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A NEW DIAGNOSTIC METHOD OF FAULTY TRANSISTOR IN A THREE-PHASE INVERTER

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ABSTRACT

This paper describes a method of detection and identification of transistor base drive open-circuit fault of 3-phase voltage source inverter (VSI), feeding an open loop controlled induction motor. The detection mechanism is based on a novel technique of wavelet transform. In this method, the stator currents will be used as an input to the system. No direct access to the induction motor is required. The simulation results are presented.

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Keywords: *Detection, Voltage Inverter Faults, Induction motor, Stator, dc offset.*

1. INTRODUCTION

The increase of productivity requirements and better performance specifications lead to more demanding operating condition of many engineering systems. Such condition will increase the possibility of the system failure, which are characterised by critical and unpredictable changes in the system dynamics. In general, feedback control algorithm, which is designed to control small perturbation that may arise under normal operating condition, cannot accommodate abnormal behaviour due to the components fault. The system may collapse completely.

Most of the power electronic devices normally operate in an environment requiring rapid speed variation, frequent stop / starting and constant overloading. The circuits are subject to constant abuse of over-current surge and voltage overswings. Although protection devices such as snubber circuits are commonly used, switching devices are physically small and thermally fragile. Even a small electrical disturbance can cause thermal rating to be exceeded resulting in rapid destruction. In many cases, occasional failures may be tolerated, but, in the case of expensive, high power systems, multi-converter integrated automation systems and safety critical systems, advanced indication of unusual performance which may lead to sudden system failure is mandatory.

Therefore, the knowledge and information about the fault behaviour of power electronic circuits is important to improve system design, protection and fault tolerant control. Unfortunately, condition monitoring of the power electronic systems only received a little attention compared with fault diagnostics of motor [1-3].

Tahar Bahi, Mohamed Fezari, George Barakat and Nasr Eddine Debbache [4], Friedrich W. Fuchs [5] used a localization domain illustrated by seven patterns built with the stator Concordia

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mean current vector. One pattern corresponds to the healthy domain and the remaining six patterns are linked to the state of each inverter switch.

This paper presents a study on open loop condition monitoring and fault detection of transistor base drive open-circuit faults of a 3-phase voltage source inverter (VSI) feeding induction motor. The fault detection algorithm is based on a simple method to investigate detection of converter faults by using the simplest criteria available in input and output waveform. The sign of DC component in current is used as main factor to detect the faults. Then the knowledge-based system is used to analyse the results.

2. INVERTER TRANSISTOR BASE DRIVE OPEN-CIRCUIT FAULT

A PWM-VSI inverter induction motor drive system is shown in figure 1. In this paper, only a single transistor base drives open-circuit fault of power converter will be considered. This fault will only reduce the operating conditions of the drive without involving the short circuit protection of the system. The drive system can operate for a considerable period of time but with degraded performance and low efficiency. The injected dc offset in the machine phase currents caused by a base drive open-circuit fault, worsen the current stress of the inverter healthy switching devices. Continuous operation in such faulty condition may lead to the catastrophic breakdown of the drive system.

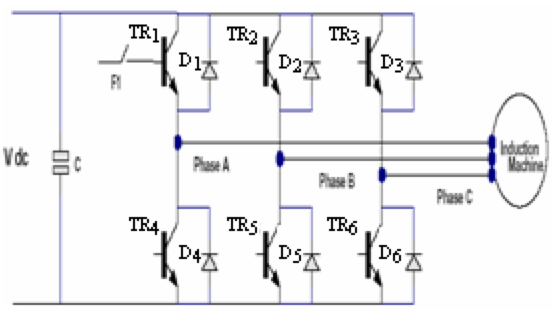


***Fig. 1:** A PWM voltage-fed inverter of induction motor drive*

To operate power transistors such as MOSFET or IGBT, an appropriate gate voltage must be applied in order to drive transistors into the saturation mode for low on-state voltage. Malfunctioning of gate drive circuit can lead to the transistor base drive open- circuit fault.

Since the transistor T1 has now an open-circuit fault (F1), the phase A of the induction machine is connected to the positive dc rail through the diode D1. The machine phase A voltage is then determined by the polarity of current and the switching pattern of transistor T4. The phase voltage (VA) will be clamped to the negative rail if stator current phase A, (iA) is positive. On the other hand, the phase voltage VA will be clamped to the negative rail when transistor T4 is switch on, and then to the positive rail when transistor T4 is off and D4 is on, if iA is negative. The phase currents will be balanced and sinusoidal with a dc offset after the fault because the phase voltages (VA, VB, VC) are balanced with the sinusoidal pwm modulation before and after the fault. The dc offset current in phase A will be equally divided between the phase B and phase C and of opposite sign. This conclusion is only valid under the assumption of magnetic linearity and infinite rotor inertia.

3. SYSTEM MODELISATION

The three-phase voltage inverter is based on three cells of commutation as shown in Fig. 2. Each commutation cell can thus be regarded as a phase of the inverter. This system is controlled by a Pulse Width Modulation (PWM) generator module. The command of the [6] complementary switch of the same cell is assumed unchanged initially. Based on this command, a mean variable voltage is applied to the motor at each commutation period. We study the effect of the damage of every switch of the inverter, respectively.

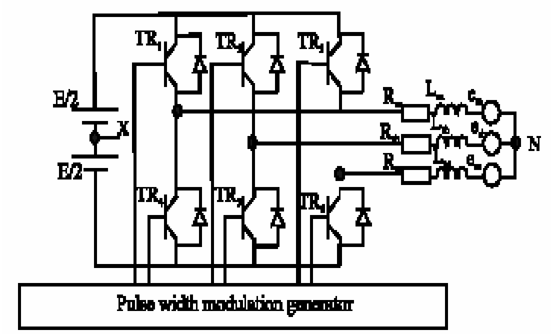


***Fig. 2:** Detailed voltage-fed inverter of induction motor drive*

From Fig. 2, the simple voltage of a motor phase is:

$$u_{\sin} = u_{six} + u_{xn} \quad \text{i=1,2,3} \tag{1}$$

Since the sum of the voltages is equal to zero ($\sum_{s=1}^{3} u_{\sin} = 0$), the instantaneous expression can be easily deducted as follows:

Table 1: *Relation between voltage and switches*

$\delta_1 = \overline{\delta_4}$	$\delta_2 = \overline{\delta_5}$	$\delta_3 = \overline{\delta_6}$	[Va Vb Vc]	Positions
0	0	0	[0 0 0]	a
0	0	1	[• E/3 • E/3 2•E/3]	b
0	1	0	[• E/3 2•E/ • E/3]	c
0	1	1	[• 2•E/3/ E/3 E/3]	d
1	0	0	[2•E/3 • •E/3 • E/3]	e
1	0	1	[E/3 • 2•E/3 E/3]	f
1	1	0	[E/3 E/3 • 2•E/3]	g
1	1	1	[0 0 0]	h

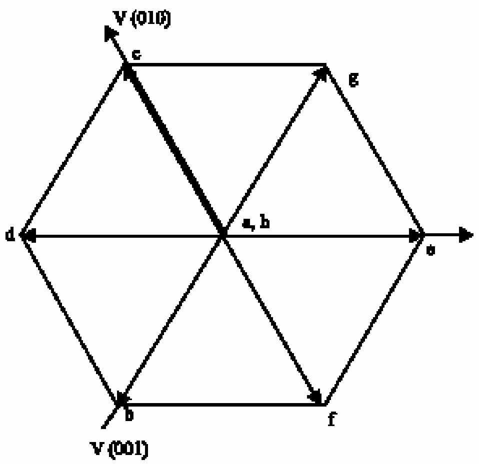


Fig. 3: *Vector u_{s1} , u_{s2} and u_{s3} representation*

$$\begin{bmatrix} u_{s1} \\ u_{s2} \\ u_{s3} \end{bmatrix} = \frac{E}{6}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} \delta_1 - \delta_4 \\ \delta_2 - \delta_5 \\ \delta_3 - \delta_6 \end{bmatrix} \tag{2}$$

With i =1 to 6.

Where, E is the DC voltage inverter input and δ_i $_{(i=1 \text{ to } 6)}$ presents the logic state corresponding to the conducting or non conducting state of the switch (TR_i), respectively. In a three-phases system, the vector components are separated from each other by an angle of 120°. We have to mention that the logic state of two switches of the same cell in the inverter is complementary.

Table 1 shows the possible combinations related to the logic state of the cells and their voltage vectors. Then, the positions of the extremities of the resulting voltage vectors are labelled a, b, c, d, e, f, g and h as (Fig. 3).

We need an induction motor model which allows simulating its behaviour. For the setting equation, we suppose that winding set out in a manner to give a sinusoidal Magneto Motrice Force (MMF) if it is fed by sinusoidal current. Also, the following assumptions are to be considered: the permeance of iron is infinite, the Foucault current and winding losses are negligible, the currents and the skin effect are negligible. With these [10,11] assumptions, the voltage equations for the stator can be written as:

$$V_s = R_s.I_s + \frac{d\phi_s}{dt} \tag{3}$$

$$\phi_s = L_{ss}.I_s + L_{sr}.I_r \tag{4}$$

$$\left.\begin{aligned} I_s &= \begin{bmatrix} i_{s1} & i_{s2} & i_{s3} \end{bmatrix}^t \\ I_r &= \begin{bmatrix} i_{r1} & i_{r2} & i_{r3} \end{bmatrix}^t \\ V_s &= \begin{bmatrix} v_{s1} & v_{s2} & v_{s3} \end{bmatrix}^t \end{aligned}\right\} \tag{5}$$

The matrix R_s consists of the resistances of each coil. Due to the conservation of energy, the matrix L_{ss} is asymetric. The mutual inductance matrix L_{sr} is a 3 by 3 matrix composed of the mutual inductances between the stator coils and rotor.

$$L_{sr} = \begin{bmatrix} L_{sraa} & L_{srab} & L_{srac} \\ L_{srba} & L_{srbb} & L_{srbc} \\ L_{srca} & L_{srcb} & L_{srcc} \end{bmatrix} \tag{6}$$

The second term of Eq. 3 can typically be written in the form:

$$\frac{d\phi_s}{dt} = L_{ss}.\frac{dI_s}{dt} + \omega_{rm}.\frac{dL_{sr}}{d\theta_{rm}}.I_r + L_{sr}.\frac{dI_r}{dt} \tag{7}$$

Where, θ_{rm} is the spatial position of the rotor and the mechanical speed is:

$$\omega_{rm} = \frac{d\theta_{rm}}{dt} \quad (8)$$

The voltage equations for the rotor are:

$$V_r = R_r . I_r + \frac{d\phi_r}{dt} \quad (9)$$

Where,

$$V_r = \begin{bmatrix} v_{r1} & v_{r2} & v_{r3} \end{bmatrix}^t = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^t \quad (10)$$

The rotor flux linkages Φ_r can be written as:

$$\phi_r = L_{rr} . I_r + L_{sr}^t . I_s \quad (11)$$

Where, the matrix L_{sr}^t is the transpose of the matrix L_{sr}.

The mechanical equation of motion depends upon the characteristics of the load which may differ widely from one application to another. We will assume here, for simplicity, that the torque which opposes that produced by the machine consists only of an inertial torque and an external load torque which are known explicitly. In this case the mechanical equation of motion is simply.

$$T_e = J \frac{d^2\theta_{rm}}{dt^2} + T_L \quad (12)$$

Where, T_L is the load torque and T_e is the electromagnetic torque produced by the machine.

4. PROPOSED METHOD

Change detection of stator currents

A change in stator current waveform is defined as the instant at which a sudden increase or decrease is observed in the DC offset component of the current. A change is considered to have occurred in the stator current DC offset component of the current exceeds or falls below a given band.

If the open circuit faulty transistor is one of the upper transistors of the inverter, the current of the phase linked to that leg will have a negative DC component and the two other phases currents will have a positive ones.

If the open circuit faulty transistor is one of the lower transistors of the inverter, the current of the phase linked to that leg will have a positive DC component and the two other phases currents will have a negative ones.

An artificial intelligent system such as Expert system is recommended to be used to identify the faulty device, as classified in Table 2.

Table 2: *DC current Offset polarity corresponding to faulty open circuit transistor*

Faulty Device	DC Current Offset Polarity		
	Phase1	Phase2	Phase3
TR_1	negative	positive	positive
TR_2	positive	negative	positive
TR_3	positive	positive	negative
TR_4	positive	negative	negative
TR_5	negative	positive	negative
TR_6	negative	negative	positive

The DC component of current is extracted by using a low pass filter. Its transfer function is like follow:

$$\frac{I_{cs}}{I_s} = \frac{1}{1+\tau . S} \quad (13)$$

Where Ics is the DC current in Is and τ is the filter time constant.

$$\tau = \frac{1}{Fc} \quad (14)$$

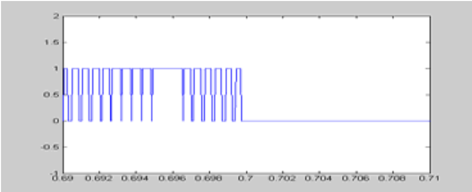
Fc is the cut off frequency of the low pass filter.

5. SIMULATION RESULTS

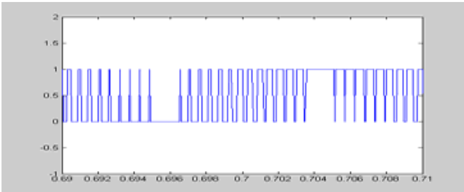
The motor simulated is a 3-phase rotor wound motor with following parameters:

Nominal voltage U_n =220/380 V
Nominal current I_n =21/12 A
Nominal frequency F = 50 Hz
Nominal power P_n =5.5 kW
Poles paires number P = 2
One phase stator resistance R_s =2.25 Ohm
One phase rotor resistance R_r =0.7 Ohm
Cyclic stator inductance L_s =0.1232 H
Cyclic rotor inductance L_r =0.1122 H
Cyclic mutual inductance stator –rotor M =0.1118 H
Inertia moment J_m =0.038 Kg.m^2
Friction constant F_m =0.0 N.m.s/rad

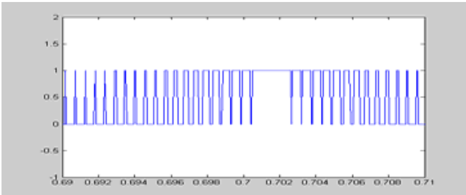
The low pass filter has the time constant of 0.053s (cut off frequency of 3 Hz)
Current band maximal and minimal offset values = ±5 A.



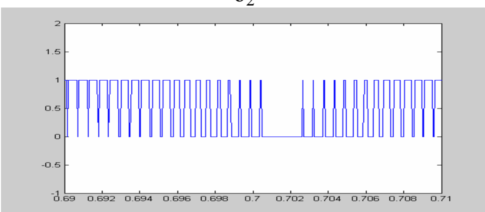
δ_1



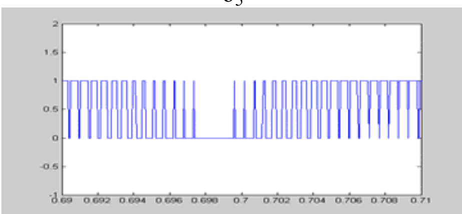
δ_4



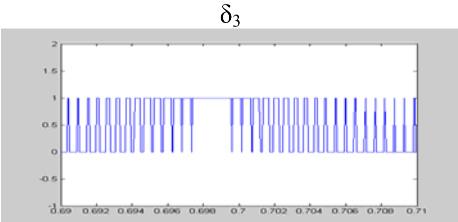
δ_2



δ_5

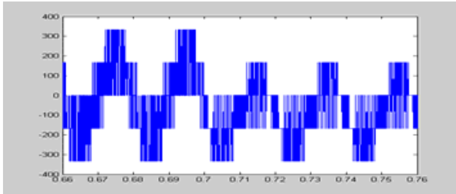


δ_3

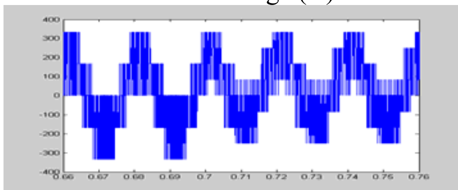


δ_6

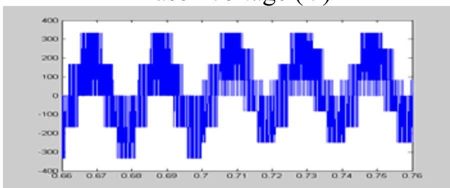
Fig. 4: *Logic states of transistors (before and after TR_1 open circuit fault)*



Phase1 voltage (V)

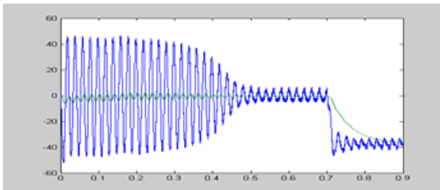


Phase2 voltage (V)

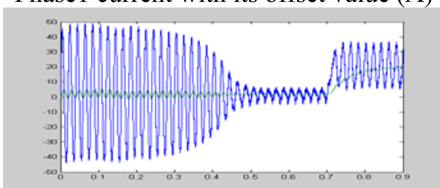


Phase3 voltage (V)

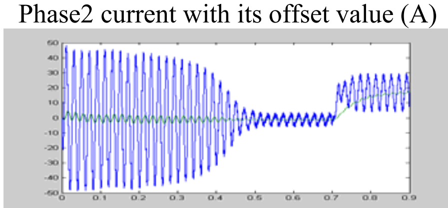
Fig. 5: *Inverter output simple voltages (before and after TR_1 open circuit fault)*



Phase1 current with its offset value (A)

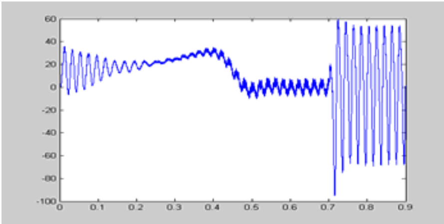


Phase2 current with its offset value (A)

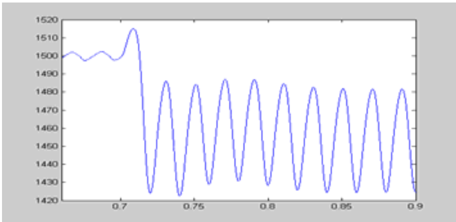


Phase3 current with its offset value (A)

Fig. 6: *Induction machine phases currents with their offset currents (before and after TR_1 open circuit fault)*

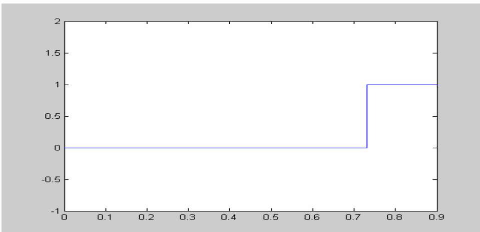


Electromagnetic torque (N.m)

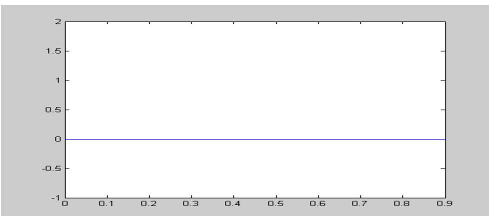


Rotor speed (rpm)

Fig. 7: *Induction machine electromagnetic torque and rotor speed (before and after* TR_1 *open circuit fault)*



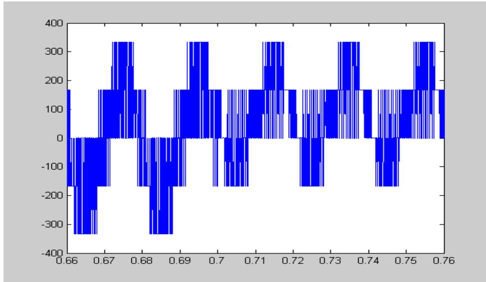
TR_1 fault condition



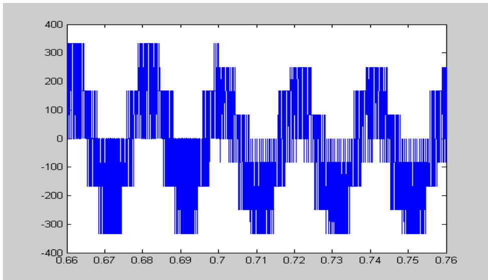
TR_i fault condition (i=2 to 6)

Fig. 8: *Detection algorithm Boolean outputs (before and after* TR_1 *open circuit fault)*

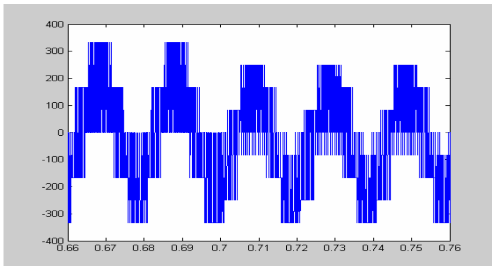
TR_4 Fault condition



Phase1 voltage (V)

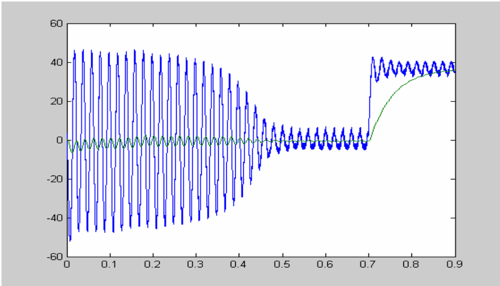


Phase2 voltage (V)

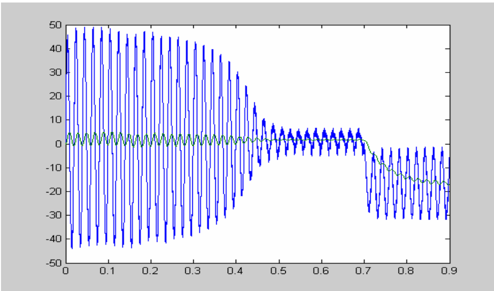


Phase3 voltage (V)

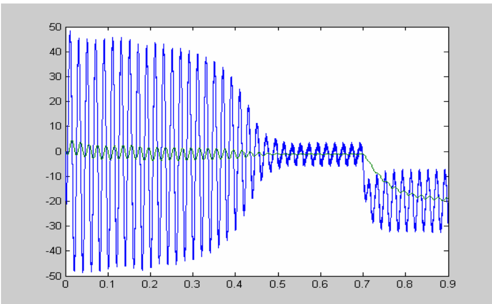
Fig. 9: *Inverter output simple voltages (before and after* TR_4 *open circuit fault)*



Phase1 current with its offset value (A)

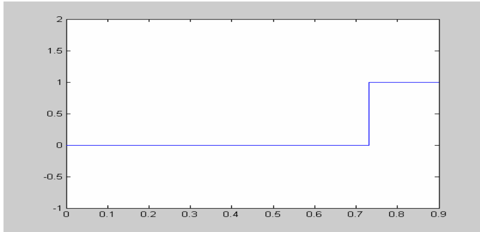


Phase2 current with its offset value (A)

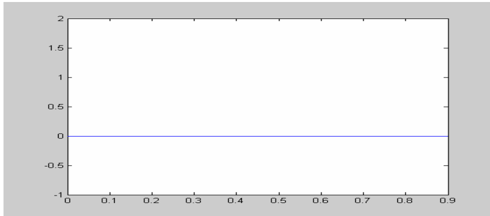


Phase3 current with its offset value (A)

Fig. 10: *Induction machine phases currents with their offset currents (before and after TR_4 open circuit fault)*



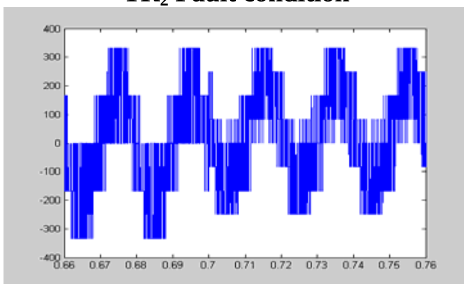
TR_4 fault condition



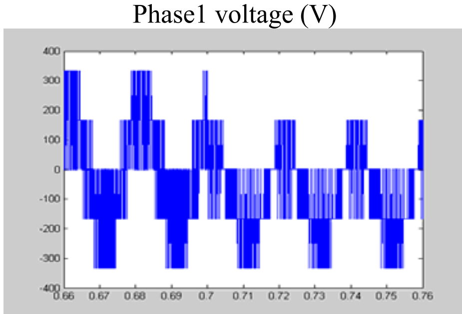
TR_i fault condition (i=1,2,3,5,6)

Fig. 11: *Detection algorithm Boolean outputs (before and after TR_4 open circuit fault)*

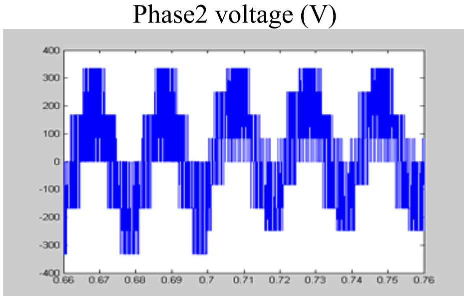
TR_2 Fault condition



Phase1 voltage (V)

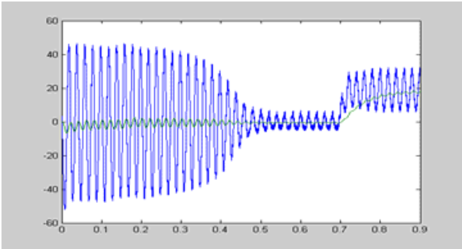


Phase2 voltage (V)

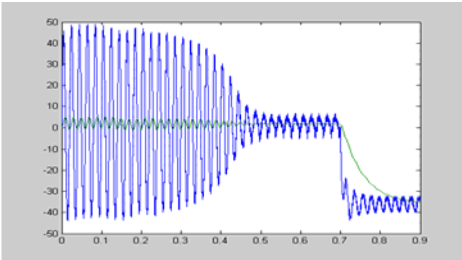


Phase3 voltage (V)

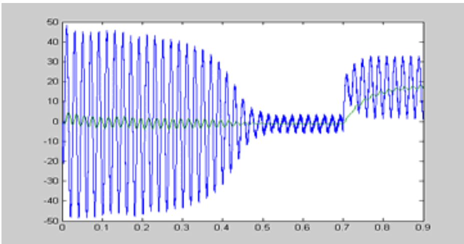
Fig. 12: *Inverter output simple voltages (before and after TR_2 open circuit fault)*



Phase1 current with its offset value (A)

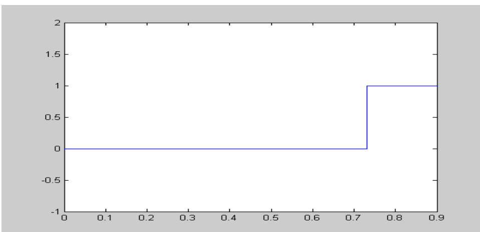


Phase2 current with its offset value (A)

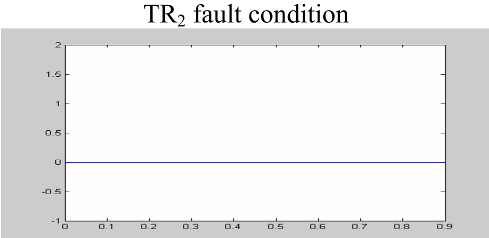


Phase3 current with its offset value (A)

Fig. 13: *Induction machine phases currents with their offset currents (before and after TR_2 open circuit fault)*



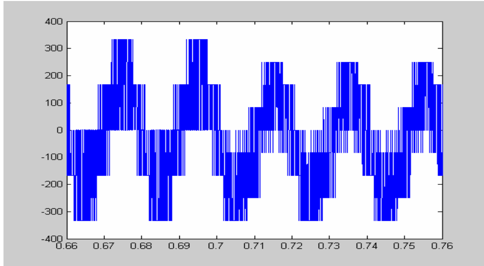
TR_2 fault condition



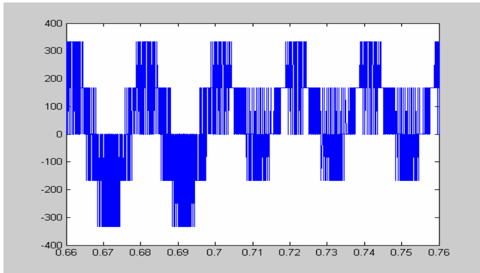
TR_i fault condition (i=1,3,4,5,6)

Fig. 14: *Detection algorithm Boolean outputs (before and after TR_2 open circuit fault)*

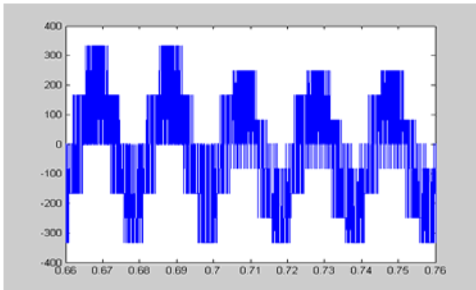
TR_5 Fault condition



Phase1 voltage (V)

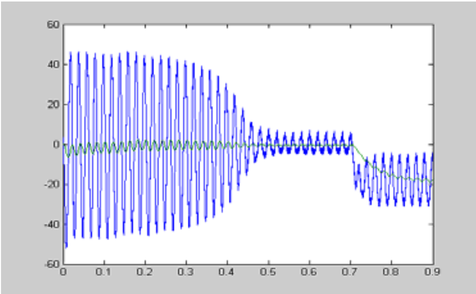


Phase2 voltage (V)

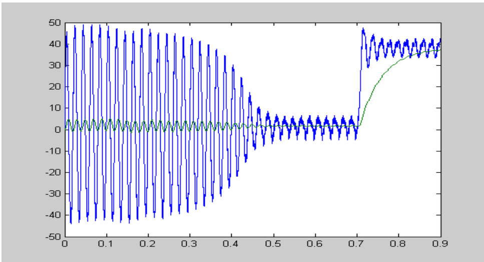


Phase3 voltage (V)

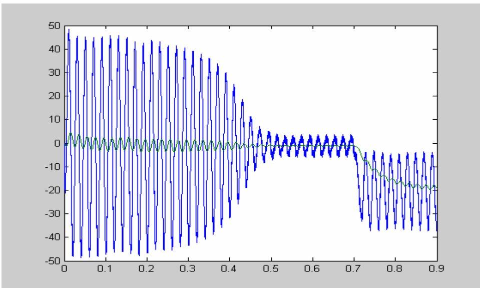
Fig. 15: *Inverter output simple voltages (before and after TR_5 open circuit fault)*



Phase1 current with its offset value (A)

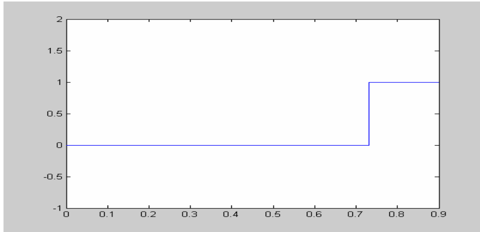


Phase2 current with its offset value (A)

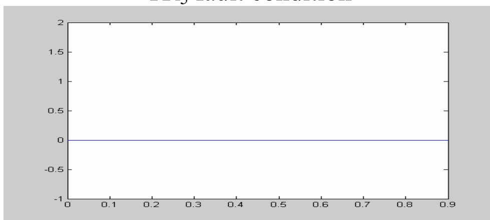


Phase3 current with its offset value (A)

***Fig. 16**: Induction machine phases currents with their offset currents (before and after TR_5 open circuit fault)*



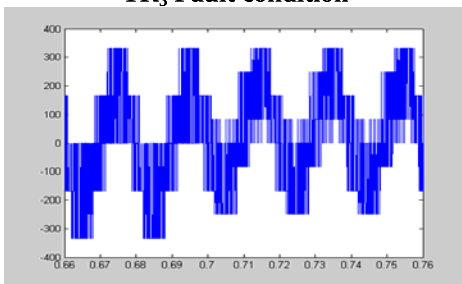
TR_5 fault condition



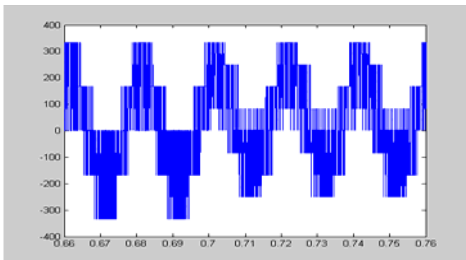
TR_i fault condition (i=1,2,3,4,6)

***Fig. 17:** Detection algorithm Boolean outputs (before and after TR_5 open circuit fault)*

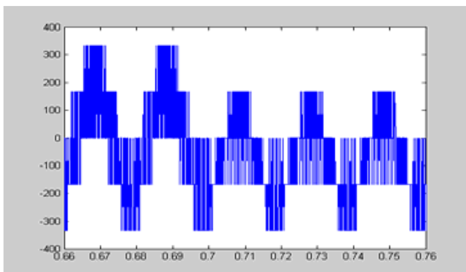
TR_3 Fault condition



Phase1 voltage (V)

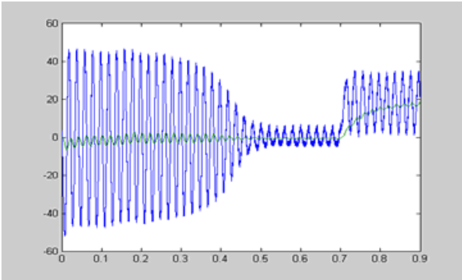


Phase2 voltage (V)

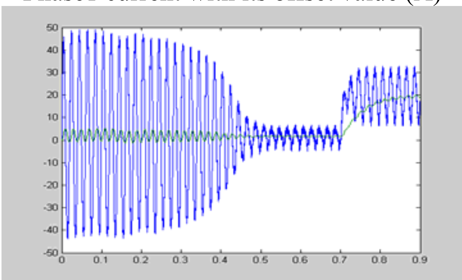


Phase3 voltage (V)

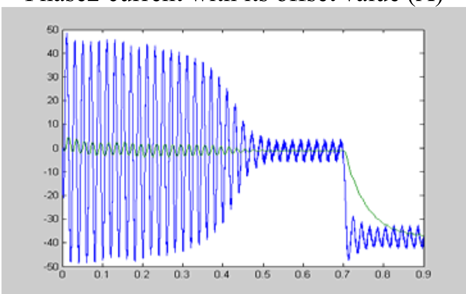
***Fig. 18:** Inverter output simple voltages (before and after TR_3 open circuit fault)*



Phase1 current with its offset value (A)

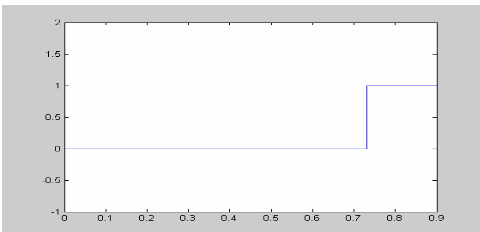


Phase2 current with its offset value (A)

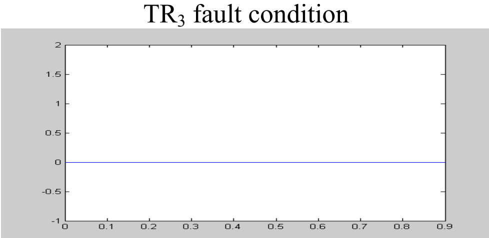


Phase3 current with its offset value (A)

Fig. 19: *Induction machine phases currents with their offset currents (before and after TR_3 open circuit fault)*



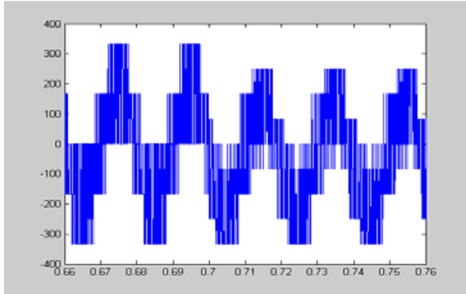
TR_3 fault condition



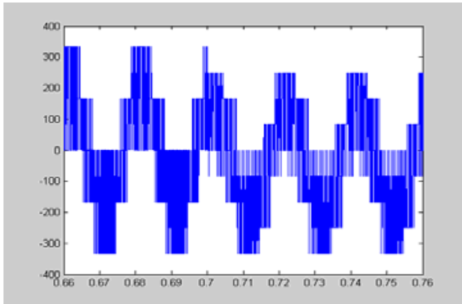
TR_i fault condition (i=1,2,4,5,6)

Fig. 20: *Detection algorithm Boolean outputs (before and after TR_3 open circuit fault)*

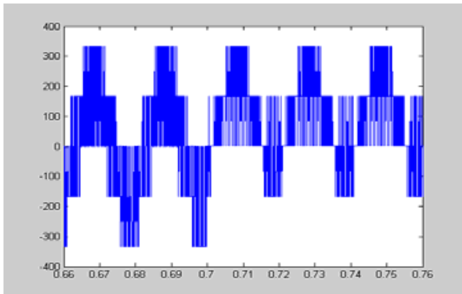
TR_6 Fault condition



Phase1 voltage (V)

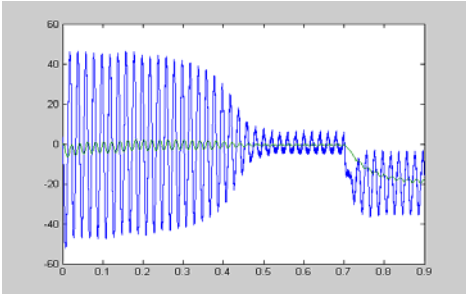


Phase2 voltage (V)

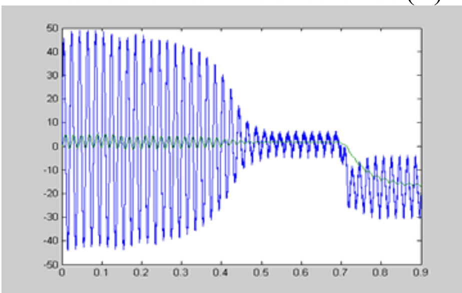


Phase3 voltage (V)

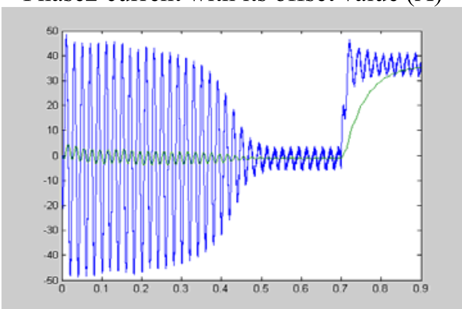
Fig. 21: *Inverter output simple voltages (before and after TR_6 open circuit fault)*



Phase1 current with its offset value (A)

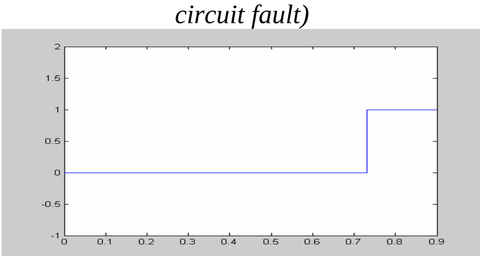


Phase2 current with its offset value (A)

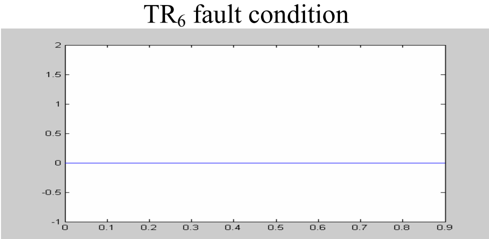


Phase3 current with its offset value (A)

Fig. 22: *Induction machine phases currents with their offset currents (before and after TR_6 open circuit fault)*



TR_6 fault condition



TR_i fault condition (i=1 to 5)

Fig. 23: *Detection algorithm Boolean outputs (before and after TR_6 open circuit fault)*

The speed was kept constant at 1500 rpm with 500 Vdc supply (Fig. 7).

Fig. 4 shows the Logic states of transistors (before and after TR_1 open circuit fault). The complementary command is obvious.

Fig. 5, Fig. 9, Fig. 12, Fig. 15, Fig. 18, Fig. 21 show inverter output simple voltages (before and after TR_i open circuit fault i=0 to 6).

Fig. 6, Fig. 10, Fig. 13, Fig. 16, Fig. 19, Fig. 22 show the stator current waveforms for normal operation. Then, the base drive open circuit fault (Tri i=1 to 6) is introduced and stator currents are examined as a function of failure mode. These figures show six different stator currents corresponding to the individual transistor base drive open-circuit fault of TR_1, TR_2, TR_3, TR_4, TR_5 and TR_6. It can be seen that, in all six cases, this fault introduces a non-zero dc offset.

Fig. 8, Fig. 11, Fig. 14, Fig. 17, Fig. 20, Fig. 23 show Detection algorithm Boolean outputs (before and after TR_i open circuit fault (i=1 to 6)). It is noticed that the detection system is performing in open circuit transistors fault detection. However, there is a little delay time of 3 seconds between fault occurrence time and fault detection time. This delay time depend on low pass filter used in DC current extraction and the width of the DC current tolerance band. This band was chosen to avoid a faulty detection during the starting period of the induction motor (the band may be increased or decreased depend on the value of operating stator currents).

6. CONCLUSION

This paper presents systematically the novel approach to detect the inverter faults of open loop controlled induction motor. The wavelet transform of stator currents has been used to identify the inverter faults.

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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