Inverter topology comparison for remedial solution in transistor faulty case

DOC Caroline, LANFRANCHI Vincent, FRIEDRICH Guy
Laboratoire d'Electromécanique de Compiègne – U.T.C. (E.A. 1006)
B.P. 20529
60205 Compiègne Cedex, FRANCE
Tel.: +33 /.(0) – 344234507
Fax: +33 / (0) – 344237937.
E-Mail: caroline.doc@utc.fr ; vincent.lanfranchi@utc.fr ; guy.friedrich@utc.fr

Keywords:

«Converter circuit», «fault handling strategy», «mechatronics», «permanent magnet motor», «reliability», «simulation», «three phase system»

Abstract

Electric actuators are more and more used for application requiring high reliability. A study of different inverter topologies to increase reliability and avoid an expensive redundancy is presented. To illustrate our words, remedial operations are applied to the case of short-circuited transistor of the inverter.

Introduction

Nowadays, electric actuators are more and more used for applications requiring high reliability, like X-by-wire or plane actuators. In aeronautic, several actuators are used for the same function. Thus, when a fault occurs, the motor and the inverter are disconnected. This kind of redundancy is not acceptable in car industry because of required compactness and low cost. That is why in a faulty case, the actuator has to still be operating, even with lower performance in order to park the car or to reach home.

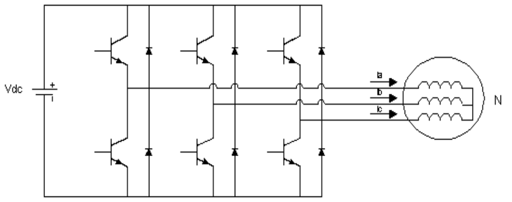


Fig. 1: Topology of 3-leg half bridge inverter

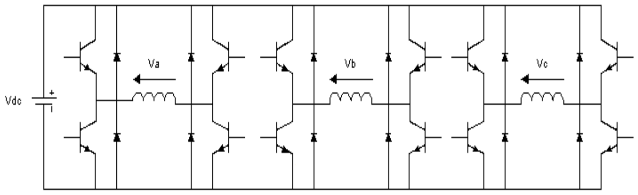


Fig. 2: Topology of 3-leg full-bridge inverter

To improve the reliability of the inverter-machine system, the commonly admitted idea is to increase the redundancy, for example, in increasing the number of motor phases or the complexity of the inverter. An other solution is to design the system to limit the effects of a fault. In [1], Mecrow advises to separate the phases. Mechanical separation, realized by having one slot per winding, prevents from having inter-phase short circuit. Electrical separation allows controlling phases independently, which is possible with a full bridge since phases are electrically separated. The reliability considerations can be taken into account from the motor conception, by instance, to have the lowest short-circuit current [1].

A full bridge creates a redundancy by using twice as many components as a half bridge inverter but allows disconnecting easily the faulty phase without any consequences on the remaining phases. However, if we can drive the motor with only two phases of the half bridge inverter too, there will be no more advantages in using a full bridge inverter. The main advantage of half bridge inverter is that it needs fewer components.

Besides, in usual dq motor models, we supposed that the system is balanced. In this case, the sum of the currents is null that is why the zero-sequence component is not calculated and fixed to 0. In case of fault, whatever the type or the location, the system is not balanced anymore. The zero sequence components is different from zero but if we use classical dq model for motor, it will still be fixed to 0 and results will be wrong. The real value of zero sequence component is needed to compute the phase currents in order to control the system in faulty case.

In the case of this study, we use a permanent magnet synchronous motor that has a low failure rate because of the absence of mechanical commutator. Moreover, according to [6], most of the failures are due to a dysfunction of a switching component. The weak part of the system is definitely the inverter. That is why this study is focused on inverter.

This article presents a comparison between full bridge inverter (or H-bridge), 3-leg and 4-leg half bridge inverter for supplying a 3-phase motor when a fault occurs. A simplified model based on electrical representation, including computation of zero sequence components, is used to test different strategies in the occurrence of a short circuit fault on a transistor, which occurs 80% of the whole failure rate [6]. The simulation results allow us to foresee and compare their behaviour but also to improve them by using a remedial strategy of control.

In a first part, we describe the studied system and the modelisation used. Then, we simulate the effects of default on a 3-leg half bridge inverter. In a third part, we study how the use of a full-bridge inverter could improve the system behaviour in case of fault. And finally, we test the case of a 4-leg half bridge inverter, which presents a good compromise.

Description of system and modelisation

The system we simulated is a simplified electric model of a 3-phase permanent magnet synchronous motor and its inverter. Each phase of the motor is modelized as a resistor, an inductance and a voltage source, which represents the e.m.f., in series. This electrical circuit is modelised thanks to Matlab Simulink toolbox Power BlockSet. We “measure” (I_a, I_b, I_c), which pass through the modelised phases, then, calculate (I_d, I_q, I_0) with Park transformation (Equations (1), (2)), in order to compute the produced torque according to the Equation (3) and, later, to control the motor. In case of disconnection of a faulty phase, the Equation (3) could be modified. Indeed, Ld and Lq, direct and quadratic inductances, could change because of the modification of the mutual inductance.

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = C^{-1} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} \qquad (1)$$

$$C^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \text{ where } \theta \text{ is the electric angle} \qquad (2)$$

$$Te = \frac{3}{2} p(i_q F + (L_d - L_q) i_d i_q) \qquad (3)$$

The motor will be star-mounted when a 3-leg inverter is used. When a H-bridge inverter will be used, each winding connection will be plugged to a leg of the H-bridge. The winding connections will thus have to be available. To use the 4-leg inverter, the motor will be star mounted and the neutral point will be plugged to the forth leg.

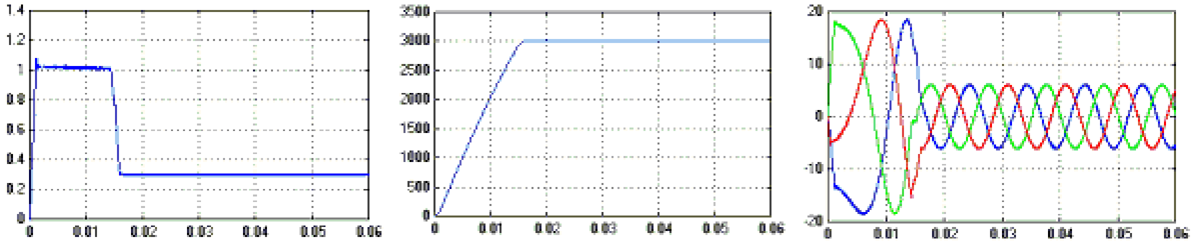
For all the legs, the switching components of the same leg are forced to be in opposition. In the faulty case, if a transistor is in short-circuit, then the other stay opened and the source could not be short-circuited. All the transistors plus free-wheel diodes are modelized by an ideal switch block of the Power BlockSet toolbox but could, as well, been modelized with the Mosfet block. Mosfet block simulates both transistor and diode. Both solutions have been tested and lead to a different results only in open-circuit fault due to the fact that current could not return through the open switch as it could through the free-wheel diode. In the case of short-circuited transistor, which is the one studied here, results of both simulations are the same. That is why the ideal switch could be used to reduce simulation time.

a) Ideal switch b) Mosfet

Fig. 3: Power BlockSet Block

The targeted reference is the motor speed. For all the simulation, a PID controls the system. A resistive torque is applied. This torque is proportional to the speed. From 0 ms to 18 ms, the motor runs in a transient mode. During this transient mode, the speed is rising until reaching the target speed (here 3000 rpm). After t=18 ms, the system is in established mode and the speed is then constant and equal to the target.

The Figure (4) shows the results of simulation in the unfaulty case (whatever the used inverter). The instantaneous torque, speed and effective currents are presented.



a) Torque (Nm) b) Speed (rpm) c) Currents Ia Ib Ic (A)

Fig. 4: Simulation results for unfaulty case

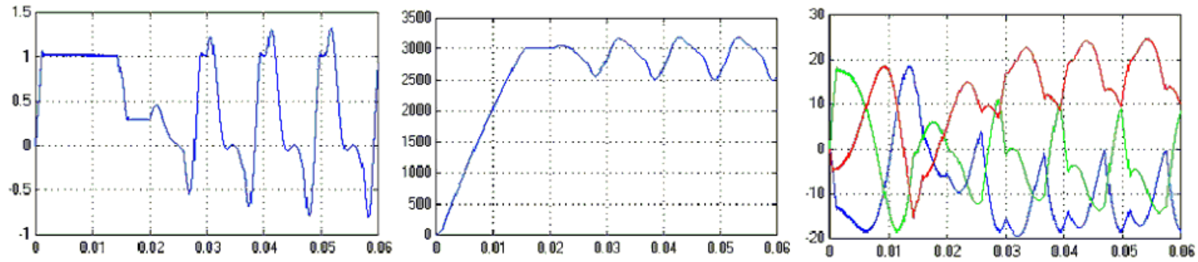
3-leg inverter

We point out that, for the 3-leg inverter, the motor is star-mounted and thus, the sum of currents has to be null.

The simulated fault is a short circuit on the upper transistor, which means that the ideal switch, modelising it, is always in closed position. As mentioned before, this fault is the most frequent one. As the lower transistor is in opposite position, it is always opened.

The fault occurs at t=20 ms. This study is limited to the disfunctionment take place after the transient ends. If the point was about reaching a position within a given time, even in faulty case, a fault could as well been triggered at t=0 ms.

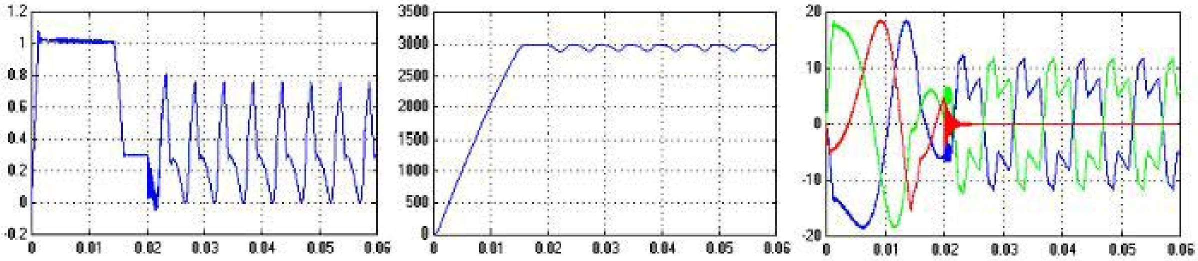
The Figure (5) shows the consequences on torque, speed and currents of a short circuit on upper transistor of half bridge inverter if no remedial solution would be applied. We can notice first that I_c is always bigger than zero. Indeed, the C-leg of the inverter could only be linked with the positive connection of the battery. Moreover, we can see that torque and speed oscillations are not negligible. In a current application, this would lead to harmful vibrations, which could lead from simple discomfort to mechanical disfunctionment. Our goal was then to find a solution to reduce these oscillations and reach the speed reference.



a) Torque (Nm) b) Speed (rpm) c) Currents Ia Ib Ic (A)

Fig. 5 : Simulation results for short-circuited upper transistor of 3-leg half bridge inverter

The first idea was to disconnect the faulty phase since this phase is out of control. However, the motor is star-mounted, so $I_a= -I_b$. The results of such a solution are shown in Figure (6). We can notice that the amplitude of oscillating speed is smaller than the case without any modification but the cogging torque remain important. Furthermore, the zero sequence component is then null which reduce the losses.



a) Torque (Nm) b) Speed (rpm) c) Currents Ia Ib Ic (A)

Fig. 6: Simulation results for faulty phase disconnected of 3-leg half bridge inverter

H- bridge

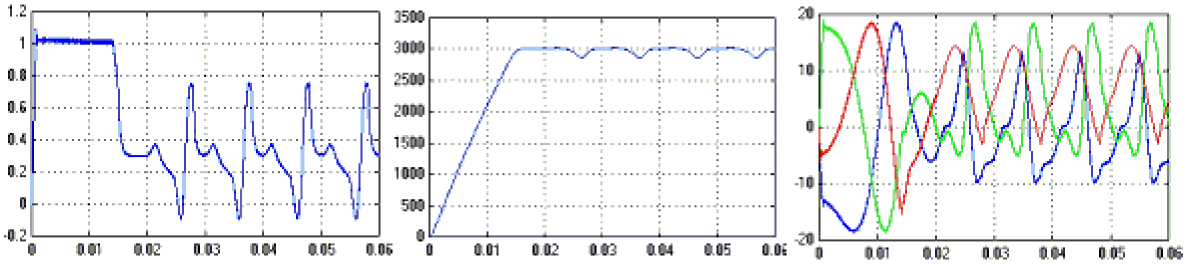
Thus, the 3-leg inverter doesn't offer a satisfying solution, the solution that comes immediately, is to increase redundancy in order to increase reliability. However, the H-bridge is the inverter that offers the maximum of redundancy. That is why H-bridge could be used in application requiring a high rate of reliability, in spite of the over cost it implies.

Full bridges are used for three main reasons:

- When a transistor breaks, there is no change on the healthy phases because current path are independent [1]
- It is still existing a way for current to circulate in the faulty phase because when a transistor is short-circuited, it freezes only one half of the H-bridge. Two values of tension are still accessible (for a upper short circuited transistor, tension of winding can be 0V or Vdc)
- It is easier to disconnect the faulty phase thus opening all the transistors, which remain under control, disconnect the faulty phase.

We can compare the produced torque with the torque created by a 3-leg half bridge inverter with a short circuit on the upper transistor. When a fault occurs, we open the complementary transistor to avoid having a short circuit on the power supply. Then we could either open the two remaining transistors to disconnect the faulty phase, or continue to drive them for having a less effective but still operative phase. The faulty phase has to be disconnected in order to prevent from unforeseeable behaviour [1].

In this case, we obtain torque and speed oscillations (Figure (7)) whose amplitudes are equal to those of the 3-leg bridge inverter case. So, despite the redundancy, results are not better. Nevertheless, the case showed in the Figure (6) doesn't induce an over-cost because the modification is carried out by a modification of the control laws. In this case, there would be no advantages to use a H-brige.



a) Torque (Nm) b) Speed (rpm) c) Currents Ia Ib Ic (A)

Fig. 7: Simulation of a fault H-bridge (faulted phases still connected)

At this moment, we have only modified the topogy of the inverter, but not its control laws. The system is controled in order to get the control laws shown in Equation (4), which are the classical laws.

$$\begin{cases} i_a{}^* = i_d{}^* \cos\theta + i_q{}^* \sin\theta \\ i_b{}^* = i_d{}^* \cos(\theta - \frac{\pi}{3}) + i_q{}^* \sin(\theta - \frac{\pi}{3}) \\ i_c{}^* = i_d{}^* \cos(\theta + \frac{\pi}{3}) + i_q{}^* \sin(\theta + \frac{\pi}{3}) \end{cases} \qquad (4)$$

The obtained results are not as satisfying as expected compared to the over cost linked to the redundancy. But a better torque could be obtained by modifying the control laws to take into account default [2], [3], [9]. Indeed, since we disconnect the faulty phase (we assumed the faulty phase is the phase C), no current could pass through it anymore. According to [4], we can use Equation (5):

$$\begin{cases} i_a{}^* = i_\alpha{}^* + i_0{}^* \\ i_b{}^* = -\frac{i_\alpha{}^*}{2} + \frac{\sqrt{3}}{2} i_\beta{}^* + i_0{}^* \\ i_c{}^* = -\frac{i_\alpha{}^*}{2} - \frac{\sqrt{3}}{2} i_\beta{}^* + i_0{}^* \end{cases} \qquad (5)$$

So, we can fix $I_c=0$ as a reference and then make disappear i_0 component.

$$\begin{cases} i_a{}^* = \frac{3}{2} i_\alpha{}^* + \frac{\sqrt{3}}{2} i_\beta{}^* \\ i_b{}^* = \sqrt{3} i_\beta{}^* \\ i_c{}^* = 0 \end{cases} \qquad (6)$$

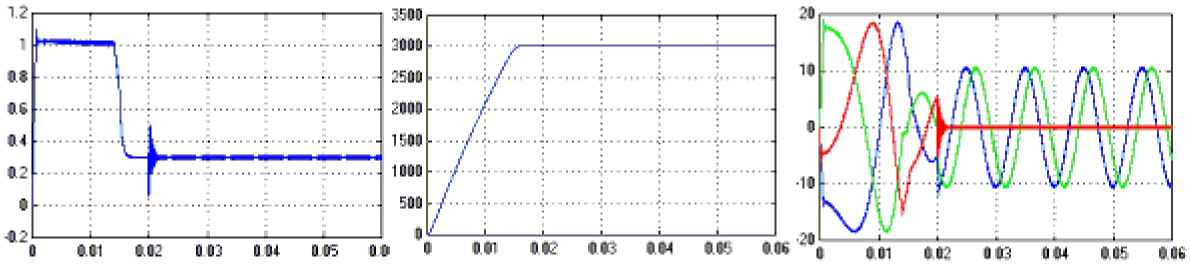
In order to keep constant torque, I_d and I_q must still be the same. That is why we have:

$$\begin{cases} i_\alpha{}^* = i_d{}^* \cos\theta - i_q{}^* \sin\theta \\ i_\beta{}^* = i_d{}^* \sin\theta + i_q{}^* \cos\theta \end{cases} \qquad (7)$$

Putting Equation (7) in Equation (6) leads to the following adapted control laws:

$$\begin{cases} i_a{}^* = \sqrt{3} i_d{}^* \sin(\theta + \frac{\pi}{3}) + \sqrt{3} i_q{}^* \cos(\theta + \frac{\pi}{3}) \\ i_b{}^* = \sqrt{3} i_d{}^* \sin\theta + \sqrt{3} i_q{}^* \cos\theta \\ i_c{}^* = 0 \end{cases} \qquad (8)$$

We can notice in Figure (8) that, in this case, the only remaining oscillations have high frequency and are due to the simulation step size. The speed is equal to its reference. The torque waveform is almost the same as the unfaulty case. To succeed reaching the reference, we need $\sqrt{3}$ times higher current I_a and I_b. This leads to an over sizing of the global system because the inverter would have to supply this higher current, the windings not to melt because of it, and the motor yoke not to saturate. This results to an increase of the total size of the motor and of its costs. But a compromise could be found between having the full torque but $\sqrt{3}$ times higher current and having a 2/3 times lower torque but nominal currents, depending of the targeted application.



a) Torque (Nm) b) Speed (rpm) c) Currents Ia Ib Ic (A)

Fig. 8: Simulation of a faulty H-bridge with new control law

Reducing the number of transistor: 4-leg inverter

As said before, for cost limitations, the number of transistor has to be as lower as possible. That is why the 3-leg half bridge inverter is interesting and the H bridge is used only when high reliability is needed. We suppose we have a star mounted motor with an available neutral point. In case of fault, the only possible action to control the system is to disconnect the faulty phase, for example by using fast fuses or TRIACs ([5]).

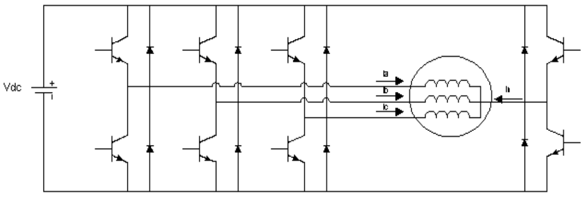
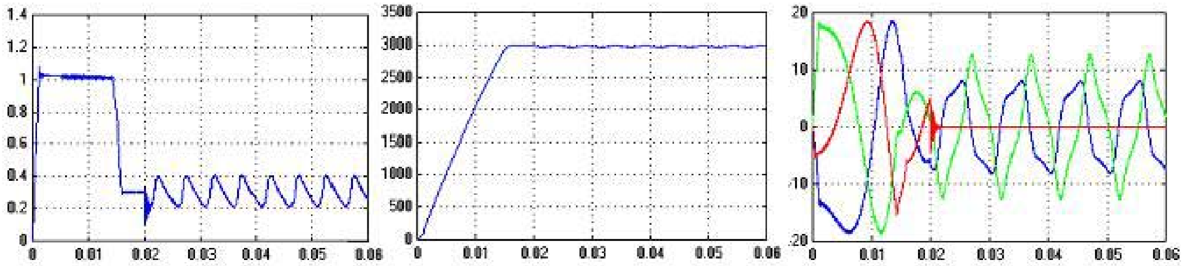


Fig. 9 : Topology of 4-leg half bridge

The problem with star-mounted motor is that, in unbalanced case, the zero sequence components is not null any longer and the I_0 current has to reach the source. To allow this, we could link the neutral point to a middle point of the supply source or link it to the source through a forth leg of inverter ([4], [5] and [7]), as shown in Figure (9). The forth leg is driven following the equation: $In = Ia + Ib + Ic$. This give In equal to the zero sequence component which then could reach the source. We can notice that the current passing through the forth leg is the same than the one passing through a wire linked to a DC mid point.

However a continuous battery without middle point supplies the inverter. A battery with a middle point is not always available. That is why the forth leg of a 4-leg invert will be linked to the ground of the battery. Then no middle point will be required.

The created torque and speed are shown in Figure (10), below.

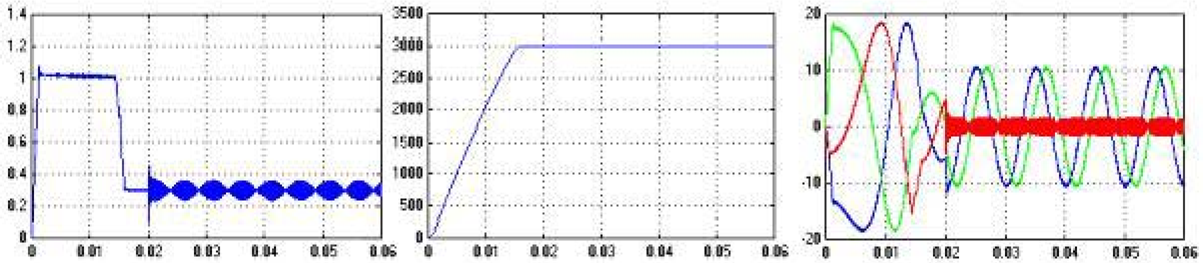


a) Torque (Nm) b) Speed (rpm) c) Currents Ia Ib Ic (A)

Fig. 10: Simulation of a faulty 4-leg inverter with control laws of Equation (4)

We can notice that, even with classical laws (not adapted to the default), the speed variations become almost null. This is due to the forth leg which allows the I_0 current to be different from zero and Ia could be different from $-I_b$. Torque ripple are still generated, even if the amplitude of the torque oscillations are 4 times smaller than those generated by a 3-leg inverter.

However, since now, we can have the sum of currents different from zero , we can use the adapted control laws as seen for the H-bridge (Equation (8)), we are able to obtain the same torque performance as with a H-bridge inverter and adapted control laws (Figure (11)) but using 4 transistors less. The torque after the default occurs can be equal to the torque before disfunctionment (here 0.3 Nm). Once more, the high frequency ondulations are due to the simulation and will not being taking into account. No more speed oscillations are produced. But, here again, the inverter and the windings must be able to carry current $\sqrt{3}$ times higher.



a) Torque (Nm) b) Speed (rpm) c) Currents Ia Ib Ic (A)

Fig. 11: Simulation of a faulty 4-leg inverter with adapted control law

Conclusion

Since, we have studied the behaviour of the system for different remedial strategies in the case of the short-circuited upper transistor, we are now able to have some words about the best solution to choose.

First, the definition of the acceptable behaviour of the system is an important point. As mentioned before, if the torque level is what matters, currents will have to be $\sqrt{3}$ times higher than in the unfaulty case, which requires that the whole actuator as to be sized in order to work with these currents. On the other hand, if we admit that 2/3 of the full torque is enough to reach the required performances in faulty case, currents would stay equal to those in normal functionment and no over-sizing would be needed. In addition, 4-leg inverter uses 4 transistors less than H-bridge and so, offers a better use rate by component [8]. Besides, the most important benefit of 4-leg bridge is the possibility to use adapted control laws. Indeed, modifying control laws doesn't lead to an over cost but, as we have seen, can improve the quality of the produced torque. That is why the 4-leg inverter with adapted control laws appears to be a valuable solution for system requiring a good reliability.

Nevertheless, when a fault occurs, it has to be detected then analysed in order to know what kind of fault it is and on what phase. Although we had only studied short circuit case, an open circuit could be possible. The difference between those two cases has to be made. This diagnostic can cost time. During the diagnostic time, the system is still being running without any modification, because as long as the fault is not identified, forth leg cannot be activated and control laws cannot be changed. We can notice that if diagnostic plus reaction time were greater than 10 ms, in our case, a more important torque ripple would be felt. If we consider Figure (5), after the default occurs, torque reaches its first 1 Nm high peak within 10 ms. other ways of considering this diagnostic time limitation could be defined.

Finally, we can remark that, when we are using the adapted control laws, zero sequence current exists. These currents don't produce any torque and could then be considered as losses. New control laws could be calculated in order to reduce I_0.

To conclude, we can say that a fault proof inverter can be found. To define what kind of inverter as to be used, some aspects have to be considered: over cost, reliability, torque quality, diagnostic and remedial time and yield. A way to study the importance of these factors on the final movement is to simulate the whole system actuator and mechanism so as to quantify the effect of a default of a switching component on the global behaviour. In this way, the reliability of the whole system can be tested and faulty behaviour can be foreseen to design safe and reliable electrically controlled mechanism.

References

[1] : Mecrow B.C., Jack A.G., Haylock J.A. and Coles J., Fault Tolerant Permanent Magnet Machine Drives, IEE Proceedings Electric Power Application; Vol 143, No. 6, pp 437-441

[2] : A.Krautstrunk, P. Mutschler, Remedial Strategy for a Permanent Magnet Synchronous Motor Drive, 8th European Conference on Power Electronics and Applications, Lausanne, Switzerland

[3] : Brian A. Welchko, Thomas M. Jahns, Wen L. Soong, James M. Nagashima, IPM Synchronous Machine Drive Response to Symmetrical and Asymmetrical Short Circuit Faults, IEEE Transactions on energy conversion, Vol. 18, No. 2,pp 291-298

[4] : N. Bianchi, S. Bolognani, M. Zigliotto and M. Zordan, Innovative Remedial Strategies for Inverter Faults in IPM Synchronous Motor Drive", IEEE Transactions on energy conversion, Vol. 18, No. 2, pp 306-314

[5] : Brian A. Welchko, Thomas M. Janhs, Thomas A. Lipo, Fault Interrupting Methods and Topologies for Interior PM Machine drives, EPE Power Electronics and Motion Control Conference, EPE-PEMC'04, Riga, Latvia

[6] : H. Schwab, A. Klönne, S. Reck, I. Ramesohl, Reliability Evaluation of a Permanent Magnet Synchronous Motor Drive for an Automotive Application, 10th European Conference on Power Electronics and Applications, Toulouse, France

[7] : Thami ELCH-HEB, Strategies de commande d'un ensemble onduleur-machine asynchrone fonctionnant en mode degrade, Thesis, Univerté des sciences et technologies de Lille, 1993

[8] : Brian A. Welchko, Thomas A. Lipo Thomas M. Jahns Steven E. Schulz, Fault Tolerant Three-Phase AC motor Drive Topologies : A Comparison of Features, Cost and Limitations, IEEE International Electric Machines and Drives Conference, June 2003

[9] : Byoung-Kuk Lee, Tae-Hyung Kim, Mehrdad Ehsani, On the Feasibility of 4 Switch 3 Phase BLDC Motor Drives for Low Cost Commercial Applications : Topology and Control, IEEE Transactions On Power Electronics, Vol.18, No. 1, pp 164-172