Research on Vector Sequence Optimization of Five-phase SVPWM

Yuanzheng Ma*, Jinghong Zhao* and Yinping Zhoub

School of Electrical Engineering, Naval University of Engineering, Wuhan, China

*Corresponding author e-mail: zhaojinghong1975@126.com, *1362039810@qq.com, 1246936000@qq.com

Abstract. In the multi-phase motor drive system, the five-phase motor is the typical representative. But the increase of the number of phases causes the number of IGBTs used by the inverter multiplied, and the use of SVPWM control with high frequency on and off causes the inverter switching loss increased, thus the inverter produces a lot of heat. In this paper, by adjusting the action order of effective vectors in SVPWM and the insertion position of zero vectors, a vector sequence optimization SVPWM technology is proposed. Compared with the conventional NFV-SVPWM technology, under the same frequency the switching times are reduced to 40% of NFV-SVPWM. The vector sequence optimization SVPWM and five-phase induction motor was simulated in Simulink. The simulation showed that the vector sequence optimization SVPWM introduced few harmonic content and the stator phase current distortion of the motor was low.

1. Introduction

With the development of multi-phase inverter technology, the modern electric power drive field gradually gets rid of the dependence on the traditional three-phase power supply [1]. At the same time, compared with the three-phase motor, the multi-phase motor can achieve high-power output with low-voltage, need lower requirements on the rated capacity of power electronic devices, be easy to achieve the fault-tolerant operation when phase fails [2]. In the application of multi-phase motor, the five-phase induction motor is a typical representative.

When adjusting the speed of the five-phase motor, the inverter mostly adopts the five-phase full-bridge inverter or the five-phase H-bridge inverter. Figure 1 is the schematic diagram of the five-phase H-bridge inverter, and usually the inverter is controlled by SVPWM technology [3]. Foreign scholars such as Hamid A. Toliyat mainly analyzes the operation characteristics and speed regulation control strategy of the five-phase motor, but the five-phase SVPWM proposed in reference [4] is only a simple expansion of the three-phase situation and has high harmonic content [4,5]. Domestic scholar Yu Fei proposes five-phase NFV-SVPWM modulation [6, 7]. In reference [8], the author proposes an NFV-SVPWM algorithm that can suppress the third harmonic wave. In reference [3], a five-phase SVPWM algorithm based on modulation function is proposed to improve the computational accuracy and speed of microprocessors such as DSP.

However, the switching loss of IGBT devices increases with the switching frequency and gradually becomes the main part of the total loss of devices. When SVPWM is adopted, a large number of
switching times cause the inverter’s temperature surges and reduce the working life of the inverter [9, 10].

Based on NFV-SVPWM, VSO-SVPWM (Vector Sequence Optimization SVPWM) is proposed in this paper by adjusting the order of vector action. Compared with NFV-SVPWM, under the same switching frequency, the switching times in a switching period is greatly reduced. The total power loss of the inverter is reduced, the heating is bated, and the working life of the inverter is extended. In addition, the mathematical model of the five-phase induction motor in the natural coordinate system is established, the VSO-SVPWM is applied to the motor model, NFV-SVPWM is also simulated as a contrast.

![Figure 1. Schematic diagram of five-phase H-bridge inverter](image)

2. Modulation principle of five-phase SVPWM

2.1. Five-phase space voltage vector

As shown in Figure 1, when A1, A4 of the phase A H-bridge is on, it is defined as the state ‘1’, and the state ‘0’ is when the A2, A3 is on. Variable \( S_a \) is used to represent the switch state of A-phase, so that the voltage of the A-phase is \( u_a = (2S_a - 1)V \), and the other four phases are the same principle. The expression of the five-phase synthesis voltage vector is shown in formula (1). Substituting the 0 and 1 states of each phase, the space voltage vector distribution can be obtained as shown in Figure 2.

\[
U = \frac{2}{5} \left( u_a e^{\frac{2\pi}{5}} + u_c e^{\frac{4\pi}{5}} + u_d e^{\frac{6\pi}{5}} + u_e e^{\frac{8\pi}{5}} \right)
\]

\[
= \frac{4}{5} V_D \left( S_a e^{\frac{2\pi}{5}} + S_c e^{\frac{4\pi}{5}} + S_d e^{\frac{6\pi}{5}} + S_e e^{\frac{8\pi}{5}} \right)
\]

Among the 32 voltage vectors, there are two zero vectors (00000 and 11111), the number of large, median and small vectors all is 10, and the amplitudes are: \( |U_L| = \frac{4}{5} V_D \left( 1 + 2 \cos \frac{2\pi}{5} \right) \), \( |U_M| = \frac{4}{5} V_D \), \( |U_S| = \frac{4}{5} V_D \left( 2 \cos \frac{2\pi}{5} \right) \). Small vector shall be avoided using in synthesizing SVPWM in vector synthesis [11].
2.2. Determination of vector action time

The sector where the $U_{ref}$ is located shall be judged according to reference [8]. Taking vector synthesis in sector $k$ as an example, assuming the action time of $T_S$ is $T_S$, the vector in the right edge of the sector is defined as $U_{MK}$, the large vector is $U_{LK}$, the vector in the left edge of the sector is $U_{MK} + 1$, and the large vector is $U_{LK} + 1$. The four vectors are used to synthesize the $U_{ref}$, and the acting time is $U_{MK}$, $U_{LK}$, $U_{MK+1}$, $U_{LK+1}$ respectively. And the four vectors are decomposed to the coordinate $\alpha\beta$ axis, and their components also conform to the principle of voltage-second balance, then formula (2) can be obtained:

$$
\begin{align*}
U_{\alpha}T_S &= |U_{MK}|T_{MK} \cos \left( \frac{(k-1)\pi}{5} \right) + |U_{LK}|T_{LK} \cos \left( \frac{(k-1)\pi}{5} \right) + \\
& \quad |U_{MK+1}|T_{MK+1} \cos \left( \frac{k\pi}{5} \right) + |U_{LK+1}|T_{LK+1} \cos \left( \frac{k\pi}{5} \right) \\
U_{\beta}T_S &= |U_{MK}|T_{MK} \sin \left( \frac{(k-1)\pi}{5} \right) + |U_{LK}|T_{LK} \sin \left( \frac{(k-1)\pi}{5} \right) + \\
& \quad |U_{MK+1}|T_{MK+1} \sin \left( \frac{k\pi}{5} \right) + |U_{LK+1}|T_{LK+1} \sin \left( \frac{k\pi}{5} \right)
\end{align*}
$$

(2)

Since the number of equations is less than the number of unknown variables, let the magnitude ratio and the action time ratio of the vector be the same, that is
\[
\frac{U_{MK}}{U_{LK}} = \frac{T_{MK}}{T_{LK}} = \frac{U_{MK+1}}{U_{LK+1}} = \frac{4}{5} \left( 1 + \cos \frac{2\pi}{5} \right) = 1 + \cos \frac{2\pi}{5} \quad (3)
\]

By substituting equation (3) into equation (2) to reduce the number of unknown variables, the equation can be solved, and the remaining time \( T_0 = T_s - T_{MK} - T_{MK+1} - T_{LK} - T_{LK+1} \) can be supplemented by the zero vector \( U_0 \).

2.3. Modulation index

It should be pointed out that due to the insertion of the medium vector, the algorithm cannot reach the maximum modulation index \( m_{\text{max}} = 0.9512 \) of the five-phase inverter when the nearest four-vector modulation is adopted. Therefore, weight should be assigned according to the amplitude of the large vector and the median vector, and the maximum modulation index of the nearest four-vector modulation can be calculated as [12].

\[
m_{\text{max}} = \left( \frac{|U_M|}{|U_M| + |U_L|} + \frac{|U_L|}{|U_M| + |U_L|} \right) \cos \left( \frac{\pi}{10} \right) = 0.8123 \quad (4)
\]

2.4. Vector action sequence

By reasonably arranging the order of vector action, when the vector switches, only one phase switching state changes while the other four phases remain unchanged, thus the switching times can be effectively reduced. The order of vector switching in two switching periods \( 2T_s \) is taken as the research object, and only the zero vector \( U_0 \) is used. Adjust the order of vector action as shown in Figure 3:

![Figure 3. Vector action sequence of VSO-SVPWM in sector 1](image)

As can be seen from Figure 3, in the first switching period, the vectors act in order of \( U_0 \rightarrow U_{16} \rightarrow U_{24} \rightarrow U_{25} \rightarrow U_{29} \), and in the second switching period, the vectors act in a reverse order. This kind of
VSO-SVPWM only has 4 times of vector switches in each switching period, while under the same frequency, the NFV-SVPWM vector switching is 10 times, so the effect of reducing inverter loss is very obvious.

3. Simulation comparison of two kinds of SVPWM

![Comparison between NFV-SVPWM and VSO-SVPWM at m=0.72](attachment:image.png)

Set the reference voltage $U_{ref} = 158.11V$, the frequency $f = 50Hz$, and IGBT switching frequency $f_s = 10kHz$. According to reference [13], the mathematical model of five-phase induction motor was established. The pole pair of the motor is $n_p = 2$, the rotational inertia is $J = 0.056kg \cdot m^2$, and the
phase resistances of the stator and rotor are $r_s = 0.9546 \Omega$, $r_r = 0.7786 \Omega$ respectively, and the self-leakage inductance of each phase in the fundamental wave space and the third-order harmonic space of the stator and the rotor are $l_{r1} = 0.006866 \text{H}$, $l_{r3} = 0.009 \text{H}$, $l_{r1} = 0.00404 \text{H}$, $l_{r3} = 0.00404 \text{H}$ respectively, and the mutual inductance fiducial value are $l_{m1} = 0.09935 \text{H}$, $l_{m3} = 0.09 \text{H}$. The simulation algorithm is ode3, the fixed step size and simulation sampling time of the simulation algorithm are $1e-6s$, and the simulation duration is $2s$. NFV-SVPWM and VSO-SVPWM are simulated respectively.

Figure 4(a)(b) is the modulation waveform comparison of NFV-SVPWM and VSO-SVPWM at the modulation index $m=0.72$; (c)(d) is the comparison of the A-phase current waveform of the motor’s stator; (e)(f) is the FFT analysis comparison of the A-phase current. It can be seen from the modulation waveforms that the NFV-SVPWM’s waveform is saddle wave, while the VSO-SVPWM’s waveform has certain distortion.

In addition, through simulation, the total harmonic distortion (THD) of stator phase current of the motor under different modulation indexes is obtained, as shown in Table 1. In the range of linear modulation, the THD of both SVPWM gradually increases as the modulation index increases. When the modulation index exceeds the maximum linear modulation index 0.8123, the two kinds of SVPWM enter the nonlinear modulation state, and the modulation waveform degenerates into an approximate trapezoidal wave, but the THD of stator phase current does not change much.

Table 1. Comparison of motor stator phase current THD under different modulation indexes

| Modulation index M | 0.64 | 0.68 | 0.72 | 0.76 | 0.81 | 0.87 | 0.94 | 1.02 |
|--------------------|------|------|------|------|------|------|------|------|
| NFV-SVPWM THD (%)  | 1.33 | 1.50 | 1.63 | 1.83 | 2.11 | 2.66 | 2.64 | 2.66 |
| VSO-SVPWM THD (%)  | 3.27 | 3.32 | 3.62 | 3.64 | 3.90 | 4.18 | 4.18 | 4.18 |

4. Conclusion

In this paper, the SVPWM control of five-phase inverter is analyzed in detail. By changing the insertion position of the zero vector and adjusting the action order of the effective vectors, the VSO-SVPWM is proposed. When VSO-SVPWM control is adopted, compared with NFV-SVPWM, the motor phase current THD increases. However, under high switching frequency, the content of high order harmonics introduced is few and easy to filter. At the same IGBT switching frequency, VSO-SVPWM only switches four times in a switching period, which significantly reduces the switching times compared with NFV-SVPWM for 10 times. In the case of inverter high-frequency on and off, using VSO-SVPWM is more conducive to reducing the heating of the inverter and extending its working life.

References

[1] KANG Mi, HUANG Jin, LIU Dong, et al. Calculation and Measurement of Parameters of A Multiphase Induction Motor, J. Proceedings of the CSEE. 30 (2010) 81-87.
[2] ZHU Peng, ZHANG Xiao-feng, QIAO Ming-zhong, et al. Five-phase induction motor SVM-DTC strategies with third harmonic voltage injection, J. Electric Machines and Control. 14(2010) 13-18.
[3] GAO Hong-wei, YANG Gui-jie, LIU Jian. SVPWM algorithm for five-phase voltage source inverter based on modulation functions, J. Electric Machines and Control. 18(2014) 56-61.
[4] Toliyat Hamid A, Ruhe Shi, Huangsheng Xu. A DSP-based vector control of five-phase synchronous reluctance motor, J. IEEE Trans. On Industry Applications. 4(2000) 432-437.
[5] Toliyat H A, Huangsheng Xu, DSP-Based Direct Torque Control (DTC) for Five-Phase Induction Machines, C. International Power Electronics Conference, Tokyo, Japan, 2000: 1195-1200.
[6] YU Fei, ZHANG Xiao-feng, LI Huai-shu, et al. Space Vector PWM Control of Five-phase Inverter, J. Proceedings of the CSEE. 25(2005) 40-45.
[7] Yu Fei, Zhang Xiaofeng, Li Huaiishu, et al. Discontinuous Space Vector PWM Control of Five-
Phase Inverter, J. Transactions of China Electrotechnical Society. 21(2006) 26-30.
[8] Tang Jun, Wang Tiecheng, Cui S’humei. Implementation Method of SVPWM for Five-Phase Inverters, J. Transactions of China Electrotechnical Society. 28(2013) 64-72.
[9] MAO Peng, XIE Shaojun, XU Zegang. Switching Transients Model and Loss Analysis of IGBT Module, J. Proceedings of the CSEE. 30(2010) 40-47.
[10] Bai Baodong, Chen Dezhi, Wang Xinbo. Loss Calculation of Inverter IGBT and Design of Cooling Device, J. Transactions of China Electrotechnical Society. 28(2013) 97-106.
[11] CAI Wei, QIAO Mingzhong, ZHANG Xiaofeng. SVPWM Control Technique for Five-phase H-bridge Induction Motor, J. Proceedings of the CSU-PSA. 20(2008) 33-38.
[12] Jing Chao. Design and Performance Analysis of Five-phase Asynchronous Motor, D. Harbin: Harbin University of Science and Technology. 2019.
[13] ZHAO Pinzhi, YANG Guijie, LIU Chunlong. Optimal SVPWM algorithm for five-phase VSI, J. 13(2009) 517-522.