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Reliability of the Park's Vector method in induction motor drives fault diagnosis-Case of IGBT open circuit fault and rotor fault-

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Abstract. Variable speed drives of induction motors have increased the use of this type in different industrial fields. Unfortunately, this association can become problematic in the case of a simultaneous fault: an IGBT open circuit fault of one of the inverter arms and a broken rotor bar fault in the induction motor. Among the conventional diagnostic methods, the Park's vector approach is a very efficient method to locate the faulty IGBT in an inverter. Also, it is very reliable in monitoring the severity of the rotor fault, provided that the induction motor is fed directly from the grid. The aim of this paper is to study the reliability of this method in the case of a simultaneous fault. To this end, several experimental tests are performed to study the performance of this method when the motor is fed by an inverter, in the case of both an IGBT open circuit fault and a broken rotor bar fault.

Keyword. Induction motor, Inverter fault, IGBT, Rotor bar fault, Stator current, Park's vector.

INTRODUCTION

In recent years, the use of inverters has steadily increased due to advancements in power electronics, particularly in semiconductor technology, which has significantly improved inverter performance (Li et al., 2019). Additionally, induction motors are well known for their simple construction, robustness, and low manufacturing cost. However, their speed variation has historically posed challenges compared to other motor types. With the development of variable speed drives, the adoption of induction motors has risen significantly (Eddine Cherif et al., 2018).

Despite these advantages, variable speed drives using voltage source inverters subject induction motors to voltages rich in harmonics, which can accelerate premature aging. This aging process is further exacerbated by potential faults occurring in both the motor and the inverter. Even with advancements in electronic component quality and reliability, inverters remain vulnerable to faults due to multiple interacting constraints, physical and technological imperfections (Errabelli and Mutschler, 2012; Mullali Kunnontakath Puthiyapurayil et al., 2022).

These accumulated constraints can lead to short-circuiting or open-circuiting of inverter switches. As a result, extensive research has been conducted on fault detection and localization in static converters, particularly in three-phase inverters (Choi et al., 2015; Kim et al., 2020). Studies indicate that 38% of faults in industrial electric drives originate from power switch failures, caused by control malfunctions, thermal overload, transient operating states, or environmental conditions. Detecting these faults is crucial to prevent production shutdowns, which can result in significant financial losses due to halted operations, equipment restoration, and delivery delays.

To diagnose inverter faults, three-phase stator currents are commonly used as diagnostic signatures (Eddine Cherif et al., 2018; Trabelsi et al., 2010). This technique, known as Motor Current Signature Analysis (MCSA), is preferred over vibration-based methods due to its simple implementation using current sensors. Various approaches have been developed to analyze these currents for fault detection and localization. Many time-domain methods rely on tracking the DC component of the stator current or extracting information from direct and quadrature currents using Park's transformation (Husari and Seshadrinath, 2020; Rourke et al., 2020). Among these, the Park's vector plot method is particularly effective in detecting faults in both the inverter and the motor. This method analyzes the quadrature component of the current against the direct component, with the resulting plot providing insights into the inverter and motor's condition, as well as the nature of the fault (Lu and Sharma, 2008; Im et al., 2012; Eddine Cherif et al., 2017).

The objective of this paper is to evaluate the performance and reliability of the Park's vector method in diagnosing simultaneous faults, specifically an IGBT open-circuit fault and an induction motor rotor fault. To achieve this, several experimental tests are conducted in the presence of both faults.

PARK'S VECTOR PLOT METHOD

Park's vector plot, commonly referred to as the Lissajous method, is a time-domain technique based on plotting two vectors derived from the three-phase stator current against each other. These vectors represent the direct component of the current vector, (t), and the quadrature component of the current vector, (t), as defined by the following equation:

$$\begin{cases} i_d(t) = \sqrt{\frac{2}{3}}\, i_{sa}(t) - \frac{1}{\sqrt{6}}\, i_{sb}(t) - \frac{1}{\sqrt{6}}\, i_{sc}(t) \\ i_q(t) = \frac{1}{\sqrt{2}}\, i_{sb}(t) - \frac{1}{\sqrt{2}}\, i_{sc}(t) \end{cases} \quad (1)$$

Where: (t),$b(t)$ and $i_{SC}(t)$,are the three-phase stator currents.

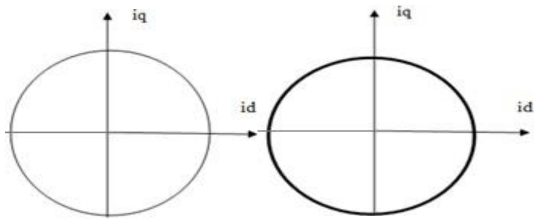
The plot of the quadrature current(t) versus the direct current$i_d(t)$ allows to know directly the global state of the electric drive. Indeed (Husari and Seshadrinath, 2020 ; Ugwiri et al., 2020).

- The electric drive is healthy, if they obtained plot is a homogeneous circle centeredat the origin. This indicates that the three stator currents are perfectly balanced.
- The electric drive exhibits faults in either the inverter or the motor if the resulting plot forms a distorted or non-uniform circle. The direction and extent of the deformation or thickness variation in the plot depend on the type and nature of the fault.

Plot of the Park's vectors in the presence of a rotor fault

The rotor fault of a squirrel cage induction motor refers to a total or partial break in the rotor bar or end ring. This type of fault is one of the most studied due to its ease of implementation on test benches (Benouzza et al., 2004). It is most commonly caused by frequent start-ups, thermal stresses, and/or mechanical stresses resulting from bearing faults, system wear, or manufacturing defects (Kathir et al., 2012).

In the presence of this fault, the analysis of three-phase stator currents using the Park's vector plot method theoretically produces the representation shown in Fig. 1 (Benouzza et al., 2004; Husari and Seshadrinath, 2020; Messaoudi et al., 2022; Siddiqui et al., 2014).



a) Healthy rotor b) Rotor with two broken bars

Fig.1.TheoreticalplotofthePark'svectorsofaninductionmotor.

Plot of Park's vectors in the case of an Inverter Fault

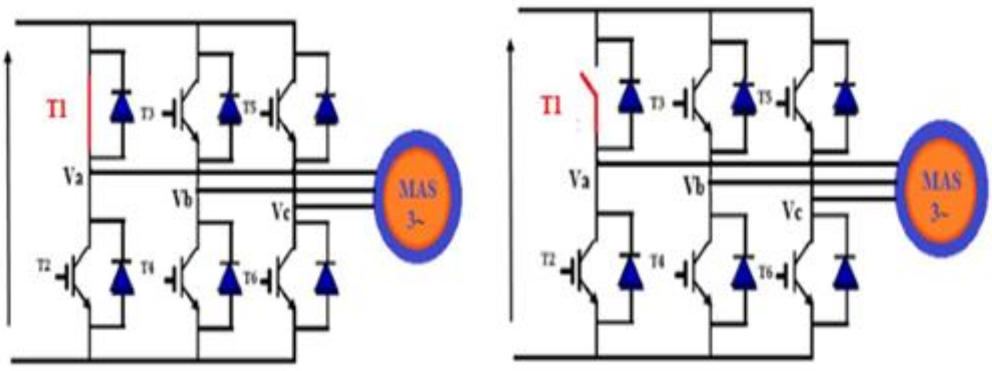
Inverters play a very important role in industry because they allow the electric motors to operate at variable speed. However, under the effect of certain electricalor mechanical constraints, failures can appear in this system. This can influence the operation of electric motors by degrading their mechanical performance. It is therefore necessary to detect these faults as soon as they appear, in order to avoid an interruption of the industrial process and thus avoid huge financial losses. Among the main faults that can affect inverters, there are (Eddine et al., 2018; Mullali Kunnontakath Puthiyapurayil et al., 2022; Kim et al., 2020; Mazari et al., 2018):

a) Short-Circuit Fault

The short-circuit of a switch (IGBT), most often causes an increase in current to limit values causing the melting of its chip or its connection. Moreover, if the detection of the faulty IGBT is not done quickly (less than 10 microseconds) to deactivate the healthy switch of the short-circuited arm in order to protect it, the source will be completely shortcircuited, a non-negligible braking torque will appear and the speed will be cancelled, which will cause the total shutdown of the motor and the damage of the whole system (Mazari et al., 2018).

b) Open-CircuitFault

This type of fault can occur when the switch (IGBT) remains stuck in the open state. This fault appears when, for some reason, this switch is disconnected, damaged or remains open due to a problem in the control signal of its gate. This type of fault is very difficult to perceive directly because the motor can continue to operate but with more oscillations in its mechanical signals (speed and torque), which of course reduces its performance Indeed, the currents of the other healthy arms increase to maintain the operation of the motor but in a degraded mode (Mazari et al., 2018). Figure 2 shows, respectively, an inverter with a short circuit fault and an open circuit fault of an IGBT.



a) Short-circuited IGBT b) Open-circuited IGBT

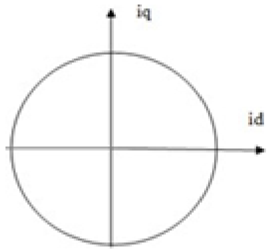
Fig. 2. Inverter IGBT faults.

In this paper, the open circuit fault is studied for its simplicity of experimental implementation. Thus, in the presence of this fault, the analysis of the three-phase stator currents by the Park's vector plot method, gives, in theory, the representations observed in figure 3 (Choi et al., 2018).

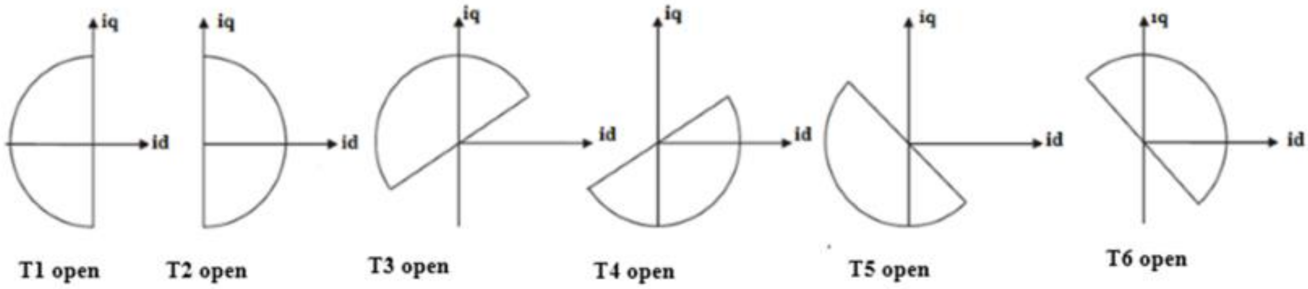
Figure 3 shows the theoretical plot of the Park's vectors of stator currents for an induction motor with no rotor fault fed by an inverter with an open-circuit fault for multiple fault location. From this figure, it is therefore easy to state that:

- The inverter is healthy (all switches are in normal operation), if the plot obtained is a homogeneous circle centered at the origin.
- The inverter has an open-circuit fault in one of its IGBTs, if the plot obtained is a homogeneous semi-circle. The orientation of the semicircle indicates the faulty IGBT (Eddine et al., 2018).

Unfortunately, in reality, these plots are not so perfect. Indeed, if the inverter control is not suitable for example, this can increase the number of harmonics in the currents signal, which affects the clarity of the plot and therefore the reliability of this method. The following section will demonstrate this statement.



a) Healthy



b) Inverter with and without open-circuit fault

Fig.3. Theoretical plot of the Park's vectors of a healthy motor fed by an inverter with and without open-circuit fault.

EXPERIMENTAL RESULTS

Testbench

The main tests carried out in this paper are carried out by the Diagnosis group at the Laboratory of Development of Electrical Drives (L.D.E.E) of the Department of Electrical Engineering (USTO-Oran). The electric drive used in these practical tests is constituted by a three-phase squirrel cage induction motor fed by a two levels voltage source inverter (SEMIKRON AN-8005) and coupled to a direct current generator used as a load. The motor parameters are: 3 kW 7 A, 1410 rpm, 4 poles. The measurement chain consists of three Hall Effect current sensors and an acquisition card. The whole setup is connected to a computer for the visualization, the processing of the acquired signals as well as the generation of the necessary control signals for the PWM inverter. These signals are obtained from a Space Vector PWM control programmed and used in these tests, for a carrier frequency fp = 6 kHz. This control is generated via the DSPACE 1104 board, as shown in figure 4.

Fig.4. Experimental setup.

All acquisitions were performed with a data acquisition time of 5 s and a sampling frequency of 3 kHz, which gives us a frequency resolution of 0.2 Hz.

Faultcreationprocedures

a) RotorFault

To create a rotor fault, 3mm diameter holes are drilled on the rotor bars to simulate a broken rotor bars fault. The experimental tests are thus carried out with two rotors of identical characteristics. The first one, considered as healthy, is without holes. The second rotor has two drilled rotor bars. Fig. 5 shows a rotor with two broken bars.

Fig. 5. Faulty rotor used with two broken bars.

b) IGBT Open-Circuit Fault

This fault is created by the disconnection of the IGBT1 (T1) gate control wire, while the motor is running on load. This procedure simulates an open-circuit fault at the IGBT control. Fig. 6 shows disconnection of switch T1 control.

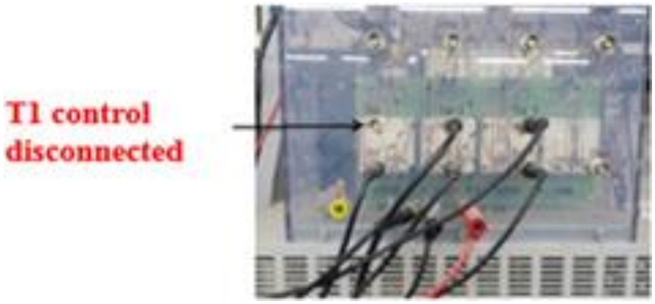


Fig. 6. DisconnectionofswitchT1control.

c) Analyzed operating modes

The operation modes studied in this paper are:

- Operation of the motor with an inverter and a rotor without faults.

- Operation of the motor with an inverter without¬ fault and a rotor with two broken rotor bars.

- Operation of the motor with a faulty switch inverter¬ with "T1 or IGBT 1 open" and a rotor without fault.

- Operation of the motor with a simultaneous fault of¬ a faulty switch inverter with "IGBT 1 open" and a rotor with two broken rotor bars.

Results and discussion

Inverter and rotor with out faults

In this first test, also called reference test, the rotor of the motor used does not present any fault. The Park's vectors ((t) and (t)) obtained from eq. (1) are shown in Fig. 7.

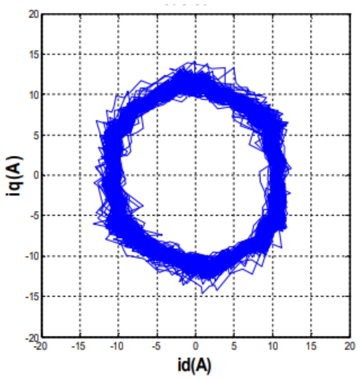
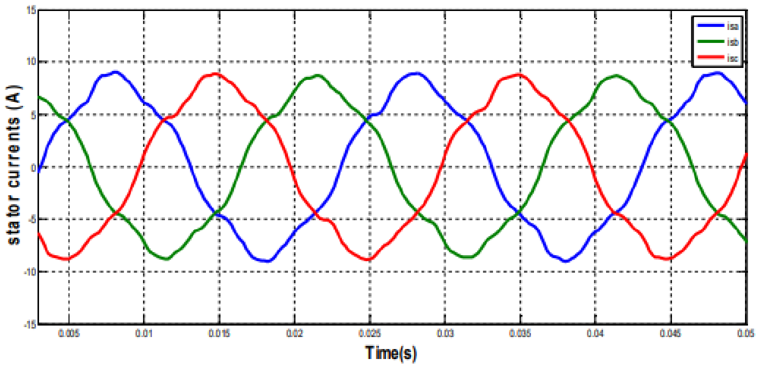
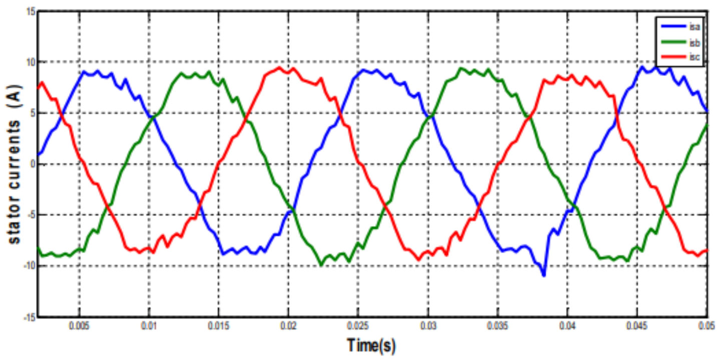


Fig.7. Plot of the Park's vectors for both inverter and rotor without faults.

The obtained plot of figure 7, shows a circle centered at the origin without any apparent deformation. This proves that all the IGBTs of the two-level inverter used, are healthy.
Nevertheless, the obtained plot shows a circle with a certain thickness. This thickness is related to the effect of harmonics generated by the inverter and not to the rotor fault.
To verify this statement, additional experimental tests are performed with this same rotor, using a power supply directly from the grid and then a power supply with inverter. Fig. 8 shows the stator currents for both power supplies used in this test.

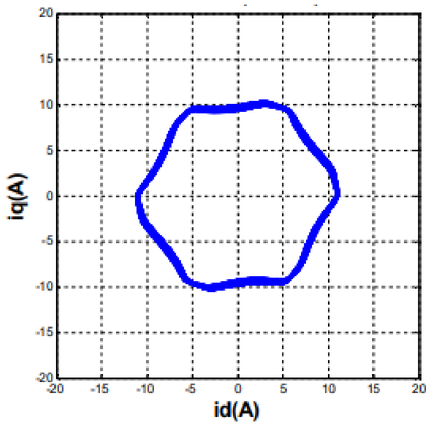


a) Grid-based power supply

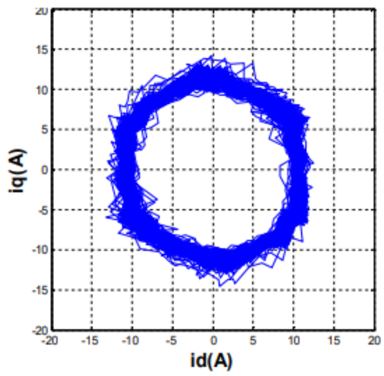


b) Inverter-based power supply.
Fig. 8. Stator currents signals for both power supplies.

The analysis in figure 8 shows that a motor fed directly from the grid has less ripples in the stator currents compared to the same motor fed by an inverter. This indicates that the number of harmonics is higher for this second type of supply, which is quite logical. For this reason, the Park's Vector plot is a thicker circle in the case of an inverter-based power supply than in the case of a grid-based power supply even if the rotor is healthy, as shown in figure 9.



a) Grid-based power supply



b) Inverter-based power supply

Fig. 9.Park's vectors plot for both power supplies.

Inverter without fault and rotor with two broken bars fault

In this second operating mode, the induction motor is fed by an inverter without any faults. However, the rotor of this motor has two broken rotor bars. Figure 10 shows the Park's vector plot for this second operating mode.

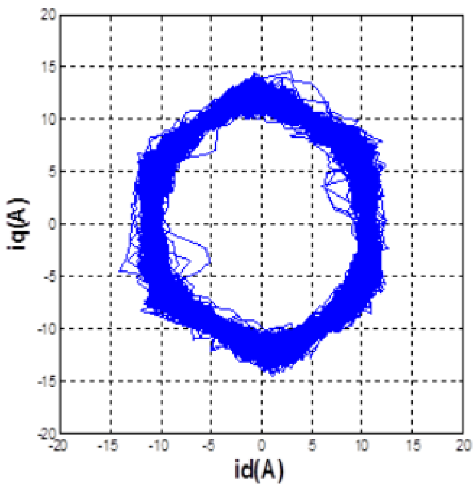


Fig. 10. Park's vectors plot in the case of an inverter without fault and a rotor with two broken bars

Figure 10 shows that the obtained circle from the Park's vectors plot, is centered and without deformation. This proves that all the IGBTs of the inverter used are healthy. On the other hand, it is very difficult to say whether the rotor has faults or not. Indeed, it is very difficult to distinguish between both operating modes by a simple comparison between the results of the healthy case (Fig.7) and the faulty case (Fig.10). The thickness of the circle is almost the same. Under these conditions, it is very difficult, even impossible, the detection or the monitoring of the rotor fault due to the inverter-based power supply. For a better analysis, it is necessary to decrease the harmonic rate by improving the characteristics of the Space Vector PWM control. The obtained results are already affirmed in references and show that the thickness of the plot of the PARK's vectors increases with the increase in the number of broken rotor bars (Benouzza et al., 2004 ; Siddiqui et al., 2014).

Inverterwith''IGBT1open-curcuit''faultand healthy rotor

For this third experimental test, the rotor used is healthy, i.e. with no broken rotor bar. The induction motor is fed by an inverter whose control of the first switch T1 (IGBT 1), located at the first arm, is disconnected to simulate an open circuit fault. Fig. 11 illustrates the plot of the Park's vectors plot for this third operating mode.

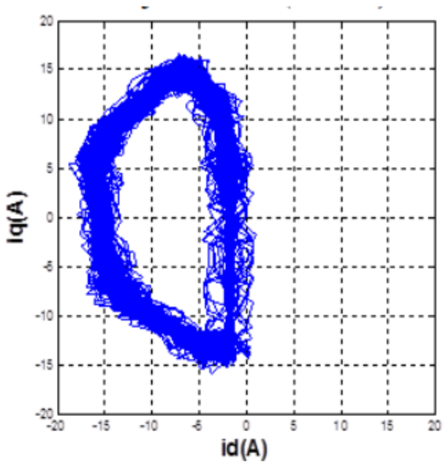


Fig.11.Park'svectorplotinthecaseaninverterwithswitchT1"IGBT1" open and a rotor without fault.

Fig. 11 shows that the Park's vectors plot is a semicircle not centered at the origin. Indeed, only the left semicircle, relating to the negative part of the current (t), appears. This indicates that the switch T1is faulty, which is confirmed by the theoretical study shown in figure 3. This result is the consequence of the absence of the positive alternation of the first phase, on Fig. 12, which is related to the faulty switch T1 (IGBT1).

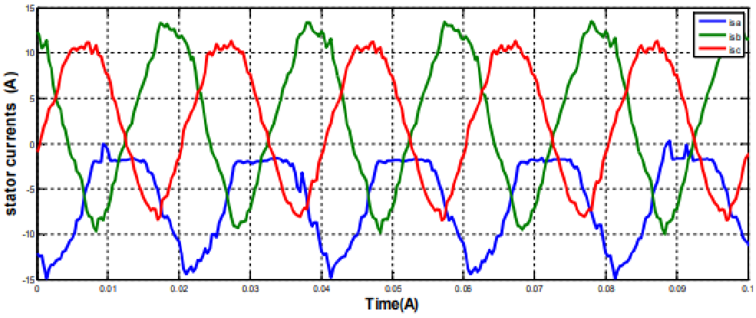


Fig. 12. StatorcurrentsinthecaseaninverterwithswitchT1"IGBT1"open and a rotor without fault.

Inverterwithfault''IGBT1open-Circuit''anda rotor with two broken rotor bars

For this last experimental test, the rotor used has two broken rotor bars. This motor is fed by an inverter whose control of the first switch T1(IGBT1)is always disconnected to simulate an open-circuit fault.Fig.13illustratestheplot of the Park's vectors for this last operating mode.

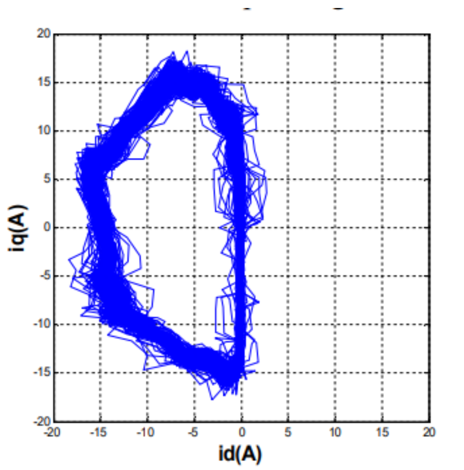


Fig. 13. Park'svectorsplotforinverterwithswitchT1"IGBT1"openand a rotor with two broken bars.

As for the previous case, the analysis of figure 13 obtained from the Park's vectors shows a semicircle not centered at the origin. Only the negative part of the current (t), ,appears which proves that the switch T1 is in faulty case. Unfortunately, it is very difficult to demonstrate the existence or the evolution of the severity of the rotor fault on the simple comparison of the thickness of the Park's vectors plots. Indeed, the thickness of both semicircles obtained in the case where the inverter presents an open-circuit fault of the switch T1 (Fig.10 and Fig.13), are almost identical. In the light of the obtained results, it is clear that the Park's vectors plot method is very effective for locating faulty switches in an inverter. On the other hand, it presents poor results when it comes to detect or follow the evolution of the rotor fault when the motor is fed by an inverter.

CONCLUSION

The aim of this paper is to study the reliability of the Park's vector plot method when the induction motor is fed by a three-phase inverter, in the case of a simultaneous fault of a broken rotor bars fault and an IGBT open-circuit fault. The experimental results obtained show that this method is very reliable in the detection of the IGBT open-circuit fault and in the localization of the faulty switch, even in the presence of a rotor fault. On the other hand, it presents poor results when it comes to detecting or monitoring the severity of the rotor fault when the motor is fed by an inverter with or without IGBT open-circuit fault. As a way forward, we propose to improve the identification power of the PARK's vector plot by combining it with the Hilbert transform in order to separate the inverter fault from the rotor bar break fault.

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