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Piotr Sobański, Teresa Orłowska-Kowalska

Application of Open-Circuit IGBT Faults Diagnostic Method in DTC-SVM Induction Motor Drive

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Original scientific paper

In this paper a simple diagnostic method of a single IGBT open-circuit fault is presented, it is dedicated for three-phase two-level voltage-inverter-fed vector controlled induction motor drive systems. A failure diagnosis is based on a transient analysis of a reference voltage space vector in stationary coordinates, without additional sensors. The diagnostic algorithm ensures detection and localization of single IGBT failures in time shorter than one period of a stator current fundamental harmonic, without regard to a drive operation point. The presented scheme of the diagnostic system can be easily applicable in the electric drives that use voltage space vector modulation algorithms. The main achievement of the research, whose results have been presented in this paper, is an experimental validation of the analyzed IGBT faults diagnosis technique in the drive with the Direct Torque Control algorithm.

Key words: Induction motor drive, Condition monitoring, Open-circuit fault, Direct torque control, Diagnostic techniquee

Primjena dijagnostičke metode za IGBT grešku otvorenog kruga u asinkronom motornom pogonu s vektorskom modulacijom i izravnim upravljanjem momentom. U ovom radu prikazana je jednostavna dijagnostička metoda jedne IGBT pogreške otvorenog kruga, namijenjena je za sustave asinkronog motornog pogona s trofaznim dvorazinskim pretvaračem s vektorskim upravljanjem. Dijagnoza pogreške zasnovana je na analizi tranzijenta referentnog vektora napona u stacionarnim koordinatama bez dodatnih senzora. Dijagnostički algoritam osigurava detekciju i lokalizaciju jedne IGBT greške u vremenu kraćem od jedne periode fundamentalnog harmonika struje statora neovisno o trenutnom operacijskom stanju pogona. Prezentirana shema dijagnostičkog sustava može se jednostavno primijeniti u električnim pogonima koji koriste algoritme vektorske modulacije naponskih vektora. Glavno postignuće istraživanja, čiji su rezultati prikazani u ovom radu, je eksperimentalna validacija analiziranih dijagnostički tehnika za IGBT greške u pogonu s algoritmom za izravno upravljanje momentom.

Ključne riječi: asinkroni motorni pogon, nadgledanje stanja, greška otvorenog kruga, Izravno upravljanje momentom, dijagnostička tehnika

1 INTRODUCTION

Faults in electrical motor drive systems constitute a current problem. Among the significant drives defects, different malfunctions occurring at the input rectifier, at the power inverter itself or at the control system stage reduce drive performance. Power electronics faults can lead to the interruption of the drive system operation,unprogrammed maintenance brakes and thus could lead to high financial losses, so the development of reliable monitoring and fast fault detection methods as well as fault-tolerant control strategies is a current demand of the industry.

Power electronics faults cause about 35% of all failures in electric motor drive applications [1, 2]. A significant part of these failures, close to 31%, are related to defects of semiconductor junctions [3] as well as transistor gate drivers malfunctions [2], resulting in drive performance reduction or even unplanned stoppage of the driving motor. Hence, fault-tolerant control (FTC) techniques, which combine transistor fault diagnostic methods, hardware redundancy and post-fault control algorithms that have recently allowed simultaneous electric drive operation, are developed [4]-[6]. Depending on application requirements, the post-fault action is performed by using power converters, whose topology is redundant. Among these converters, four-leg inverters allow to obtain full drive functionality because their faulted legs are replaced with additional ones. Nevertheless, this solution is expensive, therefore for low-cost applications four-switch inverter topologies are used. As a matter of fact, they are two ideas that are based on the three-phase voltage modulation using four transistors. The first one relies on isolation of the faulted inverter phase and circuit reconfiguration so that a connection between the neutral point of the machine and a midpoint of the inverter capacitor bank is obtained. In this case, a current flows only in two inverter phases. Moreover, its amplitude is higher than the nominal one if the nominal torque is required. Due to this fact, this solution is not recommended for long post-fault motor drive operations. The latter technique is based on the connection obtainment between the motor phase related to the faulted inverter leg and the mid-point of the capacitors. According to this solution, stator currents are not increased more than the nominal value, nevertheless only a half of the nominal speed of the drive can be obtained, contrary to the previously described case, namely 75% of the rated speed. Robustness of the diagnostic algorithm against false alarms, a proper faults localization and a fast diagnosis is crucial in the FTC drive systems concerning the correct performance of the required drive remedial action. Therefore, various diagnostic algorithms of IGBT failures have recently been developed. A survey of diagnostic methods dedicated to transistor failures can be found in [6, 7].

The most effective techniques utilize inverter voltage signals for the transistor fault detection. Additional sensors, which are required for voltage measurements, increase the cost of the solution, which is undesirable [8]. Thus the most frequently developed approaches are based on the analysis of easily accessible signals of the control structures, such as measured currents or estimated voltages. Many of them rely on monitoring of standardized errors between reference, estimated or measured diagnostic variables [8]-[13]. In [8] diagnostic signals are defined as average values of the errors between reference and measured phase currents that are normalized by the module of the measured current vector. The simpler approach is used in [9] where diagnostic signals are obtained as mean values of the measured phase currents which are divided by the module of the current vector. In the paper this approach is used in a fault-tolerant motor drive system. These two ideas have been compared in [10] with the method based on the analysis of the current hodographs which are characterized in the next part of this paper. In [11] the idea based on measured stator currents processing is described completely and formulated for the multiple transistor faults. Unlike the previously described algorithms, in [12] diagnostic signals are figured out calculating errors between the measured and estimated phase currents. This approach is effective but requires more complex computing. A similar technique is presented in [13], where for an open-phase fault diagnosis, an error between the predicted and measured stator current is used. This method is effective but it requires detailed motor parameters identification for the current prediction.

Other methods are based on the analysis of vector hodographs of fault diagnostic variables. In [14] a transistor fault diagnostic method based on an analysis of the dynamics of a reference voltage vector in the $\alpha - \beta$ stationary system are presented. This technique is dedicated to motor drive systems with space voltage vector modulation. In [15] the method based on the analysis of the current vector hodograph is presented, nevertheless this approach is load depended. Due to the fact that in DRFOC the flux is stabilized, a diagnostic signal based on rotor flux processing is not normalized [16]. In this case, a faulted transistor is localized using the information about the rotor flux vector position in the $\alpha - \beta$ system at an instant when a control error of the flux is observed. Nevertheless, the implementation of this algorithm is complicated and requires the usage of a sophisticated technique for fault features extraction. Therefore, it is desirable to develop the methods whose computational requirements are low and thereby increase their applicability.

In this paper, the simple transistor fault diagnostic algorithm presented in [14] has been developed and validated experimentally in the Direct Torque Control (DTC) induction motor drive system with the voltage Space Vector Modulation (SVM). Taking into account the survey of the transistor faults diagnostic techniques, there is a serious need of methods which allow to define diagnostic signal values that indicate the fault. In this article, the fault threshold value was assumed using a simple theoretical analysis and it was validated during a test under various healthy drive operations. This approach does not require the knowledge about the faulty condition of the drive, therefore it is easy to implement. The method was tested under transistor open-circuit faults occurring during a constant motor reference speed as well as under speed acceleration. The method consists in processing of the reference inverter voltage components using SVM, therefore it is universal and can be utilized for fault diagnosis in electric drives whose inverter voltages are modulated in accordance with SVM, namely in DTC and DRFOC as well. The diagnostic procedure ensures the detection and localization of single power switch failures in time shorter than one period of the stator current fundamental harmonic, without regard to a drive operating point.

2 INVERTER FAULT MONITORING

A basic scheme of a three-phase two-level voltage source inverter topology, whose faults are considered in this paper, is presented in Fig. 1a.

According to the proposed open-circuit IGBT fault diagnostic algorithm, faulty transistors of the inverter are recognized by using a simple analysis of reference inverter voltages which are formulated in the stationary coordinate system $\alpha - \beta$. These voltages can be realized by suitable configurations of inverter switches. In order to achieve a

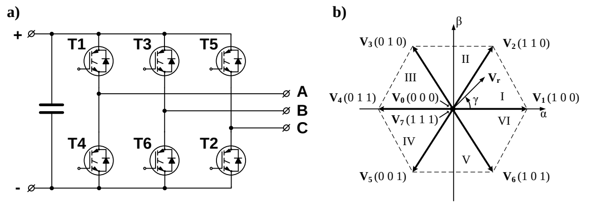

Fig. 1. Three-phase voltage source inverter: topology (a), voltage space vectors (b)

reference voltage vector $\mathbf{V_r}$, whose position in the $\alpha-\beta$ plane is defined by an angle γ, that is referred to the α axis, six active voltage vectors (**V1**,...,**V6**) and two zero ones (**V0** and **V7**) are utilized. These vectors divide the $\alpha-\beta$ plane into six sectors: I,...,VI (see Fig. 1b), in accordance with (1):

$$SN = E\left(\frac{\gamma}{\pi/3}\right) + 1, \tag{1}$$

where function *E(x)*returns an integer value of *x*.

The IGBTs condition monitoring algorithm is based on the analysis of the voltage vector presence time t_M in particular sectors of the complex $\alpha-\beta$ plane. Depending on the motor speed direction and fault location in a drive steady state, the reference voltage vector is forced in one characteristic sector during a much longer time-period than in the case of some other ones [15]. The direction of voltage vector rotation is related to the angular motor speed direction. In further considerations it was assumed that under the motoring mode of the machine, which rotates in the positive speed direction, the voltage space vector rotates with the positive direction as well. This means, the numbers of the sectors are increasingly changed. Depending on the motor speed direction and fault localization, the reference voltage vector $\mathbf{V_s}$ is forced in one characteristic sector during a much longer time-period than in the case of some other ones. This fact is clearly visible even under fast linear motor speed changes, this phenomenon will be demonstrated in the next section. According to this reasoning, the failure symptoms of the following inverter switches are integrated in Table 1. As it can be observed when analyzing Fig. 1b and the Table 1, the rotational movement of the reference voltage vectors is slower in those sectors which are indicated by the previously mentioned unavailable inverter states (unavailable voltage vectors).

This simple diagnostic method was described the first time in detail and widely tested in simulations in [14]. In this paper, an implementation scheme of this diagnostic method has been simplified and verified experimentally in DTC control structure of the induction motor drive. The new block diagram of the transistor faults diagnostic system is presented in Fig. 2.

Table 1. Position of the voltage vector depending of the faulted IGBT

Faulted switch	**Motor drive speed direction**	**Characteristic sector of the $\alpha-\beta$ plane (longer time-period of the voltage V_r presence)**
T_1	$\omega>0$	sector I
	$\omega<0$	sector VI
T_2	$\omega>0$	sector II
	$\omega<0$	sector I
T_3	$\omega>0$	sector III
	$\omega<0$	sector II
T_4	$\omega>0$	sector IV
	$\omega<0$	sector III
T_5	$\omega>0$	sector V
	$\omega<0$	sector IV
T_6	$\omega>0$	sector VI
	$\omega<0$	sector V

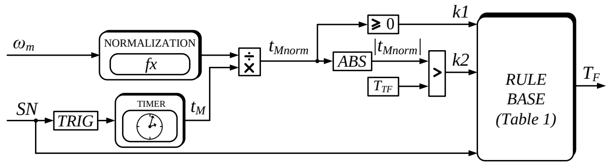

Fig. 2. Block diagram of the IGBT faults diagnostic system

In the system, the timer is set by a triggering event, which consist in a change of the sector *SN* that describes the location of the reference voltage vector on the $\mathbf{V_r}$ plane. The value of an output signal t_M is proportional to duration when the reference voltage vector is located in particular sectors. In order to normalize the diagnostic variable t_M, a simplification is assumed, namely the reference voltage frequency is proportional to the drive speed. Under the drive steady state, depending on the motor speed, t_M differs. For instance, if the speed is nominal, t_M is approximately equal to x_1, where:

$$x_1 = f_{Timer} T_N / x_2. \tag{2}$$

The f_{Timer} means the frequency of the timer which operates as a counter, T_N is the nominal supply voltage period of the motor and x_2 is equal to 6 because the $\alpha-\beta$ plane is divided into 6 sectors. Further, in general t_M can be defined as (3):

$$t_M = f_{Timer} T_U / 6 \tag{3}$$

where T_U means a period of the reference voltage. The scaling factor x_3 between the reference voltage frequency and the motor speed is described as (4):

$$x_3 = 1/\left(T_N n_N\right) \tag{4}$$

where n_N is the nominal speed of the motor. This means the frequency f_U of the reference voltage is formulated as follows (5):

$$f_U = x_3 n \tag{5}$$

where n is the drive speed. For the healthy motor drive operations, in order to obtain a constant maximum value of the diagnostic signal, whose absolute value is equal to one, an equation (6) was solved.

$$\frac{t_M}{a f_U} = 1 \tag{6}$$

As a result of the calculations, the normalized diagnostic signal is defined as follows (7):

$$t_{Mnorm} = 6 n t_M / \left(f_{Timer} T_N n_N\right) \tag{7}$$

In accordance with the system, if the absolute value $|t_{Mnorm}|$ of the signal t_{Mnorm} exceeds the constant value of the given fault threshold T_{TF}, then the transistor failure is detected. As mentioned before, to define the diagnostic signal, the simplification (5) was assumed. To avoid false alarms of the diagnostic system, the T_{TF} should be greater than one. For the research, it was assumed that $T_{TF} = 1.15$. This value is not obtained for the healthy drive operation, which was proven experimentally. In order to localize a faulty switch, the rule base, that concerns a motor speed direction, is used, in accordance with Table 2. These rules are valid for every drive control method that uses SVM for the inverter voltage regulation.

Logical variables *k1* and *k2* are related to the comparators of the diagnostic system (see Fig. 2).

Table 2. Open switch fault symptoms patterns

k1	***k2***	***SN***	**Faulted switch** T_F
1	1	1	**T1**
0	1	6	
1	1	2	**T2**
0	1	1	
1	1	3	**T3**
0	1	2	
1	1	4	**T4**
0	1	3	
1	1	5	**T5**
0	1	4	
1	1	6	**T6**
0	1	5	

3 EXPERIMANTAL RESULTS

3.1 A short description of the experimental set-up

In the following section, representative experimental results, which validated the effectiveness of the proposed IGBT open-circuit faults diagnostic method, that is dedicated to the three-phase two-level voltage inverters, are presented. The research was conducted utilizing a laboratory set-up whose schematic diagram and picture are shown in Fig. 3a and Fig. 3b, respectively. The set-up is composed of a 2.2kW induction machine connected by a stiff shaft to the load machine, namely a DC motor with controlled armature current. Nominal parameters of the induction motor are given in Appendix A, in the Table 3. For the drive speed measurements an incremental encoder (36000imp./rev.) was used. Furthermore, the LA 55-P and LV 25-P transducers were used for phase current and DC-link voltage measurements, respectively. The drive control algorithm was realized by using a dSPACE DS1103 rapid prototyping system with the sampling period $T_s = 100$ μs for measurement and 250 μs for the control structure (multisampling was utilized). The inverter operates at a switching frequency of 4 kHz. To obtain transistor faults, depending on a required failure location, an appropriate transistor gate command signal was removed. For the drive control, the direct torque control technique with the voltage space vector modulation was applied.

The experimental results, which are presented in this section, are organized in accordance with the following scenario. First, robustness against false alarms under a linear speed transient and various load torque values of the drive is analyzed. Next, the IGBT open-circuit faults are performed during the constant reference speed n_{ref} of the drive. Finally, the effectiveness of IGBT fault diagnostic method is validated for the failures which occur during motor speed acceleration.

In the figures, a pink dotted line indicates an instant of the transistor fault occurrence, but a moment of the faulty switch localization is depicted as a blue dotted line. In order to rate the time, which is necessary to carry out the transistor failure diagnosis, the normalized fault localization time t_D is defined as a part of a current period T_i that is measured before fault application.

In order to validate the effectiveness of the considered transistor open-circuit fault diagnosis method, transients of the diagnostic variable $|t_{Mnorm}|$ with the fault threshold $T_F = 1.15$ are presented. Moreover, time-domain waveforms of the phase currents $i_{sA,B,C}$, the signal *SN*, that is

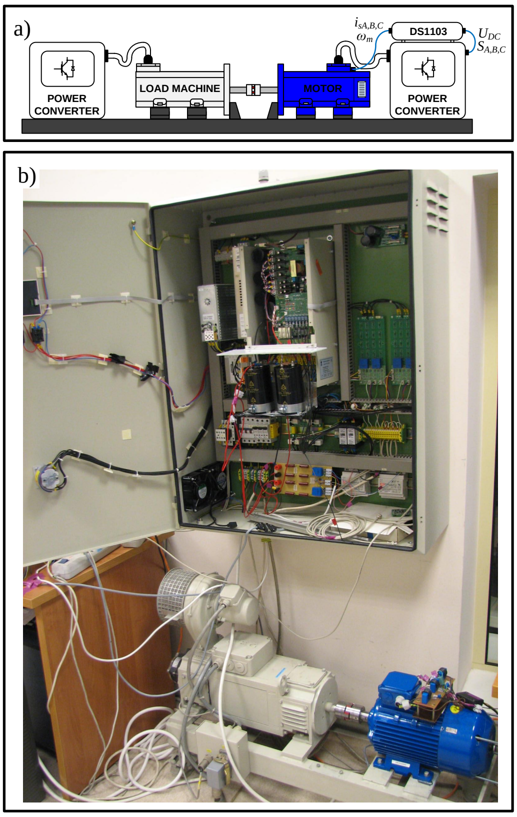

Fig. 3. The laboratory motor drive system: a schematic diagram (a), a photo of the induction motor drive (b)

related to the sector of the $\alpha - \beta$ plane, reference n_{ref} and the measured n motor speed, are depicted. The presented results concern single-switch faults of the inverter phase C, namely the transistor T5 and T2. Nevertheless, the observation for the faults in the phase A or B are analogical.

3.2 Robustness against false alarms

The broad majority of the IGBT open-circuit fault diagnosis algorithms require tuning diagnostic signal thresholds, whose exceeding signalizes failures of the power converter. Therefore, an analysis of the variable $|t_{Mnorm}|$ under various healthy drive operations should be taken into account.

First the drive operation without load torque ($m_L = 0$) was tested and presented in Fig. 4. Next the motor was loaded with $m_L = 0.8m_N$ (Fig. 5) during the changeable drive speed n=var. These tests allowed to define the transistor fault threshold $T_{TF} = 1.15$, so that T_{TF} is not exceeded during healthy drive operations.

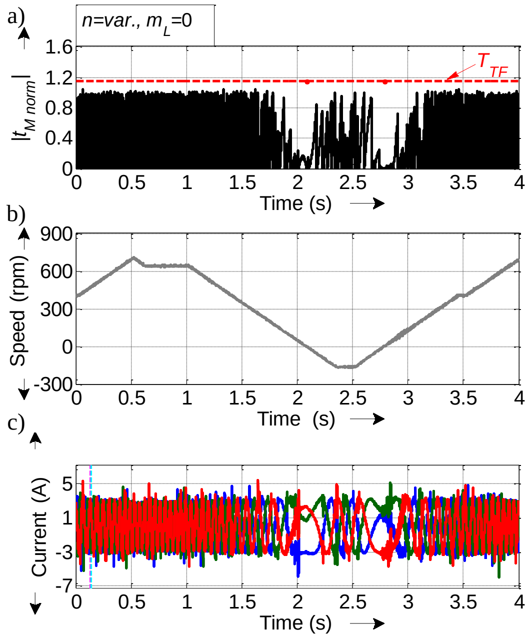

Fig. 4. Experimental results regarding the fault threshold fitting process with the time-domain waveforms of the diagnostic signal (a), the drive speed (b) and the stator currents (c) - no load test

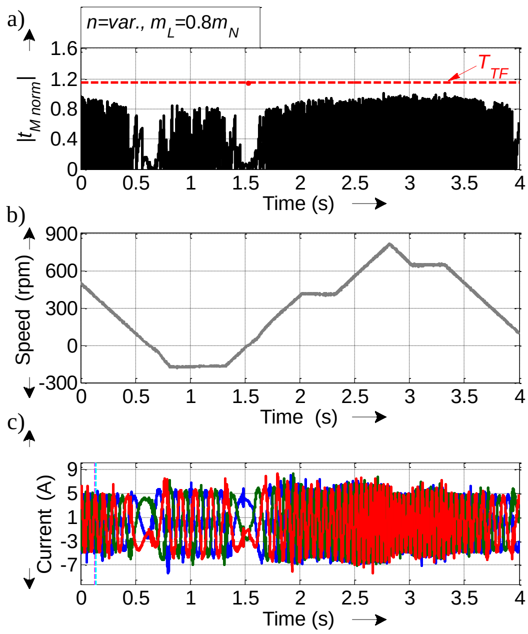

Fig. 5. Experimental results regarding the fault threshold fitting process with the time-domain waveforms of the diagnostic signal (a), the drive speed (b) and the stator currents (c) - loaded machine

3.3 Performance evaluation under the inverter transistor faults during the drive operation with a constant angular speed

Fig. 6 presents experimental results achieved for the transistor T2 fault, that occurred at the instant *t*=0.097 s, under the transistor non-conducting mode, shortly before the current of the faulty inverter phase i_{sC} achieved a zero value (see Fig. 6b). The drive operated with the low speed $n = 0.21n_N$ and with the nominal load torque $m_L = m_N$. As can be seen in Fig. 6c, d the diagnostic signal $|t_{Mnorm}|$ exceeded the fault threshold T_{TF} at $t = 0.152$ s, when the reference voltage vector was located in the 2nd sector of the $\alpha - \beta$ plane, which means that T2 transistor fault was recognized correctly. In this case, the fault diagnostic time t_{TF} comprises 0.68 of the current fundamental period T_i.

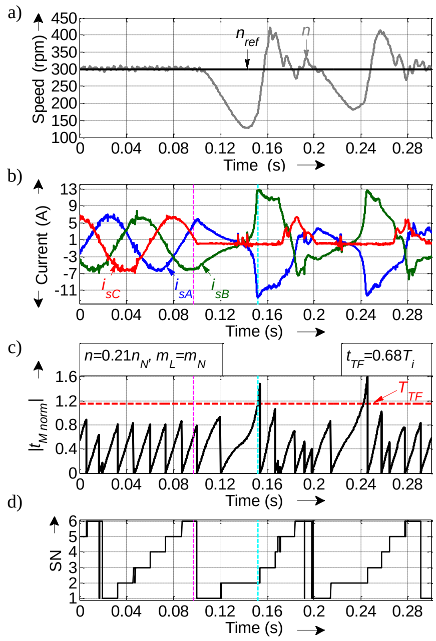

Fig. 6. Experimental transients of the drive speed (a), stator currents (b), the diagnostic variables (c, d) for a single power switch open-circuit fault in T2, during the low motor speed and nominal load torque

Fig. 7 presents the results obtained for the T2 fault, that occurred at the instant $t = 0.061$ s, under the transistor non-conducting mode, when the current of the faulty inverter phase i_{sC} achieved the peak value (see Fig. 7b).

The drive operated with the nominal speed $n = n_N$ and the nominal load torque $m_L = m_N$. As can be seen in Fig. 7c, d, the faulty transistor was correctly recognized within the time $t_{TF} = 0.55T_i$.

The results, that are shown in Fig. 8-9, deal with the open-circuit faults of the upper transistor T5 during no load motor drive operations. The faults were applied during low

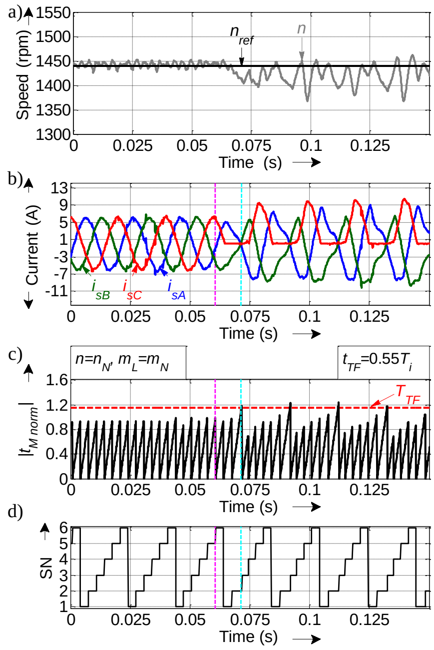

Fig. 7. Experimental transients of the drive speed (a), stator currents (b), the diagnostic variables (c, d) for a single power switch open-circuit fault in T2, during the nominal motor speed and nominal load torque

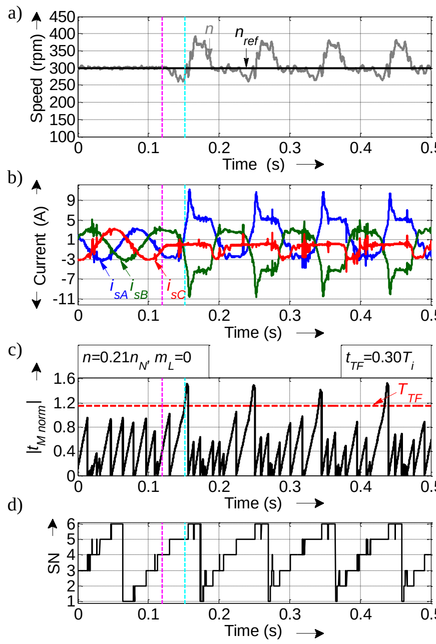

Fig. 8. Experimental transients of the drive speed (a), stator currents (b), the diagnostic variables (c, d) for a single power switch open-circuit fault in T5, during the low motor speed and no-loaded drive

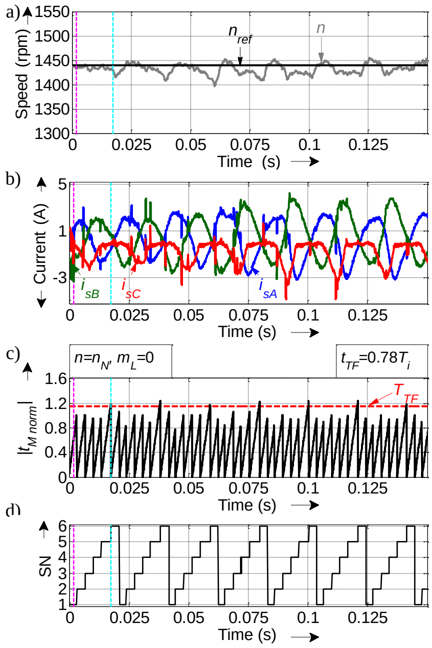

Fig. 9. Experimental transients of the drive speed (a), stator currents (b), the diagnostic variables (c, d) for a single power switch open-circuit fault in T5, during the nominal motor speed and no-loaded drive

speed motor drive operation (Fig. 8) as well as under the nominal speed of the motor (Fig. 9).

The following tests have proven the effectiveness of the fault diagnostic method regardless of the motor velocity. Additionally, it is visible that for each case the diagnostic time does not exceed the time equal to one period of the stator current fundamental harmonic that was measured before the fault occurrence.

3.4 Performance evaluation under the inverter transistor faults during the drive operation with linear changes of the angular speed

In this subsection, in Fig. 10-11 the experimental results, that concern the transistor faults which occurred during linear changes of the motor speed, are presented.

First, at the time instant $t = 0.121$ s, the open-circuit fault in the T5 transistor was introduced during the motor speed-acceleration and for the nominal loaded machine (Fig. 10). Unlike the previous case, the results related to the fault of T2, which was applied at $t = 0.135$ s, the fully-loaded motor under speed deceleration, are presented in Fig. 12. As in the case of both tests, the fault diagnostic time t_{TF} is shorter than the current fundamental period, namely $t_{TF} = 0.57T_i$ in the case of T5 failure and $t_{TF} = 0.08T_i$ for the T2 fault.

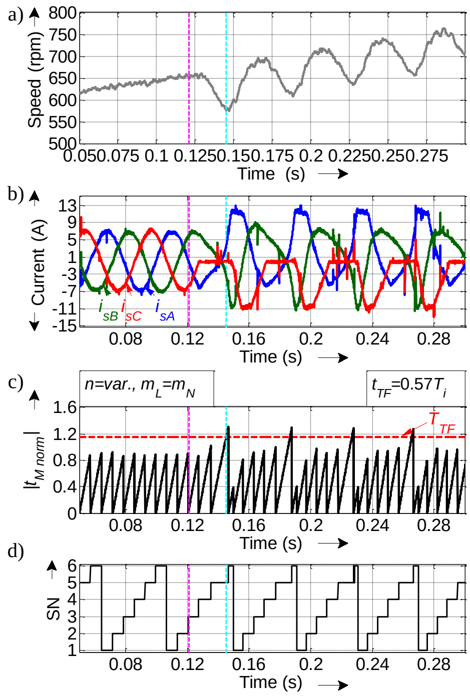

Fig. 10. Experimental transients of the drive speed (a), stator currents (b), the diagnostic variables (c, d) for a single power switch open-circuit fault in T5, during the speed acceleration of the fully-loaded drive

4 CONCLUSION

This paper discusses the open-circuit IGBT fault diagnostic method, which is dedicated to the two-level three-phase voltage inverters which operate in DTC-SVM induction motor drives. The authors have successfully validated the effectiveness of their inverter fault diagnostic algorithm [14] (with some modification in the used technique) for the first time in the DTC motor drive system. In this paper, the detailed experimental validation of the algorithm has been presented.

The developed diagnostic technique ensures the correct single-switch open-circuit fault diagnosis in a time shorter than one period of the stator current fundamental harmonic without regard to a drive operation point. As proved in the research the proposed method is robust against false alarms and easy to implement, which makes it attractive from the industrial point of view.

The presented method consists in the reference inverter voltage vector analysis therefore it is universal and can be utilized in the drive control structures with space vector modulation. In this case the computational complexity is not significantly increased.

Table 3. Data of induction motor drive

Rated data		
Quantity	***Symbol***	***Value***
Power	P_N	2.2 kW
Torque	m_N	14.6 Nm
Speed	n_N	1440 rpm
Voltage	u_N	400 V
Current	i_N	4.5A
Frequency	f_N	50 Hz
Efficiency	η	84,7 %
Power factor	$\cos\varphi$	0,83
Main inductance	L_m	307.1 mH
Leakage stator inductance	$L_{s\sigma}$	16.4 mH
Leakage rotor inductance	$L_{r'\sigma}$	16.4 mH
Stator resistance	R_s	2.77 Ω
Rotor resistance	R_r	2.97

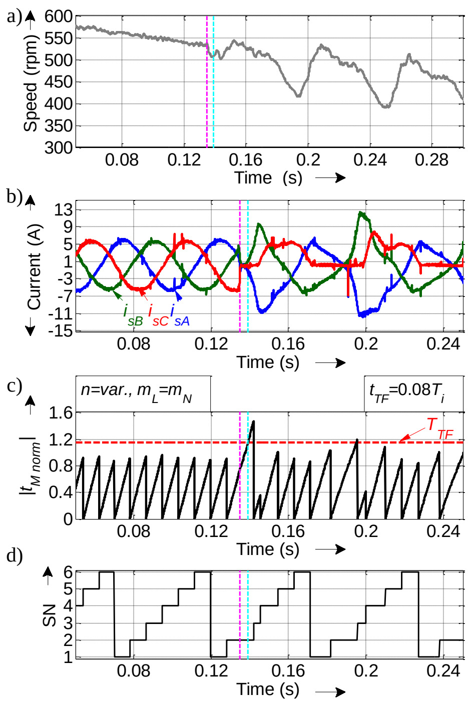

Fig. 11. Experimental transients of the drive speed (a), stator currents (b), the diagnostic variables (c, d) for a single power switch open-circuit fault in T2, during the speed deceleration of the fully-loaded drive

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APPENDIX A DATA OF THE TESTED DRIVE

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Piotr Sobański was born in Bielawa, Poland, in 1988. He received the M.Sc. degree in electrical engineering from the Wroclaw University of Technology, Poland, in 2012, where he is working toward the Ph.D. degree in the Department of Electrical Machines, Drives and Measurements. His research interests are focused on fault-tolerant systems dedicated to electrical drives.

Teresa Orlowska-Kowalska (M'93–SM'05) received the Ph.D. and D.Sc. degrees from Wroclaw University of Technology, Wroclaw, Poland, in 1976 and 1990, respectively. Since 1993, she has been a Professor of electrical engineering (since 2004 – Full Professor) and the Head of the Electrical Drives Control Chair, Institute of Electrical Machines, Drives, and Measurements, Wroclaw University of Technology. Since 2002 she has been the Director of this Institute (now the Department of Electrical Machines, Drives, and Measurements). She is the author and coauthor of over 400 journal papers and conference proceedings, two textbooks, two books, and over fifty chapters in monographs. Her research interests include controlled electrical drives, applications of artificial intelligence methods, observer theory, especially issues of sensorless vector control methods of converter-fed AC drives, control methods of mechatronic systems with multiple elastic couplings, diagnostics and fault-tolerant control methods for AC drives. Prof. Orlowska-Kowalska is a member of the Electrical Engineering Committee of the Polish Academy of Science (since 1996), the Council of Provosts of IV Division of the Polish Academy of Science (since 2011), member of the Polish Society of Theoretical and Applied Electrical Engineering and international steering committees of a few well-known conferences. She serves as a reviewer of many IEEE Transactions and other scientific journals. In the period 2004-2014 she has been an Associate Editor for the IEEE Transactions on Industrial Electronics. Presently she is an Editor in Chief of Power Electronics and Drives (Poland), as well as a member of Editorial Board of Przeglad Elektrotechniczny (Poland), MIDEM – Journal of Microelectronics, Electronic Components and Materials (Slovenia), Transactions on Electrical Engineering (Czech Republic).

AUTHORS' ADDRESSES

P. SOBANSKI, M.Sc.
Prof. T. ORLOWSKA-KOWALSKA, D.Sc., Ph.D., M.Sc.
Department of Electrical Machines, Drives and Measurements,
Faculty of Electrical Engineering,
Wroclaw University of Science and Technology,
ul. Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
email: piotr.sobanski@pwr.edu.pl,
teresa.orlowska-kowalska@pwr.edu.pl

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