Control Strategy for a Five-Leg Inverter Supplying Dual Three-Phase PMSM

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This work was supported in part by the Research Fund for the National Nature Science Foundation of China under Grant 51707157, in part by the China Postdoctoral Science Foundation under Grant 2017M623210, in part by the Natural Science Basic Research Plan in Shaanxi Province under Grant 2018JQ5066, and in part by the Specialized Research Fund for the Doctoral Program of Xi’an University of Technology under Grant 103-45117004.

ABSTRACT This study presents a novel control strategy for a five-leg inverter-fed dual three-phase permanent-magnet synchronous motor (DT-PMSM) system. Three different five-leg inverter topologies (operating modes) can be reconfigured by choosing a pair of phases for sharing the common leg. The five-leg inverter operation mode with 150° phase difference can achieve full torque output, but the utilization of DC bus voltage is low. The operation mode with 30° phase difference has higher DC bus voltage utilization but lower output torque. The modified double zero-sequence injection (DZI) PWM strategy based on carrier-based PWM (CBPWM) for five-leg inverter operating modes is proposed. This strategy can achieve the maximum DC bus voltage utilization. The five-leg inverter operating modes can be used as a fault-tolerant solution for the occurrence of a fault in one leg of the six-leg inverter. Compared with the commonly used open phases fault-tolerant control (FTC) strategies, this strategy has the advantages of without increasing the stator copper, reducing the torque ripples, and implementing easily. Experimental results verify the effectiveness and feasibility of the proposed strategy.

INDEX TERMS Five-leg inverter, dual three-phase permanent magnetic synchronous motor, double zero-sequence injection pulse width modulation strategy, DC bus voltage utilization.

I. INTRODUCTION

Multiphase machines enjoy the advantages of low voltage high power, low torque pulsation and good fault tolerant ability [1]–[3]. They have good application prospects in high-power driving applications such as electric vehicles, marine electric propulsion, and wind power generation. The phase-shifted 30° dual three-phase motor (the asymmetric six-phase motor) has a greater application advantage due to the cancellation of the sixth torque harmonic among the various types of multiphase machines [4], [5].

The high fault-tolerant capability is an important application feature of multiphase machines. Various open-circuit and short-circuit faults in the machine drive system can be converted into the open-phase fault through the fault isolation. Therefore, the research of fault-tolerant control strategies for multiphase machines are mainly focused on the open-phase fault [6]–[20]. When an open-phase fault occurs, to suppress the torque ripple, the postfault phase current references need to be modified to maintain the same rotating magnetomotive force as in prefault situation [6]. Decreasing the stator winding losses and increasing the torque operation range are two significative optimization objectives of the current references, so the minimum loss (ML) strategy (different amplitudes of currents) and the maximum torque (MT) strategy (equal amplitudes of currents) are two main strategies for the postfault current-reference generation. The full-range minimum losses (FRML) strategy which minimizes the losses in the whole torque operation range is proposed in [11]–[13]. To realize the field-oriented control operation in the open-phase fault situation, the vector space decomposition (VSD) can be implemented by using the normal decoupling transformation matrices [14]–[17] or the reduced-order transformation matrices [18]–[20]. The inner current control loops can be realized using dual PI [15] and model predictive controllers [9].

In recent years, the five-leg inverter supplied dual-machine drives have been extensive researched for reducing switching
It is only necessary to transform $\alpha-\beta$ components into the general synchronous reference $d-q$ components. The rotating transformation matrix is

$$
T_r = \begin{bmatrix}
\cos \theta & \sin \theta & 0 \\
-\sin \theta & \cos \theta & 0 \\
0 & 0 & I_4
\end{bmatrix}
$$

(2)
where $I_m$ is the phase current amplitude, and $\theta_i$ is the phase angle of the A phase current.

1. **CF-sharing mode**
   
   The common leg current $i_{COM}$ is
   
   $$i_{COM} = i_C + i_F = I_m \cos(\theta + 120^\circ) + I_m \cos(\theta + 90^\circ) = 1.932I_m \cos(\theta + 105^\circ) \tag{7}$$

   The amplitude of the common leg current is 1.932 times of the normal leg current, so the CF-sharing mode can provide 0.518 times of the rated torque of the six-leg inverter operation.

2. **BF-sharing mode**
   
   The common leg current $i_{COM}$ is
   
   $$i_{COM} = i_B + i_F = I_m \cos(\theta - 120^\circ) + I_m \cos(\theta + 90^\circ) = 0.517I_m \cos(\theta + 165^\circ) \tag{8}$$

   The common leg current amplitude is 0.517 times of the normal leg current, so the full rated torque can be provided.

3. **AF-sharing mode**
   
   The common leg current $i_{COM}$ is
   
   $$i_{COM} = i_A + i_F = I_m \cos(\theta + 120^\circ) + I_m \cos(\theta + 90^\circ) = 1.414I_m \cos(\theta + 45^\circ) \tag{9}$$

   The common leg current amplitude is 1.414 times of the normal leg current, so only 0.707 times of the rated torque can be provided.

   The CF-sharing mode of five-leg inverter fed dual three-phase machine system is shown in Fig. 3.

**IV. DC BUS VOLTAGE UTILIZATION ANALYSIS**

For a five-leg inverter fed dual three-phase machine system, since two phases as a pair to share the common leg, the control freedom is reduced, and the bus voltage utilization rate is also inevitably lowered, so the DC bus voltage utilization in different operating modes needs to be discussed.

In order to facilitate the analysis of the bus voltage utilization, the reference voltage of the $z_1$-$z_2$ subspace is set to zero, i.e., the ideal sine reference phase voltage. The modulation coefficient $m$ is the ratio of the amplitude of the phase voltage to the DC bus voltage.

$$m = \frac{|V_1|}{U_{dc}} \tag{10}$$

The reference voltages of each phase of the dual three-phase machine can be expressed as:

$$\begin{align*}
u_A &= mU_{dc} \cos \theta \\
u_B &= mU_{dc} \cos(\theta - 2\pi/3) \\
u_C &= mU_{dc} \cos(\theta + 2\pi/3) \\
u_D &= mU_{dc} \cos(\theta - \pi/6) \\
u_E &= mU_{dc} \cos(\theta - 5\pi/6) \\
u_F &= mU_{dc} \cos(\theta + \pi/2)
\end{align*} \tag{11}$$

For the dual three-phase machine system with the isolated neutrals, the line voltages between two sets of three-phase windings have no practical significance. We only need to consider the internal line voltages of one three-phase winding. Consistent with the commonly used three-phase machine, taking the line voltage $u_{AB}$ as an example, $u_{AB}$ can be expressed as:

$$u_{AB} = mU_{dc} \cos \theta - mU_{dc} \cos(\theta - 2\pi/3) = -\sqrt{3}mU_{dc} \sin(\theta - \pi/3) \tag{12}$$

According to the symmetry of the three-phase system, the remaining line voltage can also be expressed in the form of (12). The magnitude of the line voltage must be less than the DC bus voltage:

$$|u_{AB}| \leq \sqrt{3}mU_{dc} \leq U_{dc} \tag{13}$$

where $m \leq 1/\sqrt{3}$, so the dual three-phase machine system fed by the six-leg inverter has the same linear modulation range $0.577U_{dc}$ with the three-phase machine system.

For a five-leg inverter fed dual three-phase motor system:

1. **CF-sharing mode**
   
   The line voltage $u_{AD}$ between the two sets of three-phase windings can be expressed as:

   $$\begin{align*}
u_{AD} &= u_{AC} + u_D \\
&= mU_{dc} \cos \theta - mU_{dc} \cos(\theta + 2\pi/3) + mU_{dc} \cos(\theta + \pi/2) - mU_{dc} \cos(\theta - \pi/6) \\
&= 2\sqrt{3}\sin(\pi/12)mU_{dc} \cos(\theta + \pi/4)
\end{align*} \tag{14}$$
Similarly, line voltages \( u_{AE}, u_{BD} \) and \( u_{BE} \) can be obtained:

\[
u_{AE} = u_{AC} + u_{FE} = \sqrt{3}mU_{dc}\cos(\theta + \pi/12) \quad (15)
\]

\[
u_{BD} = u_{BC} + u_{FD} = -2\sqrt{3}\sin(\pi/12)mU_{dc}\cos(\theta + \pi/12) \quad (16)
\]

\[
u_{BE} = u_{AC} + u_{FE} = 2\sqrt{3}\sin(\pi/12)mU_{dc}\cos(\theta - \pi/12) \quad (17)
\]

The maximum amplitude of the line voltages is \( u_{AE} \) according to (14)-(17), it needs to meet

\[
|u_{AE}| \leq \sqrt{3}mU_{dc} \leq U_{dc} \quad (18)
\]

where \( m \leq 1/\sqrt{6} \), so the maximum linear modulation range of the five-leg inverter fed dual three-phase machine (CF-sharing) is 0.408\(U_{dc}\), which is 70.7% of the six-leg inverter operation.

(2) BF-sharing mode

Using the same method as CF-sharing mode, the maximum amplitude of the line voltages is \( u_{AE} \)

\[
u_{AE} = u_{AB} + u_{FE} = -2\sqrt{3}\cos(\pi/12)mU_{dc}\sin(\theta - \pi/4) \quad (19)
\]

It needs to meet

\[
|u_{AE}| \leq 2\sqrt{3}\cos(\pi/12)mU_{dc} \leq U_{dc} \quad (20)
\]

where \( m \leq 0.299 \), so the maximum linear modulation range in the BF-sharing mode is 0.299\(U_{dc}\), which is 51.8% of the six-leg inverter operation.

(3) AF-sharing mode

Similarly, the maximum amplitude of the line voltage is \( u_{CD} \)

\[
u_{CD} = u_{CA} + u_{FD} = -2\sqrt{3}\cos(\pi/12)mU_{dc}\sin(\theta + \pi/4) \quad (21)
\]

It needs to meet

\[
|u_{CD}| \leq 2\sqrt{3}\cos(\pi/12)mU_{dc} \leq U_{dc} \quad (22)
\]

where \( m \leq 0.299 \), so the maximum linear modulation range is 0.299\(U_{dc}\), which is 51.8% of the six-leg inverter operation.

The above analyses all assume that the reference voltage of the \( z_1-z_2 \) subspace is zero, which is corresponding to the two-dimensional current control. However, in actual applications, the reference voltage of the \( z_1-z_2 \) subspace is not zero due to the four-dimensional current control, so the linear modulation range is slightly reduced.

From the above analyses, the performance indexes under the same load condition in different control methods are listed in Table 1. The minimum loss strategy with the isolated neutrals [15] is used for the open-phase fault-tolerant operation in Table 1.

| Performance indexes | Healthy six-leg inverter operation | Five-leg inverter operation | Open-phase fault-tolerant operation |
|---------------------|----------------------------------|-----------------------------|-----------------------------------|
| Stator copper loss (p.u.) | 1 | 1 | 1 | 1.5 |
| Maximum amplitude of leg currents(p.u.) | 1 | 1.932 | 1(0.517) | 1.414 | 1.803 |
| Linear modulation range | 0.577 | 0.408 | 0.299 | 0.299 |

V. THE MODIFIED DZI PWM STRATEGY FOR THE FIVE-LEG INVERTER

For a five-leg inverter fed dual three-phase motor system, since two phases as a pair to share the common leg, the number of voltage vectors is reduced to 32. Taking the CF-sharing mode as an example, since the phase C and phase F share the common leg, the switching function \( S_c = S_F \). The voltage vector diagrams of the \( \alpha-\beta \) and \( z_1-z_2 \) subspaces are shown in Fig.4.

It can be seen from Fig.4 that it is very difficult to analyze the PWM strategy based on SVPWM, so the DZI PWM strategy based on CBPWM is adopted in this paper. The four-dimensional current vector control is adopted to suppress the harmonic currents in this paper. The four-dimensional current vector control of the dual three-phase motor system is shown in Fig.5.

The double zero-sequence injection PWM strategy is shown in Fig. 6. For the healthy six-leg inverter operation, the mean zero-sequence components injection is frequently
example, the modulation voltage (Inverter output terminal to
pendent of each other. Taking the CF-sharing mode as an
operation are consistent, but the injected zero sequence volt-
mum values of the three phase voltages, respectively [33].

where

And the zero-sequence components can be written
as:

\[
\begin{aligned}
    u_{o1} &= -0.5 (u_{\text{max}} + u_{\text{mid}}) + 0.5 u_{\text{min}} \\
    u_{o2} &= -0.5 (u_{\text{max}} + u_{\text{min}}) + 0.5 u_{\text{mid}}
\end{aligned}
\]  
(23)

where \(u_{\text{max}}\), \(u_{\text{mid}}\), and \(u_{\text{min}}\) are maximum, middle, and mini-
imum values of the three phase voltages, respectively [33].

The principles of the DZI PWM strategy used for the
five-leg inverter operation and the healthy six-leg inverter
operation are consistent, but the injected zero sequence volt-
ages for two sets of three-phase system are no longer inde-
pendent of each other. Taking the CF-sharing mode as an
example, the modulation voltage (Inverter output terminal to
DC bus midpoint) of the com leg must be equal, i.e., \(u_{\text{COM}}^* = u_{\text{F}}^*\). So the zero sequence voltages can be defined as

\[
\begin{aligned}
    u_{o1} &= u_o + u_F \\
    u_{o2} &= u_o + u_C
\end{aligned}
\]  
(24)

And the modulation voltages can be written as:

\[
\begin{aligned}
    u_A^* &= u_A + u_{o1} = u_A + u_o + u_F \\
    u_B^* &= u_B + u_{o1} = u_B + u_o + u_F \\
    u_C^* &= u_C + u_{o1} = u_C + u_o + u_F \\
    u_D^* &= u_D + u_{o2} = u_D + u_o + u_F \\
    u_E^* &= u_E + u_{o2} = u_E + u_o + u_C \\
    u_F^* &= u_F + u_{o2} = u_F + u_o + u_C
\end{aligned}
\]  
(25)

The amplitudes of modulation voltages must be less than
0.5\(U_{\text{dc}}\), so the limited condition of the zero-sequence voltages in two three-phase systems can be expressed as

\[
\begin{aligned}
    -0.5 - u_{\text{min}} 1 &\leq u_{o1} \leq 0.5 - u_{\text{max}} 1 \\
    -0.5 - u_{\text{min}} 2 &\leq u_{o2} \leq 0.5 - u_{\text{max}} 2
\end{aligned}
\]  
(26)

The voltage is normalized by the DC bus voltage \(U_{\text{dc}}\). Substituting (24) into (26):

\[
\begin{aligned}
    -0.5 - u_{\text{min}} 1 &\leq u_o + u_F \leq 0.5 - u_{\text{max}} 1 \\
    -0.5 - u_{\text{min}} 2 &\leq u_o + u_C \leq 0.5 - u_{\text{max}} 2
\end{aligned}
\]  
(27)

The limited condition of the zero-sequence voltage \(u_o\) is

\[
\begin{aligned}
    -0.5 - u_{\text{min}} 1 - u_F &\leq u_o \leq 0.5 - u_{\text{max}} 1 - u_F \\
    -0.5 - u_{\text{min}} 2 - u_C &\leq u_o \leq 0.5 - u_{\text{max}} 2 - u_C
\end{aligned}
\]  
(28)

So the minimum and maximum values of \(u_o\) can be written as

\[
\begin{aligned}
    u_{o\text{min}} &= \max \{-0.5 - u_{\text{min}} 1 - u_F, -0.5 - u_{\text{min}} 2 - u_C\} \\
    u_{o\text{max}} &= \min \{0.5 - u_{\text{max}} 1 - u_F, 0.5 - u_{\text{max}} 2 - u_C\}
\end{aligned}
\]  
(29)

The necessary and sufficient condition for the existence of
\(u_o\) is \(u_{o\text{min}} \leq u_{o\text{max}}\).
consistent with the healthy six-leg inverter operation, frequently used mean continuous pulse width modulation (CPWM) is:

\[ u_0 = \frac{(u_{0\text{ min}} + u_{0\text{ max}})}{2} \quad (30) \]

For BF-sharing mode, it is only needed to change the \( u_C \) in (24)-(29) to \( u_B \).

A five-leg voltage source inverter simulation model based on Matlab/Simulink is constructed to validate the DZI PWM strategy in this paper. The reference phase voltage frequency \( f \) is 10Hz. Fig.7 shows the voltage waveforms in the CF-sharing mode when the reference phase voltage amplitude is 0.408 \( U_{dc} \). Fig.8 shows the voltage waveforms in the BF-sharing mode when the reference phase voltage amplitude is 0.299 \( U_{dc} \).

According to Fig.7(a) and Fig.8(a), the maximum amplitudes of the modulation voltages exactly reach 0.5 \( U_{dc} \), which indicates that DZI PWM strategy in this paper can achieve the maximum DC bus voltage utilization. Apart from the modified DZI PWM strategy, there is no difference in the control strategy of the five-leg inverter and the six-leg inverter.

VI. EXPERIMENTAL RESULTS

In order to verify the effectiveness of the five-leg control strategy in this paper, an experimental verification is carried
FIGURE 10. Phase current waveforms under different control methods. (a) two-dimensional current control of the six-leg inverter. (b) two-dimensional current control of the five-leg inverter. (c) four-dimensional current control of the five-leg inverter.

out on a surface-modified DT-PMSM. The parameters of the DT-PMSM are listed as follows: \( P_n = 3, R_s = 1.4\Omega, L_D = 2.04\text{mH}, L_Q = 2.04\text{mH}, \) and \( \psi_{fd} = 0.28\text{Wb} \). The prototype of the experimental system platform is shown in Fig. 9.

The CF-sharing mode is used in the experiment. The DC bus voltage is 200V. PWM switching frequency is 10kHz. The dead time is 1.5\text{us}, and the motor load is constantly at 7\text{Nm}. Phase currents \( i_A, i_B, i_C, i_D \), and the phase current \( i_C \) harmonic spectra under different control methods are shown in Figs. 10. The motor speed is 200\text{r/min}.

Fig.10(a) is the current waveform under the two-dimensional current control of the healthy six-leg inverter. The phase current only contain the 5th, 7th harmonics due to the effect of VSI dead-time and other nonlinear factors. Fig.10(b) is the current waveform under the two-dimensional current control of the five-leg inverter. In addition to containing 5th, 7th harmonics, the phase currents also contain 3rd harmonic, which is due to the internal asymmetry of the two sets of three-phase system when phase C and F share a common leg. Fig.10(c) is the current waveform under the four-dimensional current control of the five-leg inverter. Phase currents contain almost no harmonic currents. The four-dimensional current control can effectively suppress harmonic currents due to the asymmetry of the five-leg inverter non-linearity [32].

Fig.11 shows the current waveforms of the \( \alpha-\beta \) and \( z_1-z_2 \) subspaces under different control methods. It can be seen that the difference among them is only the harmonic current of the \( z_1-z_2 \) subspace. In addition to the 5th, 7th harmonics caused by the dead-time effect, the harmonic currents in the \( z_1-z_2 \) subspaces are more serious under the two-dimensional current control of the five-leg inverter, because there is the
internal asymmetry of the two sets of three-phase system when phase C and F share a common leg. The harmonic currents are well suppressed through the currents closed loop control in the $z_1$-$z_2$ subspace. It has no obvious difference in the $\alpha$-$\beta$ subspace, so the torque output effect has no obvious difference among three different control methods.

Fig.12 shows modulation voltages and phase currents under different control methods. The motor speed is 300r/min. In the health six-leg inverter operation, modulation voltages of phase C and F are given. In the five-leg inverter operation, because modulation voltages of phase C and F are the same (phase COM), modulation voltages of the phase E and COM are given. The experimental results are consistent with the simulation analysis in the Fig.7(a).

In order to verify the dynamic performance of the five-leg inverter control in this paper, Fig.13 shows the motor starting waveforms of the healthy six-leg and five-leg operation under the same control parameters. The reference speed is 300r/min. It can be seen that there is no obvious difference in the speed response time between the five-leg inverter and the six-leg inverter operation, which indicates that the five-leg inverter control strategy in this paper has good dynamic response.

VII. CONCLUSION

In this paper, a novel control strategy for a five-leg inverter fed DT-PMSM system is investigated. Three different five-leg inverter operating modes can be reconfigured by choosing a pair of phases for sharing the common leg. The BF-sharing mode can achieve full torque output, but the DC bus voltage utilization is reduced from $0.577U_{dc}$ to $0.299U_{dc}$. The CF-sharing mode has higher DC bus voltage utilization $0.408U_{dc}$, but only 0.518 times of the rated torque can be provided. Apart from the modified DZI PWM strategy, there is no difference in the control strategy of the five-leg inverter and the six-leg inverter. The four-dimensional current vector control can effectively suppress harmonic currents due to the asymmetry of the five-leg inverter non-linearity.

The five-leg inverter operating modes can be used as a fault-tolerant solution for the occurrence of a fault in one leg of the six-leg inverter. Compared with the commonly used open phases fault-tolerant control strategies, this strategy has the advantages of without increasing the stator copper, reducing the torque ripples, and implementing easily.

REFERENCES

[1] E. Levi, “Advances in converter control and innovative exploitation of additional degrees of freedom for multiphase machines,” IEEE Trans. Ind. Electron., vol. 63, no. 1, pp. 433–448, Jan. 2016.
[2] F. Barrero and M. J. Duran, “Recent advances in the design, modeling and control of multiphase machines—Part I,” IEEE Trans. Ind. Electron., vol. 63, no. 1, pp. 449–458, Jan. 2016.
[3] M. J. Duran and F. Barrero, “Recent advances in the design, modeling, and control of multiphase machines—Part II,” IEEE Trans. Ind. Electron., vol. 63, no. 1, pp. 459–468, Jan. 2016.
[4] Y. Zhao and T. A. Lipo, “Space vector PWM control of dual three-phase induction machine using vector space decomposition,” IEEE Trans. Ind. Appl., vol. 31, no. 5, pp. 1100–1109, Sep./Oct. 1995.
[5] R. Bojoi, M. Lazzari, F. Profumo, and A. Tencconi, “Digital field-oriented control for dual three-phase induction motor drives,” IEEE Trans. Ind. Appl., vol. 39, no. 3, pp. 752–760, May 2003.
[6] J.-R. Fu and T. A. Lipo, “Disturbance-free operation of a multiphase current-regulated motor drive with an opened phase,” IEEE Trans. Ind. Appl., vol. 30, no. 5, pp. 1267–1274, Oct. 1994.
[7] Y. F. Zhao and T. A. Lipo, “Modeling and control of a multi-phase induction machine with structural unbalance, Part I-Machine modeling and multi-dimensional current regulation,” IEEE Trans. Energy Convers., vol. 11, no. 3, pp. 570–577, Sep. 1996.
[8] Y. F. Zhao and T. A. Lipo, “Modeling and control of a multi-phase induction machine with structural unbalance, Part II-Field-oriented control and experimental verification,” IEEE Trans. Energy Convers., vol. 11, no. 3, pp. 378–384, Sep. 1996.

[9] I. Gonzalez-Prieto, M. J. Duran, M. Bermudez, F. Barrero, and C. Martin, “Assessment of virtual-voltage-based model predictive controllers in six-phase drives under open-phase faults,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 8, no. 3, pp. 2634–2644, Sep. 2020.

[10] M. Bermudez, I. Gonzalez-Prieto, F. Barrero, H. Guzman, M. J. Duran, and X. Kestelyn, “Open-phase fault-tolerant direct torque control technique for five-phase induction motor drives,” IEEE Trans. Ind. Electron., vol. 64, no. 2, pp. 902–911, Feb. 2017.

[11] F. Baneira, J. Doval-Gandoy, A. G. Yepes, O. Lopez, and D. Perez-Estevete, “Control strategy for multiphase drives with minimum losses in the full torque operation range under single open-phase fault,” IEEE Trans. Power Electron., vol. 32, no. 8, pp. 6275–6285, Aug. 2017.

[12] F. Baneira, J. Doval-Gandoy, A. G. Yepes, O. Lopez, and D. Perez-Estevete, “Control strategy for dual-three-phase PMSMs with minimum losses in the full torque operation range under single open-phase fault,” in Proc. IEEE Energy Convers. Congr. Expo. (ECCE), Milwaukee, WI, USA, Sep. 2016, pp. 1–8.

[13] A. G. Yepes, J. Doval-Gandoy, F. Baneira, and H. A. Toliyat, “Control strategy for dual three-phase machines with two open phases providing minimum loss in the full torque operation range,” IEEE Trans. Power Electron., vol. 33, no. 12, pp. 10044–10050, Dec. 2018.

[14] A. Tani, M. Mengoni, L. Zanini, G. Serra, and D. Casadei, “Control of multiphase induction motors with an odd number of phases under open-circuit phase faults,” IEEE Trans. Power Electron., vol. 27, no. 2, pp. 565–577, Feb. 2012.

[15] H. S. Che, M. J. Duran, E. Levi, M. Jones, W.-P. Hew, and N. A. Rahim, “Postfault operation of an asymmetrical six-phase induction machine with single and two isolated neutral points,” IEEE Trans. Power Electron., vol. 29, no. 10, pp. 5406–5416, Oct. 2014.

[16] I. G. Prieto, M. J. Duran, P. Garcia-Entrambasaguas, and M. Bermudez, “Field-oriented control of multiphase drives with passive fault tolerance,” IEEE Trans. Ind. Electron., vol. 67, no. 9, pp. 7228–7238, Sep. 2020.

[17] A. S. Abdel-Khalik, R. A. Hamdy, A. M. Massoud, and S. Ahmed, “Postfault control of scalar (V/f) controlled asymmetrical six-phase induction machines,” IEEE Access, vol. 6, pp. 59211–59220, 2018.

[18] H.-M. Rya, J.-W. Kim, and S.-K. Sul, “Synchronous-frame current control of multiphase synchronous motor under asymmetric fault condition due to open phases,” IEEE Trans. Ind. Appl., vol. 42, no. 4, pp. 1062–1070, Jul. 2006.

[19] H. Zhou, W. Zhao, G. Liu, R. Cheng, and Y. Xie, “Remedial field-oriented control of five-phase fault-tolerant permanent-magnet motor by using reduced-order transformation matrices,” IEEE Trans. Ind. Electron., vol. 64, no. 1, pp. 169–178, Jan. 2017.

[20] L. Cheng, Y. Sui, P. Zheng, P. Wang, and F. Wu, “Implementation of postfault decoupling vector control and mitigation of current ripple for five-phase fault-tolerant PM machine under single-phase open-circuit fault,” IEEE Trans. Power Electron., vol. 33, no. 10, pp. 8623–8636, Oct. 2018.

[21] K. Oka, Y. Nozawa, and K. Matsuse, “An improved method of voltage utility factor for PWM control of a five-leg inverter in two induction motor drives,” IEIE Trans. Electr. Electron. Eng., vol. 1, no. 1, pp. 108–111, May 2006.

[22] K. Oka and K. Matsuse, “A novel PWM technique with switching-loss reduction for independent drive of two 3-phase AC motors fed by a five-leg inverter,” IEEJ Trans. Electr. Electron. Eng., vol. 6, no. 3, pp. 260–265, May 2011.

[23] T. Tanaka, A. Hara, and M. Iwashita, “Characteristics of independent vector control of two induction motors fed by a five-leg inverter with space vector modulation,” in Proc. 7th Int. Power Electron. Motion Control Conf., Harbin, China, 2012, pp. 2431–2438.

[24] M. S. K. Hizume, “Independent vector control of parallel connected two induction motors by a five-leg inverter,” in Proc. Eur. Power Electron. Appl. Conf., Toulouse, France, 2003, pp. 1–7.

[25] Y.-S. Lim, J.-S. Lee, and K.-B. Lee, “Advanced speed control for a five-leg inverter driving a dual-induction motor system,” IEEE Trans. Ind. Electron., vol. 56, no. 1, pp. 707–716, Jan. 2009.

[26] M. Jones, S. N. Vukosavic, D. Dujic, E. Levi and P. Wright, “Five-leg inverter PWM technique for reduced switch count two-motor constant power applications,” IET Electr. Power Appl., vol. 2, no. 5, pp. 275–287, Sep. 2008.

[27] W. Wang, Z. Zhang and M. Cheng, “A dual-level hysteresis current control for one five-leg VSI to control two PMSMs,” IEEE Trans. Power Electron., vol. 32, no. 1, pp. 804–814, Jan. 2017.

[28] J. Wei, T. Zhang, P. Liu, W. Tao, and B. Zhou, “Investigation of a fault-tolerant control method for a multiprotocol dual-stator doubly salient electromagnetic machine drive,” IEEE Trans. Ind. Electron., vol. 66, no. 1, pp. 750–761, Jan. 2019.

[29] Y. Hu, S. Huang, X. Wu, and X. Li, “Control of dual three-phase permanent magnet synchronous machine based on five-leg inverter,” IEEE Trans. Power Electron., vol. 34, no. 11, pp. 11071–11079, Nov. 2019.

[30] C. S. Lim et al., “A fault-tolerant two-motor drive with FCS-MP-Based flux and torque control,” IEEE Trans. Ind. Electron., vol. 61, no. 12, pp. 6603–6614, Dec. 2014.

[31] D. Dujic, M. Jones, S. N. Vukosavic, and E. Levi, “A general PWM method for a (2n+1)-leg inverter supplying n-three-phase machines,” IEEE Trans. Ind. Electron., vol. 56, no. 10, pp. 4107–4118, Oct. 2009.

[32] H. S. Che, E. Levi, M. Jones, W.-P. Hew, and N. A. Rahim, “Current control methods for an asymmetrical six-phase induction motor drive,” IEEE Trans. Power Electron., vol. 29, no. 1, pp. 407–417, Jan. 2014.

[33] C. Zhou, G. Yang, and J. Su, “PWM strategy with minimum harmonic distortion for dual three-phase permanent-magnet synchronous motor drives operating in the overmodulation region,” IEEE Trans. Power Electron., vol. 31, no. 2, pp. 1367–1380, Feb. 2016.  

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