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Fault Tolerant Control of Multiphase Multilevel Motor Drives – Technical Review

Zheng Wang, Xueqing Wang, Yibo Wang, Jian Chen, and Ming Cheng*

(School of Electrical Engineering, Southeast University, Nanjing, 210096, China)

Abstract: The multiphase multilevel motor drives are a promising solution for some high-power and high-reliability applications, since they have multiple power conversion routes, a large amount of redundant voltage vectors, higher equivalent switching frequencies and superior harmonic performance. It has great significance to exploit their remedial control strategies in depth to fully utilize their high fault tolerant capabilities. This paper will present an updated technical review of fault tolerant control schemes for multiphase multilevel motor drives. Based on exemplification of the diode neutral-point-clamping three-level (DNPC-3L) inverters and T-type NPC three-level (TNPC-3L) inverters fed asymmetric six-phase PMSM drives, the study is taken for both phase-leg faults and switch faults. Furthermore, the discussion on multiple-switch faults, short-circuit switch faults and switch and leg hybrid faulty conditions are discussed in this paper.

Keywords: Fault tolerant control, multiphase multilevel drives, modulation strategy, phase-level faults, switch-level faults.

1 Introduction

With increasing demands of high reliability and large capacity for electric drive systems, multiphase drives have been widely applied in various fields such as elevators, aircrafts, electric vehicles, ship propulsion, etc[1]. The main advantages of multiphase motor drives over three-phase ones can be summarized as lower torque pulsations, lower current stress, lower DC link current harmonics, higher power density and higher fault tolerant capability[2]. On the other hand, by using multilevel converter techniques, the rated voltages of drives are increased. The multilevel converters fed drives provide better harmonic performance in output voltages, which facilitates low switching-frequency operation of high-power drives[3-4]. The combination of techniques of multiphase drives and multilevel inverters fed drives could incorporate their merits, and are suitable for high-power and high-reliability applications[5-6].

The fault tolerant control schemes have been studied intensively for both multiphase drives and multilevel inverters. For multiphase drives, most of fault tolerant control schemes are focused on open-phase faults in drives since redundant phases are available for multiphase drives. But previous research are still limited in two-level inverters fed drives. The related remedial control solutions are classified into the following categories: The first method is developed with field-oriented control schemes, where the armature currents are decomposed and controlled aligning with a rotating synchronous frame of rotor flux[7-10]. The proportional-integrator (PI) controller is usually used for current regulation. The second method is to decompose current components under natural frame onto torque-generation subspace, harmonics subspaces and zero-sequence subspace based on vector space decomposition(VSD). The resonant controllers, hysteresis controllers and model-based predictive controllers are usually used to track those periodic current references on those orthogonal subspaces[11-13]. The third category of methods are with direct torque control, where current controllers are omitted. Under faulty conditions, the remaining switching voltage vectors are used to synthesize desired voltage components on torque-generating subspace, which are generated by stator flux and torque comparators. The current component on an additional dimension could be considered to achieve a circular stator magnetic motion force(MMF) and keep copper loss minimum[14-15]. However, all the discussion are limited in two-level inverter fed drives. For two-level inverter fed drives, the faulty phase leg has to be removed when any power switch fails in this phase leg.

On the other hand, the multilevel inverters have redundant voltage vectors because of more power switches in one phase leg. The remedial strategies of switch faults in multilevel inverters include reconfiguration of power circuit with additional hardware and modification of switching strategies with remaining switching vectors[16-18]. But almost all research work on fault tolerant control of multilevel inverters have been taken on three-phase systems. As aforementioned, with increasing requirements of high-power high-reliability application, the multiphase multilevel motor drives become a promising solution, which offer advantages of high output power ability, good harmonics and torque performance, and high fault tolerant capability. Some research works on multiphase multilevel motor drives are taken on design and optimize modulation strategies[19-22]. Compared to those, the work on fault tolerant control on multiphase multilevel motor drives are still rare.

The purpose of this paper is to present a technical review and comprehensive investigation for recent work on fault tolerant control of multiphase

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* Corresponding Author, E-mail: zwang@seu.edu.cn.

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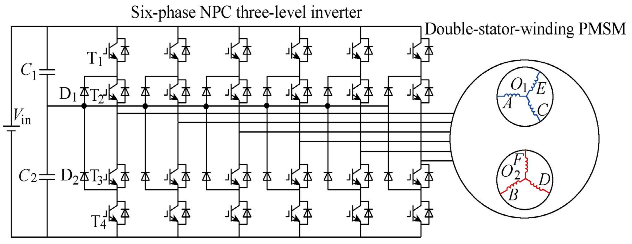
multilevel motor drives. Both study on phase leg faults and switch faults will be included. Essentially, two challenges have been addressed particularly for operation of multiphase multilevel motor drives under faulty conditions: one is mid-point voltage control in DC link, and the other is reconfiguration of voltage synthesis. In section 2, three control methods for phase-leg faults, namely phase-independent control, vector space decomposition(VSD) control and voltage compensation based control are reviewed. their corresponding modulation strategies are also discussed. In section 3, the switch faults and remedial strategies are investigated for multiphase multilevel inverters fed drives, where both open-circuit faults and short-circuit faults are taken into consideration. The solutions are classified into the methods based on multiple SVM schemes and VSD schemes. The asymmetric six-phase PMSM motor drives fed by T-type NPC three-level (TNPC-3L) inverters and diode-clamping NPC three-level (DNPC-3L) inverters are used for exemplification. Fig.1 shows the system configuration illustrated in this paper.

2 Phase-leg faults

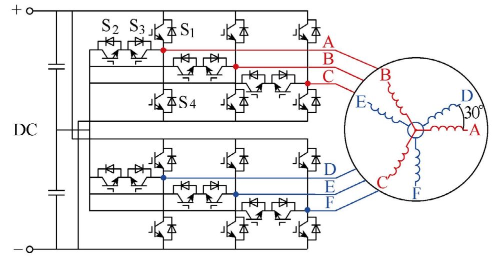
Normally, the fault isolation circuit can be used to isolate faulty phase legs from the drive. The fault isolation circuit is usually formed by energy storage, bidirectional triac and fast fuses[25]. With fault isolation circuits, both short-circuit faults and open-circuits faults can be isolated.

2.1 Phase-independent control

Fig.2 shows the block diagram of fault tolerant control with carrier modulation when open-phase faults occur. For providing smooth torque under open-phase conditions, the phase windings must stand asymmetric currents. The asymmetric currents in different phases can be controlled separately. The carrier modulation is convenient to implement the phase-independent current control. The in-phase disposition(IPD) multi-carrier modulation is one of the carrier based modulation strategy for multilevel drives. The principle is plotted as shown in Fig.3. By comparing two IPD carriers v_{C1} and v_{C2} with modulating signal v_m, the switching pulses will be generated for power switches in Fig.3(a). Furthermore, by injecting zero-sequence component into modulating signals, the utilization of DC link voltage could be increased by 15% in Fig.3(b). On the other hand, oscillation in mid-point voltage of DC link becomes sever due to open-phase operation under faulty conditions. The zero-sequence component injected to modulation signals can help mitigate oscillation of mid-point voltage in DC link.



(a) DNPC-3L[23]



(b) TPNC-3L[24]

Fig.1 System configuration of multilevel inverters fed asymmetrical six-phase PMSM drive

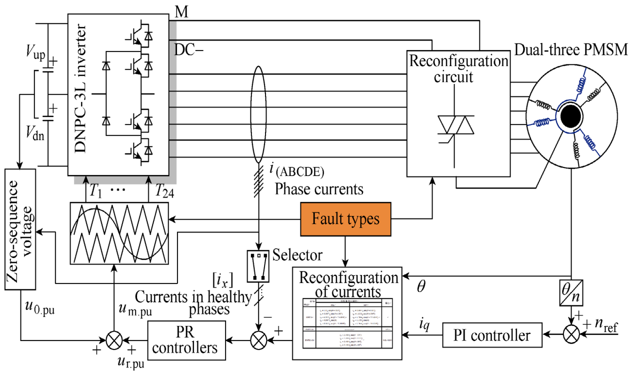
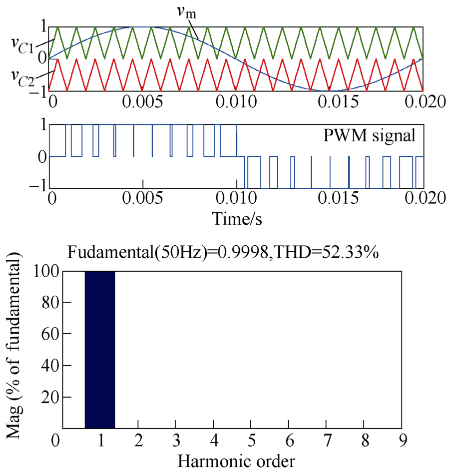
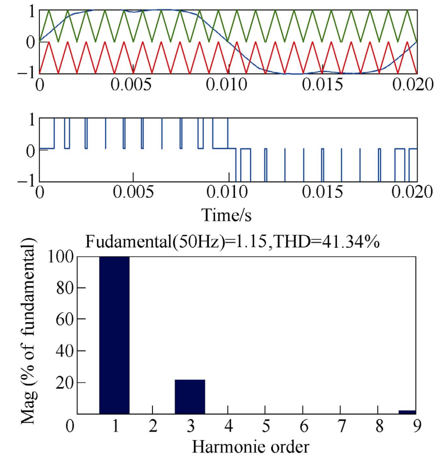


Fig.2 Fault tolerant control of open-phase faults for DNPC-3L inverters fed asymmetric six-phase PMSM drives with phase-independent control



(a) Standard



(b) Injection of zero-sequence component into modulation signal

Fig.3 Principle of IPD level-shifted multicarrier modulation

For suppressing oscillation in mid-point voltage of DC link, the injected zero-sequence voltage is derived as following[24]:

$$u_{0,\mathrm{pu}} = \frac{C\Delta V_c(k-1)T_{\mathrm{s}} - \sum_{x=A}^{E}\mathrm{Sign}(u_{rx,\mathrm{pu}})u_{rx,\mathrm{pu}}i_x}{\sum_{x=A}^{E}\mathrm{Sign}(u_{rx,\mathrm{pu}})i_x} \tag{1}$$

where k is the kth control period, ΔV_c is the voltage deviation between the upper capacitor voltage and the lower capacitor voltage. $u_{rx,\mathrm{pu}}$ is the per unit value of output modulating voltage from current controller. The function of $\mathrm{Sign}(u_{mx,\mathrm{pu}})$ is defined as:

$$\mathrm{Sign}(u_{mx,\mathrm{pu}})=\begin{cases}1 & u_{mx,\mathrm{pu}}>0\\ 0 & u_{mx,\mathrm{pu}}=0\\ -1 & u_{mx,\mathrm{pu}}<0\end{cases} \tag{2}$$

With torque requirements and feedback of rotor position, the optimal current references can be derived. Based on components on $\alpha-\beta$ subspace, the circular trajectory should be kept in order to eliminate the torque oscillation after fault[23]:

$$\begin{cases}2i_A^* + \sqrt{3}i_B^* - i_C^* - \sqrt{3}i_D^* - i_E^* = -6i_q^*\sin\theta\\ i_B^* + \sqrt{3}i_C^* + i_D^* - \sqrt{3}i_E^* - 2i_F^* = 6i_q^*\cos\theta\end{cases} \tag{3}$$

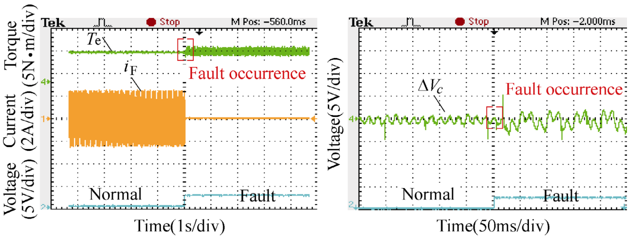
where θ is phase angle between d-axis of rotor frame and phase A winding. In addition to suppression of torque oscillation, different optimization objectives are usually achieved for fault tolerant operation. For instance, the minimum current amplitude and the minimum copper loss control. Rewriting phase current references as $i_j^* = x_j\sin\theta + y_j\cos\theta$ ($i = A,\cdots,F$), and the objective of minimization of copper loss and minimization of current amplitude are expressed as in Eq.(4) and Eq.(5), respectively.

$$F_{PM}(x_A,\cdots,x_F,y_A,\cdots y_F) = \sum_{i=A}^{F}R_{\mathrm{i}}(x_i^2+y_i^2) \tag{4}$$

$$\begin{aligned}&F_{PM}(x_A,\cdots,x_F,y_A,\cdots,y_F)\\ &=\frac{1}{6-n_F}\sum_{i=A}^{F}R_s(x_i^2+y_i^2)-\left[\frac{1}{6-n_F}\sum_{i=A}^{F}\sqrt{x_i^2+y_i^2}\right]^2\end{aligned} \tag{5}$$

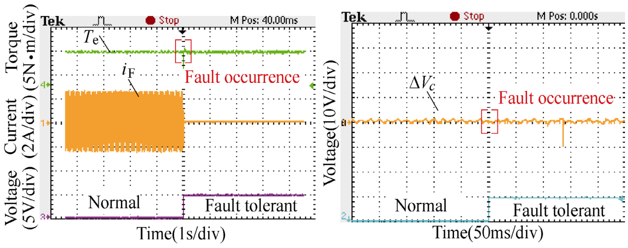
where R_i is stator resistor of phase i, and n_F is the number of faulty phases. The values of x_i and y_i are zero when open-phase fault occurs in phase i. With optimal current references, the current controllers are used to regulate phase currents separately. For controlling asymmetric currents, the PI control, hysteresis current control, and predictive control can be used. However, the PI control shows limits in regulating periodic signals effectively, and the hysteresis current control suffers from variable switching frequencies. The predictive control is more dependent of system modeling and parameters. On the other hand, the PR control, as a kind of internal-mode control, offers features of periodic signal tracking capability, constant switching frequency and simple implementation.

Fig.4 and Fig.5 present the performance of phase-independent fault tolerant control for DNPC-3L inverters fed asymmetric six-phase PMSM drives when phase leg F is open. Without fault tolerant control, large oscillations appear in torque and mid-point voltage of DC link, as shown in Fig.4. On the other hand, the oscillations in torque and mid-point voltage of DC link are suppressed well with fault tolerant control in Fig.5(a) and (b). It is noted that zero-sequence component into modulation signals for controlling mid-point voltage of DC link. The asymmetric currents are controlled well by using current controller in each phase independently, as shown in Fig.5(c) and (d). By comparison, it is observed that there exists clear control error in phase current with only P control in Fig.5(e) while the error is suppressed with PR controller in Fig.5(f).

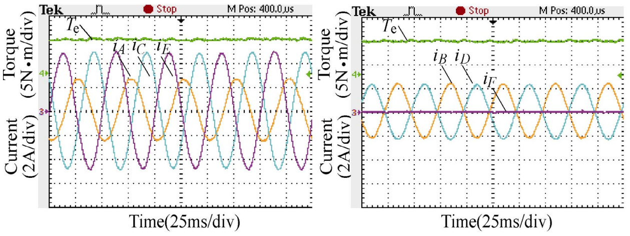


(a) Torque and faulty phase current (b) Mid-point voltage in DC link

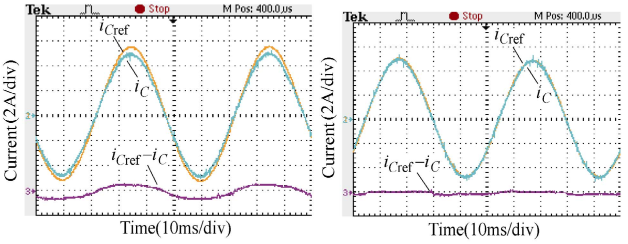
Fig.4 Experimental results of DNPC-3L inverters fed asymmetric six-phase PMSM drives without fault tolerant control



(a) Torque and faulty phase current (b) Mid-point voltage in DC link



(c) Phase currents in healthy winding (d) Phase currents in faulty winding



(e) Phase current with only P control (f) Phase current with PR control

Fig.5 Experimental results of DNPC-3L inverters fed asymmetric six-phase PMSM drives with fault tolerant control

2.2 Vector space decomposition control

Different from phase-independent control on natural frames, the vector space decomposition (VSD) can be used to control asymmetric phase currents under synchronous frames. With VSD, the physical components on natural frame are converted onto several orthogonal subspaces: torque-generating subspace, harmonic subspaces and zero-sequence subspace. When open-circuit faults occur, the dimension of drive system will be reduced. The orthogonal subspaces will be reconstructed. The principle of VSD based fault tolerant control is presented in Fig.6. The steps are summarized as:

(1) Construct new orthogonal subspaces with remaining dimensions, and decompose physical variables onto new subspaces.

(2) Apply Park transform to convert components on torque-generating subspace into d-axis and q-axis components on synchronous frame.

(3) One linearization matrix, namely $\boldsymbol{C}(\theta)$ is used to convert d-axis and q-axis components into intermediate variables, namely g-axis and h-axis components, in such a way that linear controllers such as PI can be used for current regulation.

(4) The feedforward terms Δu_g and Δu_h are added to output of the closed-loop current controller.

(5) The PR controller could be used to regulate periodic component on z-subspace for various optimization goals.

(6) After converting the components on orthogonal subspaces back to voltage references on natural frame, the multicarrier modulation is adopted to generate switching pulses based on voltage references.

Fig.7 presents the performance of VSD based fault tolerant control. Before fault tolerant control used, the mid-point voltage in DC link suffers from clear oscillation in Fig.7(a). The torque and input power also show clear ripples in their waveforms of Fig.7(b). After using VSD based fault tolerant control, the z-sequence current is controlled as a periodic signal for optimization of minimal current amplitude. The oscillations in mid-point voltage in DC link, torque and input power are mitigated effectively in Fig.7. Fig.8 shows the dynamic performance of VSD based fault tolerant control under open-circuit fault in phase F. The mid-point voltage in DC link is stabilized well except for slight variance due to load changes.

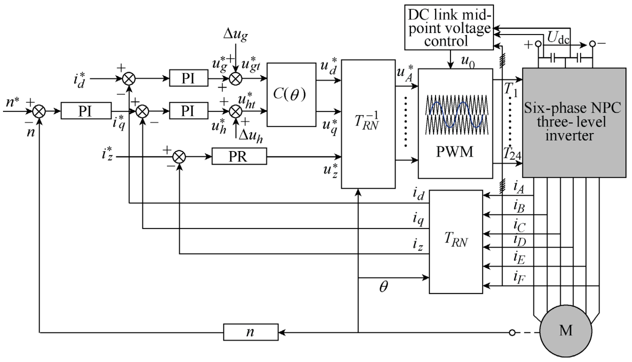
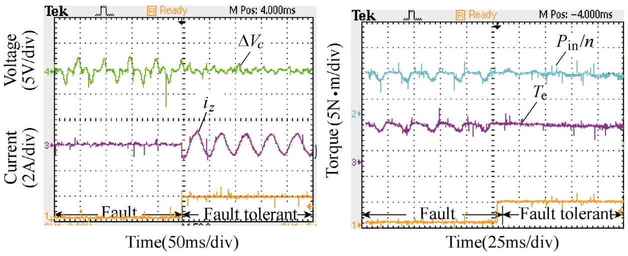
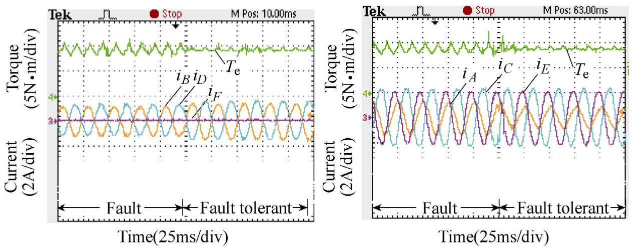


Fig.6 Fault tolerant control of open-phase faults with vector space decomposition

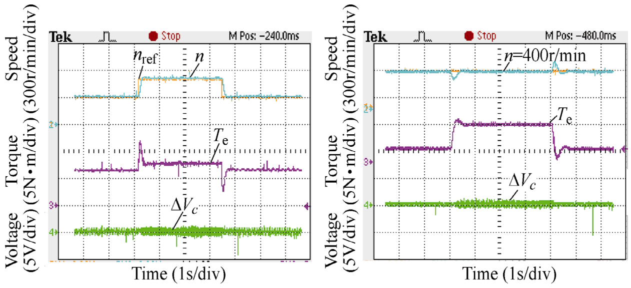


(a) Mid-point voltage of DC link and z-subspace component (b) Input power and output torque



(c) Phase currents in faulty winding (d) Phase currents in healthy winding

Fig.7 Experimental results of DNPC-3L inverters fed asymmetric six-phase PMSM drives with VSD based fault tolerant control



(a) Speed response (b) Torque response

Fig.8 Measured dynamic performance of DNPC-3L inverters fed asymmetric six-phase PMSM drives with VSD based fault tolerant control

2.3 Voltage compensation based control

Different from carrier based modulation, the space vector modulation (SVM) offers merits of digital implementation, high utilization of DC link voltage and well-defined switching status. However, the symmetry of the drive will be lost when open-phase faults occur. The SVM is difficult to be used for unbalanced operation. Recently, a novel remedial strategy is proposed to put voltage compensation on terminal voltages of healthy phase legs while the switching strategy is maintained as before[24]. Hence, the SVM strategy could be used under open-circuit faults. The key is to derive the voltage difference between terminal voltage of the faulty phase under normal condition and the back-EMF of the faulty phase under open-circuit fault. Then, the voltage difference will be compensated purposely by other healthy phases. As shown in Fig.9, phase F falls in open-circuit fault. The terminal voltage of phase F under normal condition is u_F, and the induced voltage of the faulty winding is u_ind. Thus, the voltage different Δu_F can be derived by theoretical analysis with mathematical modelling.

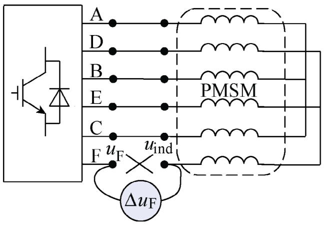


Fig.9 The diagram of open-circuit fault in phase F

Based on mathematical model of asymmetric six-phase PMSM machine, it is derived that the constraints $i_A+i_B+i_C=0$, $i_D+i_E+i_F=0$, $u_A+u_B+u_C=0$ and $u_D+u_E+u_F=0$ are still valid under open-phase faults. Thus, the induced of phase F, u_{ind} is derived as[24]:

$$\begin{aligned} u_F &= -R_s(i_D+i_E)-\frac{d}{dt}(\psi_D+\psi_E) \\ &= -\frac{\sqrt{3}}{3}\left[u_{BC}-R_s(i_B-i_C)-L_{ls}\frac{d}{dt}(i_B-i_C)\right] \end{aligned} \tag{6}$$

The terminal voltages on asymmetric six-phase windings are presented to be:

$$\begin{bmatrix} u_{\alpha 1} \\ u_{\beta 1} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \end{bmatrix} = \begin{bmatrix} \frac{2}{3}u_{AB}+\frac{1}{3}u_{BC} \\ \frac{\sqrt{3}}{3}u_{BC} \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} u_{\alpha 2} \\ u_{\beta 2} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} & 0 \\ \frac{1}{3} & \frac{1}{3} & -\frac{2}{3} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{3}u_{DE} \\ -u_F \end{bmatrix} \tag{8}$$

From Eqs.(7-8), it is observed that the voltages on α-axis are not changed before and after faults. The total voltage on β-axis is $u_\beta=u_{\beta 1}+u_{\beta 2}=2u_{\beta 1}$ under healthy condition. But $u_{\beta 2}$ is changed to be $-u_F$, which is expressed by Eq.(6). To keep the total voltage on β-axis u_β same as that before fault, the voltage reference of $u_{\beta 1}$ of healthy winding has to be modified with voltage compensation, which is expressed to be:

$$\Delta u_{\beta 1}=\frac{\sqrt{3}}{6}\left[R_s(i_B-i_C)+L_{ls}\frac{d}{dt}(i_B-i_C)\right] \tag{9}$$

Fig.10 shows the block diagram of the double SVM based control scheme for TPNC-3L inverter fed asymmetric six-phase PMSM drive. The direct torque control (DTC) is applied based on double SVM[26]. The torque of the two three-phase windings is controlled on α-β subspace as a whole, while the closed-loop control is provided to suppress harmonics on x-y subspace. The voltage compensation derived in Eq.(9) can be added to voltage references for double three-phase SVM. Fig.11 shows the fault tolerant operating performance for open-phase fault in phase F with voltage compensation method. It is observed that the torque ripple deduced from open-phase fault is suppressed effectively after introducing direct voltage compensation. The perturbation on current waveforms and oscillation in mid-point voltage of DC link are slight when the fault tolerant control is put into effect.

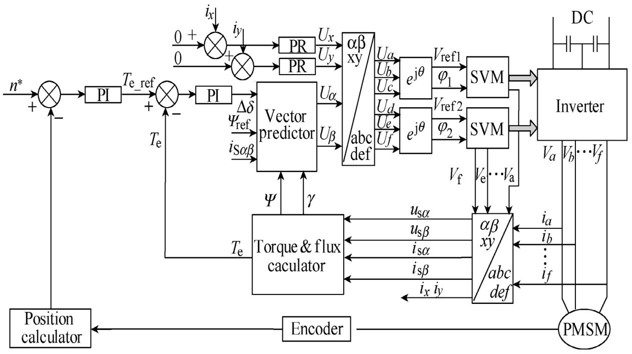
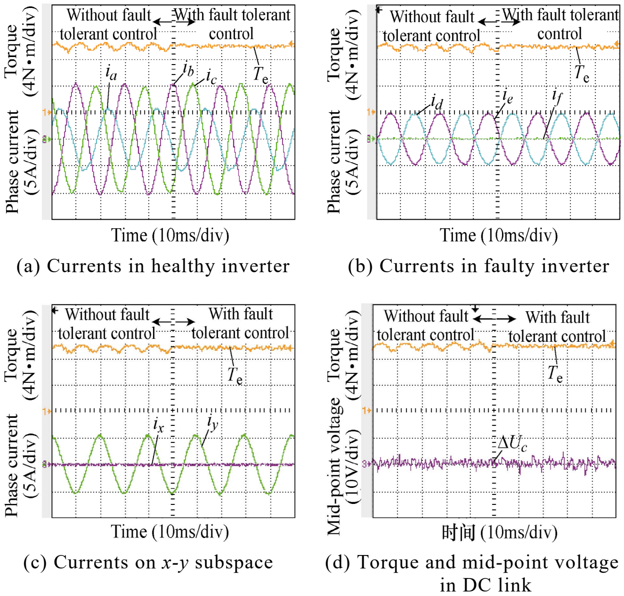


Fig.10 Block diagram of double SVM based control for TNPC-3L inverters fed asymmetric six-phase PMSM drive

In [26], a hybrid fault tolerant control is presented for TNPC-3L inverters fed asymmetric six-phase PMSM drives. As shown in Fig.12, the healthy inverter keeps using DTC operation and SVM strategy to regulate the total torque of drive system, while the faulty inverter uses phase independent control of phase currents for minimum copper loss.



(a) Currents in healthy inverter (b) Currents in faulty inverter

(c) Currents on x-y subspace (d) Torque and mid-point voltage in DC link

Fig.11 Experimental results of TNPC-3L inverters fed asymmetric six-phase PMSM drives with voltage compensation based control under open-phase fault

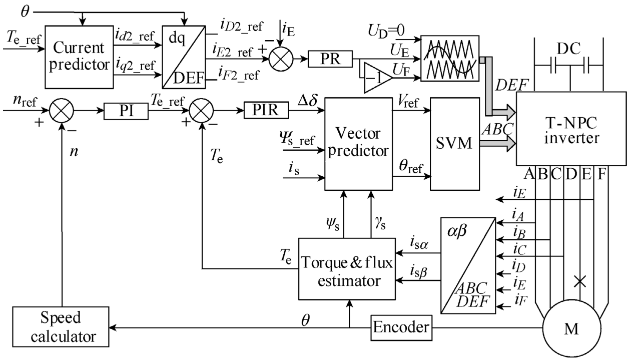


Fig.12 Block diagram of hybrid fault tolerant control for TNPC-3L inverters fed asymmetric six-phase PMSM drive

3 Open-switch faults

As aforementioned, the multilevel inverter has better fault tolerant capability due to redundant voltage vectors. In addition, the multilevel inverter fed multiphase drives have more switching legs and thus more controllability in suppression of mid-point voltage fluctuation in DC link. In this section, remedial strategies for open-switch faults will be presented with TNPC-3L inverter fed asymmetric six PMSM drives.

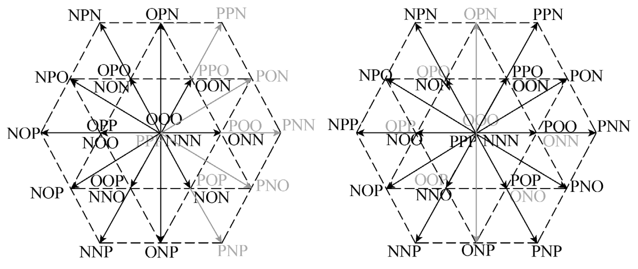
3.1 Remedial strategy based on multiple SVM

When the phase number of drive is multiple of three, the modulation can be achieved with several three-phase SVM. The space vector diagram of three-phase TNPC inverter under open-switch faults are shown in Fig.13. The gray parts represent the missing voltage vectors due to open-switch faults. The remedial strategies are explained by two cases: the open-switch fault occurring in half-bridge switches S_1/S_4 and the open-switch fault occurring in mid-point switches S_2/S_3.

3.1.1 Open-circuit fault in half-bridge switches S_{A1}/S_{A4}

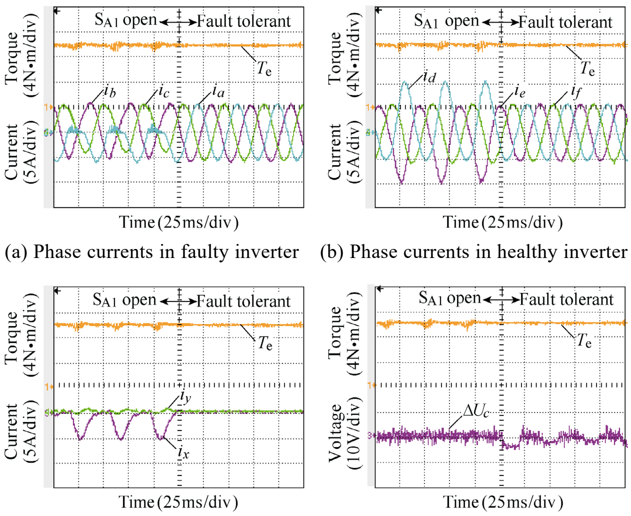
When switch S_{A1} fails, the remaining vectors can not construct a complete large hexagon, as shown in Fig.13(a). Therefore, the modulation index should be reduced to ensure that the voltage reference is located in the inner small hexagon. By this way, symmetric operation is maintained in the drive. The reduction of modulation index could be achieved by slowing down the drive speed. As shown in Fig.13(a), the open-circuit fault in switch S_{A1} will cause loss of positive small voltage vectors. They have to be replaced by negative small voltage vectors. Thus, the faulty inverter may lose the ability in balancing the mid-point voltage in DC link. This issue can not be solved for the three-phase system. Fortunately, the healthy three-phase inverter of the six-phase TNPC-3L system can partly mitigate the fluctuation in mid-point voltage in DC link by using redundant small vectors.

Fig.14 shows the fault tolerant operation when switch S_{A1} fall in open-circuit fault. To reduce modulation index, the motor speed is decreased from rated 1000r/min to 500r/min under 10N·m. After introduction of fault tolerant control, the torque ripple is suppressed, and the phase currents are restored to symmetric states, as shown in Fig.14(a) and (b). The harmonic currents are also mitigated in Fig.14(c). It is observed in Fig.14(d) that the mid-point voltage has slight deviation in every half fundamental period. The reason is due to that the voltage deviation caused by the lost small vectors can not be compensated effectively by the healthy three-phase inverter. On the other hand, the mid-point voltage fluctuation is smaller even without using fault tolerant control. The reason lies in that the lost small vector could be forced to another small vector, which still benefits balancing mid-point voltage fluctuations. For example, the original action of the lost small vector POP will be taken by the small vector OOP, as shown in Fig.13(a).



(a) Faults in switch S_{A1} (b) Faults in switch S_{A2}/S_{A3}

Fig.13 Space vector diagram of open-switch faults in TPNC-3L inverter:



(a) Phase currents in faulty inverter (b) Phase currents in healthy inverter

(c) Harmonic currents (d) Mid-point voltage in DC link

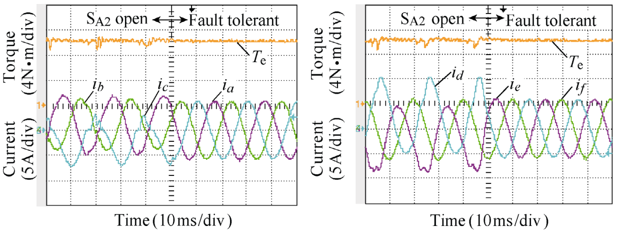
Fig.14 Experimental results with remedial strategy under open-circuit fault in switch S_{A1}

3.1.2 Open-circuit fault in mid-point switches S_{A2}/S_{A3}

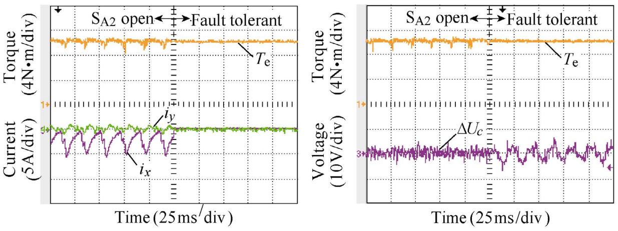
When the switch S_{A2} or S_{A3} fails, the loss of voltage level O in phase A will cause loss of two middle vectors (OPN and ONP) and six small vectors (OPO, OPP, OOP, ONO, ONN and OON), as shown in Fig.13(b). Two remedial strategies are available for open-switch fault in S_{A2}/S_{A3}[27]. The first strategy synthesizes the lost middle voltage vectors by two closest large vectors. For example, the lost middle vector OPN is synthesized by NPN and PPN. The lost small vectors will be replaced by the remaining redundant small vectors. Due to loss of small voltage vectors, the balance of mid-point voltage in DC link completely depends on the compensation from the other healthy three-phase inverter. So, the balance ability is limited.

The second strategy is to use the voltage level P and N to synthesize the lost voltage level O for both middle vectors and small vectors. For instance, the lost small vector OOP is synthesized by POP and NOP. The POP can collaborate with NNO to balance the mid-point voltage fluctuation. Thus, the second strategy has better controllability of mid-point voltage in DC link. But the voltage shift between P level and N level occurs more frequently than the first strategy, which will cause relatively larger current harmonics than the first strategy.

Fig.15 and Fig.16 show the performance of two remedial strategies for switch S_{A2} open-fault. Both of them can guarantee sinusoidal and symmetric phase currents. The THD of phase-A current with the first strategy is 3.51% and that value with the second strategy is 3.94%. It verifies that better current quality can be obtained by the first strategy. As shown in Fig.15(d), a slight pulsation appears in the mid-point voltage due to the insufficient compensation only with remaining small voltage vectors in the first strategy. On the other hand, the fluctuation in mid-point voltage is suppressed effectively with the second fault tolerant scheme by using P and N voltage levels to synthesize the lost O level in small voltage vectors.

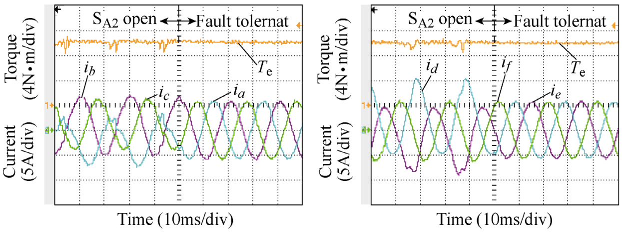


(a) Phase currents in faulty inverter (b) Phase currents in healthy inverter

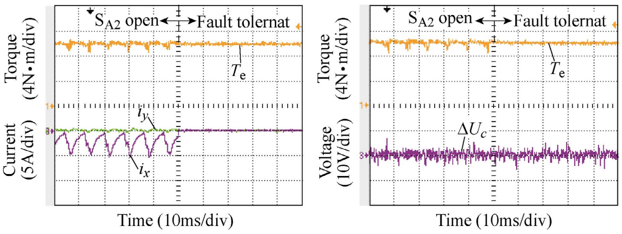


(c) Harmonic currents (d) Mid-point voltage deviation in DC link

Fig.15 Experimental results of the first remedial strategy under switch S_{A2} fault



(a) Phase currents in faulty inverter (b) Phase currents in healthy inverter



(c) Harmonic currents (d) Mid-point voltage deviation in DC link

Fig.16 Experimental results of the second remedial strategy under switch S_{A2} fault

3.2 Remedial strategy based on VSD-SVM

When the phase number of drive is an arbitrary value not multiples of three, the multiple three-phase SVM scheme can not work. The VSD-SVM based remedial strategy has to be applied.

3.2.1 Open-circuit fault in half-bridge switches S_{A1}/S_{A4}

When switch S_{A1} falls in open-circuit fault, the voltage level P of faulty leg A is lost. The remaining voltage vectors are shown in Fig.17, where the gray parts represent lost vectors[24]. The vectors in the right half of the space vector diagram are almost all lost. Since the lost vectors can not be replaced or synthesized by remaining vectors, new space vector diagram under faulty conditions are required.

The six-phase voltage vector can be regarded as combination of two three-phase voltage vectors. For instance, the six-phase vector PPOPOO is the combination of small voltage vector PPO of phase ABC and small voltage vector POO of phase DEF. Based on the following principles, the primitive vectors are selected as shown in Fig.18.

(1) No voltage level transition between P and N in a single switching period.

(2) Full utilization of DC link voltage.

(3) The average volt-seconds of voltage vectors on *x*-*y* subspace zero.

As Fig.18 shows, the vectors of group L_1 and L_2 with same directions on α-β subspace are with opposite directions on *x*-*y* subspace. The proposed fault-tolerant control scheme adopts the two-step vector synthesis approach[26]. In the first step, the

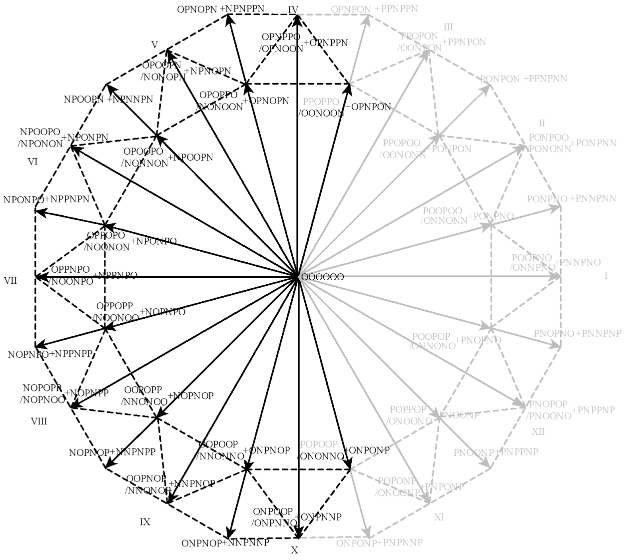
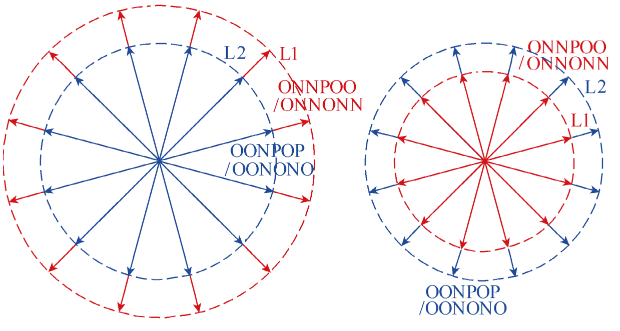


Fig.17 Remaining voltage vectors of TNPC-3L six-phase inverter under open-circuit fault of S_{A1}



(a) α-β subspace (b) *x*-*y* subspace

Fig.18 Selected voltage vectors

vectors with the same direction on α-β subspace of L_1 and L_2, are selected to compose the new harmonic-free vectors L_{12}, as shown in Fig.19. Twelve sectors are divided based on new synthesized vectors. The maximum voltage utilization ratio of the fault-tolerant SVM scheme is $0.2887U_{dc}$ for linear modulation, which is half of that under normal state.

The second step is to select two harmonic-free vectors to compose the reference voltage vector based on sector location and mid-point voltage in DC link. Since some positive small voltage vectors are lost, the redundant negative small vectors have to be used. But the performance will become worse in balancing DC link mid-point voltage. For instance, if the reference voltage is located in sector V and the mid-point voltage of DC link is lower than $U_{dc}/2$, primitive vectors OPOPPO, OONOPO, OPOOPO and NOOPPO participate in the synthesis process, as shown in Fig.19. For the second primary vector OONOPO, the redundant negative small voltage vector OON has to be used to replace the lost positive small vector PPO due to fault of S_{A1}. Then, in the fourth primary vector NOOPPO, the three-phase vector NOO is used instead of OPP, in such a way that the voltage level transition between P and N is avoided in phase C within a single switching period.

Fig.20 shows the performance of remedial strategy for S_{A1} open-switch fault. After use of fault tolerant control, the torque ripple is eliminated, and the phase currents are almost restored to normal state. The harmonic currents are mitigated in Fig.20(c). It should be noted that the mid-point voltage has slight deviation in every half fundamental period. The reason is due to that the lost favorable small voltage vectors for stabilizing DC capacitor voltages have to be replaced by undesired ones. On the other hand, the mid-point voltage fluctuation is smaller even without using fault tolerant control in Fig.20(d). The reason lies in that the lost small vector could be forced to another small vector, which still benefits balancing mid-point voltage fluctuations.

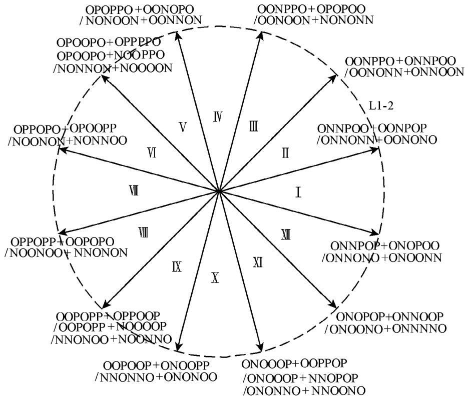
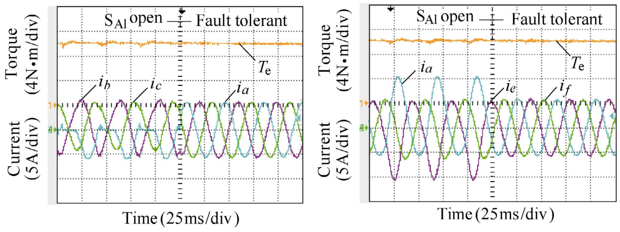
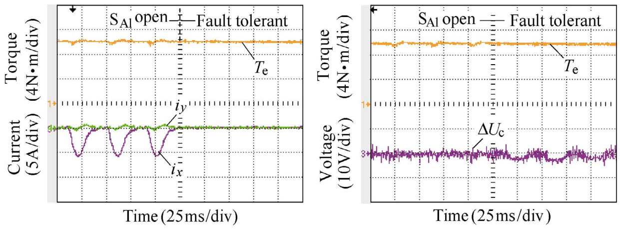


Fig.19 Harmonic-free vectors on α-β subspace



(a) Currents in faulty inverter (b) Currents in healthy inverter



(c) Harmonic currents (d) Mid-point voltage in DC link

Fig.20 Experimental results with VSD-SVM based remedial strategy for TNPC-3L inverters fed asymmetric six-phase drives under open-circuit fault in S_{A1}

3.2.2 Open-circuit fault in mid-point switches S_{A2}/S_{A3}

When switch S_{A2}/S_{A3} fails, the voltage level O of phase A is lost. The remaining voltage vectors are shown in Fig.21, where the gray parts represent the lost vectors. It is found that the vectors on sectors IV and X are all impossible. Different from selecting the primary vectors within the remaining voltage vectors, a fault-tolerant control scheme is designed only for faulty phase[26]. Based on the volt-second balancing principle, the dwelling time of lost voltage level O in faulty phase is distributed to level P and level N equally. The lost vector OXXXXX is actually synthesized by PXXXXX and NXXXXX. For instance, the lost vector OPNPON is synthesized by voltage vectors PPNPON and NPNPON. By using this fault-tolerant control, the drive system can achieve the performance under normal state. But there will be slight increase of harmonics due to the voltage transition between P voltage level and N voltage level of the faulty phase voltage in one switching period.

Fig.22 shows the performance of the remedial strategy for open-circuit fault in S_{A2} of TNPC-3L inverters fed asymmetric six-phase PMSM drives. Sinusoidal and symmetric phase currents are provided with the fault tolerant control scheme in Fig.22(a) and Fig.22(b). The harmonic currents are suppressed effectively in Fig.22(c). Furthermore, the mid-point voltage in DC link is controlled well in Fig.22(d).

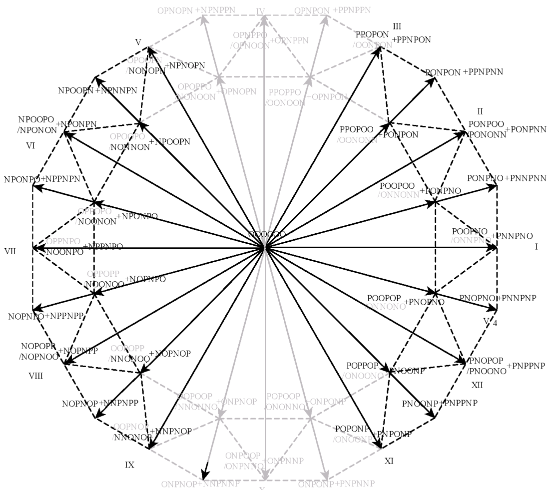
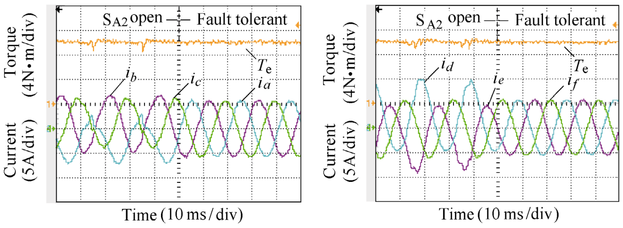
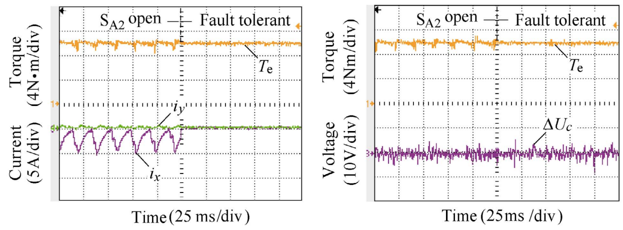


Fig.21 Remaining voltage vectors of TNPC-3L six-phase inverter under open-circuit fault of S_{A2}/S_{A3}



(a) Currents in faulty inverter (b) Currents in healthy inverter



(c) Harmonic currents (d) Mid-point voltage in DC link

Fig.22 Experimental results with VSD-SVM based remedial strategy for TNPC-3L inverters fed asymmetric six-phase drives under open-circuit fault in S_{A2}

4 Further discussion

4.1 Multiple-switch faults

When multiple switches fall in open-circuit faults, more voltage vectors will be lost in multiphase multilevel motor drives, which brings more challenges in reconstructing symmetrical voltage trajectories and controlling mid-point voltage in DC link. Thus, the corresponding remedial strategies will be classified according to severities of faults. The countermeasures include using P and N voltage levels to synthesize the missing O voltage levels, reducing modulation index, adopting remaining redundant small voltage vectors for control of mid-point voltage, using medium voltage vectors to synthesize missing small voltage vectors and removal of faulty phase legs as well as the total three-phase inverter channel.

4.2 Short-circuit faults in switches

When short-circuit faults occur in switches, some voltage levels have to be prohibited to avoid short-circuit faults in phase legs. For example, short-circuit in mid-point switches S_2 or S_3 of TNPC-3L inverter will force this phase leg to be with O voltage level, and both P voltage level and N voltage level have to be prohibited. This condition is actually converted to the open-circuit faults in S_1 and S_4. Thus, the remedial strategies for multiple open-switch faults can be used. When short-circuit faults occur in S_1 or S_4, O voltage level has to be prohibited together with P or N voltage level. This phase leg must be removed from the system, and this condition is converted to open-phase fault.

4.3 Simultaneous fault of switches and phase legs

When switch faults and open-phase faults occur simultaneously in multiphase multilevel motor drives, the conditions become very complex. One possible solution of remedial operation is to use voltage compensation control in section 2.3 to generate voltage compensation on healthy windings, in such a way that torque oscillation caused by open-phase faults is mitigated and analysis of space vector diagram for switch faults in section 3 can be maintained. The other solution is to adopt the idea in section 3.2 to reconstruct primary voltage vectors available after removal of faulty phase leg.

The details of fault tolerant control on multiple-switch faults, short-circuit faults in switches and simultaneous faults of switches and phase legs will be presented in another paper of authors to be published.

5 Conclusion

A technical review has been presented for fault tolerant control schemes of multiphase multilevel motor drives in this paper. The suppression of torque oscillation, avoidance of distorted currents and stabilization of mid-point voltage in DC link become main challenges in operation. When some phase legs are removed from the drive system due to open-circuit faults or short-circuit faults, the windings must stand asymmetric phase currents in the drives to mitigate the possible torque oscillation. The phase-independent control, the VSD control and the voltage compensation control are discussed for phase-leg faults in detail. For open-circuit faults in switches, the remedial strategies are designed with multiple SVM and VSD-SVM, which are suitable for multiphase drives with phase number multiple of three and arbitrary value, respectively. Finally, the forecast of remedial strategies for multiple-switch faults, short-circuit switch faults and switch-leg hybrid faults are presented. The principles, implementation procedures and experimental verification are provided.

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Zheng Wang (S’05–M’09-SM’14) received the B.Eng. and M.Eng. degrees from Southeast University, Nanjing, China, in 2000 and 2003, respectively, and the Ph.D. degree from The University of Hong Kong, Hong Kong, in 2008, all in electrical engineering.

From 2008 to 2009, he was a Post-doctoral Fellow in Ryerson University, Toronto, ON, Canada. He is currently a full Professor in the School of Electrical Engineering, Southeast University, China. His research interests include electric drives, renewable power and distributed generation. He has authored or coauthored over 80 internationally refereed papers and four books in these areas.

Prof. Wang received several academic awards including IEEE PES Chapter Outstanding Engineer Award, Best Paper Award of International Conference on Electrical Machines and Systems (ICMES), Best Session Paper Award of IEEE Annual Meeting of Industrial Electronics (IECON), and Science and Technology Award of Jiangsu Province of China. He is an editor of Journal of Power Electronics.

Xueqing Wang (S’16) received the B.S. degree from Tianjin University of Science and Technology, Tianjin, China, and the M.S. degree from Southeast University, Nanjing, China, in 2014 and 2016, respectively, both in electrical engineering. He is currently working toward the Ph.D. degree in electrical engineering at Southeast University, Nanjing, China. His research interests include multilevel PWM strategy and control of multiphase permanent magnet synchronous motor.

Yibo Wang received the B.S. degree in electrical engineering from Southeast University, Nanjing, China, in 2015. He is currently working toward the M.S. degree in Southeast University, Nanjing, China. His research interests include multilevel converter, multilevel PWM strategy, control of multiphase permanent magnet synchronous motor, and fault tolerant control of multiphase motor.

Jian Chen received the B.S. degree from Anhui University of Science & Technology, Huainan, China, in 2013, and the M.S degree from Southeast University, Nanjing, China, in 2016, all in electrical engineering. He is an electrical engineer with the Shenzhen Inovance Technology Co., LTD., where he works on R&D low voltage drives system.

Ming Cheng (M’01–SM’02-F’15) received the B.Sc. and M. Sc. degrees from the Department of Electrical Engineering, Southeast University, Nanjing, China, in 1982 and 1987, respectively, and the Ph. D. degree from the Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong, in 2001, all in electrical engineering.

Since 1987, he has been with Southeast University, where he is currently a Distinguished Professor at the School of Electrical Engineering and the Director of the Research Center for Wind Power Generation. From January to April 2011, he was a Visiting Professor with the Wisconsin Electric Machine and Power Electronics Consortium, University of Wisconsin, Madison, WI, USA. His teaching and research interests include electrical machines, motor drives for EV, and renewable energy generation. He has authored or co-authored more than 300 technical papers and four books, and is the holder of 70 patents in these areas.

Prof. Cheng is a Fellow of the Institution of Engineering and Technology. He has served as the Chair and an Organizing Committee Member for many international conferences. He is a Distinguished Lecturer of the IEEE Industry Applications Society for 2015/2016.