A New Approach for Real-Time Multiple Open-Circuit Fault Diagnosis in Voltage-Source Inverters

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***Abstract*—Practically all the diagnostic methods for open-circuit faults in voltage-source inverters (VSI) developed during the last decades are focused on the occurrence of single faults and do not have the capability to handle and identify multiple failures. This paper presents a new method for real-time diagnostics of multiple open-circuit faults in VSI feeding ac machines. In contrast with the majority of the methods found in the literature which are based on the motor phase currents average values, the average absolute values are used here as principal quantities to formulate the diagnostic variables. These prove to be more robust against the issue of false alarms, carrying also information about multiple open-circuit failures. Furthermore, by the combination of these variables with the machine phase currents average values, it is possible to obtain characteristic signatures, which allow for the detection and identification of single and multiple open-circuit faults.**

***Index Terms*—ac motor drives, fault diagnosis, multiple insulated gate bipolar transistor (IGBT) open-circuit faults, voltage-source inverter (VSI).**

I. Introduction

CURRENTLY, three-phase pulsewidth modulation (PWM) inverters are utilized in a variety of industry applications such as variable speed electric motor drives, uninterruptible power system, active power filters, and more recently, in renewable energy conversion systems and hybrid vehicles. Although this technology has already achieved a certain level of maturity, due to their complexity and considering that inverters are often exposed to high stresses, unexpected faults may occur, influencing negatively the entire system. Therefore, to preclude this harmful influence as well as to improve the system reliability, the development of fault diagnostic methods has gained a lot of interest during the last years.

The great susceptibility of these power converters to suffer critical failures is confirmed by some statistical studies that show that about 38% of the failures in variable-speed ac drives in industry are concentrated in the power equipment and 53% in the control circuits [1]. More recently, an industry-based survey regarding the reliability in power electronic converters also show that power devices, capacitors, and gate control circuits are the most susceptible components [2]. Another study shows that semiconductor, soldering, and printed circuit board failures in device modules total 60% of converter system failures [3].

In general, power device failures in the inverter can be broadly classified as open-circuit faults and short-circuit faults. Although the protection against power transistor overcurrent or short-circuit has become a standard feature for industrial drives, the open-circuit failures have not yet received so much attention [4]. This kind of failure will not necessarily cause the system shutdown and can remain undetected for an extended period of time. This may lead to secondary faults in the converter or in the remaining drive components, resulting in the total system shutdown and high repairing costs.

For these reasons, the development of online methods that can detect open-circuit faults in voltage-source-inverter (VSI)-fed ac drives has become an important research field. The use of Park's vector approach as an effective fault diagnostic tool for voltage source inverter faults was firstly proposed in [5]. Based on the same principle, other scientific works were then developed and published by other authors [6], [7]. However, this approach requires very complex pattern recognition algorithms which are not suitable for integration into the drive controller.

The localization of the faulty switch can also be performed by the analysis of the current space vector trajectory diameter [8]. Its slope is used to identify the faulty leg and the missing half-cycle of the current waveform is used to locate the faulty switch. An improved version of this technique was presented in [9] with the capability to detect multiple faults. Nevertheless, this technique has serious drawbacks related to slow detection, tuning, and problems under low current values.

Through the voltages analysis, on the inverter ac side or on the machine side, it is also possible to detect a fault occurrence [10]. Under open-circuit faults, these voltages show some characteristic irregularities that can be detected, which give a direct localization of the faulty device. Although lower detection times can be achieved with these methods, additional voltage sensors are required, which in many cases is not desirable since it increases the drive costs and complexity. Another approach was presented in [11] where photocouplers were used to

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obtained the ac side voltages. However, to avoid false alarms, some time-delay values must be correctly defined which can be very difficult since they depend on several variables.

A different technique, based on the average current Park's vector approach was proposed in [12]–[14]. This technique presents some problems regarding the tuning effort related to the fact that it is load dependent, together with some false alarm issues.

These problems were mitigated by the normalization of the diagnostic variables, as proposed in [15]. More recently, this fault diagnostic method was enhanced by the use of the currents' average absolute values as normalization quantities [16]. Furthermore, by the calculation of additional diagnostic signals, the technique robustness was improved, having simultaneously the capability to detect multiple power switch open-circuit failures. Despite of these advantages, these enhancements bring some drawbacks such as a higher complexity and larger detection times.

Some reviews and surveys can also be found in the literature regarding the analysis and performance comparison of several fault diagnostic methods for VSI power switch open-circuit faults [4], [17]–[19].

A new diagnostic method based on the calculation of the errors of the normalized currents average absolute values was proposed in [20]. It was demonstrated that this approach can detect single insulated gate bipolar transistor (IGBT) open-circuit faults, being simultaneously independent of the machine load and speed conditions and showing a very robust behavior to the issue of false alarms.

An observer-based diagnosis scheme for single and simultaneous open-switch faults in induction motor drives was addressed in [21]. The algorithm proves to be load independent and does not require additional sensors. However, as main drawbacks, the method implementation is not straightforward, being computationally demanding and requiring the knowledge of the machine parameters.

A simple fault diagnostic method based on the operating characteristics of brushless direct current motor drives was presented in [22] where the diagnosis is accomplished without using additional sensors or electrical devices. This allows to embed it into the existing drive software as a subroutine without excessive computation effort.

Fast detection of open-circuit faults and short-circuit faults in IGBTs was addressed in [23]. A novel failure-detection technique and its analog circuit were proposed and applied to a three-phase induction motor drive. The obtained results prove that a fast detection time lower than 10 μs can be achieved. Nevertheless, the analog circuit requires some voltage measurements, which increases the system complexity, and the technique cannot be applied to all power devices since it strongly depends on the power device characteristics.

A new method for single power switch open-circuit fault diagnosis based on the reference current errors was also presented in [24], showing a fast detection time equivalent to 5% of the motor phase current fundamental period.

The literature review shows that, despite of all the existing work done by several authors concerning the diagnostic methods for VSI open-circuit faults, there is a great lack of research regarding the development of algorithms that can detect single and multiple faults, having simultaneously other mandatory features such as the requirement of no extra sensors or electric devices, simple implementation, and operating condition independence. Considering this, in this paper, a fault diagnostic method for open-circuit faults is presented, which takes into account all these important features.

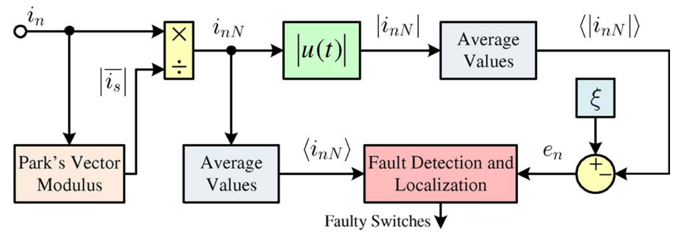

Fig. 1. Block diagram of the proposed fault diagnostic method.

To test and validate the proposed method, single and multiple open-circuit faults are introduced in the VSI of a vector-controlled permanent magnet synchronous motor (PMSM) drive. Simulation and experimental results are presented, showing the technique performance regarding the detection and localization of different faulty power switches.

II. Proposed Fault Diagnostic Method

The proposed diagnostic method results from an improved version of the algorithm presented in [20], where the formulation of the diagnostic variables was improved and simplified. A block diagram of the new algorithm is shown in Fig. 1. The three motor phase currents are the unique inputs required by this technique since it is desirable that the fault diagnostic method utilizes variables already used by the main control, avoiding the use of extra sensors and the inherent increase of the system complexity.

To overcome the problems associated to the machine mechanical operating condition dependency and the issue of false diagnostics, the measured motor phase currents are normalized using the modulus of Park's vector, defined as

$$i_d = \sqrt{\frac{2}{3}} i_a - \frac{1}{\sqrt{6}} i_b - \frac{1}{\sqrt{6}} i_c \tag{1}$$

$$i_q = \frac{1}{\sqrt{2}} i_b - \frac{1}{\sqrt{2}} i_c \tag{2}$$

where i_d and i_q are the Park's vector components and i_a, i_b, and i_c the motor phase currents. The Park's vector modulus $|\overline{i_s}|$ is given by

$$|\overline{i_s}| = \sqrt{i_d^2 + i_q^2}. \tag{3}$$

The normalization is performed by dividing the motor phase currents by Park's vector modulus. The obtained normalized motor phase currents i_{nN} are given by

$$i_{nN} = \frac{i_n}{|\overline{i_s}|} \tag{4}$$

where $n = a, b, c$. Therefore, assuming that the motor is fed by a healthy inverter generating a perfectly balanced three-phase sinusoidal current system

$$i_n = \begin{cases} i_a = I_m \sin(\omega_s t + \phi) \\ i_b = I_m \sin\left(\omega_s t - \frac{2\pi}{3} + \phi\right) \\ i_c = I_m \sin\left(\omega_s t + \frac{2\pi}{3} + \phi\right) \end{cases} \tag{5}$$

where I_m is the currents maximum amplitude, ω_s is the motor currents frequency, and ϕ is the initial phase angle, it can be proven that Park's vector modulus can be given by

$$|\overline{i_s}| = I_m \sqrt{\frac{3}{2}}. \tag{6}$$

As a consequence of this normalization process, the normalized motor phase currents will always take values within the range of $\pm\sqrt{2/3}$, independent of the measured motor phase currents amplitude, since

$$i_{nN} = \begin{cases} i_{aN} = \sqrt{\frac{2}{3}} \sin(\omega_s t + \phi) \\ i_{bN} = \sqrt{\frac{2}{3}} \sin\left(\omega_s t - \frac{2\pi}{3} + \phi\right) \\ i_{cN} = \sqrt{\frac{2}{3}} \sin\left(\omega_s t + \frac{2\pi}{3} + \phi\right) \end{cases}. \tag{7}$$

Under these conditions, the average absolute values of the three normalized motor phase currents $\langle |i_{nN}| \rangle$ are given by

$$\frac{\omega_s}{2\pi} \int_0^{\frac{2\pi}{\omega_s}} |i_{nN}| dt = \frac{1}{\pi} \sqrt{\frac{8}{3}}. \tag{8}$$

Finally, the three diagnostic variables e_n are obtained from the errors of the normalized currents' average absolute values, given by

$$e_n = \xi - \langle |i_{nN}| \rangle \tag{9}$$

where ξ is a constant value equivalent to the average absolute value of the normalized motor phase currents under normal operating conditions given by (8), that is

$$\xi = \frac{1}{\pi} \sqrt{\frac{8}{3}} \approx 0.5198. \tag{10}$$

The three diagnostic variables defined in (9) have specific characteristics which allow for the inverter fault diagnosis. When the drive is operating under normal operating conditions, all the diagnostic variables will take values near to zero. However, if an inverter open-circuit fault is introduced, at least one of the diagnostic variables will assume a distinct positive value. Consequently, the errors e_n can be effectively used to detect an anomalous inverter behavior.

On the other side, these variables are not capable to perform a complete inverter diagnostic since they just carry information about the affected phases. Hence, this information together with the currents' average values $\langle i_{nN} \rangle$ can be used to identify the faulty power switches. To achieve this, fault symptom variables can be formulated according to the following expressions:

$$E_n = \begin{cases} N & \text{if } e_n < 0 \\ 0 & \text{if } 0 \le e_n < k_f \\ P & \text{if } k_f \le e_n < k_d \\ D & \text{if } e_n \ge k_d \end{cases} \tag{11}$$

$$M_n = \begin{cases} L & \text{if } \langle i_{nN} \rangle < 0 \\ H & \text{if } \langle i_{nN} \rangle > 0 \end{cases}. \tag{12}$$

The values taken by E_n and M_n allow to generate a distinct fault signature which corresponds to a specific faulty operating condition. The threshold value k_f is directly related to any fault detection, while k_d performs an important role in case of a double failure in the same inverter phase. Since the method is normalized, it is not required to adjust these values for each load and speed conditions. They can be empirically established by simply analyzing the variables' behavior for different faulty operating conditions. Taking this into account, the obtained simulation and experimental results allowed to generate 15 distinct fault signatures, which enable the effective fault detection and localization of an equal number of different VSI failure combinations. As a result, considering a typical motor drive system with a VSI supplying an ac motor (Fig. 2), the 15 fault combinations can be detected and identified using Table I.

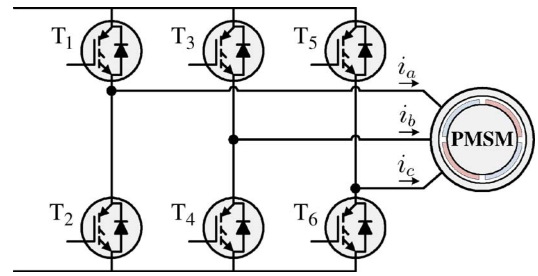

Fig. 2. Diagram of a typical VSI feeding a PMSM.

TABLE I
DIAGNOSTIC SIGNATURES FOR THE FAULTY SWITCH IDENTIFICATION

Faulty Switches	E_a	E_b	E_c	M_a	M_b	M_c
T1	P	N	N	L	–	–
T2	P	N	N	H	–	–
T3	N	P	N	–	L	–
T4	N	P	N	–	H	–
T5	N	N	P	–	–	L
T6	N	N	P	–	–	H
T1, T2	D	–	–	–	–	–
T3, T4	–	D	–	–	–	–
T5, T6	–	–	D	–	–	–
T1, T3	P	P	N	L	L	H
T2, T4	P	P	N	H	H	L
T3, T5	P	N	P	L	H	L
T4, T6	P	N	P	H	L	H
T1, T5	N	P	P	H	L	L
T2, T6	N	P	P	L	H	H

III. Simulation Results

The modeling and simulation of the drive system as well as the implementation of the diagnostic method were carried out using the Matlab/Simulink environment, in association with

TABLE II
PERMANENT-MAGNET SYNCHRONOUS MOTOR PARAMETERS

Power	P	2.2 kW
Speed	n	1750 rpm
Voltage	V	316 V
Current	I	5.3 A
Number of pole pairs	p	5
Armature resistance	R_s	1.72 Ω
Magnet flux linkage	ψ_{PM}	0.244 Wb
d-axis inductance	L_d	20.5 mH
q-axis inductance	L_q	20.5 mH
Moment of inertia	J	0.007 Kg.m^2

the Power System Blockset software toolbox. A three-phase VSI feeding a star-connected permanent magnet synchronous machine was considered (Fig. 2). A rotor field-oriented control strategy employing hysteresis current controllers was applied to the inverter to control the PMSM mechanical speed.

The machine dynamic model employed is described in [25], and its parameters are presented in Table II.

Some results are presented to evaluate the diagnostic method performance under different failure configurations. In this context, three distinct faulty operating conditions are considered: a single IGBT open-circuit fault, a single-phase open-circuit fault (double fault in the same inverter leg), and a double power switch open-circuit fault. All the power switch open-circuit faults are performed by removing their respective gate signals, keeping the antiparallel diodes still connected.

Taking into consideration that some features such as the method robustness against the issue of false alarms and its independency of the motor speed and load level have already been discussed in [20], in this paper, special attention is given to the multiple fault diagnosis and to the method fault detection time.

For all the considered operating conditions, a load level equivalent to 30% of the PMSM rated torque is assumed, together with a reference speed of 1200 revolutions per minute. The threshold values k_f and k_d for (11) are chosen to be equal to 0.08 and 0.32, respectively.

A. Single IGBT Open-Circuit Fault

Fig. 3 shows the time-domain waveforms of the motor phase currents together with the diagnostic variables and the normalized currents' average values. At $t = 0.25$ s, a load torque step from no load to rated load is introduced. At $t = 0.3$ s, the load decreases to a level of about 30% of the PMSM rated torque. Finally, at $t = 0.357$ s, an IGBT open-circuit fault in transistor T1 is introduced, by removing its corresponding gate signal.

The obtained results allow to verify that despite the strong load transient introduced, both the diagnostic variables and the normalized currents' average values do not show noticeable variations, proving the algorithm robustness against these phenomena.

When the fault in IGBT T1 occurs, the diagnostic variable of the corresponding affected phase e_a immediately increases, converging to a value of 0.23. The other two remaining errors

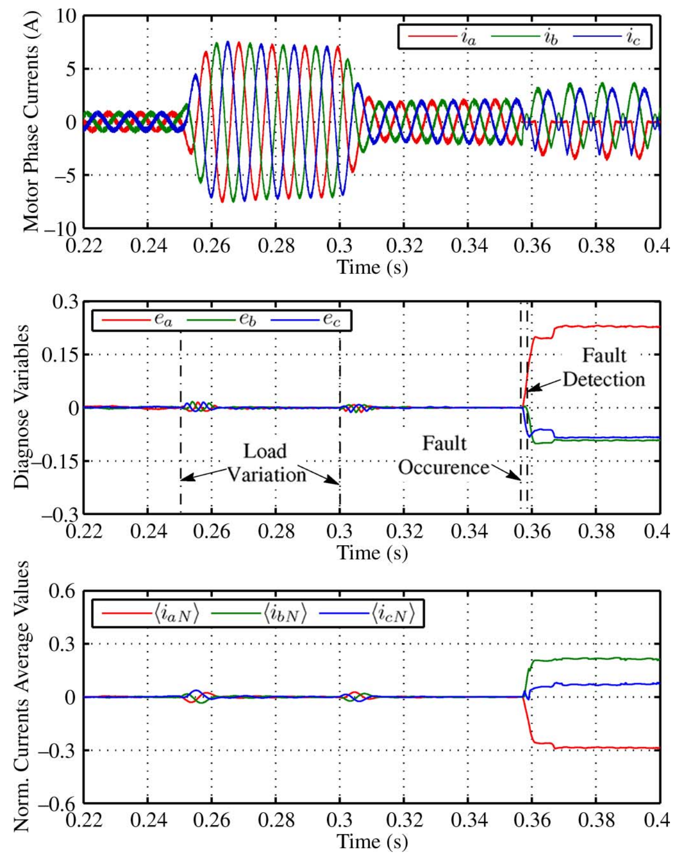

Fig. 3. Simulation results concerning the time-domain waveforms of the motor phase currents, the diagnostic variables, and the normalized currents average values, for a single power switch open-circuit fault in IGBT T1.

will decrease until they reach a value of approximately -0.09. Regarding the normalized currents' average values, since the phase a top switch is in open circuit, the current flow can just be made by the bottom IGBT, resulting in a large negative average value in this phase.

Regarding the fault detection time, considering the defined threshold values and Table I, the open-circuit fault is detected 1.3 ms after the fault occurrence. From a different point of view, this value represents a detection time of about 13% of the motor phase currents' fundamental period.

B. Single-Phase Open-Circuit Fault

Fig. 4 shows the time-domain waveforms of the motor phase currents together with the diagnostic variables and the normalized currents average values, for a double failure in power switches T1 and T2. The same load transients verified for the last situation are also introduced.

In this case, at the instant $t = 0.357$ s, the gate signals are removed from IGBTs T1 and T2, resulting in a single-phase open-circuit fault in phase a. As a result, the diagnostic variable e_a will immediately increase to a final value of 0.49. With respect to the two remaining variables, they will decrease, converging both to a value of about -0.18.

Comparing these values with the previous situation, it can be concluded that the final values for a single-phase open-circuit

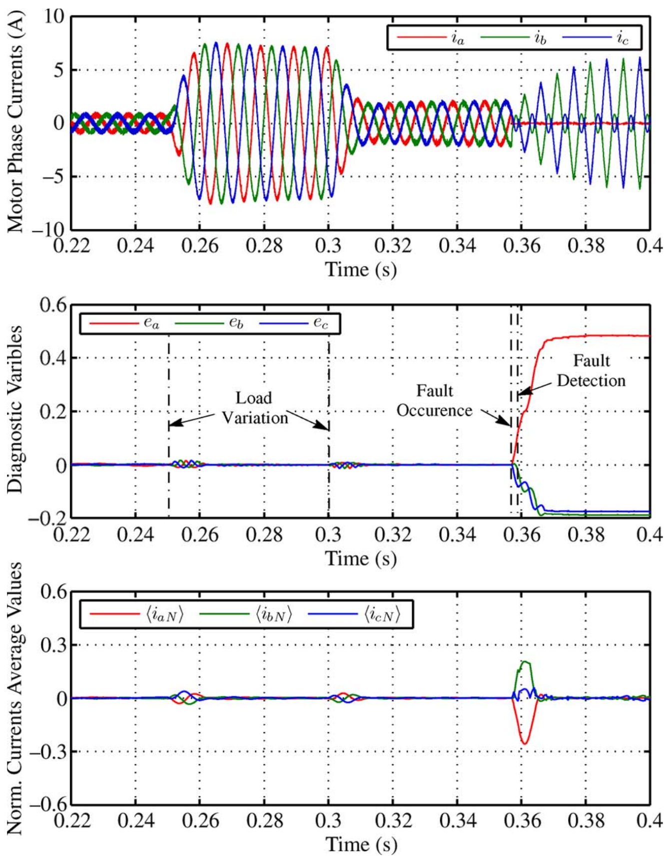

Fig. 4. Simulation results concerning the time-domain waveforms of the motor phase currents, the diagnostic variables, and the normalized currents average values, for a single-phase open-circuit fault in phase a.

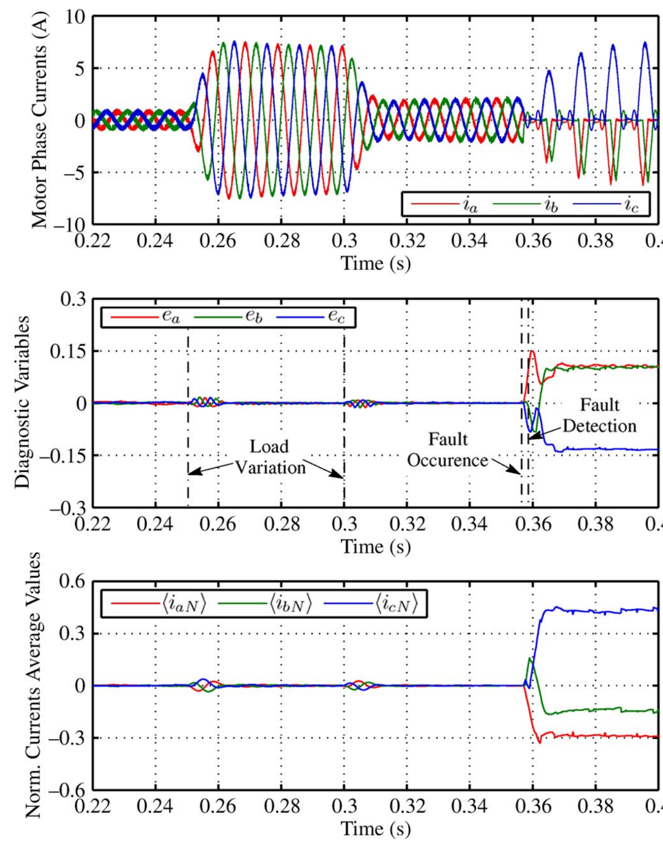

Fig. 5. Simulation results concerning the time-domain waveforms of the motor phase currents, the diagnostic variables, and the normalized currents average values, for a double power switch open-circuit fault in IGBTs T1 and T3.

fault are approximately twice than the obtained ones for a single power switch open-circuit fault.

With respect to the normalized currents' average values, some transient variations are generated when the fault occurs, converging then all values to zero.

Taking into account the same threshold values and the diagnostic signatures in Table I, the abnormal behavior in phase a is also detected 1.3 ms after the fault occurrence. The final confirmation of a double fault in this inverter leg is accomplished 6.6 ms after the fault occurrence, when the variable e_a reaches the threshold k_d.

C. Double Power Switch Open-Circuit Fault

Fig. 5 shows the time-domain waveforms of the motor phase currents together with the diagnostic variables and the normalized currents' average values, for a double fault in power switches T1 and T3.

When the faults in transistors T1 and T3 at the instant $t = 0.357$ s are introduced, both the diagnostic variables e_a and e_b will increase and reach values higher than k_f, as a result of a faulty device on the corresponding phases. On the other side, the diagnostic variable of the healthy phase will converge for a negative value.

Regarding the normalized currents' average values, it can be seen that the values of the faulty phases will have negative values, while the phase c value becomes positive. Therefore, considering the defined threshold values, a unique diagnostic signature is generated, allowing the detection and localization of the faulty IGBTs, according to Table I.

Further simulation results also proved that the other remaining 12 faulty switch combinations shown in Table I can be effectively detected and localized.

IV. Experimental Results

The experimental setup basically comprises a PMSM coupled to a four-quadrant servomotor test system (Fig. 6), a three-phase diode bridge rectifier, a Semikron SKiiP three-phase VSI, a dSPACE DS1103 digital controller, and two precision digital power analyzers (Fig. 7). The voltage and current signals as well as all the IGBTs gate commands are connected to the dSPACE controller trough interface and isolation boards (Fig. 8). Two digital power analyzers Yokogawa WT3000 were connected in series in the power circuit to measure important variables. The rated parameters of the PMSM used for the experimental tests are the same reported in Table II. The real-time interface board library for the DS1103 controller is designed as a common Matlab/Simulink Blockset that provides blocks to implement the I/O capabilities in Simulink models [26].

A rotor field-oriented control strategy employing hysteresis current controllers and the developed diagnostic algorithm were also implemented for the DS1103 digital controller board, using

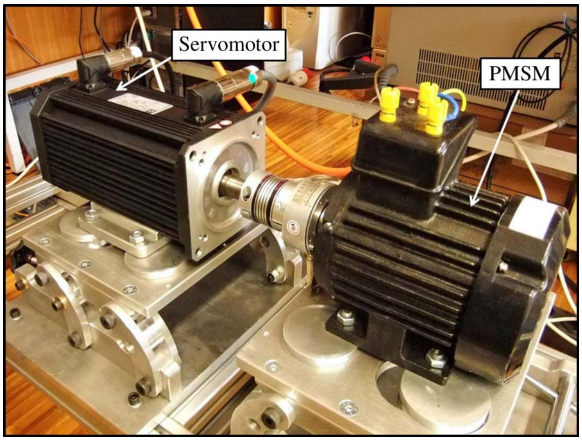

Fig. 6. Detail of the PMSM coupled to the servo machine.

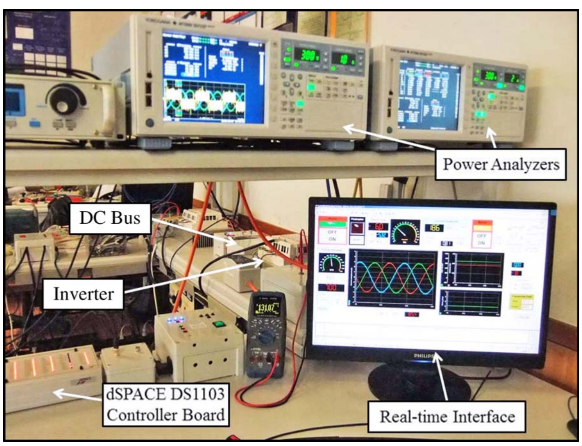

Fig. 7. General view of the power and control stages.

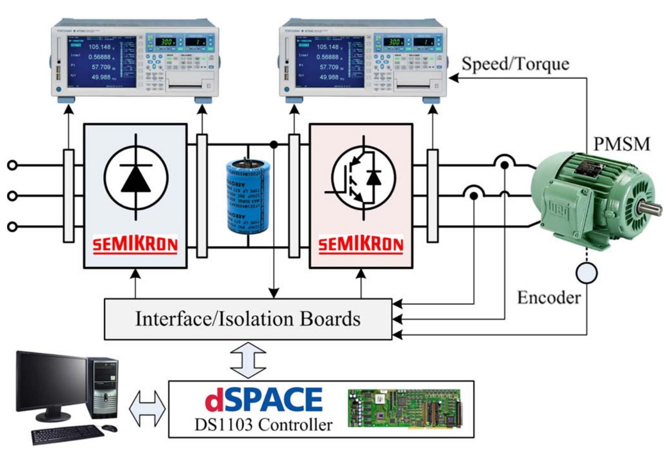

Fig. 8. Block diagram with the components of the experimental setup.

a sampling time of 25 μs. The rotor position is obtained by an incremental encoder with 1024 pulses per revolution.

Inverter power switch faults are controlled by the user using the dSPACE ControlDesk software. These are accomplished by removing the gate command signals of the required IGBTs.

Experimental results were obtained for a VSI single power switch open-circuit fault and for a double power switch open-circuit fault. For both the considered faulty operating conditions, a load level equivalent to 30% of the PMSM rated torque

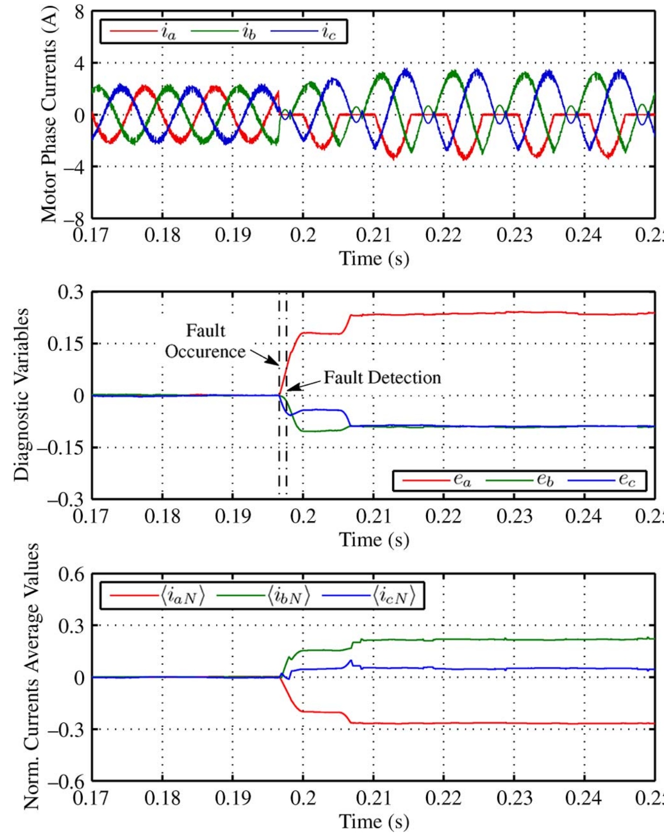

Fig. 9. Experimental results concerning the time-domain waveforms of the motor phase currents, the diagnostic variables, and the normalized currents' average values, for a single power switch open-circuit fault in IGBT T1.

is assumed, together with a reference speed of 1200 revolutions per minute. The threshold values are also chosen to be equal to the ones used for the presented simulation results, with the aim to perform a better comparison.

A. *Single IGBT Open-Circuit Fault*

Fig. 9 shows the experimental results regarding the time-domain waveforms of the motor phase currents together with the diagnostic variables and the normalized currents' average values, for a single IGBT open-circuit fault in transistor T1.

Comparing these results with the ones in Fig. 3, it can be seen that the experimental and simulation results have some similarities. Under normal operating conditions, both the three diagnostic errors as well as the normalized currents' average values are equal to zero. When a fault is introduced at the instant $t = 0.1965$ s, all variables show an analogous behavior comparing with the theoretical results. Therefore, considering the defined threshold values and the diagnostic signatures in Table I, the faulty power switch can be identified 1.13 ms after the fault occurrence, which corresponds to approximately 11% of the motor phase currents' fundamental period.

B. *Double Power Switch Open-Circuit Fault*

Results regarding the experimental time-domain waveforms of the motor phase currents together with the diagnostic variables and the normalized currents' average values for a double

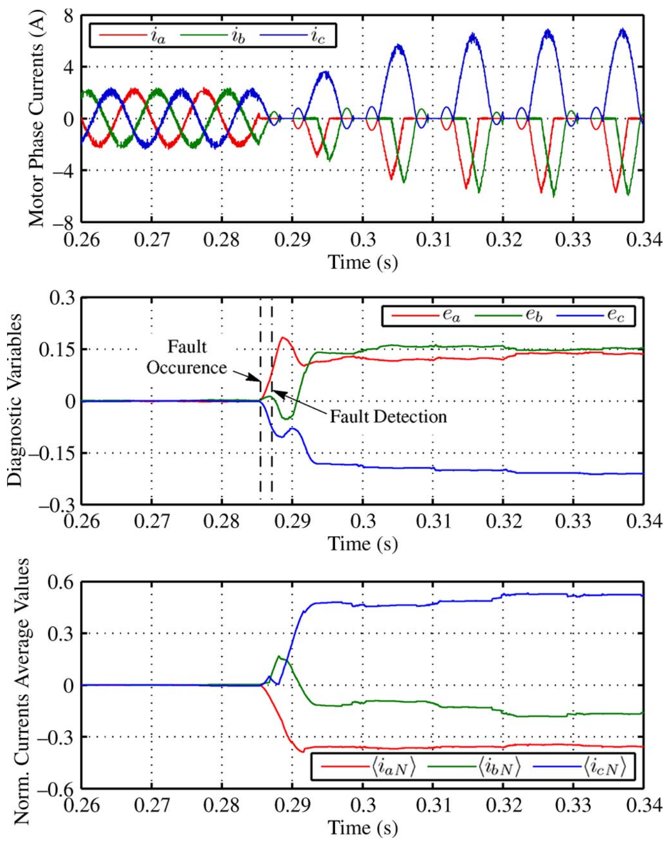

Fig. 10. Experimental results concerning the time-domain waveforms of the motor phase currents, the diagnostic variables, and the normalized currents' average values, for a double power switch open-circuit fault in IGBTs T1 and T3.

power switch open-circuit fault in transistors T1 and T3 are presented in Fig. 10.

The obtained results for this case also allow to verify that the diagnostic variable behavior is similar to the simulation one. After the fault occurrence, the errors of the faulty phases will pass the threshold k_f, converging then to approximately the same positive value, while e_c will assume a negative value.

Regarding the normalized currents' average values, their behavior is also identical to the results shown in Fig. 5, since all the three variables converge to approximately the same values. As a result, the generated fault signature is also the same, and by considering Table I, the faulty IGBTs T1 and T3 are effectively detected and localized.

It must be noticed that the algorithm detection speed depends on the time instant when the fault occurs. If a fault happens during a positive current half-cycle and in the top IGBT of that phase, the effect can be clearly seen since the current tends to zero immediately. An equivalent result is also verified during a negative current half-cycle for a fault in the respective bottom transistor of that phase. For these cases, the detection and localization are relatively fast.

However, if the fault occurs during a current half-cycle where the faulty IGBT does not affect it immediately, the fault effects will just be noticed at the next current half-cycle. Under these conditions, the fault can remain undetected for a period of time that can reach more than one-half of the motor phase currents' fundamental period.

Considering all this, additional experimental tests allow to verify that the diagnostic detection speed can be as fast as 11% and as slow as 77% of the motor phase currents' fundamental period.

Additional experimental tests also allow to prove that the other remaining 13 faulty switch combinations shown in Table I can be effectively detected and localized.

V. Conclusion

A new approach for real-time multiple open-circuit fault diagnosis for voltage-fed PWM motor drives has been proposed in this paper. The method uses as inputs just the three motor phase currents which are already available for the main control system, avoiding the use of extra sensors and the subsequent increase of the system complexity and costs.

The diagnostic variables based on the errors of the normalized currents average absolute values, beyond carrying diagnostic information on inverter failures, present a very high immunity against the issue of false alarms. As a result, the proposed method can handle large transients such as load and speed variations, without emitting false diagnostics.

Moreover, thanks to the use of normalized quantities, the algorithm behavior does not depend on the motor load level neither on its mechanical speed. Accordingly, two universal threshold values can be defined, independent of the machine operating conditions. The obtained results allow to conclude that the threshold values empirically established allow to accommodate large asymmetries and transients, keeping simultaneously a good detection performance.

Taking into account these threshold values and considering the diagnostic variables together with the normalized currents' average values, 15 distinct fault signatures are generated, each one corresponding to a unique inverter failure combination. Using these signatures, the algorithm can effectively detect and identify a great number of faulty situations.

Regarding the diagnostic method detection speed, the obtained results show that a faulty switch can be detected within a time equivalent to one ninth of the motor phase currents' fundamental period, which can be considered, comparing with similar techniques, relatively fast.

Finally, since the algorithm is quite simple, it can be easily integrated into the main control system without great effort. Furthermore, if it only required the knowledge of the faulty phases, some calculations and conditions can be removed, making the algorithm even simpler and less computationally demanding.

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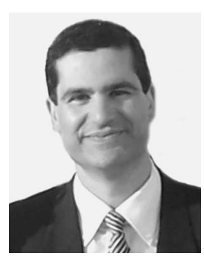

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