Control Strategies for Fault Tolerant PM Drives Using Series Architecture

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***Abstract*–A fault tolerant drive based on a series architecture (one or two DC sources, two voltage source inverters and a PMSM) is studied in this paper. Three different operating modes are considered: normal mode, open-circuit degraded mode and short-circuit degraded mode. For each case, an adapted torque control strategy is proposed, applied and tested. The main contribution lies in the control strategies for degraded modes. For the open phase mode, different operating criteria are considered. For short-circuit faults, two solutions are proposed. The proposed strategies in this paper are tested on a drive realized for aerospace applications. The proposed techniques here allow operating under fault conditions in real-time and their implementation is easy. The experimental results show the validity of the proposed methods.**

***Index Terms*–Fault tolerant drives, PMSM, open phase fault, short-circuit fault.**

I. INTRODUCTION

Permanent Magnet Synchronous machines (PMSM) are well adapted for transportation applications because of their good torque/mass ratio. Obviously, the reliability is an important issue in these applications where the PMSM are supplied by one or two (if available) DC voltage sources through voltage source inverters (VSIs). More, in these applications it is necessary that the system can operate in degraded mode under the presence of almost any fault in one of the electromechanical elements of the energy conversion chain. It is why fault tolerant drives have attracted more and more attention since early nineties [1]-[14]. A solution to obtain the required level of reliability is to modify the architecture of the drive by replacing each device of low reliability by two or several modular devices of the same nature (in parallel or in series). Voltage source inverters, which have several components, may be considered as the least reliable elements of the system [9]. It is why in some applications, two VSIs are employed in series for supplying the machine (Fig. 1). There are two options: supplying by one electrical source with three H-bridges (Fig. 1a) or using two independent electric sources (Fig. 1b) in some air and sea transport systems where two independent generators are available. The both cases are called here series architecture.

In this paper, normal and degraded operating modes of this drive architecture are studied. Two degraded modes are considered: T_a in open-circuit and T_a in short-circuit. To improve the torque control performances, proper current control strategies are presented for degraded modes.

This paper is organized in three sections. The model of the drive with one or two DC sources is given in the next section. Then, different operating modes (normal, under open-circuit and under short-circuit faults) are studied in detail. For each mode, analytical and experimental results are given. In the third section, conclusions are presented.

II. DRIVE MODEL AND ITS OPERATING MODES

It is obvious from Fig. 1a that the phase voltages are the following:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} v_{am} \\ v_{bm} \\ v_{cm} \end{bmatrix} - \begin{bmatrix} v_{a'm} \\ v_{b'm} \\ v_{c'm} \end{bmatrix} = U_0 \cdot \begin{bmatrix} C_a - C_{a'} \\ C_b - C_{b'} \\ C_c - C_{c'} \end{bmatrix} \tag{1}$$

where C_a denotes the "conduction state" of the whole switch containing T_a and its parallel diode together (1=conducting, 0=blocking). Then, the model of the machine is written as follow:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_s \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_s \cdot \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2}$$

with e_a and i_a as respectively the back-EMF and the current of the phase a.

For the architecture shown in Fig. 1b, we have $i_a+i_b+i_c=0$. Then, we can write:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = T_{33} \cdot \left(\begin{bmatrix} v_{am1} \\ v_{bm1} \\ v_{cm1} \end{bmatrix} - \begin{bmatrix} v_{a'm2} \\ v_{b'm2} \\ v_{c'm2} \end{bmatrix} + \begin{bmatrix} v_{m1m2} \\ v_{m1m2} \\ v_{m1m2} \end{bmatrix} \right) \tag{3}$$

which gives:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = U_{01} T_{33} \cdot \begin{bmatrix} C_a \\ C_b \\ C_c \end{bmatrix} - U_{02} T_{33} \cdot \begin{bmatrix} C_{a'} \\ C_{b'} \\ C_{c'} \end{bmatrix} \tag{4}$$

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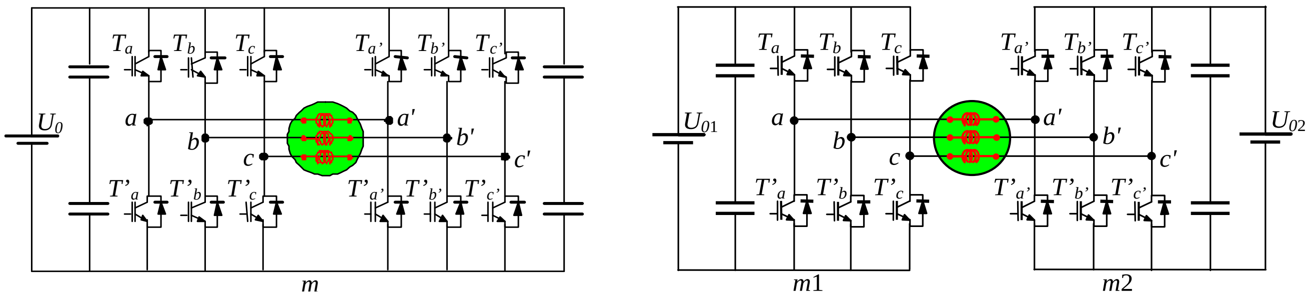

Fig. 1. PMSM supplied with one (left) or two (right) DC voltage source(s) and two inverters (series architecture).

with:
$$T_{33} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (5)$$

In this paper, we consider three cases: normal operating, $T_{a'}$ open-circuited and $T_{a'}$ short-circuited. For each case, the corresponding torque control strategy is studied. For this study, the back-EMF is supposed sinusoidal as follows:

$$\begin{cases} e_a = -\sqrt{\frac{2}{3}}\Psi_f P\Omega\, sin(\theta) = -k\Omega\, sin(\theta) \\ e_b = -\sqrt{\frac{2}{3}}\Psi_f P\Omega\, sin\left(\theta - \frac{2\pi}{3}\right) = -k\Omega\, sin\left(\theta - \frac{2\pi}{3}\right) \\ e_c = -\sqrt{\frac{2}{3}}\Psi_f P\Omega\, sin\left(\theta + \frac{2\pi}{3}\right) = -k\Omega\, sin\left(\theta + \frac{2\pi}{3}\right) \end{cases} \quad (6)$$

Knowing that the motor torque expression is the following:

$$\Gamma_m = \frac{e_a i_a + e_b i_b + e_c i_c}{\Omega} \quad (7)$$

It is obvious that the torque control strategy consists in determining the phase currents references. This will be done at first in *abc* frame for each studied case, then the obtained current references will be transformed in a synchronous frame (*dq* frame).

a) Case 1: Normal operating mode

This mode is studied for giving a comparison base with faulty modes. To get a non pulsating motor torque in normal operating mode, it is sufficient to have balanced sinusoidal phase currents:

$$\begin{cases} i_a = -I_m \sin(\theta) \\ i_b = -I_m \sin(\theta - 2\pi/3) \\ i_c = -I_m \sin(\theta + 2\pi/3) \end{cases} \quad (8)$$

Then, the motor torque is the following:

$$\Gamma_m = \frac{3}{2} k I_m \quad (9)$$

As usual, a synchronous rotating frame (*dq*) can be defined to make easier the current controller design and to get more robust current controllers. We have:

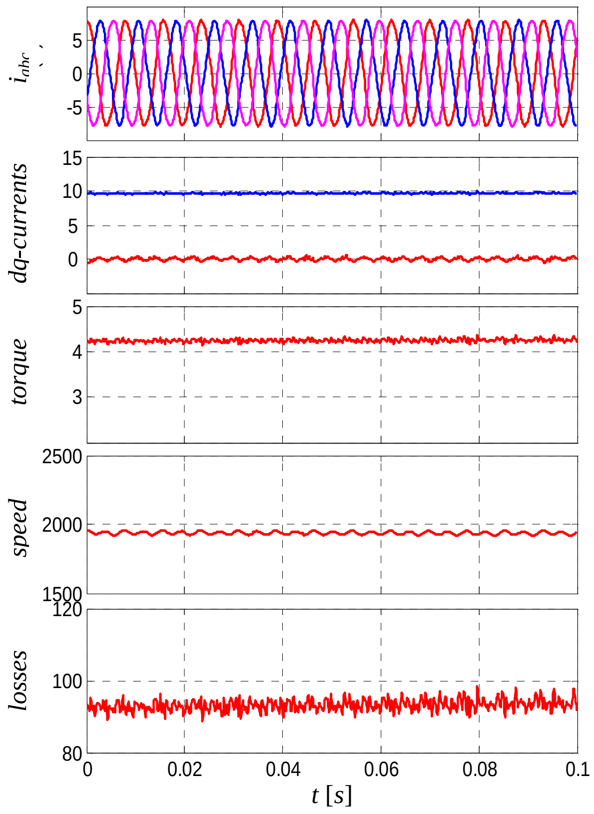

Fig. 2- Experimental results under normal operating mode: phase currents (i_{abc}) [A], *dq*-currents [A], torque [Nm], speed [rpm] and losses [W].

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = P(-\theta)\cdot T_{32}^T \cdot \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (10)$$

with: $T_{32} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}$, $P(\theta) = \begin{bmatrix} cos\,\theta & -sin\,\theta \\ sin\,\theta & cos\,\theta \end{bmatrix}$ (11)

in which θ is the electrical position of the rotor and x=v, e or i. The motor torque expression in this dq-frame is:

$$\Gamma_m = \sqrt{3/2}\cdot k \cdot i_q \quad (12)$$

It is clear from (12) that q-current should be constant to obtain a constant non pulsating motor torque.

Fig. 2 illustrates experimental results for the normal operating mode. The motor torque (estimated according to (7)) does not oscillate and dq-currents are almost constant. The phase currents (i_{abc}) are balanced. The experimental set-up and its parameters are described in Appendix.

Note- To maximize the available voltage for operating at high speed, the command signals of the inverters are forced to be complementary ($C_a = \overline{C}_{a'}, C'_a = \overline{C'}_{a'}, \ldots$).

b) Case 2: $T_{a'}$ open-circuited

When $T_{a'}$ is open-circuited, i_a can no more be controlled. We have to commutate to a degraded mode. Two different strategies may be adopted:

- forcing i_a to zero (Fig. 3),
- or forming a neutral point by connecting the points *a'*, *b'* and *c'* (Fig. 4).

The latter solution is easy to implement and well adapted to the architecture shown in Fig. 1b because i_a+i_b+i_c=0. But it reduces the available voltage and consequently the maximum achievable speed as it is obvious from Fig. 4.

The former solution is more suitable for the architecture in Fig. 1a. For forcing i_a to zero, we open the other three transistors related to the phase *a* ($T'_{a'}$, T_a and T'_a) as illustrated on Fig. 3. Then, the remaining phase currents (i_b and i_c) can be controlled independently and should be modified to suppress the resulting pulsating torque due to unbalance. To do that, it is known that the opened phase current should be put, in the opposite sign, to one of the healthy phases. In our case, $-i_{ahealthy}$=$+I_m.sin(\theta)$ (see (8)) should be the reference of i_b or i_c under fault condition. This choice leads to a non pulsating motor torque which can be easily verified from (7). Here, we choose $i_{cfaulty}$=$-i_{ahealthy}$:

$$\begin{cases} i_a = 0 \\ i_b = -I_m\,sin(\theta - 2\pi/3) \\ i_c = +I_m\,sin(\theta) \end{cases} \quad (13)$$

Replacing (13) and (6) in (7), we have:

$$\Gamma_m = \frac{3}{4} k I_m \quad (14)$$

Comparing (14) with (9), one can conclude that the motor torque under fault condition is the half of that in normal operating mode.

Fig. 5 shows experimental results when the phase *a* is opened and current references in (13) are used to control the motor torque. As it was expected, the motor torque is about 2.1 Nm (for 4.2 Nm in normal mode). The pulsating torque is not completely suppressed because of the current controller dynamic. It should be noted that the current control is realized in the synchronous frame.

One may ask if it is possible to improve the average torque in faulty mode. The question is how should change the remaining phase currents (i_b and i_c) to suppress the pulsating torque and to maximize the average torque. To study that, we put:

$$\begin{cases} i_a = 0 \\ i_b = -I_m\,sin(\theta - \beta) \\ i_c = -I'_m\,sin(\theta - \gamma) \end{cases} \quad (15)$$

Then, from (6), (7) and (15), the motor torque expression is given in Eq. (16):

$$\Gamma_m = kI_m \cdot sin(\theta-\beta)\cdot sin(\theta - 2\pi/3) + kI'_m \cdot sin(\theta-\gamma)\cdot sin(\theta+2\pi/3) \quad (16)$$

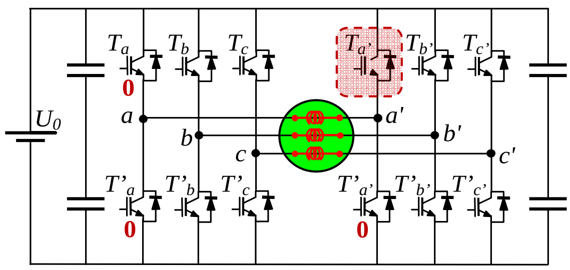

Fig. 3. Series architecture with an open-circuit fault (one source).

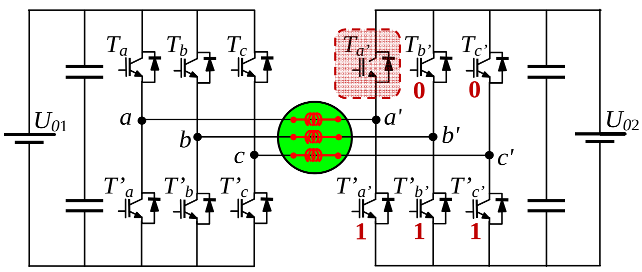

Fig. 4. Series architecture with an open-circuit fault (two independent sources).

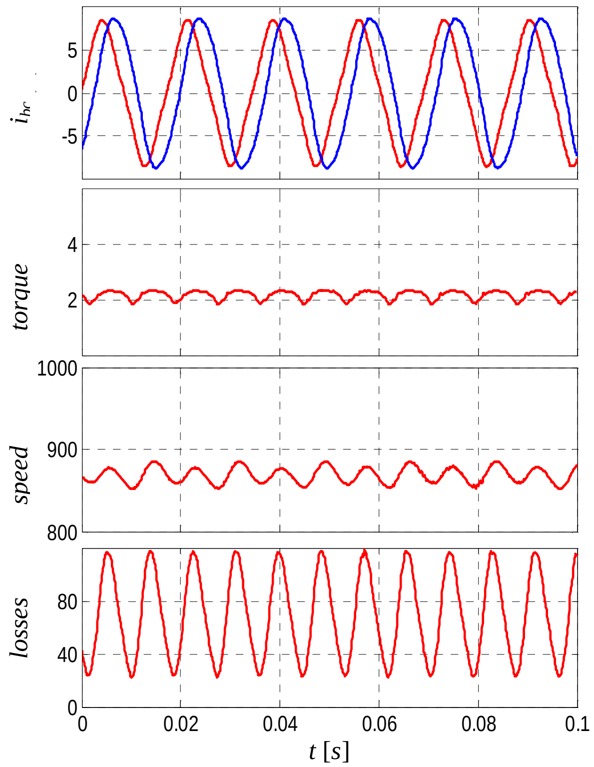

Fig. 5- Experimental results under open phase fault using (13): phase currents (i_{abc}) [A], torque [Nm], speed [rpm] and losses [W].

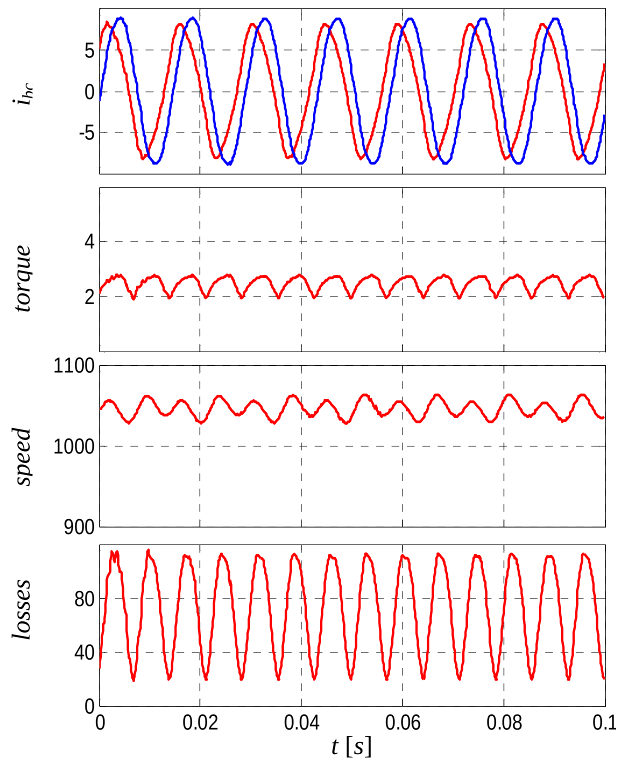

Fig. 6- Experimental results under open phase fault using (15): phase currents (i_{abc}) [A], torque [Nm], speed [rpm] and losses [W].

After simplification, we get:

$$\Gamma_m = \frac{kI_m}{2}\left(cos(2\theta-\beta-2\pi/3)+cos(\beta-2\pi/3)\right) + \frac{kI'_m}{2}\left(cos(2\theta-\gamma+2\pi/3)+cos(\gamma+2\pi/3)\right) \quad (17)$$

Then, to suppress the pulsating torque, we have the following:

$$\begin{cases} I_m = -I'_m \\ \gamma-\beta = \dfrac{4\pi}{3} \end{cases} \quad (18)$$

which leads to the following constant torque:

$$\Gamma_m = \frac{kI_m}{2}\left(cos(\beta-2\pi/3)-cos(\beta)\right) \quad (19)$$

This torque will be maximal if:

$$\beta = \frac{5\pi}{6}, \ \gamma = \frac{\pi}{6} \quad (20)$$

Replacing (20) in (19), we obtain the following constant torque under open-phase fault condition:

$$\Gamma_m = \frac{\sqrt{3}}{2}kI_m \quad (21)$$

It is clearly more advantageous to choose i_b and i_c according to (15), (18) and (20), because the torque in (21) is 15% greater than that in (14).

Fig. 6 illustrates experimental results under open phase conditions when Eq. (15) is used to fix the phase current references. It is obvious from the angular speed that the average torque is slightly greater than that in Fig. 5.

In the same manner, one may minimize the losses. Here, because of space restrictions, we give only main theoretical results and some experimental ones.

To minimize the losses, the following should be verified:

$$\frac{e_b}{i_b} = \frac{e_c}{i_c} \quad (22)$$

From (22), (6) and (7), we obtain:

$$\begin{cases} i_b = \dfrac{4}{5}\cdot\dfrac{sin(\theta-2\pi/3)}{3/2-sin^2(\theta)}\cdot I_m \\ i_c = \dfrac{4}{5}\cdot\dfrac{sin(\theta+2\pi/3)}{3/2-sin^2(\theta)}\cdot I_m \end{cases} \quad (23)$$

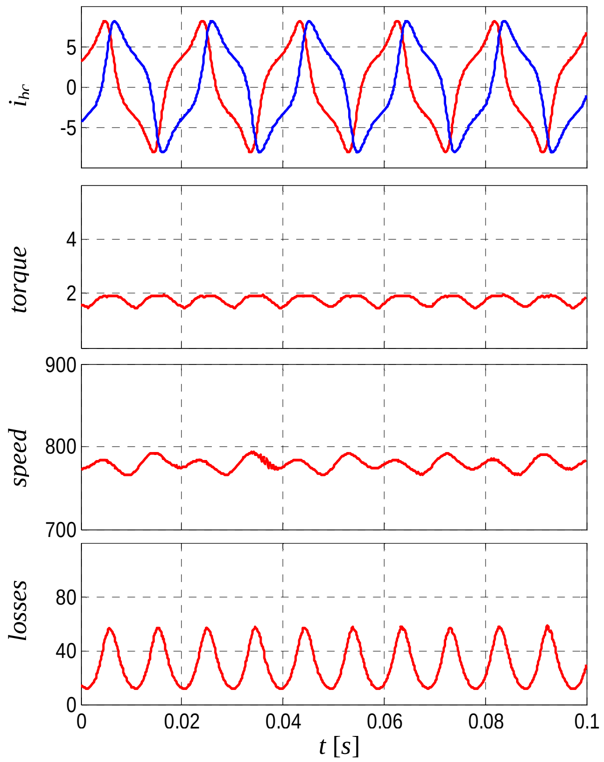

Fig. 7- Experimental results under open phase fault using (23): phase currents (i_{abc}) [A], torque [Nm], speed [rpm] and losses [W].

Fig. 7 depicts experimental results under open phase conditions when healthy phases are set to (23). The machine losses, calculated from measured currents, reduced significantly with respect to the previous torque control strategies (compare with Figs. 5 and 6). The pulsating torque is negligible and the average torque is slightly less than those in Figs. 5 and 6. It should be noted that the current references in (23) requires big efforts from the current controllers because of their special shape.

c) Case 3: $T_{a'}$ short-circuited

In the case of short-circuit fault on $T_{a'}$, i_a is no more controllable and we have to commutate to a degraded mode. The only solution that we propose here is to form a neutral point by connecting the points *a'*, *b'* and *c'* as shown in Fig. 8. Then, the machine will be controlled with the healthy inverter as a simple three phase machine. It is obvious that the available voltage will reduce with this strategy and the rated speed may not be achieved in the degraded mode.

If there is only one DC source for supplying the both inverters, then the solution consists in short-circuiting the faulty phase by proper command signals (Fig. 9). But in this case, the machine should be well studied and designed in order to limit the short-circuit current.

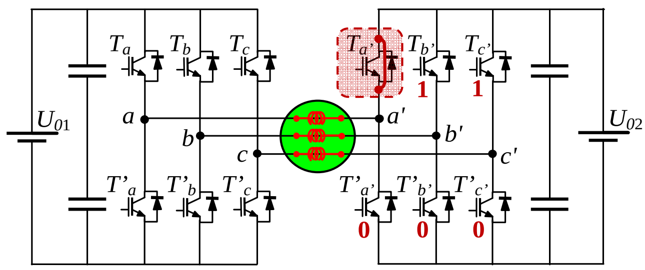

Fig. 8. Series architecture with a short-circuit fault (two independent sources).

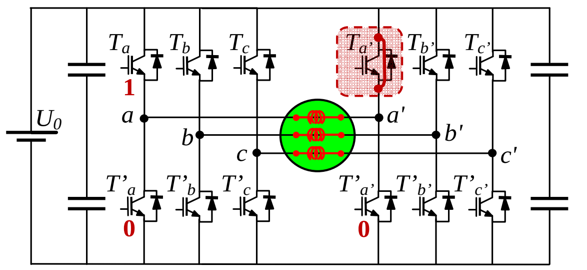

Fig. 9. Series architecture with a short-circuit fault (one source).

Conclusion

A series architecture consisting of one or two DC sources, two voltage source inverters and a PMSM is studied in this paper. The objective is to realize a fault tolerant drive for aerospace applications. Three different operating modes are considered: normal mode, open-circuit degraded mode and short-circuit degraded mode. Different torque control strategies are studied and compared. For the open phase mode, according to the number of independent sources, two general strategies are studied. The pulsating torque and the motor losses are minimized under fault conditions. In the case of short-circuit faults, a simple strategy is proposed. For the case of one DC source, it needs some precautions while designing the machine. The proposed strategies in this paper are effectively applied to a test bench. They allowed operating under fault conditions in real-time and their implementation is easy. The experimental results show the validity of the proposed methods.

Appendix

The experimental set-up is shown in Fig. 10 and its parameters are given in Table 1. The machine is a permanent magnet synchronous one. Two voltage source inverters supply the machine. The drive is controlled by a dSPACE digital control card (DS1005) whose sampling period is 100 μs. It sends PWM commands to an interface card and then to IGBTs. The DC source voltage is set to 200 V. The load is a PM synchronous generator supplying a variable resistance.

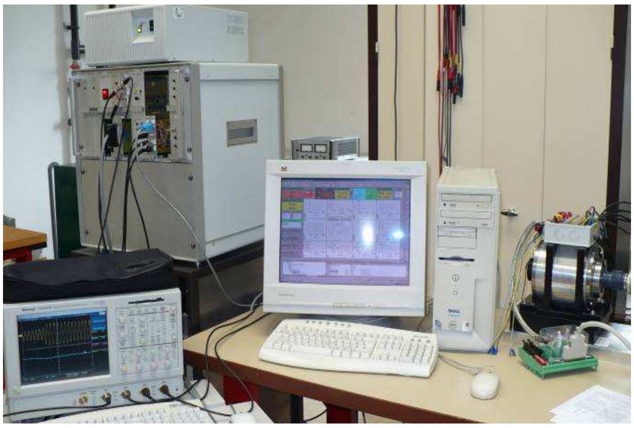

Fig. 10- Experimental set-up.

TABLE 1
EXPERIMENTAL SYSTEM PARAMETERS

no. of poles	8
Rated output	1 kW
DC-bus voltage	200 V
Switching frequency	10 kHz
Rated speed	1800 rpm
Rated torque	5.8 Nm
Stator resistance	0.5 Ω
Stator inductance	3.1 mH
Torque coefficient	24×10^{-3} Kg.m²/s
Inertia coefficient	3×10^{-3} Kg.m²

REFERENCES

[1] J.R. Fu, and T.A. Lipo, "Disturbance-free operation of a multiphase current-regulated motor drive with an open phase," *IEEE Trans Ind. Applicat.*, vol. 30, no. 5, pp. 1267-1274, Sept./Oct. 1994.

[2] E. Schaeffer, E. Le Carpentier, M.E. Zaim, Luc Loron, "Failure detection in induction machines by means of parametric identification", *Computational Engineering in Systems applications*, 1998.

[3] A. Bouscayrol, B. Davat, B. De Fornel, B. François, J.P. Hautier, F. Meibody-Tabar, and M. Pietrzak-David, "Multi-machine multi-converter systems: applications to electromechanical drives," *EPJ Applied Physics*, vol. 10, no. 2, pp. 131-147, May 2000.

[4] B. Nahid-Mobarakeh, F. Meibody-Tabar, F.M. Sargos, "Robustness study of a model-based technique for mechanical sensorless PMSM," in *Proc. PESC'01*, pp. 811-816, Vancouver, 2001.

[5] G. Didier, H. Razik, H. Rezzoug , " On the modeling of induction motor model including the first space harmonics for diagnostics purposes", *ICEM'2002* [CD-ROM], Bruges, Belgium, Jan. 2004.

[6] C.B. Jacobina, R.S. Miranda, M.B. De R. Corrêa, and A.M.N. Lima, "Disturbance-free operation of a six-phase AC motor drive system," in *Proc. the 35th IEEE Annual Power Electronics Specialists Conference* (*PESC'04*), vol. 2, pp. 925-931, Aachen, June 2004.

[7] Dan Sun, Yikang He, "A modified direct torque control for PMSM under inverter fault," in *Proc. ICEMS'05* [CD-ROM], pp. 2473 – 2473, 2005.

[8] A.M. Mendes, and A.J. Marques Cardoso, "Fault-Tolerant Operating Strategies Applied to Three-Phase Induction-Motor Drives**,"** *IEEE Trans. Ind. Electron.*, vol. 53, no. 6, pp. 1807-1817, Dec. 2006.

[9] M.E.H. Benbouzid, D. Diallo, and M. Zeraoulia, "Advanced Fault-Tolerant Control of Induction-Motor Drives for EV/HEV Traction Applications: From Conventional to Modern and Intelligent Control Techniques," *IEEE Trans. Vehicular Technology*, vol. 56, no. 2, pp. 519-528, March 2007.

[10] O. Wallmark, L. Harnefors, and O. Carlson, "Control Algorithms for a Fault-Tolerant PMSM Drive," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 1973-1980, Aug. 2007.

[11] T. Boileau, B. Nahid-Mobarakeh, F. Meibody-Tabar, "Back-EMF based detection of stator winding inter-turn fault for PM Synchronous Motor Drives", *VPPC'2007* [CD-ROM], Arlington, Texas, U.S.A, Sept. 2007.

[12] M.A. Shamsi-Nejad, B. Nahid-Mobarakeh, S. Pierfederici, F. Meibody-Tabar, "Fault tolerant and minimum loss control of double-star synchronous machines under open phase conditions," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 5, pp. 1956-1965, May 2008.

[13] S. Khwan-on, L. de Lillo, L. Empringham, P. Wheeler, C. Gerada, N.M. Othman, O. Jasim and J. Clare, "Fault tolerant power converter topologies for PMSM drives in aerospace applications," in *Proc. EPE'09* [CD-ROM], Barcelona, Sept. 2009.

[14] Hai Lin, Hong Li, Yintao Wang, Mingfeng Li, Peng Wen, Chunhui Zhang, "On inverter fault-tolerant operation vector control of a PMSM drive," in *Proc. ICIS'09* [CD-ROM], pp. 522 – 526, 2009.

[15] R.A. Hanna, and S. Prabhu, "Medium-voltage adjustable speed drives – Users and manufacturers experiences," *IEEE Trans. Ind. Applicat.*, vol. 33, no. 6, pp. 1407-1415, Nov./Dec. 1997.