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FAULT TOLERANT CONTROL OF A PMSM DRIVE IN THE SELECTED EMERGENCY CONDITIONS

The paper describes an investigation of fault tolerant control strategies for permanent magnet synchronous motor (PMSM) driven by a fault-tolerant inverter. The inverter is a topology-modified inverter with fault-tolerant capability, which can be configured as the standard 3-phase 6-switch inverter and reconfigured as 3-phase 4-switch or 2-phase 4-switch inverter under the fault condition. By analyzing operating principle of a fault-tolerant inverter and the mathematical model of PMSM, fault tolerant control algorithms are investigated. There is a conclusion that three phase stator windings of PMSM can be effectively operated by controlling only two phase currents. Simulation results show the validity of the proposed methods.

1. INTRODUCTION

The use of fault-tolerant electric drives becomes inevitable in many critical applications, in which the failures can endanger safety of the user or machine. The inverter's standard topology for the drive with PMSM motor is susceptible to failures of both, the power electronics part, as well as the motor itself. The failure of a motor phase or even of a single power transistor usually prevents its further operation, even if there had been no further escalation of failure. With regard to the above, the development of structures that are fault-tolerant and capable to maintain continuous operation becomes very important. The use of inverter's redundant structure in the case of failure, allows for reconfiguration of inverter-motor connection and introduction of FTC – Fault Tolerant Control [1].

The article presents fault tolerant control with the use of inverter, equipped with redundant leg of capacitors. After the occurrence of failure and reconfiguration of inverter, the control of PMSM motor is executed with the use of only four transistor switches.

2. TOPOLOGY OF A FAULT-TOLERANT INVERTER

The use of a standard inverter structure does not allow for application of fault tolerant control. Minimal redundant topology of the fault tolerant inverter is shown

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in the Figure 1a. This system is equipped with the additional branch, consisting of two ‘split’ capacitors that form mid-point of supply voltage [2].

After the occurrence of any damage to one of inverter’s transistor legs, in order to prevent further damages, it is necessary to reconfigure the topology of the inverter. The proposed solution (Fig. 1b) enables the switching of the motor phase, in which the failure occurred (in the figure below phase C), to the redundant branch of capacitors. This leads to achievements of topology 4S3P (*4-switch 3-phase*), in which the control is executed with the use of four transistors (the control of two motor phases), while the third phase is connected to mid-point of DC supply voltage by TRIAC. This topology allows for discretionary forming of stator current, just like in the case of basic topology.

The occurrence of motor phase failure does not allow for the use of the above mentioned reconfiguration. In this case, in order to enable the further operation of the drive, it is necessary to use the motor neutral point. The proposed solution (Fig. 1c) enables the connection of the motor neutral point to the redundant leg of capacitors. This leads to the acquirement of topology 4S2P (*4-switch 2-phase*), in which the control is executed with the use of four transistors. This topology allows for discretionary forming of stator current, just like in the case of basic topology, however, it also requires a change in the control algorithm, which is due to the occurrence of current in the neutral line.

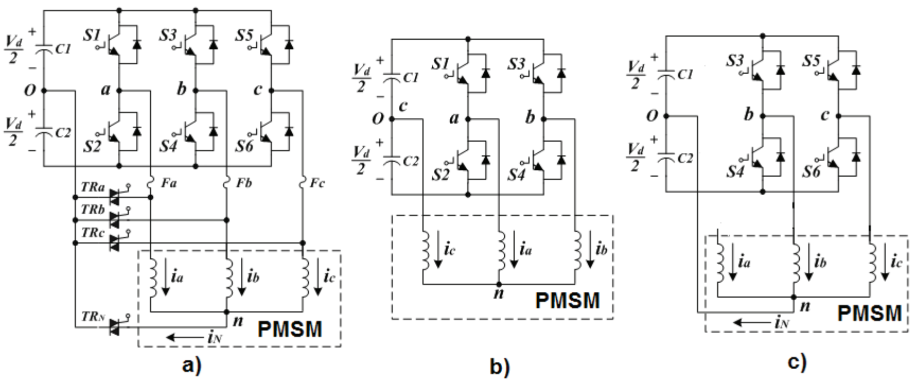

Fig. 1. Fault tolerant inverter: a) basic topology, b) failure of transistor leg, c) failure of motor phase

3. FAULT TOLERANT CONTROL

3.1. Fault tolerant control in 4S3P configuration of the inverter

During normal operation of inverter, the primary voltage vector is defined by the following equation:

$$\overrightarrow{V_s}(V_{an},V_{bn},V_{cn}) = \tfrac{2}{3}(V_{an} + \alpha V_{bn} + \alpha^2 V_{cn}) \tag{1}$$

where $\alpha=e^{j2\pi/3}$ and V_{an}, V_{bn}, V_{cn} are the instantaneous values of motor phase voltages against the neutral point, and V_d is the supply voltage of the inverter.

By defining three variables (S_a, S_b and S_c) you can describe phase instantaneous voltages. These variables represent the switch state of three phase legs and can assume values '1' or '0'. Value '1' represents turning on of the upper transistor and turning off of the bottom transistor, and the value '0' represents the opposite state. The correlation of phase voltages and switches states of the inverter is described by the following equation:

$$\begin{cases} V_{an} = \frac{1}{3}V_d(2S_a - S_b - S_c) \\ V_{bn} = \frac{1}{3}V_d(-S_a + 2S_b - S_c) \\ V_{cn} = \frac{1}{3}V_d(-S_a - S_b + 2S_c) \end{cases} \tag{2}$$

After the transformation of the above equation to the stationary frame in the coordinates $\alpha\beta$, one get:

$$\begin{cases} V_{s\alpha} = \frac{1}{3}V_d(2S_a - S_b - S_c) \\ V_{s\beta} = \frac{1}{\sqrt{3}}V_d(S_b - S_c) \end{cases} \tag{3}$$

According to (1) and (2), the voltage vector can be defined as the following:

$$\vec{V_s}(S_a, S_b, S_c) = \frac{2}{3}V_d(S_a + \alpha S_b + \alpha^2 S_c) \tag{4}$$

The inverter with six switches, taking into account all combinations of variables S_a, S_b and S_c, enables the generation of six non-zero voltage vectors and two zero vectors. The voltage vectors that are possible to obtain, are shown in the Table 1 and in the Figure 2.

Table 1. Basic voltage vectors for the inverter in the topology 6S3P

$V_0(000)$	$V_1(100)$	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$	$V_6(101)$	$V_7(111)$
0	$\frac{2}{3}V_d$	$\frac{2}{3}V_d e^{j\frac{1}{3}\pi}$	$\frac{2}{3}V_d e^{j\frac{2}{3}\pi}$	$-\frac{2}{3}V_d$	$\frac{2}{3}V_d e^{j\frac{4}{3}\pi}$	$\frac{2}{3}V_d e^{j\frac{5}{3}\pi}$	0

After the failure of transistor branch in phase C and reconfiguration of the inverter to the topology 4S3P, the phase voltages can be described as [3]:

$$\begin{cases} V_{an} = \frac{1}{3}V_d(2S_a - S_b - 0.5) \\ V_{bn} = \frac{1}{3}V_d(-S_a + 2S_b - 0.5) \\ V_{cn} = \frac{1}{3}V_d(-S_a - S_b + 1) \end{cases} \tag{5}$$

The transformation to the stationary frame $\alpha\beta$:

$$\begin{cases} V_{s\alpha} = \frac{1}{3} V_d (2S_a - S_b - 0.5) \\ V_{s\beta} = \frac{1}{\sqrt{3}} V_d (S_a - S_b) \end{cases} \tag{6}$$

Taking into account the equations (1) and (5), we obtain the voltage vector with the failure of transistor leg in phase C, defined as:

$$\vec{V_s}(S_a, S_b) = \tfrac{2}{3} V_d (S_a + \alpha S_b + 0.5\alpha^2) \tag{7}$$

Failure of the other transistor leg, leads to achievements of voltage vector, described by equation (8) with the fault of inverter leg in phase A and equation (9) with the fault of inverter leg in phase B.

$$\vec{V_s}(S_b, S_c) = \tfrac{2}{3} V_d (0.5 + \alpha S_b + \alpha^2 S_c) \tag{8}$$

$$\vec{V_s}(S_a, S_c) = \tfrac{2}{3} V_d (S_a + 0.5\alpha + \alpha^2 S_c) \tag{9}$$

For the inverter in topology 4S3P, while changing switches state, one can obtain four voltage vectors. These vectors are shown in Table 2 for various possible failures of inverter transistor legs.

Table 2. Basic voltage vectors for the inverter in topology 4S3P, for the various faults

Transistor leg fault in	V_1'(00)	V_2'(10)	V_3'(11)	V_4'(01)
Phase A	$\frac{1}{3}V_d$	$\frac{1}{\sqrt{3}}V_d e^{j\frac{1}{2}\pi}$	$\frac{1}{3}V_d e^{j\pi}$	$\frac{1}{\sqrt{3}}V_d e^{j\frac{3}{2}\pi}$
Phase B	$\frac{1}{3}V_d e^{j\frac{2}{3}\pi}$	$\frac{1}{\sqrt{3}}V_d e^{j\frac{7}{6}\pi}$	$\frac{1}{3}V_d e^{j\frac{5}{3}\pi}$	$\frac{1}{\sqrt{3}}V_d e^{j\frac{1}{6}\pi}$
Phase C	$\frac{1}{3}V_d e^{j\frac{4}{3}\pi}$	$\frac{1}{\sqrt{3}}V_d e^{-j\frac{1}{6}\pi}$	$\frac{1}{3}V_d e^{j\frac{1}{3}\pi}$	$\frac{1}{\sqrt{3}}V_d e^{j\frac{5}{6}\pi}$

In accordance with the voltage vectors described in Table 1 and Table 2, for traditional inverter with six keys and inverter with four keys, allowing for motor operation after occurrence of failure in the one of the inverter legs, in the Figure 2, there has been shown the voltages vectors in $\alpha\beta$ coordinates.

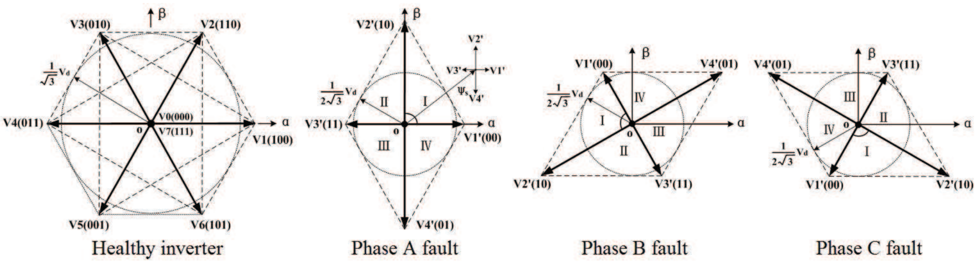

Fig. 2. Space voltage vectors generated by the inverter in topology 6S3P and 4S3P for various faults

It is seen from Figure 2 that the health inverter allows for generation of six symmetrical non-zero voltage vectors, and the inverter with failures in topology 4S3P, allows only for generation of four non-symmetric voltage vectors. By using PWM modulation for control of the inverter's switches, one can generate voltage with the maximum amplitude of $\frac{1}{2\sqrt{3}}V_d$, which constitutes a half of voltage generated by healthy inverter.

After a change in inverter's topology, the current in the motor phase, connected to redundant capacitors branch, cannot be controlled directly by transistor switches. Considering PMSM motor without the neutral wire, the sum of currents of three motor phases in the neutral point is zero, therefore the current in damaged phase C can be described by the following equation:

$$i_c = -i_a - i_b \tag{10}$$

Equation (10) shows that the current in phase C can be easily and indirectly controlled by the regulation of currents in phases A and B. The above considerations shows that in order to obtain vector control of PMSM motor, one just need an access to the two undamaged motor phases, while the third phase is connected to a pair of capacitors. Presented topology of the inverter does not require a change in the control algorithm after the occurrence of failure.

3.2. Fault tolerant control in 4S2P configuration of the inverter

For development of control algorithm for PMSM motor with inverter of structure 4S2P a model in *dq0* coordinates was used:

$$V_d = R_s i_d - L_q i_q \omega_e + L_d \frac{\mathrm{d}i_d}{\mathrm{d}t} \tag{11}$$

$$V_q = R_s i_q + L_d i_d \omega_e + \omega_e \psi_f + L_q \frac{\mathrm{d}i_q}{\mathrm{d}t} \tag{12}$$

$$V_0 = R_s i_0 - L_0 \frac{\mathrm{d}i_0}{\mathrm{d}t} \tag{13}$$

where R_s – stator resistance, L_d and L_q – stator inductance in the axis d and q respectively, L_0 – leakage inductance, ψ_f – amplitude of flux from the permanent magnets, ω_e – electric angular velocity of the rotor.

The transformation of *dq0* coordinate system to *abc* is presented below:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{14}$$

With the symmetry of the power system of motor phases (there is no current in the neutral line), the current i_0 is 0. The current in axis *0* can be described with the equation (15) and the motor neutral current is defined in (16):

$$i_0 = \tfrac{1}{3}(i_a + i_b + i_c) \tag{15}$$

$$i_n = i_a + i_b + i_c = 3i_0 \tag{16}$$

Having defined the model of PMSM motor in the coordinates *dq0*, the control algorithm for motor with failure is defined. Considering the transformation (14) one obtain the following equations:

$$i_a = i_d \cos(\theta) - i_q \sin(\theta) + i_0 \tag{17}$$

$$i_b = i_d \cos(\theta - \tfrac{2\pi}{3}) - i_q \sin(\theta - \tfrac{2\pi}{3}) + i_0 \tag{18}$$

$$i_c = i_d \cos(\theta + \tfrac{2\pi}{3}) - i_q \sin(\theta + \tfrac{2\pi}{3}) + i_0 \tag{19}$$

After the occurrence of an open-phase fault in any phase of motor, and attaching the motor's neutral point to the redundant leg of capacitors, flow of current in the neutral wire is possible, and it causes appearance of current in axis *0*. In the case of discontinuance of phase A of motor, the flow of current in this phase is not possible, therefore $i_a = 0$. By substituting this correlation to the equation (17), one get that current i_0 is:

$$i_0 = i_q \sin(\theta) - i_d \cos(\theta) \tag{20}$$

By substituting equation (20) to equations (18) and (19), one get the following:

$$i_b = \sqrt{3}\left[i_d \cos(\theta - \tfrac{5\pi}{6}) - i_q \sin(\theta - \tfrac{5\pi}{6})\right] \tag{21}$$

$$i_c = \sqrt{3}\left[i_d \cos(\theta + \tfrac{5\pi}{6}) - i_q \sin(\theta + \tfrac{5\pi}{6})\right] \tag{22}$$

The above equations describe the new principle of controlling PMSM motor with the failure of phase A. The developed control algorithm will allow for further operation of the damaged motor, with the smallest possible decrease in the control quality. However, this requires an increase of phase currents amounting to $\sqrt{3}$ times and their offset of 30° (Fig. 3) as compared to operation without failures [4].

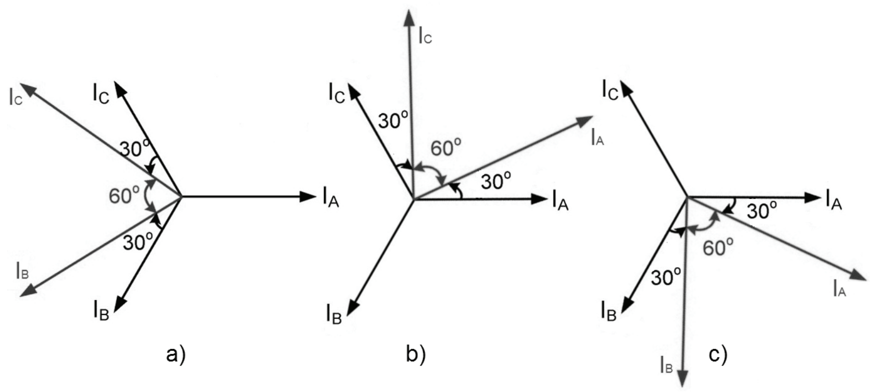

Fig. 3. Current phasor relationship after an open-phase fault on: a) phase A b) phase B c) phase C

4. SIMULATION RESULTS

The verification of developed fault tolerant control method was conducted on simulation model in the Matlab/Simulink software. The figure 4 shows the results of research of PMSM motor, before and after the occurrence of failure in transistor branch for phase C (topology 4S3P) and failure in motor's phase A (topology 4S2P).

The Figure 4 (left side) shows the results of simulation research, before and after the occurrence of failure in one of the inverter's branches.

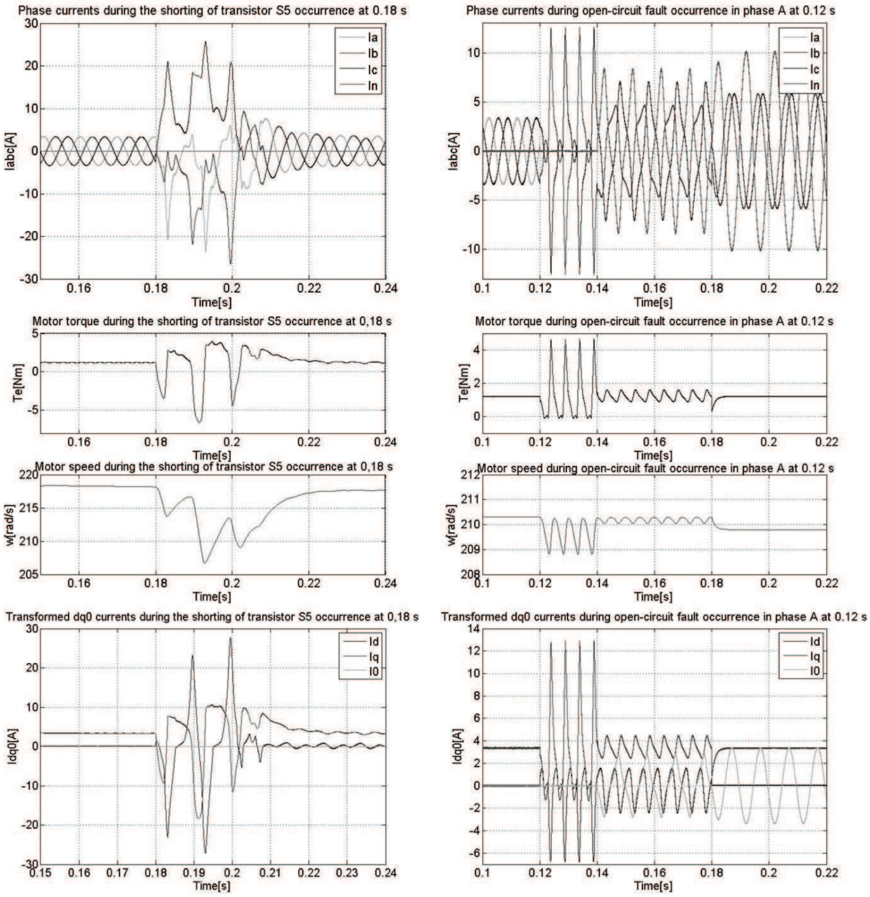

Fig. 4. Fault tolerant control for topology 4S3P (left side) and topology 4S2P (right side)

In the moment $t_1 = 0.18$ s, the shorting of upper transistor in phase C has taken place, which resulted in a large increase of phase currents, rush of torque, high oscillation and decrease of rotational speed. Assuming that after 20 ms the failure was detected, in the moment $t_2 = 0.20$ s inverter's topology has been changed to a topology 4S3P, allowing the drive to return to the operating state before the failure. The control algorithm remained unchanged.

In the moment t_1 = 0.12 s, the discontinuance of motor's phase A has taken place (Fig. 4 (right side)), which resulted in an increase in the currents flowing in two undamaged phases, large rushes of torque, decrease and oscillation of rotational speed and occurrence of current in the axis d. After the detection of failure, in moment t_2 = 0.14 s, a change of inverter's topology to topology 4S2P has taken place, without a change in the control algorithm. This resulted in the occurrence of current in motor's neutral conductor, and the decrease in torque fluctuations and rotational speed. However, due to the lack of balance of two phase currents, a fairly large torque ripples have remained. Only after the switch, at the moment t_3 = 0.18 s, of control algorithm to the above developed fault tolerant control algorithm, the drive began to work correctly with reduction in control quality taken into account. The new control algorithm enabled a significant reduction of the torque ripples and PMSM motor speed, and eliminated the current in axis d, which appeared after the occurrence of failure.

5. CONCLUSION

This paper presents two fault tolerant topologies of inverter, which can be applied to PMSM drive in order to improve the reliability of the system under various faults of inverter and motor. These fault tolerant topologies are based on the reconfiguration of inverter's structure by connecting the redundant leg of capacitors. To keep the motor operating under faulty conditions with minimum performance degradation, two control strategies are proposed. The simulation results demonstrate that the proposed algorithms have good static and dynamic performance. To verify the proposed method effectively, the experimental research will be further continued in the future.

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