The Research on Energy Transfer Efficiency of PMSM with Stochastic PWM

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Abstract. The pulse width modulation (PWM) technique is widely used in control of permanent magnet synchronous motor (PMSM). The switching process with fixed switching frequency results in useless harmonics. In an inverter with PWM, the dead time result in harmonics to the drive systems. And the dead time will reduce the energy transfer efficiency in PMSM drives. This paper proposes PWM controller with random dead time for voltage-source inverters used in PMSM drives. The proposed method will directly add random factors to dead time to realize the randomness of PWM. This technique can effectively reduce the harmonics in this systems. Therefore, the purpose of improving PMSM control technology energy transfer efficiency is achieved. Finally, effectiveness of the proposed strategy is validated by simulation.

1. Introduction
Permanent magnet synchronous motors (PMSM) are widely used in industrial applications due to their excellent efficiency [1, 2, 3, 4]. Pulse width modulation (PWM) technique is also widely used in PMSM drive systems. And the inverter with PWM will leads to useless harmonics [5].

The random PWM (RPWM) technology is proposed to reduce the harmonics and acoustic noise in drives [6, 7]. In [8], a theoretical power spectrum analysis for RPWM is presented. The multiple carriers based random carrier pulse-width modulation (MCBRCPWM) scheme for the voltage-source inverter fed induction motor, presented in [9], drive to enhance the harmonic power spreading ability of the modulator. In order to elimination the noise at a selected frequency, a novel technique is proposed for the two-level three-phase inverter, when it is driven by random space-vector pulse-width modulation [10]. The conventional RPWM methods may cause system resonant frequency excitation. Therefore, it can increase the acoustic noise and vibration in loads of inverters, especially ac motors. The discontinuous random space vector PWM method is reported to reduce the switching losses [11]. Many novel random technologies have been proposed in recent years. A novel randomized wrapped-around pulse position modulation (RWAPPM) scheme for digital modulators of dc-dc converters is proposed that features a simple algorithm [12]. And a new random type of carrier wave for modulation is proposed, which is easy to implement digitally [13]. However, over some fundamental cycles, the average inverter losses are similar to those of conventional PWM strategies, but are not controllable within a fundamental cycle. In [14], a nearest level modulation strategy for cascaded VSI is proposed. This modulation is not the most common one in the carrier-based PWM methods family. Some random methods combined with other technologies have also been properly studied, such as bee algorithm and random forest regression algorithm [15, 16]. At the same time, the dead time is
deployed in switching signals to prevent the circuit shorts. Dead time would result in distortion of the magneto motive force (MMF). And the distortion can generate additional harmonics, which leads to the decrease of the energy transfer efficiency [17].

To solve the problems mentioned above, a random dead time PWM technique is presented in this paper to reduce the distortion and harmonics. This paper is organized as follows. Firstly, the conventional PWM control strategy is presented in Section II. The random dead time PWM technology is presented in Section III. After that simulation is given in Section IV. Finally, the conclusions of paper are given in Section V.

2. Conventional PWM control strategy for permanent magnet synchronous motor

The PMSM model based on an inverter control shown in Fig. 1 is studied.

![Inverter model for PMSM drive.](image)

Figure 1. Inverter model for PMSM drive.

When using PWM control strategy, the drive signals are obtained by closed-loop controller. The two bridge of each arm in the inverter are alternately turned on to generate the required PWM waveform. Actually, dead time is reserved to protect the circuit due to the power switches turn-on/off delay times.

3. Proposed random dead time pwm control strategy

3.1. Model of PMSM

The voltage equation of PMSM in d-q synchronous reference frame can be expressed as [18]

\[
\begin{aligned}
    u_q &= R_i q + p\psi_q + \omega_e \psi_d \\
    u_d &= R_i d + p\psi_d - \omega_e \psi_q
\end{aligned}
\]  

(1)

Where \( u_q, u_d, i_q, i_d, R, \) and \( \omega_e \) represent the stator voltages, currents, resistance, and the rotor speed, respectively; And \( P \) represents the differential operator, while \( \psi_d \) and \( \psi_q \) are the flux linkages and can be expressed as

\[
\begin{aligned}
    \psi_q &= L_q i_q \\
    \psi_d &= L_d i_d + \psi_f
\end{aligned}
\]  

(2)

Where \( L_q, L_d, \) and \( \psi_f \) are the d-q frame inductances and the permanent magnet flux linkage, respectively. The electromagnetic torque \( T_e \) for the PMSM can be expressed as

\[
T_e = Jp\omega_m + B\omega_m + T_L
\]  

(3)
Where $J$ is the inertia constant, $\omega_m$ is the mechanical angular velocity, $T_L$ is the load torque, and $B$ is the coefficient of friction.

3.2. Modulated harmonic analysis

The PWM harmonic component is derived as follows. When the carrier signal is present as

$$ x(t) = \omega_c t + \theta_c $$

And fundamental signal is present as

$$ y(t) = \omega_o t + \theta_o $$

Where $\omega_c = 2\pi / T_c$ is the carrier angular frequency, $T_c$ is carrier cycle, $\theta_c$ is phase offset Angle of carrier wave, while $\omega_o = 2\pi / T_o$, $\omega_o < \omega_c$ is the fundamental angular frequency, $T_o$ is fundamental cycle, $\theta_o$ is phase offset Angle of fundamental wave. And output voltage of the phase bridge arm can be present as

$$ f(t) = f[x(t), y(t)] $$

According to the theory of Fourier transform, the harmonic components can be present in [19]

$$ f(t) = \frac{A_{00}}{2} + \sum_{n=1}^{\infty} \left[ A_{0n} \cos(n(\omega_c t + \theta_c)) + B_{0n} \sin(n(\omega_c t + \theta_c)) \right] $$

$$ + \sum_{m=1}^{\infty} \left[ A_{m0} \cos(m(\omega_o t + \theta_o)) + B_{m0} \sin(m(\omega_o t + \theta_o)) \right] $$

$$ + \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \left[ A_{mn} \cos(m(\omega_c t + \theta_c) + n(\omega_o t + \theta_o)) + B_{mn} \sin(m(\omega_c t + \theta_c) + n(\omega_o t + \theta_o)) \right] $$

$$ A_{mn} = \frac{1}{2\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} f(x,y) \cos(mx + ny) dx dy $$

$$ B_{mn} = \frac{1}{2\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} f(x,y) \sin(mx + ny) dx dy $$

Where $m$ is the index variable of the carrier, and $n$ is the index variable of fundamental band. For (7), the second term in the right side represents fundamental wave components and fundamental band harmonics, the third term represents carrier harmonics, and the fourth term represents sideband harmonics.

And dead time would result in the redundant harmonics in the second term for (7). Then random dead time PWM technology is proposed in this paper. It can effectively reduce the generation of fundamental harmonics as mentioned above. Therefore, the energy transfer efficiency will be improved.
3.3. Proposed random dead time PWM

PWM strategy with dead time results in a discontinuity of the PWM waveform. And dead time will be blank area in the process of different bridge arm. Then blank area will result in the distortion of the MMF, the generation of harmonics, and the reduction of motor energy transfer efficiency.

The random dead time PWM technology is proposed in this paper. And the technique is used to increase randomness of PWM technology by adding random factors in dead time, as shown in Fig. 2. It can effectively reduce the distortion of MMF and the generation of harmonics. Therefore, the purpose of improving energy transfer efficiency of the motor is achieved. The random dead time ($T_r$) can be expressed as in (10).

$$T_r = T_d (1 + \alpha) \quad |\alpha| < 0.5$$

Where $T_d$ and $\alpha$ are dead time and random factors, respectively.

The equivalent MMF waveform of the stator with fixed dead time is shown in Fig. 3(a), wherein $T_s$ is the switching cycle. In Fig. 3(a), dead time results in distortion of the MMF waveform. Then the MMF waveform with random dead time is shown in Fig. 3(b). The duration of the dead time is different in each cycle with random factors. Error of the duration is very small compared with the switching cycle. So the effect of this error on motor speed is negligible. However, the period of the dead time is changed. Therefore, the harmonics caused by dead time are suppressed. While the sub-harmonic of the carrier wave is generated.

And this result can be verified by using the power spectrum estimation analysis method. The Fourier transform is often used as a display of the frequency components of a deterministic signal, but the Fourier transform expression of random signal is a random function. So we chose power spectrum as a benchmark to compare system performances. The power spectrum of random process is deterministic so that the frequency characteristic of the process can be analyzed.

For a sample sequence $x_n, n = 0 \ldots N-1$, if the Fourier transform is $X_N(\omega)$, the power spectrum can be obtained by

$$P_N(\omega) = \frac{1}{N} |X_N(\omega)|^2$$

The square of the magnitude of $X_N(\omega)$ in Eq. (11) gives the energy density at $\omega$. After dividing the sequence length $N$, it becomes the power density. Therefore, the estimated power spectrum has the same shape with the energy spectrum $|X_N(\omega)|^2$.
4. Simulation results
Simulation studies in a MATLAB/Simulink environment are performed. And block diagram of the PMSM drive is shown in Fig. 4. The simulation work of three different control strategies is carried out respectively in no dead time, fixed dead time and random dead time.

Fig. 5 shows the motor speed of the three modulation profiles. By comparing with Fig. 5(a) and Fig. 5 (b), it reveals the speed effect of the dead time. While the distortion is suppressed with random dead time technology as show in Fig. 5 (c). And Fig. 6 shows the power spectrum of the motor speed waveform using three methods. It clearly shows that random dead time strategies give a harmonic reduction greater than the fixed dead time as show in Fig. 6(c).

Figure 4. Block diagram of the PMSM drive.

Figure 5. Motor speed waveform. (a) no dead time. (b) fixed dead time. (c) random dead time.
Figure 6. Power spectrum of the motor speed. (a) no dead time. (b) fixed dead time. (c) random dead time.

Fig. 7 shows the motor torque waveform. It can be seen that the distortion effect of the dead time. Then the torque waveform will perform better with random dead time method. And Fig. 8 shows the power spectrum of motor torque. An extra harmonic attenuation with random dead time is shown in Fig. 8(c). So the energy transfer efficiency of the PMSM can be improved with reduction of the harmonics.
Figure 7. Motor torque waveform. (a) no dead time. (b) fixed dead time. (c) random dead time.
5. Conclusion
The PWM technology is generally used in PMSM control. And dead time must be preserved to protect the circuit. However, dead time can lead to distortion of electromotive force. Then the distortions generate excess harmonics. These harmonics will reduce energy transfer efficiency of the motor. In this paper, a random dead time PWM technology is proposed to reduce the generation of harmonics. And the energy transfer efficiency of the motor is also improved. Finally, the reliability and effectiveness of the proposed controller is verified by MATLAB/Simulink.

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