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# A NEW TECHNIQUE FOR SIMULTANEOUS DETECTION OF ONE TO TWO OPEN–SWITCH FAULTS IN THREE PHASE VOLTAGE–INVERTER–FED PM BRUSHLESS DC MOTOR DRIVE

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The faulty performance of permanent-magnet (PM) brushless dc motor drives is studied under one and simultaneous two open-switches faults conditions. This DC motor is supplied with a three phase two level six IGBT voltage source inverter. The three phases currents mean values of the DC motor are used as diagnostic indices. A knowledge algorithm is based to get information on which IGBT is in open-switch fault condition. This algorithm testing shows that the system could not only detect the open-switch fault, but also identify the faulty switch. Presented simulation results confirm the effectiveness of the proposed methodology.

K e y w o r d s: brushless dc motors, fault diagnosis, IGBT, one open-switch, two open- switches, mean value, min and max value, logic functions, Boolean value

## 1 INTRODUCTION

Automatic fault detection of electric machines and drive systems is a challenging task that has recently attracted increasing attention. An intelligent regime of online condition monitoring leading to fault identification, fault location, and fault-severity evaluation represents the far goal. Precise diagnosis and early detection of incipient faults help to avoid harmful, sometimes devastative consequences of the fault. Repair requirements and the time frame could be preset based on the automatic diagnostics, which reflects lower cost. Temporary remedial actions that allow the machine to continue running under fault are firmly based on the online diagnostics and highly recommended for fault-tolerant systems.

Certain procedures are to be followed in order to achieve the automatic diagnosis mission. Studying system performance under specific fault conditions and comparing it with healthy performance yields one or more characteristic waveforms that could identify the fault. Features extracted from the characteristic waveform(s) are used as input data to the online diagnosis process.

Various techniques for open-switch fault detection in voltage source inverter (VSI)-fed pulse width-modulation (PWM) asynchronous motor drives were presented in [1]. Monitoring voltages at key points of the system and comparing them with respective references could successfully diagnose the fault. Temporary remedial actions under similar faults on permanent-magnet (PM) synchronous motor drives were prescribed for fault- tolerant operation [2]. Converter topology with eight switches helped the machine to produce more torque under fault than the classical six-switch configuration.

Expert systems, artificial neural networks (ANNs), fuzzy and adaptive-fuzzy systems, and genetic algorithms (GAs) represent the modern AI tools, which have been used in the area [3], [4]. Adaptive neuro-fuzzy inference systems (ANFIS) are composed of fuzzy inference systems implemented in the framework of adaptive networks [5]. Pattern classification through learning, nonlinear mapping and utilization of human expertise are examples of the powerful features of ANFIS. New and promising research horizons in the area of motor fault detection could be explored using fuzzy inference systems implemented on neural architectures [6].

Tahar Bahi, Mohamed Fezari, George Barakat and Nasr Eddine Debbache [7], Friedrich W. Fuchs [8] used a localization domain illustrated by seven patterns built with the stator Concordia mean current vector. One pattern corresponds to the healthy domain and the remaining six patterns are linked to the state of each inverter switch.

The present work introduces a simple diagnostic technique for one and simultaneous two open-switches faults on the inverter bridge of voltage-source inverter (VSI)-fed PM brushless dc motor drives. Healthy and faulty system were simulated in PLECs/MATLAB program. Fault impact on each one of the three phases currents mean values is observed to conceive the appropriate diagnosis algorithm basing on the value and the polarity of the currents mean values under fault condition. This technique testing shows its effectiveness in detecting and locating the open-switch fault.

Implementation of the proposed method should be straightforward on a processor loaded with three currents sensors and one speed sensor.

## 2 BRUSHLESS DC DRIVES SYSTEM

The VSI-fed PM brushless DC motor drive considered in this work is presented in Fig. 1, with: DC supply 300 V;

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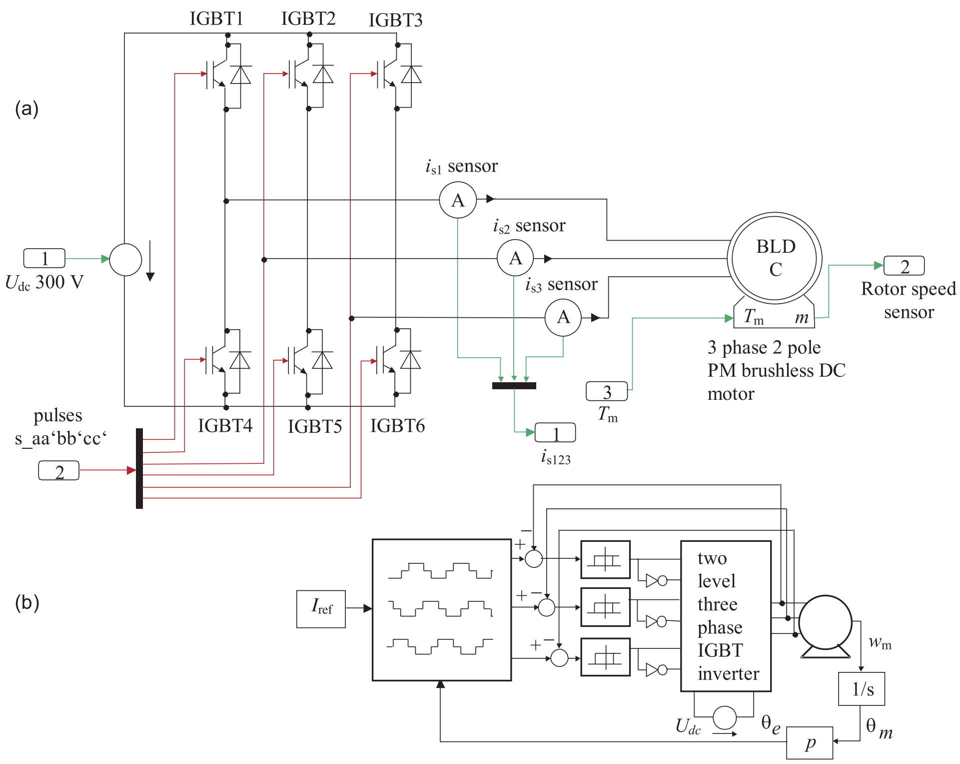


**Fig. 1.** Schematic diagram of the drive system:(a) - Electrical power part of the systems (Plecs/Matlab), (b) - Global of the system

IGBT-based three-phase inverter bridge; Three current sensors; Three-phase motor having trapezoidal back electromotive force (emf) and two poles PM rotor with rotor speed sensor.

**Table 1.** Polarity of the Mean value of phase currents and limits of Min and Max values corresponding to faulty open circuit IGBT.

| Phase | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
|---|---|---|---|---|---|---|---|---|---|
| Faulty IGBT | $i_{s123}$ Mean | | | $i_{s123}$ Min | | | $i_{s123}$ Max | | |
| 1 | − | + | + | $< -\mathbf{h}$ | $< -\mathbf{h}$ | $< -\mathbf{h}$ | 0 | $> h$ | $> h$ |
| 2 | + | − | + | $< -h$ | $< -h$ | $< -h$ | $> h$ | 0 | $> h$ |
| 3 | + | + | − | $< -h$ | $< -h$ | $< -h$ | $> h$ | $> h$ | 0 |
| 4 | + | − | − | 0 | $< -h$ | $< -h$ | $> \mathbf{h}$ | $> \mathbf{h}$ | $> \mathbf{h}$ |
| 5 | − | + | − | $< -h$ | 0 | $< -h$ | $> h$ | $> h$ | $> h$ |
| 6 | − | − | + | $< -h$ | $< -h$ | 0 | $> h$ | $> h$ | $> h$ |
| 5,6 | − | + | + | $< -\mathbf{h}$ | $-\mathbf{h}$ | $-\mathbf{h}$ | $h$ | $> h$ | $> h$ |
| 4,6 | + | − | + | $-h$ | $< -h$ | $-h$ | $> h$ | $h$ | $> h$ |
| 4,5 | + | + | − | $-h$ | $-h$ | $< -h$ | $> h$ | $> h$ | $h$ |
| 2,3 | + | − | − | $-h$ | $< -h$ | $< -h$ | $> \mathbf{h}$ | $\mathbf{h}$ | $\mathbf{h}$ |
| 1,3 | − | + | − | $< -h$ | $-h$ | $< -h$ | $h$ | $> h$ | $h$ |
| 1,2 | − | − | + | $< -h$ | $< -h$ | $-h$ | $h$ | $h$ | $> h$ |

## 3 SIMULATION

The drive was modelled using a PLECS/MATLAB program. Machine windings were represented by resistance, inductance and back emf in series. Measured values of the phase resistance and inductance as well as measured waveforms of the trapezoidal back emf were used in the simulation. Fourier series expansion was used to compute instantaneous values of the phase emfs at different rotor position angles. Each switch was represented by a nonlinear resistor that attains a very low value when the switch is ON and a very high value when it is OFF. The current command value was input to the software model, and open speed loop operation was assumed.

### 3.1 PROPOSED METHOD PRINCIPLE (CHANGE DETECTION OF STATOR CURRENTS)

Simulation results under both normal and faulty conditions will be used eventually to conceive the diagnosing algorithm basing on currents zero harmonic components and their maximum and minimum values and their polarities. Normal operating condition is characterized by, theorically, a nil zero harmonic component value and specific maximum and minimum values of each phase current. As remarked in Fig. 3, in normal operating condition, currents zero harmonic components values are almost nil (0 A). A change in phase currents waveforms is defined as the instant at which a sudden increase or decrease is observed in zero harmonic components values of three phases currents. A change is considered to have occurred in three phases values when they exceed or fall below a given band (±0.5 A).

Basing on zero harmonic components values may not be sufficient to make difference between one open-switch

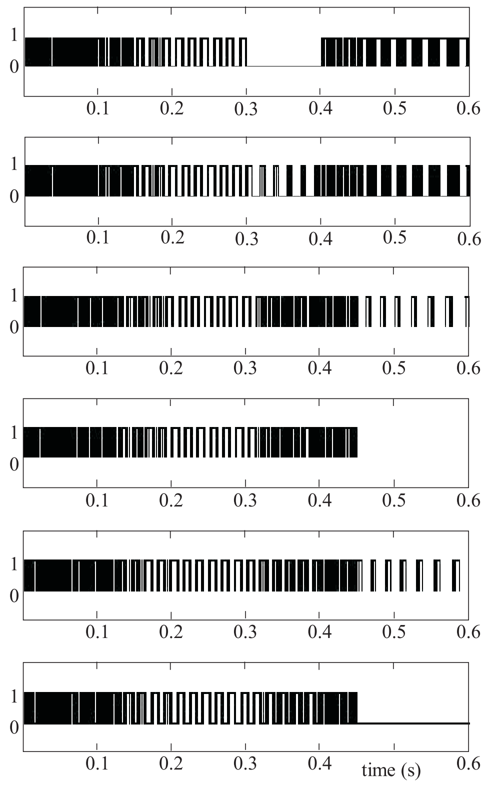


**Fig. 2.** Boolean firing signals in safe and open switch fault condition (IGBT1 open gate fault condition and IGBT5 and IGBT6 open gate fault condition). From the top to the bottom: IGBT1, IGBT4, IGBT2, IGBT5, IGBT3, IGBT6.

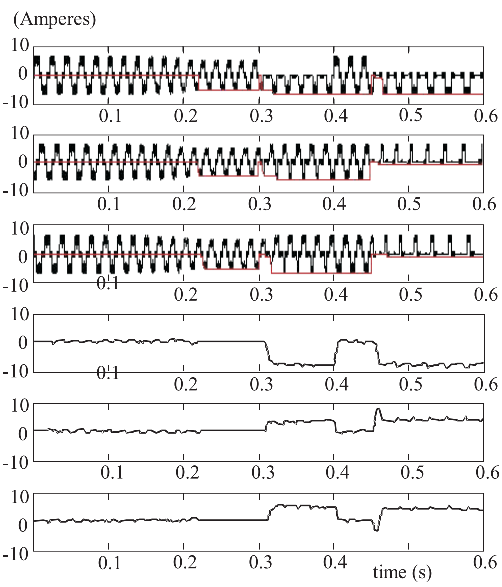


**Fig. 3.** Phases currents waveforms in safe and open switch fault condition (IGBT1 open gate fault condition and IGBT5 and IGBT6 open gate fault condition). From the top to the bottom: ($i_{s1}$, $i_{s1,\min}$), ($i_{s2}$, $i_{s2,\min}$), ($i_{s3}$, $i_{s3,\min}$), $i_{s1,\mathrm{mean}}, i_{s2,\mathrm{mean}}, i_{s3,\mathrm{mean}}$.

fault of an upper IGBT of one leg and simultaneous open-switch fault of lower IGBTs of other legs. In both cases, one phase current zero harmonic component is of a sign that is different from the other two phases currents zero harmonic components ($i_{s1,\mathrm{mean}} = 0$ A to $-1.6$ A to 0 A to $-1.6$ A, $i_{s2,\mathrm{mean}} = 0$ A to $+0.75$ A to 0 A to $+0.8$ A, $i_{s3,\mathrm{mean}} = 0$ A to $+0.75$ A to 0 A to $+0.8$ A) (Fig. 3).

Therefore, another parameter is introduced to make the difference between one open- switch fault of an upper IGBT of one leg and simultaneous open-switch fault of lower IGBTs of other legs. This parameter is the minimum value of currents. In the case of one open-switch fault of an upper IGBT of one leg, minimum values of the other phases, linked to safe legs, currents are negative. But, in the case of simultaneous two open-switch fault of the lower IGBTs of the other two legs, minimum values of the other phases, linked to these legs, currents are nil ($i_{s1,\min} = 0$ A to $-5$ A to $-6$ A, $i_{s2,\min} = 0$ A to $-5$ A to $-6$ A to $-1$ A, $i_{s3,\min} = 0$ A to $-5$ A to $-6$ A to $-1$ A) (Fig. 3).

In the case of one open-switch fault of a lower IGBT of one leg and simultaneous open-switch fault of upper IGBTs of other legs, currents minimum values will be used to make the difference between these two fault conditions (Fig. 3).

Currents zero harmonic components are calculated using the discrete variable- frequency FFT calculation block in Simulink/Matlab with sample time of 0.0001 s and input signal (phase current) frequency determined basing on the rotor speed.

Phases currents waveforms with their mean values and minimum values are presented in Fig. 3 and rotor speed and electromagnetic torque waveforms are presented in Fig. 4.

The phase current varies around a preset current reference that yields the desired torque value.

Figure 5 shows the detection algorithm Boolean outputs before and after IGBT1 open circuit fault. It is noticed that the detection system is performing in open circuit IGBTs fault detection. However, there is a short delay time of 0.02 seconds between fault occurrence time and fault detection time. This delay time is due to the delay introduced by the mean value calculation algorithm as well as the width of the mean value hysteresis tolerance band ($\pm h_1$). This band was chosen to avoid a faulty detection during the starting period of the DC brushless motor (the band may be increased or decreased depending on the value of operating stator currents) in this case, current Hysteresis Band$= \pm 0.4$ A.

The band reserved for Min and Max values of currents was chosen basing one the currents controllers hysteresis bands ($h$ currents $= \pm 1$ A). So the currents Min/Max values hysteresis band$= \pm h\,(\text{currents} + \Psi)$ with ($\Psi = 0.5$ A).

An artificial intelligent system such as a expert system is recommended to be used to identify the faulty device, as classified in Table 1.

Simulation results show that when the base drive open circuit fault (IGBT$i$, $i = 1, \dots, 6$) is introduced and stator currents are examined as a function of failure mode, there will be six different stator currents corresponding to the individual transistor base drive open-circuit fault of IGBT1, IGBT2, IGBT3, IGBT4, IGBT5 and IGBT6. In all six cases, this fault introduces a non-nil zero harmonic

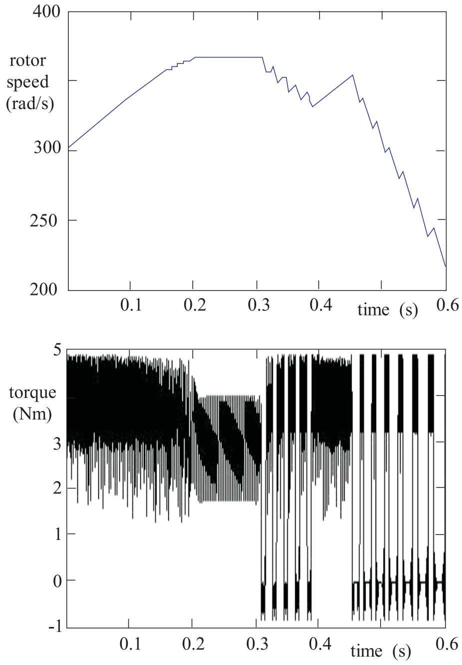


**Fig. 4.** Rotor speed and electromagnetic torque in safe and open switch fault condition (IGBT1 open gate fault condition and IGBT5 and IGBT6 open gate fault condition) From the top to the bottom: rotor speed (rad/sec), electromagnetic torque (Nm).

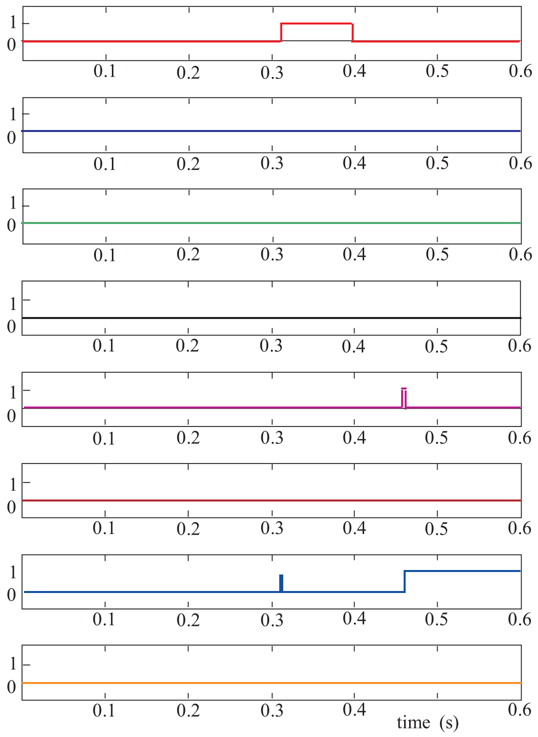


**Fig. 5.** Diagnostic system Boolean output signals in safe and open switch fault condition (IGBT1 safe and open switch fault condition and simultaneous IGBT5, IGBT6 safe and open switches fault condition). From the top to the bottom T1, T2, T3, T4, T5, T6, simultaneous T5 and T6 open-switch fault, simultaneous T1 and T2 open-switch fault.

component values in three phase currents with polarity specified to each IGBT fault condition. This technique allows only individual transistor open-switch fault detection.

In the case of simultaneous two open-switch fault IGBTs, another parameter is introduced to make the difference between one open-switch fault of an upper IGBT of one leg and simultaneous open-switch fault of lower IGBTs of other legs and vice versa.

## 5 CONCLUSION

This paper presents systematically a novel simple approach to detect the inverter faults of one and simultaneous two open switches fault condition for open loop controlled PM brushless DC motor drives. The zero harmonic component values of stator currents as well as their Max/Min values have been used to identify the inverter faults.

Implementation of this technique requires only three currents sensors, signal acquisition system and calculation processor.

The results are extremely important for the monitoring and fault detection of the inverter in drives system. The work can be extended to other converter configurations or drives.

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