Research on Control Strategy for Vibration and Noise Reduction of Permanent Magnet Synchronous Motor

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Abstract. In order to reduce the vibration and noise of permanent magnet synchronous motors, this paper proposes a control strategy by analyzing the relationship between the vibration and noise of the permanent magnet synchronous motor and the current harmonics of the inverter based on actual project applications. Some methods include random switching frequency modulation technology, random pulse position modulation technology and dead zone compensation technology on current harmonics are analyzed respectively in this paper. Then this paper proposed a mixed control strategy, which combined with random switching frequency-random and pulse position-dead zone compensation methods. Matlab tools are used to simulation and verification the Mixed control strategy. Simulation and experimental results show that this control strategy can effectively reduce the total underwater noise level of permanent magnet synchronous motors.
1. Introduction
Permanent magnet synchronous motors have been widely used in aviation, aerospace, navigation, electric vehicles, household appliances and other fields due to their superior performance such as small torque ripple, high efficiency, wide speed range, fast dynamic response, and higher power density. Compared with other types of motors, the vibration and noise problems of permanent magnet synchronous motors are not particularly prominent, but in some specific fields, such as the propulsion device of combat unmanned underwater vehicles, it is still a problem that needs to be addressed.

The propulsion device is the main power device of the unmanned underwater vehicle, and its noise level directly affects the concealment of the entire equipment. The sources of vibration noise are electromagnetic noise, mechanical vibration noise and air noise of permanent magnet synchronous motors, especially electromagnetic noise is the most prominent and difficult to eliminate. Electromagnetic noise is caused by the electromagnetic force of the motor. On the one hand, it produces the torque that makes the motor rotate, and on the other hand, it causes the stator and rotor of the motor to undergo radial deformation and vibration [1]. At the same time, due to the existence of the motor manufacturing process, air gap magnetic field distortion and dead zone effect, the permanent magnet synchronous motor current contains a large number of high-order harmonics, resulting in higher electromagnetic vibration.

The generation of electromagnetic noise has an inseparable relationship with the PWM frequency control technology of the inverter. This paper analyzed the relationship between the electromagnetic noise of the permanent magnet synchronous motor and the inverter’s current harmonics is analyzed, and the research on the vibration and noise reduction control strategy of the permanent magnet synchronous motor is carried out.

2. Random pulse width modulation technology
Space vector pulse width modulation (SVPWM, Space Vector Pulse Width Modulation) is commonly used in motor vector control systems. In traditional applications, the switching frequency of power devices is fixed, so that the harmonic energy in the output current is mainly concentrated on the switch. The frequency and the switching frequency are close to integer multiples, which will cause the motor to produce large torque ripple and vibration noise. The random pulse width modulation technology randomizes the switching frequency of the power device, which can evenly disperse the harmonic energy near the switching frequency and its multiples to a wider frequency band during fixed switching frequency modulation to a certain extent, the amplitude of higher harmonics is weakened, so as to achieve the purpose of vibration reduction and noise reduction.

2.1. Random switching frequency SVPWM
Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

The random switching frequency SVPWM control method is to randomly change the carrier frequency to achieve the purpose of randomizing the switching frequency when the duty cycle is unchanged. To achieve the purpose of randomizing the switching frequency by using a triangular wave as a carrier, firstly generate a triangular wave whose frequency can be changed randomly. The triangular wave is an isosceles triangle in each cycle and changes randomly in each cycle. After generating a random variable frequency triangular wave, use the triangular wave as the carrier to compare with the sine wave to generate a trigger pulse to randomly change the switching frequency to achieve the purpose of discretizing the harmonic components.

Take a single-chip computer with a system clock of 120MHz as an example to generate triangular carrier waves of 8kHz, 10kHz, and 12kHz. When the duty cycle is 60%, the power device switching control state is shown in Figure 1.
In C language, the random number generation function `rand()` can be called to generate random numbers as the switching frequency. The format of the random function `rand` is:

\[ A = \text{rand()} \% Y + X \]  

The meaning of this sentence is to automatically generate a random number with \( X \) as the lower limit and \( X+Y \) as the upper limit, and assign the result to \( A \), that is, \( A \) is a random number between \( X \) and \( X+Y \). Therefore, when \( X \) is 8, \( Y \) is 4, the random switching frequency value will be randomly generated among 8, 9, 10, 11, and 12.

### 2.2. Random pulse position SVPWM

The random pulse position SVPWM means that the position of the switching signal is randomly generated within a switching cycle. The traditionally generated pulse position is based on the apex of the triangular carrier as the symmetry point. This control strategy is to randomly place the pulse position within a switching cycle. The voltage control of the PWM inverter is achieved by controlling the duty cycle of the switching device, but the duty cycle has nothing to do with the position of the turn-on moment in the switching cycle (i.e., the pulse position). However, the change of the conduction position affects the spectral distribution of the output voltage. If the conduction position is changed in a random manner under the premise that the conduction time, that is, the duty cycle remains unchanged, the inverter output voltage can obtain a wide and uniform continuous spectrum without the fundamental component. Thereby harmonic components with larger amplitudes can be effectively suppressed.

Regardless of the dead time, the pulse position can be randomly placed to the left and right shaded parts within a switching cycle without changing the duty cycle, as shown in Figure 2.

### 2.3. Mixed random SVPWM

Mixed random SVPWM is a control strategy that combines random switching frequency SVPWM and random pulse position SVPWM. Based on the SVPWM control principle of the permanent magnet synchronous motor, using Matlab as simulation tools, a vector control simulation model of the permanent magnet synchronous motor is established, as shown in Figure 3. The output current of the
The inverter was analyzed by FFT with a fixed switching frequency of 10kHz and a mixed random control strategy of 8-12kHz. The simulation results are shown in Figure 4.

Figure 3 Permanent magnet synchronous motor vector control simulation model

Figure 4 FFT analysis results of phase currents under different control strategies

It can be seen from the simulation results:

1. Compared with the current spectrum obtained by fixed switching frequency modulation, the current frequency spectrum obtained by the mixed random control strategy has greatly reduced the amplitude of the current harmonics at the switching frequency and multiplication frequency of the mixed random control strategy, and the current harmonics are more dispersed. The wide frequency band enables the vibration and noise of the motor at the switching frequency and multiplication frequency to be dispersed to a wider range, so as to obtain a good acoustic quality of the motor;

2. In the low frequency band, the current harmonic amplitude output by the mixed random control strategy is not significantly reduced compared to the fixed switching frequency.

From the above analysis, it can be seen that the mixed random control strategy can reduce the current harmonic amplitude at the switching frequency and the multiplication frequency, and the harmonic distribution is more uniform in the entire frequency spectrum, thereby effectively reducing the switching
frequency multiplication of the motor at the inverter. But it cannot reduce the vibration and noise amplitude in low-frequency current harmonics and the total electromagnetic noise energy.

3. Dead zone compensation

3.1. PWM dead zone harmonic analysis

The three-phase general-purpose PWM inverter topology is shown in Figure 5, the typical space vector PWM gate trigger circuit, and the typical space vector gate trigger signal is shown in Figure 6.

![Typical gate trigger circuit of space vector PWM](image)

In the working process of the inverter driving the motor, in order to prevent the "through" phenomenon of the upper and lower switch tubes of the same bridge arm of the power device, the dead time Td is increased in the control system of the power device. In the entire dead time period Td, the two power devices of the same bridge arm are all turned off and only one of the diodes is turned on. If the current flows to the load, the diode of the lower bridge arm is turned on, otherwise, the diode of the upper bridge wall is turned on.

For easier understanding, take Phase A as an example, assuming that the phase current i_{as} flows to the load, that is, i_{as}>0. Figure 6(a) shows the ideal gate trigger signal, and Figure 6(b) shows the actual trigger pulse signal waveform. When the switch tube of the bridge arm is planned to be turned on at T1, the upper bridge arm pulse is turned on at T1+Td, and the lower bridge arm pulse is turned off at T1. When the lower bridge arm switch tube is expected to be turned on at T2, the upper bridge arm trigger pulse will be turned off at T2, and due to the addition of the dead time, the actual lower bridge arm trigger pulse will be turned on at T2+Td. Taking into account the switching delay and voltage rise time of the switching tube during the application process, the final inverter output voltage Van is shown in Figure 6(c) and 6(d). Among them, (c) is the waveform of the inverter output voltage Van when i_{as}>0, and (d) is the inverter output voltage when i_{as}<0.

![Dead zone effect analysis diagram](image)
Through the above analysis, it can be seen that the disturbance voltage \( \Delta V \) generated by the dead zone is related to the current direction, and the following formula can be obtained:

\[
\Delta V = \frac{-T_s - T_{on} + T_{off} \cdot V_0}{T_s} \quad i_{as} > 0
\]

\[
\Delta V = \frac{-T_s - T_{on} + T_{off} \cdot V_0}{T_s} \quad i_{as} < 0
\]

Among them, \( T_s, T_{on}, \) and \( T_{off} \) are the current sampling period and the turn-on and turn-off time of the power device, respectively. The relationship between the three-phase average voltage disturbance and the current direction can be written as follows:

\[
v'_{cs} = \frac{-T_s - T_{on} + T_{off} \cdot V_0}{T_s} \left\{ \frac{2 \text{sign} (i_{as}) - \text{sign} (i_{bs}) - \text{sign} (i_{cs})}{3} \right\}
\]

\[
v'_{bs} = \frac{-T_s - T_{on} + T_{off} \cdot V_0}{T_s} \left\{ \frac{2 \text{sign} (i_{bs}) - \text{sign} (i_{as}) - \text{sign} (i_{cs})}{3} \right\}
\]

\[
v'_{cs} = \frac{-T_s - T_{on} + T_{off} \cdot V_0}{T_s} \left\{ \frac{2 \text{sign} (i_{cs}) - \text{sign} (i_{as}) - \text{sign} (i_{bs})}{3} \right\}
\]

Among them

\[
\text{sign}(i) = \begin{cases} 
  1: & i > 0 \\
  -1: & i < 0 
\end{cases}
\]

It can be seen that due to the existence of the dead zone, the motor voltage is disturbed, which affects the current distortion.

3.2. Dead zone compensation method

Aiming at the current harmonics generated by the voltage drop of the power switching device and the switching dead zone in the actual permanent magnet synchronous motor drive controller, the influence of the nonlinear factor of this part of the power device can be weakened by means of compensation. At present, the main compensation methods are dead-zone switch control method, time compensation method, voltage compensation method, harmonic current compensation method, etc. The voltage compensation method is used to compensate the dead zone in this paper.

A compensation voltage is used, which equal to the error voltage and opposite in polarity to compensate the error voltage caused by the dead time and tube voltage drop. Based on the analysis of the factors affecting the dead zone effect and the equivalent dead zone time expression, the error voltage generated by the equivalent dead zone time is compensated in a two-phase stationary shaft system. In order to improve the accuracy of current polarity detection, the excitation current and torque current components in the rotating shaft system are used to undergo coordinate inverse transformation to determine the sector where the current is located in the two-phase stationary shaft system to determine the compensation voltage that needs to be applied [4].

3.3. Simulation analysis of dead zone compensation effect

The voltage compensation method is used for simulation analysis. When the motor is running at 400 rpm, the three-phase current waveforms of the motor when the dead zone is not added, the dead zone is added, and the dead zone compensation is added.
Figure 7  Simulation analysis of dead zone compensation effect

It can be seen from Figure 7, after the dead zone is added, the current waveform will have a relatively large distortion, especially when the current zero-crossing point, the current waveform has been well improved after compensation, and the overall waveform has a better sine.

4. Experiment
The control object of this project is a permanent magnet synchronous motor with a rated input voltage of 300VDC, a rated speed of 400rpm, and a rated output power of 6kW. In order to verify the effect of vibration and noise suppression under different hybrid control strategies, underwater noise tests were carried out in an anechoic pool. The results were shown in Table 1.
Figure 8 Physical image of underwater noise test

| Serial number | Control Strategy | Total noise level (dB) |
|---------------|------------------|------------------------|
|               | Fixed switching frequency (10kHz) | Random switching frequency (8kHz~12kHz) | Random pulse position | No dead zone compensation | dead zone compensation |                      |
| 1             | √                | √                      | √                      | 128.5                   |                      |                      |
| 2             | √                | √                      | √                      | 128.3                   |                      |                      |
| 3             | √                | √                      | √                      | 128.6                   |                      |                      |
| 4             | √                | √                      | √                      | 128.2                   |                      |                      |
| 5             | √                | √                      | √                      | 128.4                   |                      |                      |
| 6             | √                | √                      | √                      | 126.9                   |                      |                      |
| 7             | √                | √                      | √                      | 128.3                   |                      |                      |
| 8             | √                | √                      | √                      | 126.1                   |                      |                      |

5. Conclusion
Simulation analysis and experimental verification results show that under the condition of not changing the hardware, the mixed random switching frequency-random pulse position-dead zone compensation combined software control strategy can effectively reduce the total noise level of the motor's underwater radiation. At the same time, the portability of the software is good, and the implementation of the algorithm is flexible and convenient to meet the low noise requirements of permanent magnet synchronous motors in specific fields.

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