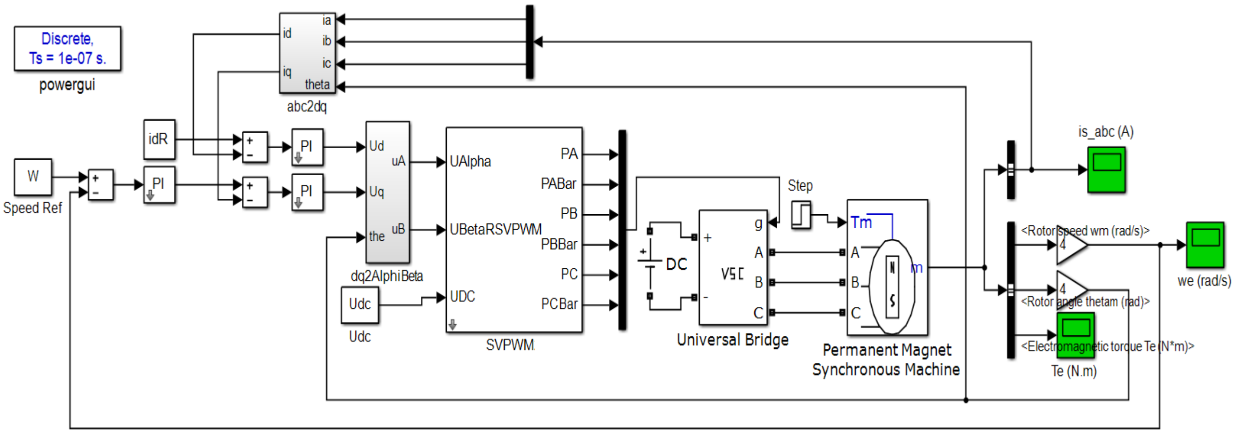


*Figure 4: Simulation model of PMSM vector control using random space vector PWM*

## 4. Result and Discussion

The experiment is conducted using the simulation model. The DC link voltage is 400V, the stator phase resistance Rs of the PMSM is 0.0113 Ω, the d and q inductances are 0.000175H and 0.000284H respectively, the flux linkage is 0.08424Wb, and the number of the pole pairs is 4. The command electrical angular frequency $\omega_0$ is 300 rad/s and 700 rad/s respectively, and the motor load is 20Nm. The switching period is [1/11000, 1/9000]s for the PWM schemes with the random switching frequency, and 1/10000s for the deterministic switching frequency.

The simulation results are shown from Figs 5 to 10.

From Figs. 5 to 10, some phenomena and characteristics can be found as follows.

(1) The clustering harmonics have been significantly suppressed by using random SVPWM schemes.

(2) The RSFPWM scheme has excellent performance on suppressing harmonic peaks at any speed and modulation index, because the randomized range is only determined by the switching period.

(3) The RZDPWM scheme can significantly suppress the harmonics with maximum amplitudes around the double switching frequencies. The waveform of the TSVPWM scheme shown in Fig. 2 is symmetrical in the switching period, so the harmonic current of the phase has some symmetry to a great extent in the switching period and in the half switching period. Therefore, the phase current and the electromagnetic torque exhibit great amplitude harmonics around the double switching frequencies and the quadruple frequencies. The symmetry tendency is randomly destroyed in the RZDPWM scheme, so the harmonics around the double switching frequencies are significantly suppressed.

(4) Although the RPPPWM scheme has also excellent performance on suppressing the harmonic amplitude peak. In RPPPWM scheme, the periodicity of the switching period is heavily destroyed, which makes the harmonics with non-negligible amplitudes move to the band less than the switching frequency.

(5) The HRPWM can get more excellent performance on suppressing the harmonic amplitude peak of the electromagnetic torque.

(6) The random distribution law has heavy influence on the harmonic suppressing performance. The bigger the standard deviation is, the more excellent performance of the random scheme is. To a random variable on the interval [a,b], the standard deviation is $(b-a)/2\sqrt{3} \approx 0.2887(b-a)$ for the uniform distribution, about $(b-a)/6 \approx 0.1667(b-a)$ for the normal distribution, and $(b-a)/2\sqrt{6} \approx 0.2041(b-a)$ for the triangular distribution. From Fig 19 to 21, it can be found that the uniform distribution has more excellent performance than the normal distribution and triangular distribution.

(7) The random modulation schemes have no feeble influence on the constant component, the fundamental and the harmonics with low frequencies.

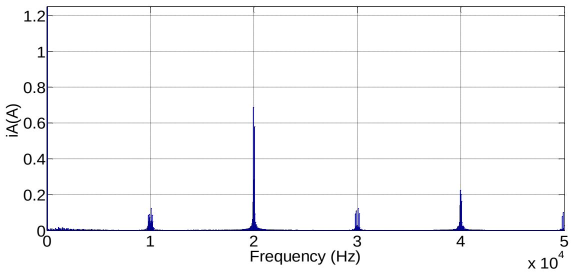


*Figure 5: Phase A current spectrogram for TSVPWM at 300 rad/s.*

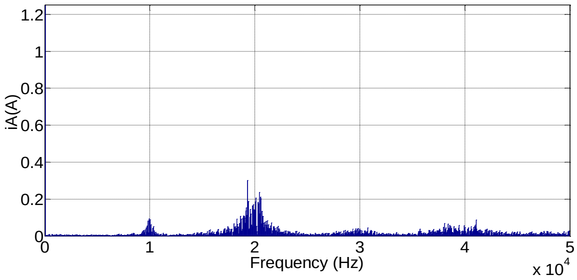


*Figure 6: Phase A current spectrogram for SFPWM (Uniform distribution) at 300 rad/s/.*

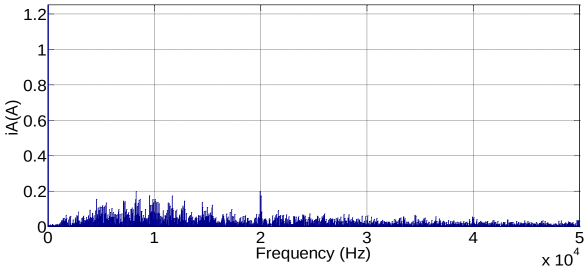


*Figure 7: Phase A current spectrogram for RZDPWM (Uniform distribution) at 300 rad/s.*

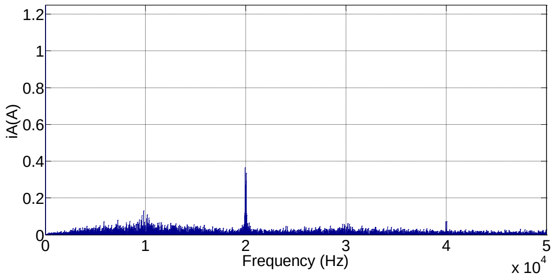


*Figure 8: Phase A current spectrogram for RZDPWM (Mormal distribution) at 300 rad/s.*

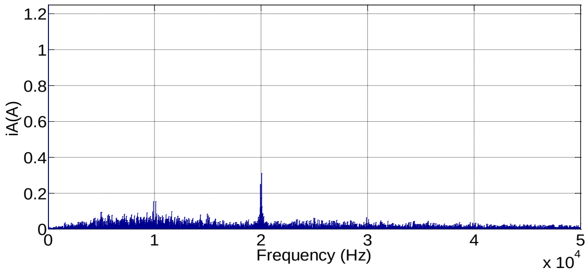


*Figure 9: Phase A current spectrogram for RZDPWM (Triangular distribution) at 300 rad/s.*

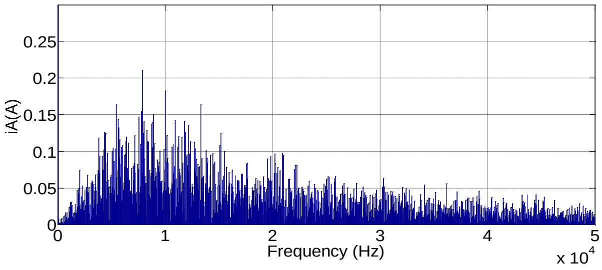


*Figure 10: Phase A current spectrogram for HRPWM (hybrid PWM of RZDPWM and RSFPWM, uniform distribution) at 300 rad/s*

## 5. Conclusions

The principle of the random SVPWM strategy has been detailed. First, the expression for the randomization scheme is given, and then a comprehensive working time expression for RSFPWM, RZDPWM, RPPPWM and HRPWM schemes has been derived, which helps to facilitate the simulation. The realization method for simulation in MATLAB/Simulink is presented. An experimental validation has been done on the simulation model. The excellent performance on suppressing the harmonic amplitude peak of the currents and the electromagnetic torque has been verified. It should be noticed the theoretical study and simulation validation has been carried out in the study and an experimental setup will be developed in future.

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