Fault Tolerant Power Converter Topologies for PMSM Drives in Aerospace Applications

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Abstract

This paper proposes two fault tolerant power converter permanent magnet synchronous motor (PMSM) drive topologies. A reconfigured conventional DC link/two-level VSI converter and a reconfigured conventional matrix converter are presented to improve the reliability of the drive system under open phase fault operating condition. Additional phase redundancy and its control technique are included. Simulation and experimental results are shown to verify the effectiveness of the proposed topologies.

Introduction

Permanent magnet synchronous machines are increasingly considered the best choice of machine in several applications due to their high power density and high efficiency [1]. However, fault tolerance is an essential requirement for these machines especially if used in critical applications where any types of fault would lead to disastrous effects on safety and system performance. In applications, such as aerospace applications, reliability is extremely important, therefore a fault tolerant system must be able to keep the minimum functionality in order to operate even under fault conditions. A reliability comparison of different power converter topologies suitable for aerospace applications has been presented in [2]. The power converter motor drive performance plays an important role in safety critical systems since many potential faults such as winding open-circuit, winding short-circuit, inverter switch open-circuit and inverter switch short-circuit may occur in the motor and the power converter respectively. Therefore, in order to provide fault tolerant motor drive topologies and to improve the system reliability, the proposed drive topologies must be able to operate even in the presence of fault conditions.

In recent years a great deal of research has been done on the development of fault tolerant ac drive systems. For example in [3], fault compensation strategies for PWM-VSI configurations used in induction motor drives are presented in order to provide compensation for open-circuit and short-circuit failures in the power converter devices. In addition, multiphase machines are employed under fault operating conditions as described in [4, 5]. The advantage of multiphase machines over three-phase machines is that the motor can still operate properly after a fault occurs in one or more phases due to the remaining healthy phases. However, an appropriate machine design is necessary for fault tolerant motor drive systems. A comparison of fault tolerant three phase ac motor drive topologies, where proposed solutions and changes are implemented in the drive topologies in the presence of faults occurring in the inverter, has been demonstrated in [6]. A four phase matrix converter based motor drive has been considered for electric vehicles and propulsion systems [7] to avoid open-circuit and short-circuit failures on the converter side by developing a switching function matrix.

In this paper only open phase failures in the PMSM are considered. The following section introduces two different types of power converter drive topologies, used to improve the drive system reliability and performance under fault condition. A 4 phase, two-level voltage source inverter (VSI), connected to a six-pulse rectifier via a dc-link capacitor, and a 4 phase matrix converter have been considered to implement the proposed fault tolerant drives. The proposed fault tolerant drives are based on a modification of the conventional power converter topologies by connecting the motor neutral to the fourth output phase of each converter. The fault tolerant control strategy has been modified to maintain the same motor performance as before the open phase failure. Simulation results for the proposed fault tolerant PMSM drive topologies are presented in the following sections in order to illustrate the performance of the system under open phase fault conditions. The initial experimental results are shown to validate the simulation results and to demonstrate the effectiveness of the proposed fault tolerant power converter topologies.

Fault Tolerant PMSM Drive Topologies

The simulated modified two-level VSI and matrix converter configurations, with an additional output phase connected to the neutral point of the PMSM, are shown in Fig. 1 and Fig. 2, respectively. In normal operating conditions the triac shown in Fig. 1 is turned off as well as no gating signals are sent

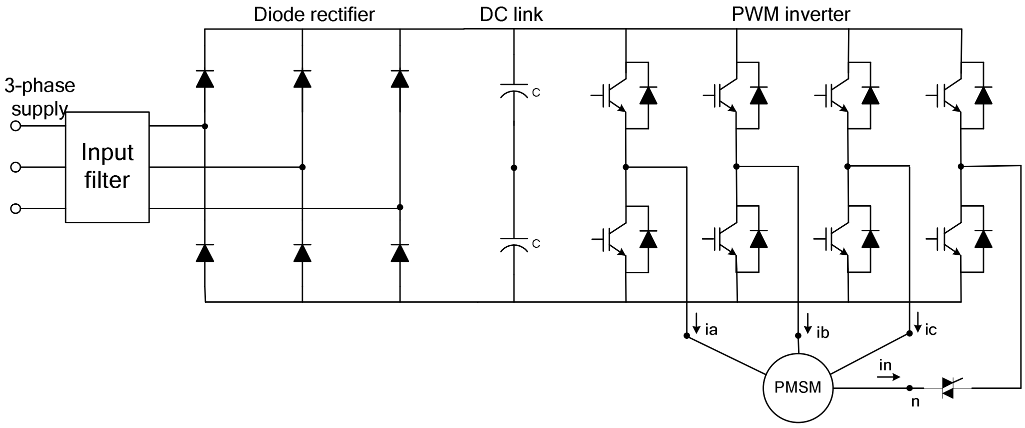


Fig.1: Fault tolerant two-level VSI motor drive configuration

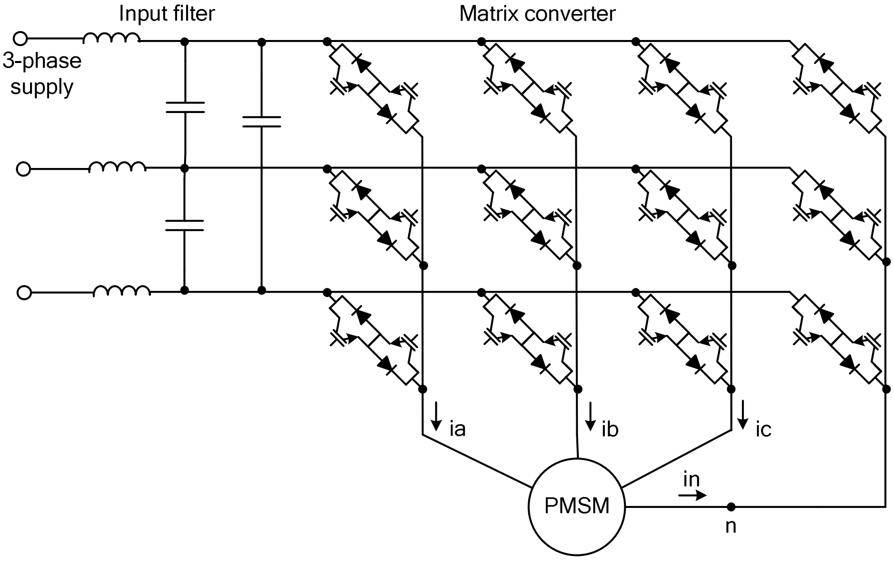


Fig.2: Fault tolerant matrix converter motor drive configuration

to the fourth leg of both configurations. Therefore the power converters will operate as conventional three-output phase converters.

In the case of an open phase fault occurring in the machine, the triac is immediately forced to turn on connecting the motor neutral to the fourth output phase of the two-level VSI as shown in Fig. 3. With the inherent characteristic of the bidirectional switch configuration used in the matrix converter topology, the motor neutral will be suddenly connected to the redundant output phase when the gating signals are transmitted to this output phase without the need for a triac. The fault tolerant configuration of the matrix converter after open phase failure is presented in Fig. 4. In order to allow the motor to operate properly in fault mode and maintain the same satisfactory performance as in normal operating condition, the fourth output phase of the two-level VSI and the matrix converter are both connected to the neutral point of the machine and are driven by the gate signals which were previously gating the power devices in the faulty phase.

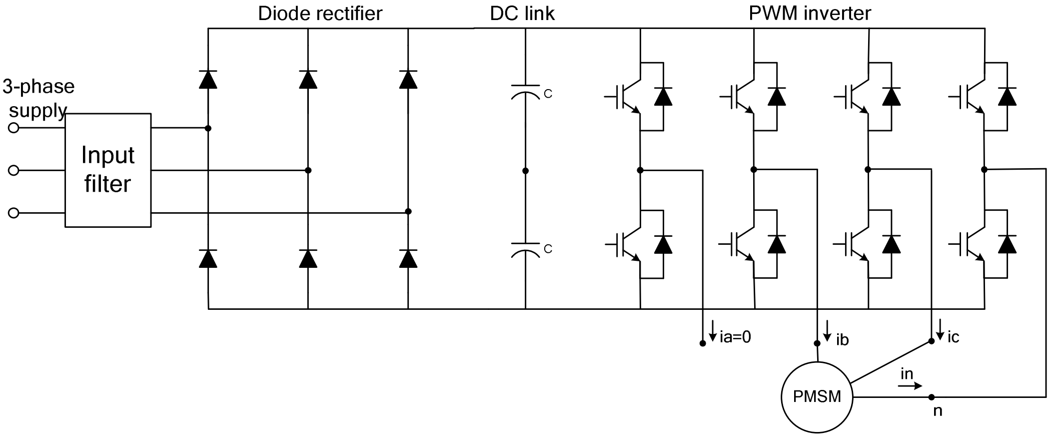


Fig.3: Post-fault tolerant two-level VSI motor drive configuration

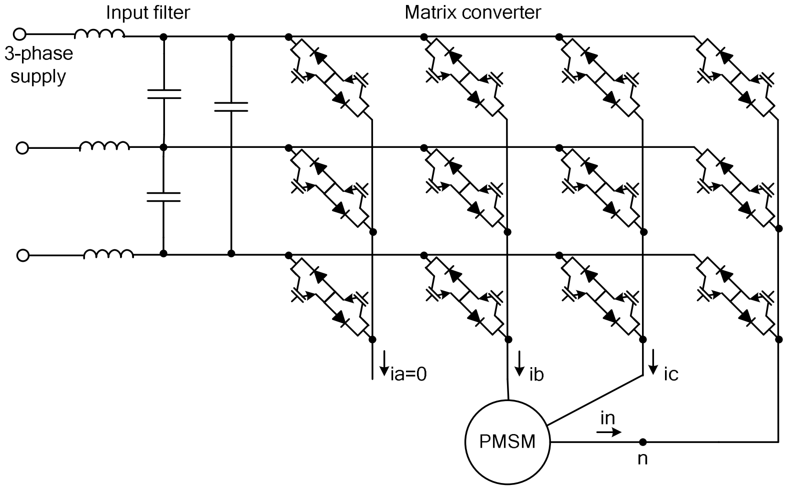


Fig.4: Post-fault tolerant matrix converter motor drive configuration

Motor Drive Modified Control Strategy Under Fault Operating Conditions

Fig. 5 shows the block diagram of the machine speed control structure when a fault occurs in phase ‘a’. In this case the current in phase ‘a’ will be zero whereas the motor neutral current will circulate in the fourth leg of the converter. The reference voltages for the reconfigured power converter topologies are generated by including torque compensation terms in order to reduce the torque ripple generated by the unbalanced remaining phase currents.

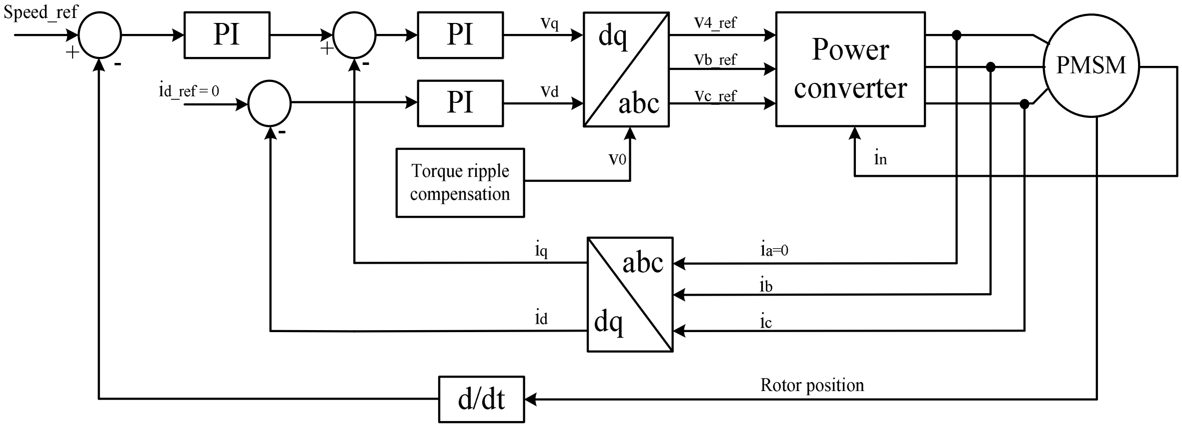


Fig. 5: PI controller structure after fault occurrence in phase ‘a’

During normal operating condition, a PI controller is implemented to generate the output reference voltages according to the modulation strategy selected for the proposed fault tolerant power converter topologies. Regular sampling modulation technique was used for the modified two level VSI and the space vector modulation technique was implemented in the modified matrix converter topology. The motor stator currents can be obtained from Park’s transformation as expressed in equation (1), where i_d and i_q are the stator currents in the synchronous reference frame and θ is electrical rotor angular position. A zero-sequence component of the stator current, i_0 , is defined in equation (2).

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} \tag{1}$$

$$i_0 = \frac{1}{3}(i_a + i_b + i_c) \tag{2}$$

When the power converters operate in normal condition the balanced three-phase stator currents can be generated. In addition, due to no connection between the motor neutral and the fourth phase of converters, i_0 is always zero while the stator currents can be written as shown in equations (3) to (5).

$$i_a = i_q \cos\theta + i_d \sin\theta \tag{3}$$

$$i_b = i_q \cos(\theta - 2\pi/3) + i_d \sin(\theta - 2\pi/3) \tag{4}$$

$$i_c = i_q \cos(\theta + 2\pi/3) + i_d \sin(\theta + 2\pi/3) \tag{5}$$

Under open phase failure, the faulty phase current suddenly drops to zero leading to unbalance in the remaining phase currents. As the motor neutral point is connected to the fourth output phase of the power converter, the stator zero-sequence current component can flow from the neutral point to the power converter drive. From equation (1) if a failure occurs in ‘a’ that means $i_a = 0$. Therefore, the stator zero-sequence current component (i_0) is obtained by equation (6) while the neutral current is $3i_0$.

$$i_0 = -(i_q \cos\theta + i_d \sin\theta) \tag{6}$$

The two remaining phase currents can be derived by substituting i_0 in equation (1) as represented in equation (7) and (8), respectively. In order to maintain the motor operation under fault mode, the remaining phase currents have to increase in magnitude by a factor of $\sqrt{3}$ as well as phase shifted 30 degrees away from the faulted phase compared to the currents under normal operating condition.

$$i_b = \sqrt{3}i_q \cos(\theta - {}^{5\pi}\!/_{6}) + \sqrt{3}i_d \sin(\theta - {}^{5\pi}\!/_{6}) \tag{7}$$

$$i_c = \sqrt{3}i_q \cos(\theta + {}^{5\pi}\!/_{6}) + \sqrt{3}i_d \sin(\theta + {}^{5\pi}\!/_{6}) \tag{8}$$

However, the unbalanced phase currents resulting from an open phase failure lead to torque pulsations in the machine. In order to maintain the same motor drive performance, a torque compensation technique is employed to reduce the torque ripple. Fig. 5 shows the torque ripple compensation block, developed by analyzing the stator zero-sequence voltage component of the motor. This component is then used in the dq to abc transformation to generate the appropriate motor currents which will reduce the torque ripple. The motor voltage equations can be expressed as equations (9) to (11).

$$V_d = R_s i_d - L_q i_q \omega_e + L_d \frac{di_d}{dt} \tag{9}$$

$$V_q = R_s i_q + \omega_e \lambda + L_d i_d \omega_e + L_q \frac{di_q}{dt} \tag{10}$$

$$V_o = R_s i_o + L_{ls} \frac{di_o}{dt} \tag{11}$$

Where, R_s is the stator resistance, L_d and L_q are d- and q-axis stator inductance, L_{ls} is the linkage inductance, λ is the peak flux linkage and ω_e is the electrical angular velocity. The torque compensation term can be achieved by replacing equation (6) in equation (11) as indicated in equation (12).

$$V_o = \left(L_{ls}\omega_e i_q - R_s i_d\right)\sin\theta - \left(L_{ls}\omega_e i_d + R_s i_q\right)\cos\theta \tag{12}$$

Simulation Results

The simulation of the PMSM drive systems, described earlier in the paper, has been carried out using SABER. Fig. 6 and Fig. 7, respectively show the simulation results when a fault in phase ‘a’ occurs in the machine at t = 0.35s in both the two-level VSI and the matrix converter topologies. The PMSM operates at a speed of 1000 rpm with a 10 Nm torque applied to the motor. After the fault occurs, the fourth phase of both power converters is connected to the motor neutral immediately. As already mentioned the two unbalanced remaining currents will generate considerable torque pulsations in the drives especially at higher speed as the results can show. At t=0.4s the torque compensation term is added to the control reducing to a safe margin the torque pulsations, resulting in better performance of the drives.

In addition, it is seen that the transformed currents i_q and i_d remain unchanged due to the presence of the stator zero-sequence current component flown from the motor neutral point as shown in equation

(6). To regulate the stator zero-sequence current in order to provide the unchanged i_q and i_d, the amplitude of the two remaining stator currents i_b and i_c has to increase of approximately $\sqrt{3}$ times of that under normal operating condition. Also a 60 degrees phase shift between the currents should be considered as it can be derived from equations (7) and (8). The results highlight how the proposed motor drive configurations and modified motor control strategy allow both systems to continue to operate under a fault condition without affecting their performance.

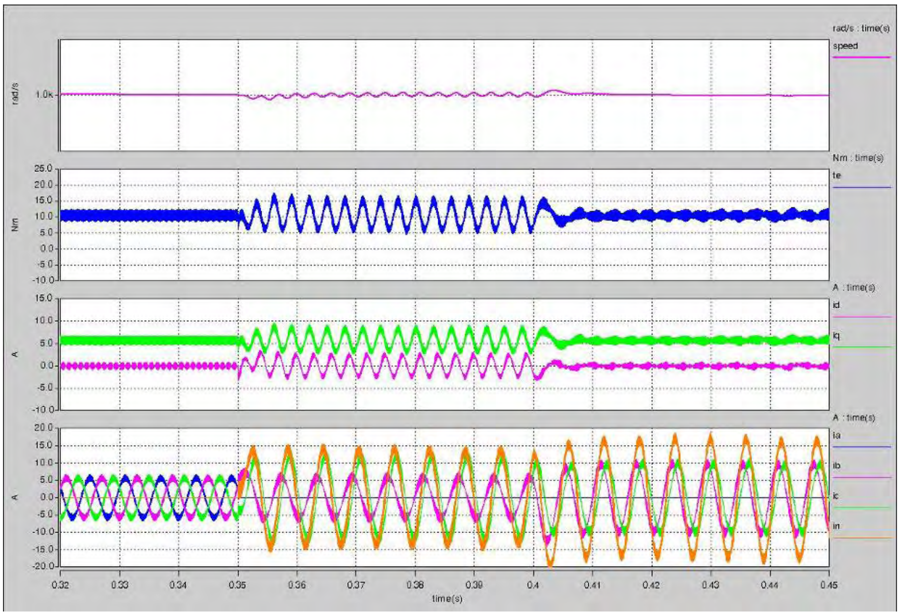


Fig. 6 Two-level VSI PMSM drive system: Torque pulsations at t=0.35s and compensation term added at t=0.4s

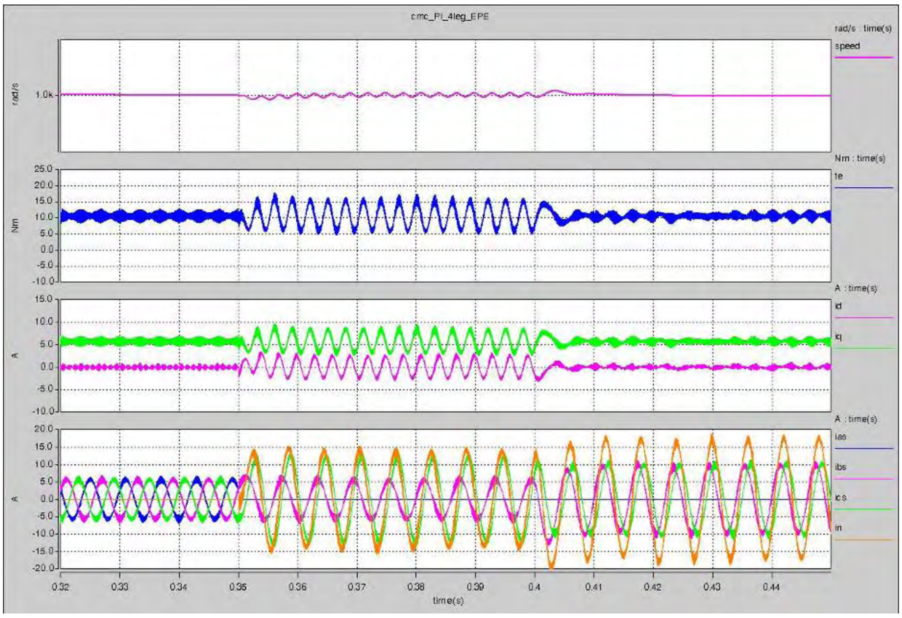


Fig. 7 Matrix converter PMSM drive system: Torque pulsations at t=0.35s and compensation term added at t=0.4s

Experimental Results

To validate the effectiveness of the proposed fault tolerant power converter topologies, the laboratory prototypes have been implemented to drive the PMSM under both normal and fault operating conditions and they are shown in Fig 8. A three phase diode bridge/DC link/six phase VSI [8,9] can be seen in Fig 8.(a) where only four phases are used in this application. Fig.8 (b) shows the prototype of a 7.5-kW four-phase matrix converter which has been constructed using common emitter bidirectional switches. The small input filter capacitors are employed to attenuate the switching harmonic for input power quality requirements. The current direction detection circuits are also included on the board for the four step current commutation. The controller was composed of the digital signal processor (DSP) and the field programmable gate array (FPGA), a Texas Instruments TMS320C6713 floating-point digital signal processor and Actel ProAsic3 FPGA respectively. A three phase 20 pole PMSM rated at 1140 rpm and 17A rms is used for the experimental set up which employs the proposed fault tolerant power converter topologies. For the tests described in this paper, the torque compensation terms have not been included. Further testing is due to be completed soon.

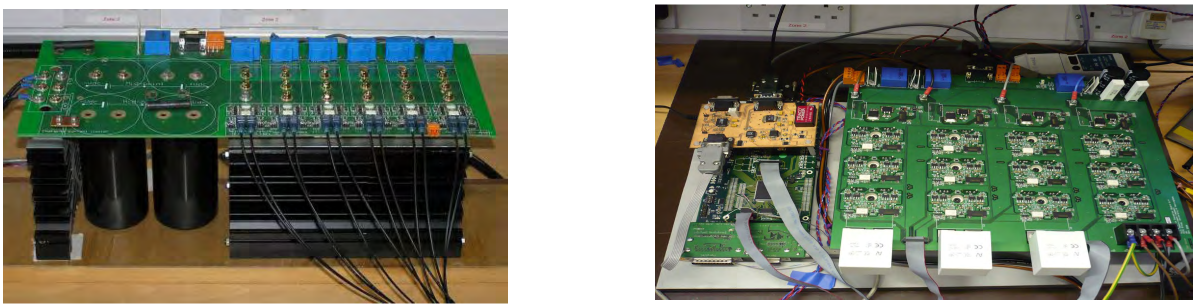


Fig.8: Laboratory prototypes (a) two-level VSI (b) 4 phase matrix converter

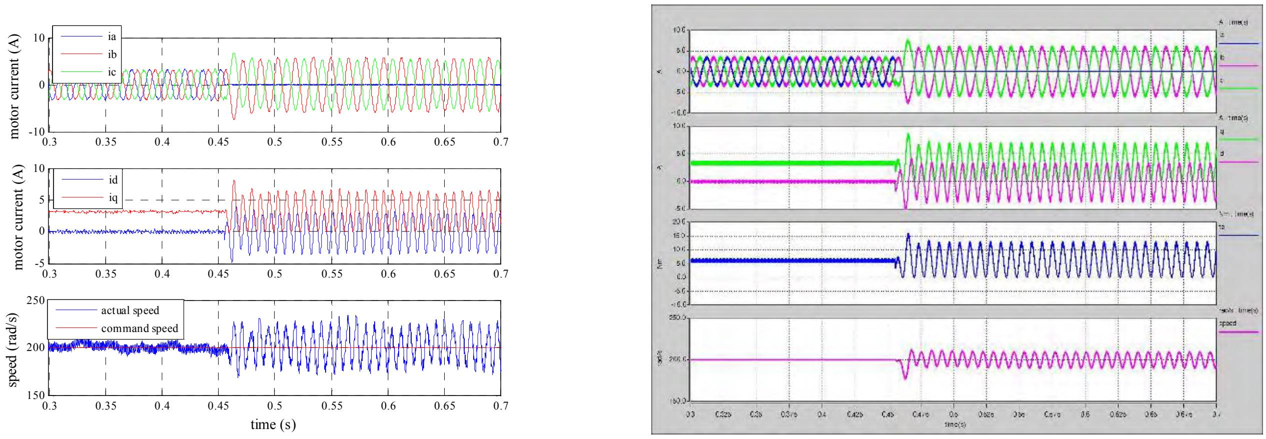
Fig. 9 (a) shows the performance of the PMSM driven by the two-level VSI. A torque load of 6 Nm is applied to the PMSM at t = 0.2s while the controller set the speed demand at 200rad/s. Under normal operating condition the two-level VSI operates as a conventional three phase inverter. The controller can regulate the currents id and iq during normal operating condition resulting in the balanced three phase output currents at the demanded speed. At t=0.45s phase 'a' of the PMSM is opened using a bidirectional switch. For this test the motor neutral is not driven with the forth phase of the inverter.

Fig. 9 (a) shows how the phase current ia suddenly drops to zero while the amplitude of the two remaining phase currents increase and they are shifted by 180 degrees with respect to each other. Moreover, the PMSM operates with speed pulsation because the controller cannot regulate the currents id and iq. The iq oscillation is directly connected to the torque ripple observed.

Using the simulation model of the VSI topology described in the previous section, in order to validate the model and the simulation analysis, the conditions and parameters used in the experimental set up have been simulated to reproduce the same results presented in Fig 9 (a). This has been achieved and shown in Fig. 9 (b)

Fig. 10 (a) presents the experimental results of the 7.5 kW matrix converter driving the PMSM under normal and faulty operating conditions. In this case, the PMSM is operated at 100 rad/s with a 7 Nm applied load torque. Under normal operating condition, the results show that the matrix converter can drive the PMSM according to the implemented vector control. At t = 0.86s, phase 'a' of the machine is opened and the motor neutral is connected to the fourth output phase of the matrix converter. The results show that at the demanded speed, the PMSM can continue to operate with little disturbance on the torque producing current, 'iq', therefore with very similar performance as before the fault occurs. The output phase current 'ia' goes to zero and at the same time the neutral current 'in' starts conducting in the machine and it is equal to the sum of the two remaining phase currents. The amplitude of the two remaining phase currents increases by about $\sqrt{3}$ compared to the same phase currents under normal operating mode and they present a phase shift of 60 degrees between each other. At t=1.1s , phase ‘a’ is connected again and the normal operating condition are restored.

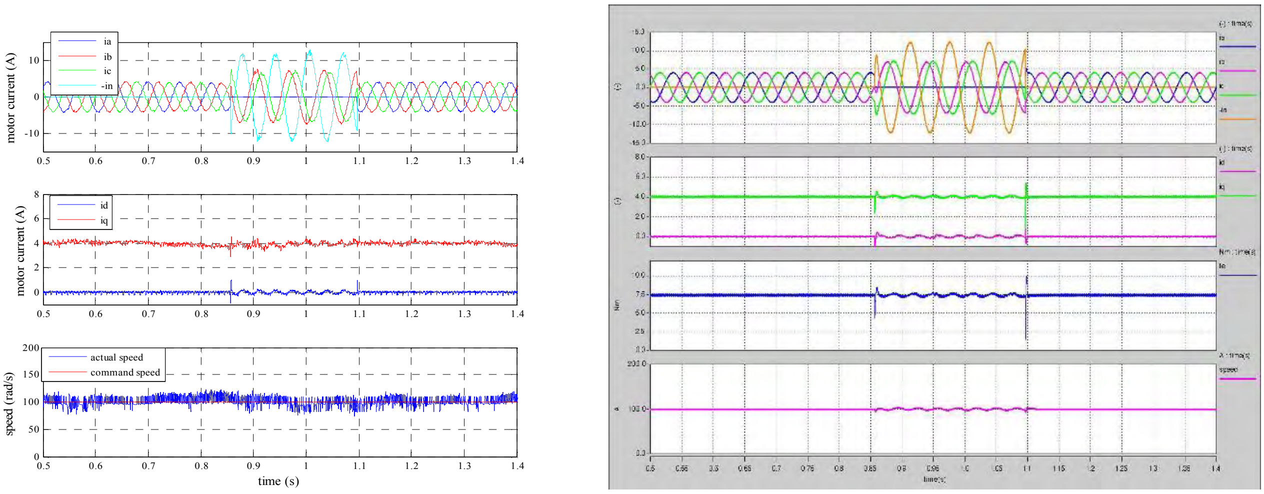
The experimental results shown in Fig.10 (a) have been used also in this case to validate the simulation analysis of the PMSM driven by a 4 phase matrix converter. The simulation results of the same experimental set up are presented in Fig.10 (b).



(a) Experimental results

(b) Simulation results

Fig. 9: Two-level VSI PMSM drivedrive performance under normal and open phase (fault) operating condition



(a) Experimental results

(b) Simulation results

Fig. 10: Four phase matrix converter PMSM drive performance under normal and open phase fault operating condition

Conclusion

In this paper two proposed fault tolerant power converter motor drive topologies for aerospace applications development have been presented. These topologies are based on a two-level VSI and a conventional Matrix Converter, both with a fourth redundant output phase leg that is connected to the neutral point of a PMSM in case of an open phase fault. The modified power converter topologies and the appropriate control strategy under faulty conditions are provided, in order to maintain good system performance and to improve the reliability of such safety critical applications. Torque ripple compensation technique is employed to reduce the torque ripple due to the unbalanced faulty system. The simulation results and the experimental results indicate that the proposed topologies, with an effective control strategy implemented, allow the proposed motor drive systems to continue to operate in the presence of the machine open circuit fault with minimum torque pulsation.

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