Fault Tolerant Control of PMSM Three-Phase Four-Switch Inverter

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Abstract. Permanent Magnet Synchronous Motor (Permanent Magnet Synchronous Motor, hereinafter referred to as PMSM) has the characteristics of small size, high efficiency, high power density and fast dynamic response, etc., and more and more applications in the transportation industry. This also has higher and higher requirements for the reliability and security of PMSM drivers. In this paper, the fault tolerant control strategy of PMSM based on three phase four switch inverter is proposed based on vector control and the simulation verification is carried out.

Keywords: Permanent magnet synchronous motor, vector control, Three phase four switch, fault-tolerant control.

1. Introduction
PMSM has its own advantages, including higher power density The advantages of the low noise high efficiency and quality of light, a electric car industry has become the mainstream of complex drive motor car driving cycle, if the malfunction of the motor drive system suddenly serious accident could occur In the motor control system, inverter is one of the most prone to failure [1-2]. In this paper, based on the three-phase six-switch space vector control mode [3-4], a fault-tolerant control strategy based on three-phase four-switch is proposed for the inverter single-phase open-circuit fault, and its effectiveness is verified by building MATLAB/Simulink simulation model.

2. Topology of the three-phase four-switch inverter
In this paper, in view of the single-phase open circuit fault of inverter, three dual-phase thyristors are added on the basis of three-phase six-switch, and connected to the midpoint of capacitor, so that the fault phase can maintain a certain voltage vector after the fault occurs, as shown in Figure 1A. Take a-phase fault as an example (this paper will be expanded with a-phase fault as an example). When the open-circuit fault occurs in the phase, the dual-phase thyristor TRa is opened and A is connected to the midpoint of the capacitor [5]. The topology of the inverter is also shown in Figure 1B.

3. Control principle of three-phase four-switch inverter
Like the three-phase six switch conduction rule, "1" represents the conduction of the upper bridge arm and "0" represents the conduction of the lower bridge arm in the same bridge arm. When an open circuit fault occurs in phase a, the switch states of phase B and phase C bridge arms are represented by
Sb and Sc respectively. On the premise of ignoring the midpoint voltage fluctuation of bus capacitance, the four switching states of Sb and Sc are (0,0), (1,0), (1,1) and (0,1). The relationship between the three-phase voltage of the motor and Sb, Sc under the four switching states is shown in formula (1). Then the phase voltages in the four states are substituted into formula (2) to four groups of basic space voltage vectors in the three-phase four switch state. Then, four groups of basic space voltages are converted to αβ Coordinate system.

Formula of relation between motor three-phase voltage and Sb, Sc:

\[
\begin{bmatrix}
U_{AN} \\
U_{BN} \\
U_{CN}
\end{bmatrix} = \frac{u_{dc}}{3} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_b \\
S_c
\end{bmatrix}
\]  

(1)

Basic space voltage vector formula:

\[
U_s = \frac{2}{3}(U_\alpha + U_b e^{j2\pi/3} + U_c e^{j4\pi/3})
\]  

(2)

Space voltage vector αβ coordinate system decomposition formula:

\[
\begin{bmatrix}
U_\alpha \\
U_\beta
\end{bmatrix} = \frac{2u_{dc}}{3} \begin{bmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
1/2 \\
S_b \\
S_c
\end{bmatrix}
\]  

(3)

In the above formula, \(U_{AN}\), \(U_{BN}\), \(U_{CN}\) is three-phase voltage of motor A, B and C respectively, and \(u_{dc}\) is dc bus voltage. \(U_s\) is the space voltage vector. \(U_\alpha\), \(U_\beta\) are the voltage components of \(U_s\) in the αβ coordinate system. The space voltage vector, its components in the αβ coordinate system and the \(S_b, S_c\) switching state can be obtained as shown in Table 1.

| \((S_b, S_c)\) | \(U_\alpha\) | \(U_\beta\) | \(U_s\) |
|---|---|---|---|
| (0,0) | \(u_{dc}/3\) | 0 | \(u_{dc} e^{j0}/3\) |
| (1,0) | \(-u_{dc}/\sqrt{3}\) | \(u_{dc} e^{j2\pi/3}/\sqrt{3}\) |  |
| (1,1) | \(-u_{dc}/\sqrt{3}\) | \(u_{dc} e^{j4\pi/3}/\sqrt{3}\) |  |
| (0,1) | \(-u_{dc}/3\) | 0 | \(-u_{dc} e^{j2\pi/3}\) |
The three-phase four-switch system after fault tolerance has only four effective voltage vectors and no zero vectors. The voltage space vector is one as shown in Figure 2.

The length of the projection on α and β axes determines the action time of the four basic vectors. The space voltage \( U_s \) can be obtained by switching different basic vectors in each sector by controlling the opening and closing time of B and C two-phase switching tubes. SVPWM is based on the ideal circular flux trajectory generated by the AC motor when the three-phase symmetric sinusoidal voltage is supplied, and the actual flux generated by the inverter in different switching modes are used to approximate the reference flux circle. Firstly, the sector position is determined by the given reference voltage, and then the four basic voltage vectors are used to synthesize the reference voltage. The basic vectors are allocated according to different SVPWM modes. Although the duty cycle of B and C phase SVPWM waveforms is determined by the given reference vector, the order of basic vector synthesis is different. The conduction time \( T_{c1} \) and \( T_{c2} \) determined by the sequence of synthesis are also different. Finally, PWM modulation is performed with triangular wave to obtain the switching signal \( S_a \) and \( S_b \) required by the four power tubes [6]. And because the three-phase four-switch inverter has no zero vector, and the use of zero vector in the motor torque is relatively stable can alleviate the torque ripple, so take two opposite vectors to form an equivalent zero vector to substitute to play the role of zero vector [7] (in this paper, \( U_1 \) , \( U_3 \) these two opposite vectors constitute the equivalent zero vector).

4. Control strategy design of three-phase four-switch inverter

In this paper, the sector definition of the three-phase four-switch inverter is determined according to the positive and negative relationship between \( U_{\alpha} \) and \( U_{\beta} \). And since the basic vector of three-phase four-switch SVPWM is a diamond as shown in Figure 2 after fixed-point connection, projection transformation is not required. Therefore, the relationship between sectors and reference vectors is shown in Table 2.

![Figure 2. Voltage space vector of fault-tolerant inverter (phase A disconnected).](image)

### Table 2. Sector judgment table

| Sector       | \( U_{\alpha} \) | \( U_{\beta} \) |
|--------------|------------------|-----------------|
| The first sector | +               | +               |
| The second sector | -               | +               |
| The third sector | -               | -               |
| The fourth sector | +               | -               |

In this paper, the generation mode of SVPWM adopts the "seven-section mode", which bisects the action time of the basic vector to form a symmetric PWM wave form. It is helpful to reduce the flux torque ripple [8-9]. In the PWM modulation cycle \( T \), according to the volt second balance characteristics:

\[
U_{ref}T = U_1T_1 + U_2T_2 + U_3T_3 + U_4T_4
\]  

(4)
\[ T = T_1 + T_2 + T_3 + T_4 \]  \hspace{1cm} (5)

In the above equation, \( U_{\text{ref}} \) is the reference voltage vector, \( T \) is the pulse width modulation period, and \( T_1, T_2, T_3, T_4 \) is the action time of the four basic voltage vectors respectively.

Make \( U_1 = -U_3, U_2 = -U_4, T_1 - T_3 = T_{13}, T_2 - T_4 = T_{24} \). There are:

\[ U_\alpha T = U_{1\alpha} T_{13} + U_{2\alpha} T_{24} \]  \hspace{1cm} (6)

\[ U_\beta T = U_{1\beta} T_{13} + U_{2\beta} T_{24} \]  \hspace{1cm} (7)

Also because \( U_{1\alpha} = U_{dc}/3, U_{1\beta} = 0, U_{2\alpha} = 0, U_{2\beta} = U_{dc}/\sqrt{3} \), so:

\[ T_{13} = 3U_\alpha T/U_{dc} \]  \hspace{1cm} (8)

\[ T_{24} = \sqrt{3}U_\beta T/U_{dc} \]  \hspace{1cm} (9)

Therefore, the zero-vector action time \( T_0 = T - T_{13} - T_{24} \) and the basic vector voltage action time of each sector are shown in Table 3:

|                  | The first sector | The second sector | The third sector | The fourth sector |
|------------------|------------------|------------------|------------------|------------------|
| \( T_1 \)        | \( T_{13} + T_0/2 \) | \( T_0/2 \)      | \( T_0/2 \)      | \( T_{13} + T_0/2 \) |
| \( T_2 \)        | \( T_{24} \)      | \( T_{24} \)      | 0                | 0                |
| \( T_3 \)        | \( T_0/2 \)      | \( -T_{13} + T_0/2 \) | \( -T_{13} + T_0/2 \) | \( T_0/2 \)      |
| \( T_4 \)        | 0                | 0                | \( -T_{24} \) | \( -T_{24} \)    |

Thus, the waveform of three-phase four-switch "seven-segment" SVPWM is shown in Figure 3:

![Figure 3. Three phase four switch "seven section" SVPWM waveform.](image)

![Figure 4. Vector composition diagram of four sectors.](image)

The horizontal axis is the time when the switch state is switched, and the vertical axis is the changing state of switch B and C. Each time the state is switched, the basic vector changes once. When the basic voltage vector \( U_{-1} \) are used instead of the zero vector, starting and ending with the basic space voltage vector \( U_{-1} \) can reduce the number of changes of the switching device on the bridge arm.
According to Figure 3, the switching state changes only twice in one cycle. Each space vector generated in each sector is shown in Figure 4.

5. Simulation Test

I order to verify the feasibility and effectiveness of the above control strategy, the same PMSM was selected to set a-phase fault and use the three-phase four-switch fault-tolerant control strategy for control. Motor speed, current, torque and other parameters during operation were observed, and the simulation model was built by Simulink, as shown in Figure 5, Figure 6 and Figure 7:

![Figure 5. Overall frame diagram of fault tolerant control model.](image1)

![Figure 6. Internal structure of the three-phase four-switch SVPWM module.](image2)

![Figure 7. Structure diagram of phase-missing inverter](image3)

Simulation parameters are shown in Table 4:

| Parameter name            | Parameter values |
|---------------------------|------------------|
| Rated speed (r/min)       | 500              |
| Inductance Ld,Lq (mH)     | 5.25/5.25        |
| The rotor inertia (Kg*m2) | 0.006329         |
| Stator resistance Rs (Ω)  | 0.9585           |
| A logarithmic P           | 4                |
| Damping coefficient B(N*M*S) | 0.0003     |
| Magnetic chain ψf (wb)    | 0.1827           |

Simulation conditions: DC side voltage $U_{dc} = 311V$, PWM switching frequency $f_{PWM} = 10Khz$, sampling period $T_s = 10\mu s$, variable step size ODE23TB algorithm, relative error 0.001, simulation time 0.4s.

In this test, the motor speed was set at a fixed value of 500rpm. After stable operation for 0.2s, the load was directly changed from 0 to $T=10N*M$. The measured motor speed test results are shown in Figure 8, 9 and 10 below.
6. Conclusion

From the simulation results, it is not difficult to see that the three-phase current waveform of permanent magnet synchronous motor basically tends to sine wave, and the motor speed tends to be stable quickly after starting, and can quickly recover to the given reference speed value after the sudden change of 0.2s load. Therefore, it can be considered that the fault-tolerant strategy of three-phase four-switch in this paper three-phase four-switch "seven-section" SVPWM modulation mode can play a better control effect when the inverter phase is out.

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