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DIFFERENT CONTROL STRATEGIES OF PMSM DRIVE IN PRESENCE OF INVERTER FAULTS

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Abstract- The use of electric drives in embedded systems, especially in the aircraft, car and naval industries is growing more and more. To improve the operation of these actuators in normal mode and in the presence of different types of defects, suitable design of electrical energy converter, their components and control strategies are indispensable. The main objective of control strategies is improving the compactness, reliability, dynamic performance and losses. Based on these criteria, the permanent magnet synchronous machines (PMSM) are increasingly used in embedded systems. In this research we limit ourselves to the defects of the inverter. We try to find control strategies in the presence of an electric fault in inverter. Several control strategies for three-phase PMSM in faulty mode proposed and validated by simulation using MATLAB software [1-6].

Keywords: Electric Drives, Faulty Mode, Short Circuit Fault, Open Circuit Fault, PMSM,

I. CONTROL OF PMSM IN NORMAL MODE

To compare the behavior of the PMSM in normal and degraded modes, firstly we have to simulate the PMSM in normal mode. The phase currents and the emfs of motor are [7-8]:

$$\begin{cases} i_a = -I_m \sin(\theta) \\ i_b = -I_m \sin(\theta - 2\pi/3) \\ i_c = -I_m \sin(\theta + 2\pi/3) \end{cases} \tag{1}$$

$$\begin{cases} e_a = -\sqrt{\frac{2}{3}}\psi_f p\Omega \sin(\theta) = -k\Omega \sin(\theta) \\ e_b = -\sqrt{\frac{2}{3}}\psi_f p\Omega \sin\left(\theta - \frac{2\pi}{3}\right) = -k\Omega \sin\left(\theta - \frac{2\pi}{3}\right) \\ e_c = -\sqrt{\frac{2}{3}}\psi_f p\Omega \sin\left(\theta + \frac{2\pi}{3}\right) = -k\Omega \sin\left(\theta + \frac{2\pi}{3}\right) \end{cases} \tag{2}$$

with $k = \sqrt{\frac{2}{3}} p\psi_f$, where ψ_f is the magnet flux of permanent magnet, p is pole pairs and Ω is angular velocity of the rotor. The torque equation in *a-b-c* frame is:

$$\Gamma_{3p} = \frac{e_a i_a + e_b i_b + e_c i_c}{\Omega} \tag{3}$$

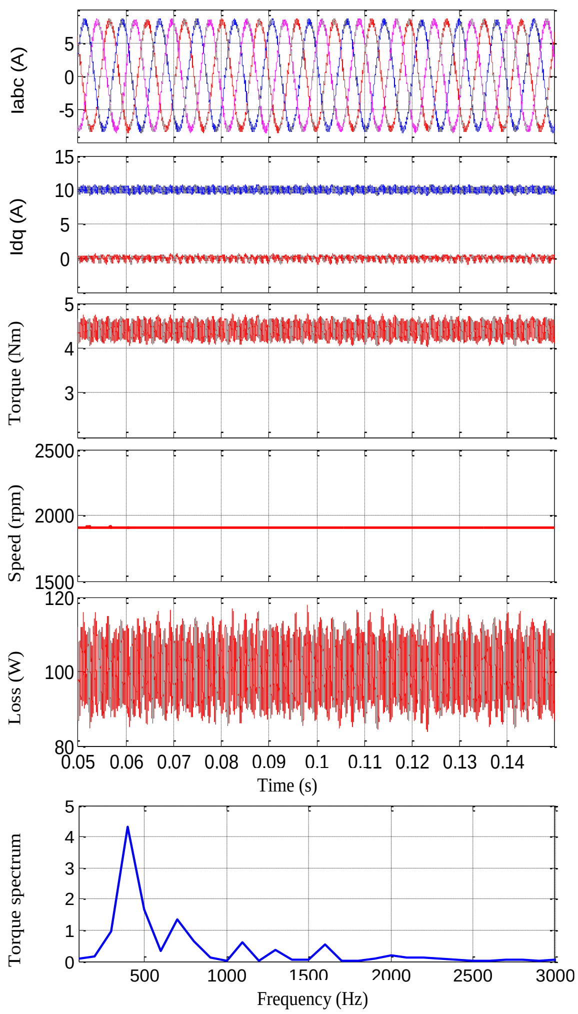

Figure 1. Simulation results of PMSM in normal mode

Substituting Equations (1) and (2) in Equation (3), the three-phase torque is:

$$\Gamma_{3p} = \frac{3}{2} k I_m \tag{4}$$

Figure 1 shows the simulation results of a PMSM drive. The DC source is set to U_0 = 200 V, carrier frequency f_p=10 kHz. The control method is PWM using PI controllers.

II. DIFFERENT CONTROL STRATEGIES OF PMSM IN DEGRADED MODE

We consider only the inverter faults. The different type of faults in an inverter or its control system conducts us to a short-circuit fault or an open-circuit fault of a component. It is already developed different architecture and different type of PMSM control method in presence of inverter fault. Some methods are based on connecting of neutral by a bidirectional switches or by adding a fourth arm. [1, 2, 9] But in this method it is necessary to add some components and thus the volume and price of system increase. In the following we study different control strategies in presence of these faults.

III. CONTROL STRATEGIES IN PRESENCE OF OPEN CIRCUIT FAULT

In the case where a component of the upper arm of inverter is open (Figure 2(a)), the current in the corresponding phase become negative and the faulty phase of the MSAP remains connected to the negative potential of DC bus by the bottom component.

In the case of PWM control with PI controller and anti-windup, the phase current decrease until it becomes zero while the current controller error increases to its upper limit value [1]. The phase current remains zero when the reference current is positive, then when the sign of phase current changes, the faulty switch no longer conduct. Thus the current can then be controlled. The currents in the other two phases deform (Figure 2(b)). So in the case of an open-circuit fault in a switch (for example: C_{ha}), we opens the complementary switch of faulty arm.

Follows the commands of the other two healthy arms is modified according to the following proposed method, tell the drive continues to work in an acceptable situation. So, in degraded mode, MSAP work with two other energized phases. We can classify the type of fault in two structures: "Not connected neutral" and "Connected neutral". In the case of not connected neutral, the sum of the currents is always zero and the torque developed by the machine oscillates. To avoid this problem, we propose then a two-phase control method by changing the drive structure and connecting the neutral point of the machine to middle point of power supply [10]. So with the control strategy, it is possible to reduce the oscillation in torque. But on the other hand, we must add an additional bidirectional power component to connect the neutral of the machine to system ground (bidirectional switch "k" in Figure 2(a)). Finally, the proposed control strategies are validated by simulation.

In the following, different control strategies for MSAP in two phases degraded mode are explained.

A. Neutral Not Connected (Objective; Maximize the Torque)

In Figure 2(a), the bidirectional switch "k" is open and C_{Ha} has open circuit fault. So we cut gate pulse of C_{Ba} and the current of i_a becomes zero (i_a=0).

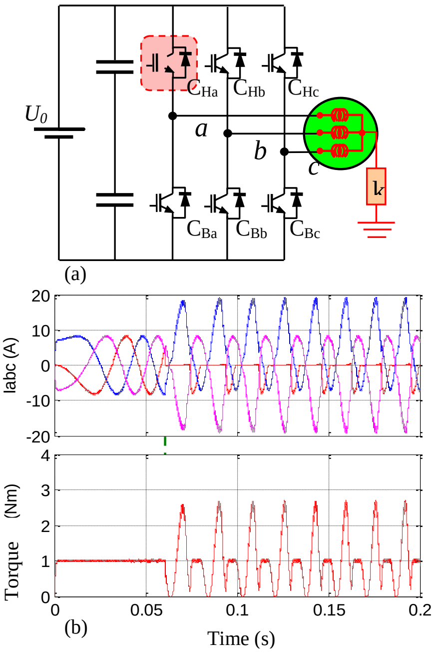

Figure 2. (a) Schematic of inverter and PMSM in the presence of open-circuit fault, (b) The simulation results of current and torque (open-circuit at "t")

We must choose i_b and i_c to have maximum torque. The currents are:

$$\begin{cases} i_a = 0 \\ i_b = -I_m \sin(\theta - \beta) \\ i_c = -i_b = I_m \sin(\theta - \beta) \end{cases} \tag{5}$$

With these currents, the torque is:

$$\Gamma_{2p} = \frac{e_b i_b + e_c i_c}{\Omega} = \frac{(e_b - e_c) i_c}{\Omega} \tag{6}$$

$$\Gamma_{2p} = k I_m \left(\sin(\theta - \frac{2\pi}{3}) - \sin(\theta + \frac{2\pi}{3}) \right) \sin(\theta - \beta) \tag{7}$$

$$\Gamma_{2p} = \sqrt{3} k I_m \left(\frac{1}{2} \sin(\beta) + \frac{1}{2} \sin(2\theta - \beta) \right) \tag{8}$$

We have to select "β" to have maximum torque. If $\beta = \pi / 2$:

$$\Gamma_{2p} = \frac{\sqrt{3}}{2} k I_m \left(1 - \cos(2\theta)\right) \tag{9}$$

$$\frac{\Gamma_{2p(av)}}{\Gamma_{3p}} = \frac{(\sqrt{3}/2) k I_m}{(3/2) k I_m} = \frac{\sqrt{3}}{3} \approx 0.57 \tag{10}$$

The torque decreases to 57% of its three-phase value and oscillates in a frequency twice the frequency of the phase current. Figure 3 shows the simulation results in two phase operating mode with not connected neutral wire. According to these results, torque and speed oscillate and also the torque value reduced from 4.2 Nm in three-phase normal mode to 2.3 Nm (57% reduction). The current frequency is almost 70 Hz and torque is 140 Hz.

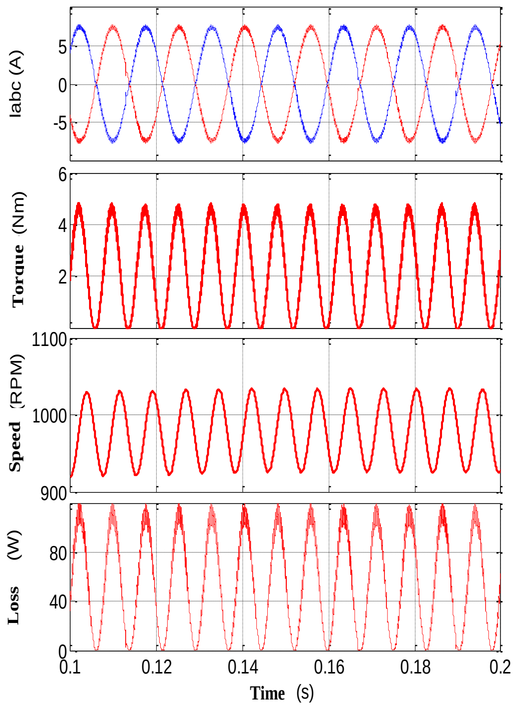

Figure 3. Simulation results of PMSM drive in faulty mode (two phases)

B. Connected Neutral (I_b , I_c = are not changed)

In Figure 2(a) the switch "k" is closed, and C_{Ha} and C_{Ba} are open and therefore the current i_a=0. The reference currents i_b and i_c don't change:

$$\begin{cases} i_a = 0 \\ i_b = -I_m \sin\left(\theta - 2\pi/3\right) \\ i_c = -I_m \sin\left(\theta + 2\pi/3\right) \end{cases} \quad (11)$$

The torque in degraded mode is:

$$\Gamma_{2p} = \frac{e_b i_b + e_c i_c}{\Omega} = kI_m\left(1 + \frac{1}{2}\cos(2\theta)\right) \quad (12)$$

The average torque is $\Gamma_{2p(av)} = kI_m$ .According to three-phase torque:

$$\frac{\Gamma_{2p(av)}}{\Gamma_{3p}} = \frac{kI_m}{(3/2)kI_m} = \frac{2}{3} = 0.66 \quad (13)$$

The torque decreases 66% and it isn't constant.

To improve the behavior of the PMSM in high speed, we must find the necessary transformation to control the drive in d-q reference. The matrices T_{22}^t and T_{22} are expressed as:

$$T_{22}^t = \frac{1}{\sqrt{2}}\begin{bmatrix} -1 & -1 \\ 1 & -1 \end{bmatrix}$$
$$T_{22} = \frac{1}{\sqrt{2}}\begin{bmatrix} -1 & 1 \\ -1 & -1 \end{bmatrix} \quad (14)$$

According to Equation (1):

$$\begin{bmatrix} i_b \\ i_c \end{bmatrix} = -I_m\begin{bmatrix} \sin(\theta - 2\pi/3) \\ \sin(\theta + 2\pi/3) \end{bmatrix}$$

To keep the current amplitude in degraded mode, we take $I_m = \sqrt{\frac{2}{3}} I_q$. The reference currents in α-β are:

$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = T_{22}^t\begin{bmatrix} i_b \\ i_c \end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix} -1 & -1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} i_b \\ i_c \end{bmatrix} \quad (15)$$

Using Equations (11):

$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \frac{-I_q}{\sqrt{3}}\begin{bmatrix} -1 & -1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} \sin(\theta - 2\pi/3) \\ \sin(\theta + 2\pi/3) \end{bmatrix} \quad (16)$$

After simplifying:

$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \frac{I_q}{\sqrt{3}}\begin{bmatrix} -\sin(\theta) \\ \sqrt{3}\cos(\theta) \end{bmatrix} \quad (17)$$

By multiplication with $p(-\theta)$ we have:

$$p(-\theta)\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \frac{I_q}{\sqrt{3}}\begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}\begin{bmatrix} -\sin(\theta) \\ \sqrt{3}\cos(\theta) \end{bmatrix} \quad (18)$$

$$p(-\theta)\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \frac{I_q}{\sqrt{3}}\begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \times$$
$$\times\left(\begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix} + \begin{bmatrix} 0 \\ (\sqrt{3}-1)\cos(\theta) \end{bmatrix}\right) \quad (19)$$

$$p(-\theta)\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = \frac{I_q}{\sqrt{3}}\left(\begin{bmatrix} 0 \\ 1 \end{bmatrix} + \frac{\sqrt{3}-1}{2}\begin{bmatrix} \sin(2\theta) \\ \cos(2\theta) \end{bmatrix} + \frac{\sqrt{3}-1}{2}\begin{bmatrix} 0 \\ 1 \end{bmatrix}\right) \quad (20)$$

We can write Equation (20) in the form of:

$$p(-\theta)\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} =$$
$$= I_q\begin{bmatrix} \frac{\sqrt{3}+1}{2\sqrt{3}} + \frac{\sqrt{3}-1}{2\sqrt{3}}\cos(2\theta) & \frac{\sqrt{3}-1}{2\sqrt{3}}\sin(2\theta) \\ -\frac{\sqrt{3}-1}{2\sqrt{3}}\sin(2\theta) & \frac{\sqrt{3}+1}{2\sqrt{3}} + \frac{\sqrt{3}-1}{2\sqrt{3}}\cos(2\theta) \end{bmatrix}\begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (21)$$

$$G(2\theta) = \begin{bmatrix} \frac{\sqrt{3}+1}{2\sqrt{3}} + \frac{\sqrt{3}-1}{2\sqrt{3}}\cos(2\theta) & \frac{\sqrt{3}-1}{2\sqrt{3}}\sin(2\theta) \\ -\frac{\sqrt{3}-1}{2\sqrt{3}}\sin(2\theta) & \frac{\sqrt{3}+1}{2\sqrt{3}} + \frac{\sqrt{3}-1}{2\sqrt{3}}\cos(2\theta) \end{bmatrix} \quad (22)$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = G(2\theta)^{-1} p(-\theta)\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix}, \quad \begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = p(\theta)G(2\theta)\begin{bmatrix} I_d \\ I_q \end{bmatrix} \quad (23)$$

In these equations I_d=0.

The Figure 4 shows the simulations results of PMSM drive. The average torque value decreases to 2.8 Nm which is like the expected value (66% of three-phase value). The current frequency is almost 85 Hz and torque frequency is 170 Hz.

To have the advantage of control in d-q frame, we made two simulations. Figure 5(a) shows the simulation result of current regulators in a-b-c frame. The current is lagging behind in its reference. By this method the speed reaches 1100 rpm, but with current control in d-q frame, the speed goes up to 1300 rpm and the average of torque is higher (Figure 5(b)). Also the current has the same phase of its reference.

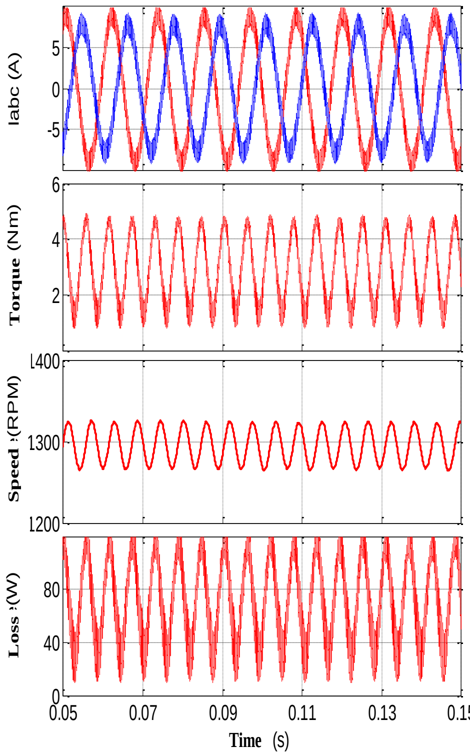

Figure 4. Simulation results of the PMSM in faulty mode (two phases)

C. Connected Neutral (I_b = changed and I_c = change so that the Torque Become Constant)

In Figure 2(a) switch "k" is closed, C_{Ha} and C_{Ba} are open and therefore the current i_a=0. The reference current i_b does not change and the reference current i_c change as torque become constant. In this case the currents are:

$$\begin{cases} i_a = 0 \\ i_b = -I_m \sin\left(\theta - 2\pi/3\right) \\ i'_c = -I'_m \sin\left(\theta - \alpha\right) \end{cases} \qquad (24)$$

We must choose α and I'_m to have a constant torque. We call Γ_f the expression of torque:

$$\Gamma_f = \frac{e_b i_b + e_c i'_c}{\Omega} = \Gamma_{2p} - \frac{e_c i_c}{\Omega} + \frac{e_c i'_c}{\Omega} \qquad (25)$$

$$\Gamma_f = k[I_m\left(1 + \frac{1}{2}\cos(2\theta)\right) - \\ -\frac{I_m}{2}\left(1 + \cos(\theta + \frac{2\pi}{3})\right) + \\ +\frac{I'_m}{2}\left(\sin(\theta + \frac{2\pi}{3})\sin(\theta - \alpha)\right)] \qquad (26)$$

After simplification:

$$\Gamma_f = \frac{kI_m}{2}\left(1 - \cos(2\theta + \frac{2\pi}{3})\right) + \\ +\frac{kI'_m}{2}\left(\cos(\alpha + \frac{2\pi}{3}) - \cos(2\theta - \alpha + \frac{2\pi}{3})\right) \qquad (27)$$

According to equation (27), to have a constant torque:

$$I_m \cos(2\theta + \frac{2\pi}{3}) = -I'_m \cos(2\theta - \alpha + \frac{2\pi}{3}) \qquad (28)$$

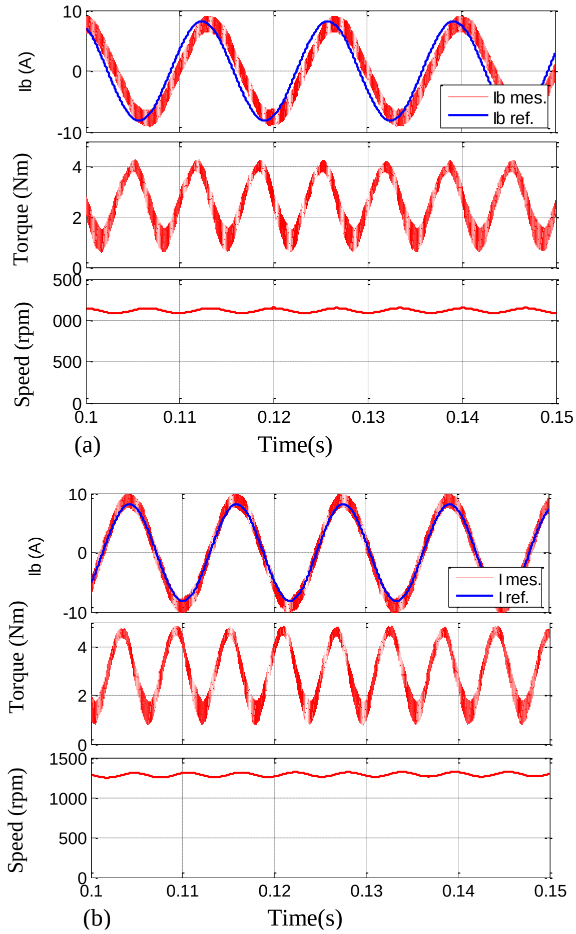

Figure 5. Simulation results of the current, torque and speed for two types of control (a): Control in *a-b-c* frame; (b) Control in *d-q* frame

Thus:

$$\begin{cases} I_m = -I'_m \\ \alpha = 0 \end{cases} \qquad (29)$$

With these values of the amplitude and phase angle, the torque is $\Gamma_f = \frac{3}{4}kI_m$ and compared to the three-phase torque it can be note:

$$\frac{\Gamma_f}{\Gamma_{3p}} = \frac{(3/4)kI_m}{(3/2)kI_m} = \frac{1}{2} \qquad (30)$$

By this control method, we put "-i_a" in the winding phase "c". The couple become constant and decrease to 50% of its three-phase value.

According to Equations (29) and (24):

$$\begin{bmatrix} i_b \\ i_c \end{bmatrix} = -\sqrt{\frac{2}{3}} I_q \begin{bmatrix} \sin(\theta - 2\pi/3) \\ -\sin(\theta) \end{bmatrix} \qquad (31)$$

By this control method, we can find a d-q transformation to improve the behavior of the PMSM in high speed. T_{22}^t and T_{22} have the same expressions as Equations (14). Using the Equation (22), the translation matrix is:

$$G(\alpha)=\begin{bmatrix} \frac{\sqrt{3}+1}{2\sqrt{3}}-\frac{\sqrt{3}-1}{2\sqrt{3}}\cos\alpha & -\frac{\sqrt{3}-1}{2\sqrt{3}}\sin\alpha \\ \frac{\sqrt{3}-1}{2\sqrt{3}}\sin\alpha & \frac{\sqrt{3}+1}{2\sqrt{3}}-\frac{\sqrt{3}-1}{2\sqrt{3}}\cos\alpha \end{bmatrix} \quad (32)$$

$$\alpha = 2(\theta+\frac{\pi}{6})$$

And:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = G\left(2(\theta+\frac{\pi}{6})\right)^{-1} p\left(-(\theta+\frac{\pi}{6})\right)\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix}$$
$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = p\,(\theta+\frac{\pi}{6})\,G\left(2(\theta+\frac{\pi}{6})\right)\begin{bmatrix} I_d \\ I_q \end{bmatrix} \quad (33)$$

Figures 6 show the simulation results of this method. According to this figure, the harmonics of torque are lower than the presented method in the previous section. The average torque value decreases until 2.2 Nm which is like its expected value (50% of three-phase value). The current frequency is almost 58 Hz and torque indicates low frequency oscillation at 116 Hz.

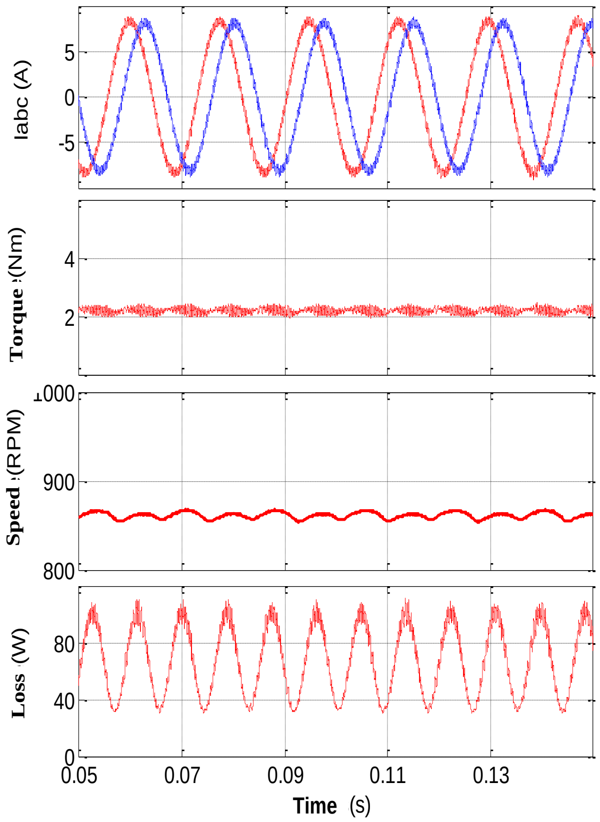

Figure 6. Simulation results of MSAP drive in faulty mode (two phases)

D. Connected Neutral (Objective: Maximize and Fix the Torque)

In Figure 2(a), the switch "k" is closed, which C_{Ha} and C_{Ba} are open and therefore the current i_a=0. The reference currents i_b and i_c must calculate so that the torque become maximum. In general we take the phase currents:

$$\begin{cases} i_a = 0 \\ i'_b = -I_m \sin(\theta-\beta) \\ i'_c = -I'_m \sin(\theta-\gamma) \end{cases} \quad (34)$$

The torque expression is:

$$\Gamma_f = \frac{e_b i'_b + e_c i'_c}{\Omega} = kI_m \sin(\theta-\beta)\sin(\theta-\frac{2\pi}{3}) + $$
$$+kI'_m \sin(\theta-\gamma)\sin(\theta+\frac{2\pi}{3}) \quad (35)$$

After simplification:

$$\Gamma_f = \frac{kI_m}{2}\left(\cos(2\theta-\beta-\frac{2\pi}{3})+\cos(\beta-\frac{2\pi}{3})\right)+$$
$$+\frac{kI'_m}{2}\left(\cos(2\theta-\gamma+\frac{2\pi}{3})+\cos(\gamma+\frac{2\pi}{3})\right) \quad (36)$$

To have a constant torque, we have to:

$$\begin{cases} I_m = -I'_m \\ \gamma-\beta = \frac{4\pi}{3} \end{cases} \quad (37)$$

The torque becomes constant:

$$\Gamma_f = \frac{kI_m}{2}\left(\cos(\beta-\frac{2\pi}{3})-\cos(\gamma+\frac{2\pi}{3})\right)=$$
$$=\frac{kI_m}{2}\left(\cos(\beta-\frac{2\pi}{3})-\cos(\beta)\right) \quad (38)$$

To have the maximum torque, we have to:

$$\beta = \frac{5\pi}{6} \text{ and } \gamma = \frac{\pi}{6} \quad (39)$$

Thus:

$$\Gamma_{f\,\max} = \frac{kI_m}{2}\left(\cos(\frac{\pi}{6})-\cos(\frac{5\pi}{6})\right) = \frac{\sqrt{3}}{2}kI_m \quad (40)$$

Compare to three-phase torque:

$$\frac{\Gamma_{f\,\max}}{\Gamma_{3p}} = \frac{\sqrt{3}/2kI_m}{(3/2)kI_m} = \frac{\sqrt{3}}{3} = 0.57 \quad (41)$$

The torque became constant and decrease to 57% (√3/3), which is 7% higher than the last method. The simulation results in Figure 7 confirm these equations. The average torque value decreases to 2.2 Nm which is like its expected value (57% three-phase value). The current frequency is almost 70 Hz and torque oscillation is 140 Hz. According to Equations (32) and (34):

$$\begin{bmatrix} i_b \\ i_c \end{bmatrix} = -\sqrt{\frac{2}{3}}I_q \begin{bmatrix} \sin(\theta-5\pi/6) \\ -\sin(\theta-\pi/6) \end{bmatrix} \quad (42)$$

With this control method, we search a d-q transformation to improve the behavior of the PMSM at high speed. T^t_{22} and T_{22} have the same expressions as Equations (14). If we take the second control method, with the translation matrix Equation (22):

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = G(2\theta)^{-1} p(-\theta)\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix}$$
$$\begin{bmatrix} i'_\alpha \\ i'_\beta \end{bmatrix} = p(\theta)\,G(\,2\theta)\begin{bmatrix} I_d \\ I_q \end{bmatrix} \quad (43)$$

E. Connected Neutral (Objective: Minimum Loss and Constant Torque)

In this case, to have minimum loss, we take [11]:

$$\frac{e_b}{i_b} = \frac{e_c}{i_c} \tag{44}$$

To have a constant torque, we change the phase currents "b" and "c" (i'_b and i'_c), Thus:

$$\Gamma_f = \frac{e_b i'_b + e_c i'_c}{\Omega} = \frac{e_b i'_b + e_c \frac{e_c}{e_b} i'_b}{\Omega} = \frac{e_b^2 + e_c^2}{\Omega e_b} i'_b \tag{45}$$

$$\begin{cases} i'_b = \dfrac{\Omega e_b}{e_b^2 + e_c^2} \Gamma_f \\ i'_c = \dfrac{\Omega e_c}{e_b^2 + e_c^2} \Gamma_f \end{cases} \tag{46}$$

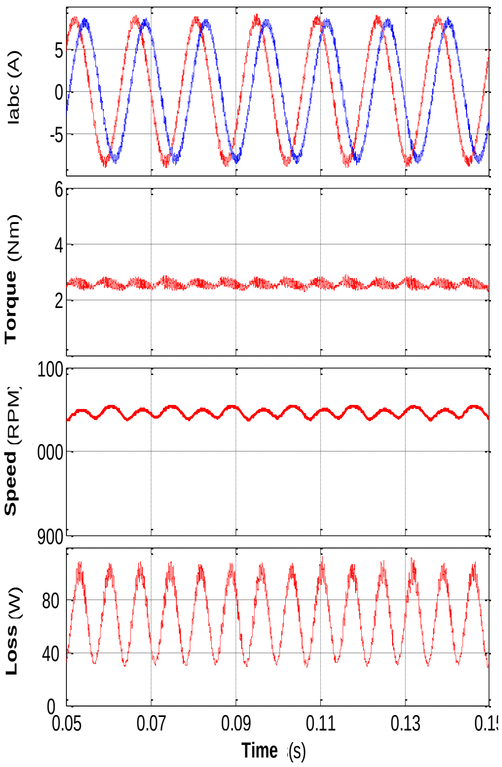

Figure 7. Simulation results of PMSM drive in faulty mode (two phases)

By replacing the Equations (2) in (46):

$$\begin{cases} i'_b = \dfrac{\Gamma'_f}{k} \dfrac{\sin(\theta - 2\pi/3)}{3/2 - \sin^2(\theta)} \\ i'_c = \dfrac{\Gamma'_f}{k} \dfrac{\sin(\theta + 2\pi/3)}{3/2 - \sin^2(\theta)} \end{cases} \tag{47}$$

By replacing the currents and the emfs in the Equation (45), the torque expression is:

$$\Gamma_f = \frac{(k\Omega)^2 \left(\sin^2(\theta - 2\pi/3) + \sin^2(\theta + 2\pi/3)\right)}{-k\Omega^2 (\sin(\theta - 2\pi/3)} \times \\ \times \frac{\Gamma'_f}{k} \cdot \frac{\sin(\theta - 2\pi/3)}{3/2 - \sin^2(\theta)} = \Gamma'_f \tag{48}$$

The current i'_b become maximum in $\theta \approx 53°$ and the maximum value of current is:

$$I'_m = \frac{5}{4} \cdot \frac{\Gamma'_f}{k} \tag{49}$$

$$\Gamma'_f = \frac{4}{5} \cdot kI'_m \tag{50}$$

$$\frac{\Gamma'_f}{\Gamma_{3p}} = \frac{4/5kI_m}{(3/2)kI_m} = \frac{8}{15} = 0.53 \tag{51}$$

The couple became constant and decrease to 53% of its three-phase value, but the loss is less than other methods. Figure 8 shows the simulation results. The average value of torque decreases to 1.9 Nm which is almost like its expected value (53% three-phase value). The current frequency is almost 50 Hz and torque is 100 Hz.

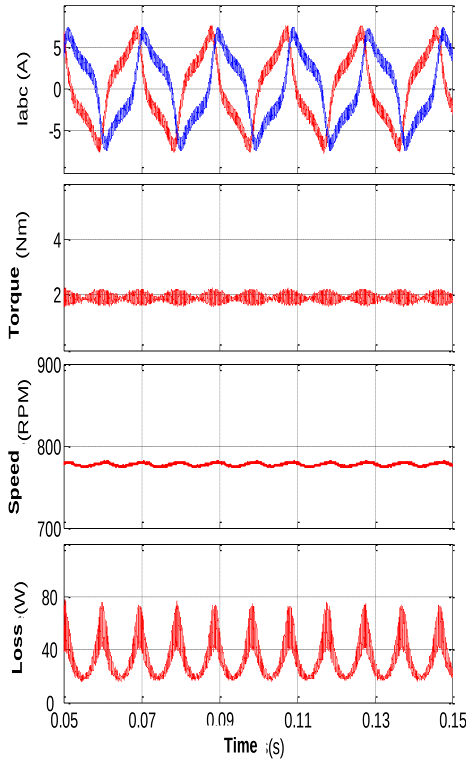

Figure 8. Simulation results of PMSM drive in faulty mode (two phases)

IV. COMPARING THE FIVE CONTROL METHODS IN OPEN CIRCUIT FAULT

Table 1 shows the comparison of control methods under open-circuit fault. The first column shows the control method, the second column shows the average value of torque in percent of three-phase torque, the third column shows the speed in rpm, the fourth column shows the RMS value of torque oscillation by canceling the average torque and the last column shows the loss value. According to this table the torque oscillation of first and second methods is high compared to other methods.

V. CONTROL STRATEGY IN PRESENCE OF SHORT CIRCUIT FAULT

A fault in switch or its control signal can result a short-circuit state when the complementary switch of defective arm become shorted. The short-circuit current is limited only by the inductance of the mesh formed by the cell with the filter capacitor and the resistance of the defective components (Figure 9, green loop). So the short-circuit current may reach excessive amplitudes. Energy dissipation in the components rises, which can cause a sudden explosion of case of IGBTs and the fault propagation around the defective arm [12].

Table 1. Comparing the control methods under open-circuit fault

Control method	Average torque (%)	Speed (rpm)	AC comp. of toque (RMS)	Loss (W)
Normal mode	100	1900	-	86
(1) Without neutral $T=T_{max}$	57	980	1.25	55
(2) With neutral $i'_b=i_b$ and $i'_c=i_c$	66	1280	0.75	70
(3) With neutral $i'_b=i_b$ and $i'_c=-i_a$	50	860	0.107	70
(4) With neutral $T=T_{max}$	57	1050	0.14	70
(5) With neutral Minimum loss	53	780	0.1	35

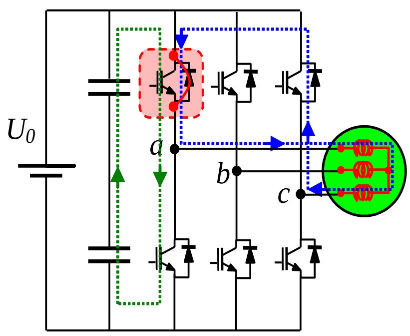

Figure 9. Representation of short-circuit current paths

To avoid these consequences, we must block the control signal of complementary IGBT within a reasonable time (a few microseconds). After a short-circuit fault and blocking the switch of faulty arm, there is another short-circuit loop. The combination of electromotive forces (*emf*s) creates positive voltages across the diodes and allows the circulation of the currents in these paths. Figure 9, the blue loop, shows the current paths at the moment which *emf* of phase "c" is greater than the *emf* of phase "a". This current can be very large and can damage the inverter components.

To consider continuity of service with this type of defect, a solution is integrating isolation switches [12]. Isolation switches are series with IGBTs. Each isolation switch is a bi-direction component and must always be connected, so they increase the conduction loss. If there is possibility of having two isolated source, there can be another structure which has less number of component and less loss and therefore robust to all types of defects of the inverter. Figure 10 shows the proposed circuit [2]. When a fault occurs in a switch of one of two voltage source inverter, the defective inverter injects a zero voltage vector.

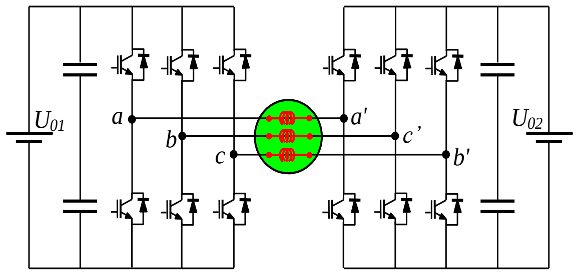

Figure 10. Three-phase PMSM supplied by two isolated sources and two three-phase inverters (structure series)

To do this, depending on the nature of the fault (short-circuit or open-circuit), three switches at the top or three switches at the bottom of the defective inverter should be ON and the other three switches should be OFF. In this case, the maximum phase voltage of the MSAP becomes half of its value in the normal operation mode.

At low speed, the machine can have its maximum torque like in normal mode. For a given torque and a voltage inverter defective, the amplitude of voltage applied to the coil is U_{01} or U_{02}, but in normal mode the voltage is $U_{01}+U_{02}$, so the maximum speed of the MSAP is almost equal to half of the maximum speed in normal mode. Because of reduction of imposed voltage on the winding in fault mode, the maximum torque decreases to half value of its normal mode.

Figure 11 show the simulation results for low speed and high speed. At 0.1 sec an open-circuit fault in a switch at the top (or short-circuit in a switch at the bottom) occur. The defective inverter imposes a zero voltage vector and the non-defective inverter controls the speed. The simulation results indicate that switching from normal mode to defective mode is without any over voltage.

According to figures 11, for the speeds less than half of the maximum speed, the speed control remains insensitive to the switching control algorithm in passage from normal mode to degraded mode. Obviously for the speeds higher than half the maximum speed, due to lack of voltage, the speed cannot reach to its reference value.

VI. CONCLUSIONS

In this paper, different control strategies of a three phase drive in faulty mode are studied. The fault can occur in each part of drive such as power supply, inverter and electric machine. In this research, we limit ourselves to the inverter faults like short-circuit or open-circuit fault of one switch. For a switch open-circuit fault, six control strategies are studied. The differences of these methods are in torque oscillation, machine copper losses and simplicity of method. In the case of short-circuit fault, we can use three-phase PMSM supplied by two isolated sources and two three-phase inverters to have a robust drive against this kind of fault.

It is shown that the presented structures can operate under open-circuit or short-circuit fault of one inverter switch. The only requirement is having a fast fault detection method to avoid the fault propagation to the other elements of the system.

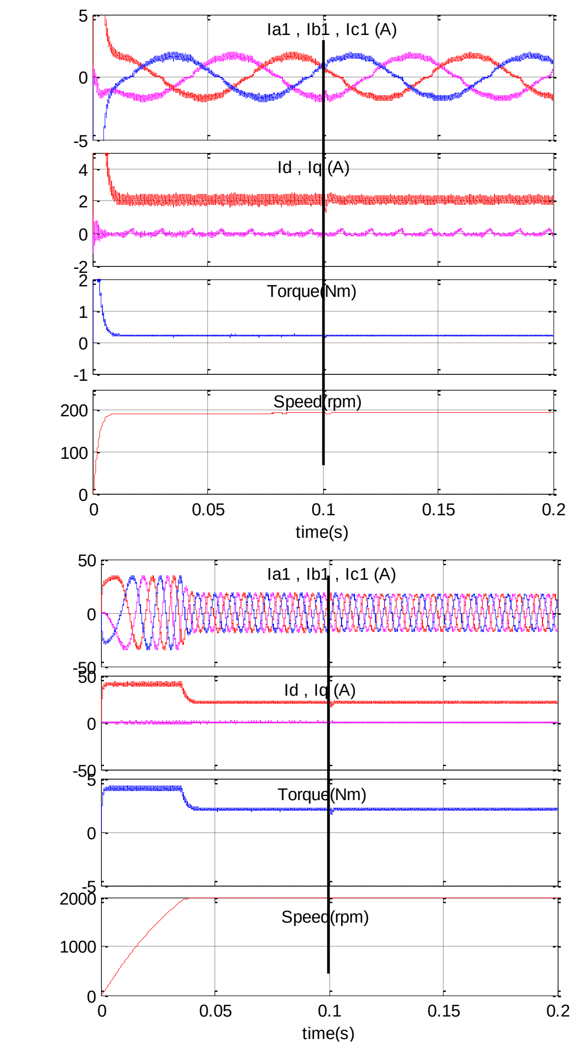

Figure 11. Simulation results for an open-circuit fault in a switch at top (or short circuit in a switch at the bottom) at 0.1 sec using proposed control strategy, (a) low speed (200 rpm) and (b) high speed (2000 rpm)

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