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Robust FDI Scheme for Open-Circuit Fault in VSI based on Artificial Neural Network

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***Abstract*— In this paper, a robust fault detection and an isolation scheme for an Insulated-Gate Bipolar Transistors open circuit faults in a Voltage Source Inverter are presented. This scheme is composed of two steps. The first is the fault detection. It based on Artificial Neural Network which used to generate the outputs voltages of the Inverter. These signals are compared to the measured ones. Hence, residuals are deduced. They are compared to a threshold which allows obtaining the Flags. The second step is based on evaluation Flags using a signature table. To improve the reliability of fault diagnosis and to avoid false alarms, the Artificial Neural Network is used to take into account the noise and the unknown inputs. This scheme is tested under healthy and single open circuit fault and it proves the target issues.**

***Keywords*—Open circuit fault, fault detection and isolation, Source Voltage Inverter, Artificial Neural Network, Induction Motor.**

I. Introduction

The Pulse-Width Modulation Voltage Source Inverters (PWM-VSIs), which fed a motor drive systems, are extensively used in many industrial applications such as aeronautics, railway traction, etc [2].

During the operating mode, the electrical drive system could be affected by various faults [3]. These faults attended 63% of the user-experienced drive faults during the first year of operation [4]. An amount of 70% of these faults are associated to power switches. There are two types: the open circuit or the short-circuit faults [5]. In this researched work, the single open circuit fault type is covered.

An open transistor fault will not necessary lead to a tripped fuse or an over current fault. The fault may therefore remain undetected and could cause secondary faults due to torque pulsation or increased current in the healthy transistors [6].

In literature, there are many techniques used in order to detect the open circuit fault. According to the available used signals, these techniques are clustered into two categories: current based methods ([7], [8], [9], [10]) and voltage based methods ([6], [11], [12]).

In order to improve the detection and isolation of open circuit fault and to minimize the false alarms caused by modeling error or the unknown inputs, we suggest a robust FDI scheme by using an Artificial Neural Network ANN used to modeling the nominal voltages of the VSI. The ANN is used in detection step and the Flags are investigated to isolation step. As a result, robust residuals are generated. They could detect the fault under transient and steady state. In the rest of this paper, the second section is dedicated to VSI feeding Induction Motor modeling. In the third section, the FDI scheme is described. The forth section exposes the different results and it discuss them. Finally, the fifth section summarizes the work.

II. Switching Function Model For VSI

The VSI is composed of three main parts:
-a dc supply,
-a classical two levels three leg inverter (PWM VSI),
-an induction motor.

The induction motor is modeling in *dq* synchronous frame. The voltages and flux expressions are given using the following equations:

$$v_{ds}(t) = R_s i_{ds}(t) + d\varphi_{ds}(t)/dt - \omega_a \varphi_{qs}(t) \quad (1)$$

$$v_{qs}(t) = R_r i_{qs}(t) + d\varphi_{qs}(t)/dt + \omega_a \varphi_{ds}(t) \quad (2)$$

$$v_{dr}(t) = R_s i_{dr} + d\varphi_{dr}(t)/dt - (\omega_a - \omega)\varphi_{qr}(t) \quad (3)$$

$$v_{qr}(t) = R_r i_{qr}(t) + d\varphi_{qr}(t)/dt + (\omega_a - \omega)\varphi_{dr}(t) \quad (4)$$

$$\varphi_{ds}(t) = L_s i_{ds}(t) + M_c i_{dr}(t) \quad (5)$$

$$\varphi_{qs}(t) = L_s i_{qs}(t) + M_c i_{qr}(t) \quad (6)$$

$$\varphi_{dr}(t) = L_r i_{dr}(t) + M_c i_{ds}(t) \quad (7)$$

$$\varphi_{qr}(t) = L_r i_{qr}(t) + M_c i_{qs}(t) \quad (8)$$

There are multiple induction motor control: the scalar (V/f), the field oriented control (FOC), etc. Since we deal with the single open circuit fault occurred in VSI open loop, it is easier to choose the scalar control. This type of control depends on the actuator's type (current inverter, voltage inverter). The voltage actuator is the widely spread in the industries, so we choose the V/f control low.

In the hypo-synchronous mode, the ratio V/f and the torque are constant. So, the desired shaft speed depends on the frequency used for the gates signals. The lasts are deduced using a Pulse Width Modulation technique PWM.

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The voltages used to supply the induction motor are the inverter's outputs. These voltages are calculated using:

$$v_{as} = \frac{V_{dc}}{3}(2S1 - S2 - S3) \quad (9)$$

$$v_{bs} = \frac{V_{dc}}{3}(-S1 + 2S2 - S3) \quad (10)$$

$$v_{cs} = \frac{V_{dc}}{3}(-S1 - S2 + 2S3) \quad (11)$$

Where S1, S2 and S3 are the gates signals. The V_{dc} is the dc supply voltage.

III. ACTUATOR FAULT SCENARIOS IN INDUCTION MOTOR

The used inverter is a two level inverter. It composed of six IGBTs. So there are six possible single open circuit faults. It is suggested to model them using an additive structure. As a result, if (v_{asf}, v_{bsf}, v_{csf}) denote the resulting faulty inverter voltages, then they are expressed by:

$$v_{asf} = v_{as} + f_a \quad (12)$$

$$v_{bsf} = v_{bs} + f_b \quad (13)$$

$$v_{csf} = v_{cs} + f_c \quad (14)$$

where (v_{as}, v_{bs}, v_{cs}) are the nominal input voltages and (f_a, f_b, f_c) the fault inputs related to each motor phase. There are six distinctive fault directions, as shown in Table 1[1].

TABLE 1

FAULT PROFILES DIRECTIONS RELATED TO EACH FAULTY SWITCH IN A VSI

Faulty switch	f_a	f_b	f_c
Phase-a			
upper switch (S1)	≤0		
lower switch (S4)	≥0		
Phase-b			
upper switch (S2)		≤0	
lower switch (S5)		≥0	
Phase-c			
upper switch (S3)			≤0
lower switch (S6)			≥0

As a consequence, the identification of these six fault signs will be the key element in the isolation step.

IV. ROBUST FDI SCHEME FOR SINGLE OPEN CIRCUIT FAULT

The purpose of the proposed FDI is to detect the fault either in steady or in transient state. On other hand, the scheme could be implemented in open or in closed loop. It also, should be robust to the noise and unknown inputs. Therefore an intelligent technique is used to achieve all these purposes. The developed scheme is based on artificial neural network. As illustrated in Fig.1. the procedure is divided into two steps; the first is the detection fault step and the second is the isolation fault step.

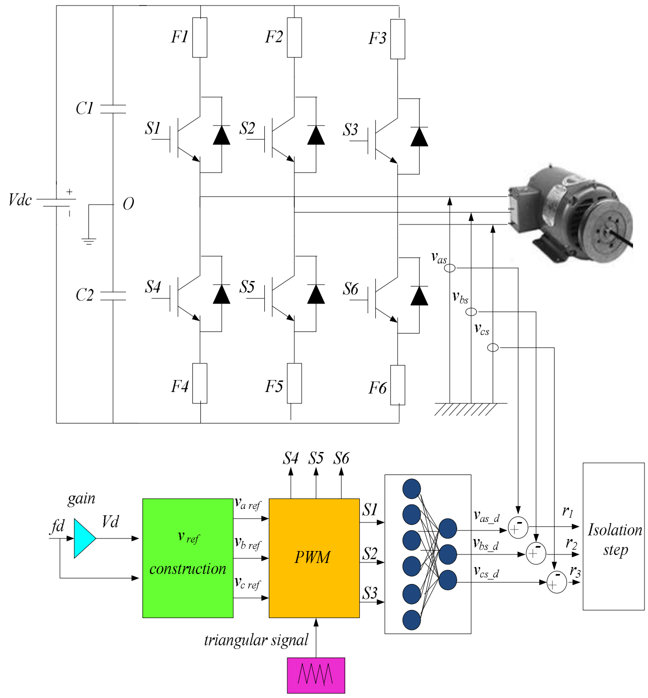

Fig. 1 Robust FDI scheme.

A. Detection fault step

The objective is to detect the occurrence of the open circuit fault. This step is composed of a one Artificial Neural Network. It aims to generate the voltages inverter outputs which are the nominal voltages. These voltages are considered the healthy ones. They denoted v_{as_d}, v_{bs_d}, v_{cs_d}.

The gates signals (S1, S2, S3) are the inputs and the three voltages (v_{as_d}, v_{bs_d}, v_{cs_d}) are the outputs.

The outputs ANN are compared then to the voltages measured (v_{as}, v_{bs}, v_{cs}). As a results, three residuals are obtained (r1, r2, r3). Each one of these residuals could be positive, negative or null. In fact, they could not be perfectly null. But, they evolve in a threshold. In that case, the mode operating is healthy. Otherwise, if they are positive or negative, the inverter operates in a faulty mode. So when the residuals deviate outside the threshold, the fault is detected.

In order to make the detection step robust to operating mode, a rich database has been built. The gate signals are obtained using different frequencies and voltages references intervals as shown in Fig 2 and 3. The outputs voltages in healthy case are used as the target outputs for the ANN. The different nominal voltages are illustrated in Fig. 4, 5 and 6.

The simulation results are obtained using Neural Network Toolbox in Simulink Matlab ©. The ANN has one hidden layer composed of six neuron perceptrons with "tansig" activating function. Except the output neuron perceptron, all the neurons are activated using tansig function. The Levenberg Marquardt algorithm is chosen for the learning procedure. The Fig.7. illustrates the graphical interface of the artificial neural network. The Fig.8. shows the learning error. It attends 9.32.10-28 at epoch 9.

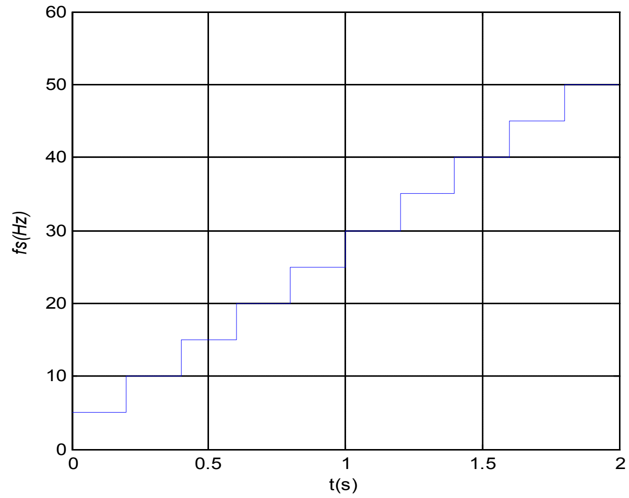

Fig. 2 Frequencies database used for V/f control.

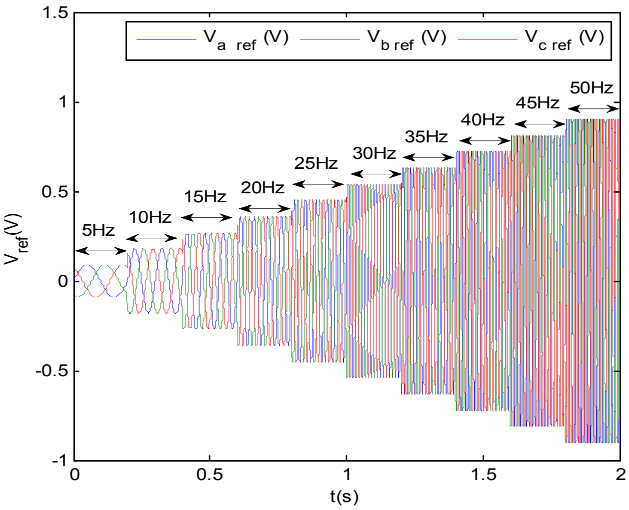

Fig. 3 Voltages references database used for V/f control.

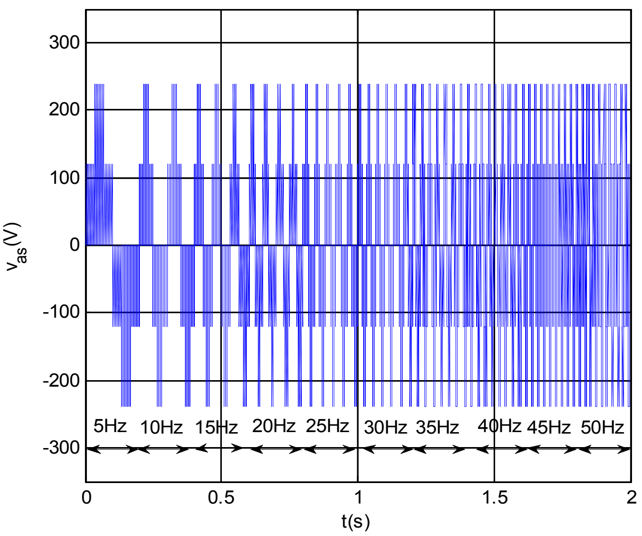

Fig. 4 VSI Voltage output phase_a.

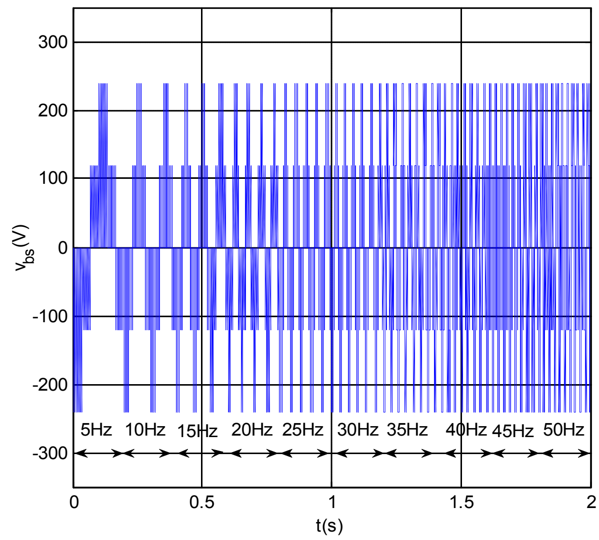

Fig. 5 VSI Voltage output phase_b.

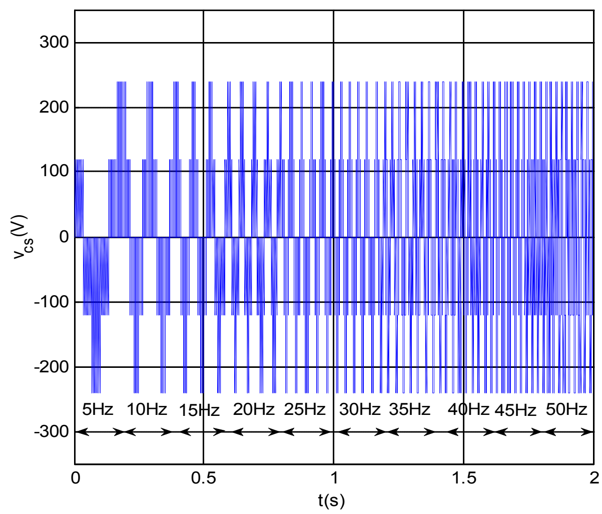

Fig. 6 VSI Voltage output phase_c.

B. Isolation fault step

This step aims to locate the faulted IGBT. It means which the IGBT between the six is faulted. The element key of this step is the identification of the residual signs. In fact, if the residual is positive, the upper IGBT of the considered leg is faulty. The proposed strategy consists in Flags generating. Hence, three Flags are deduced using a comparison with the threshold as it shows in Fig. 9. There are three possible results:

- Null, which represents the healthy case,
- Equal to 1 which represents open circuit fault occurred in upper IGBT of the considered leg,
- Equal to -1 which represents open circuit fault occurred in upper IGBT of the considered leg.

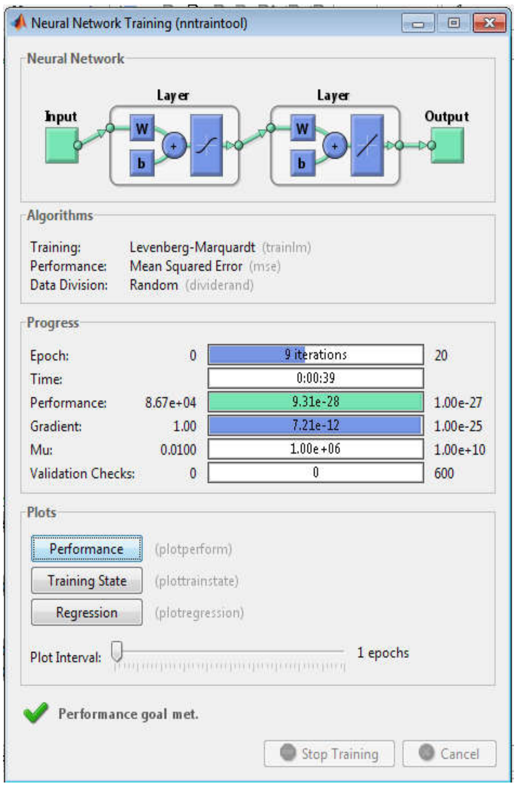

Fig. 7 ANN Learning graphical interface.

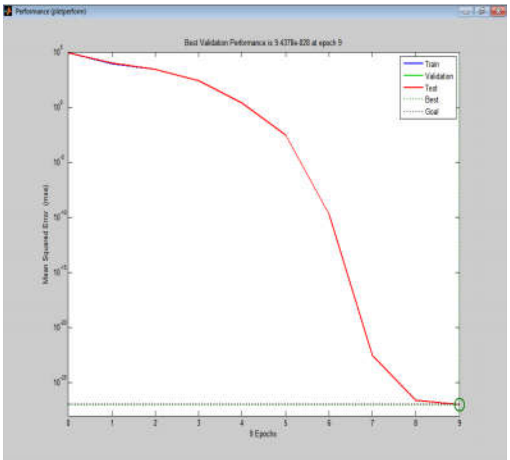

Fig. 8 ANN Learning graphical interface.

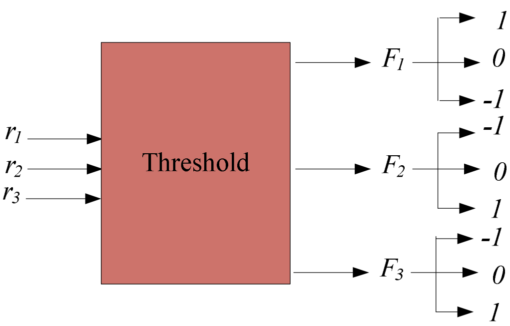

Fig. 9 Flags generating step.

The decision is made using the signature table illustrated in TABLE II.

TABLE II

SIGNATURE TABLE FOR ISOLATION STEP.

Faulty switch	F_1	F_2	F_3
Phase-a			
T1	1	0	0
T4	-1	0	0
Phase-b			
T2	0	1	0
T5	0	-1	0
Phase-c			
T3	0	0	1
T6	0	0	-1
Healthy switch	0	0	0

V. RESULTS AND DISCUSSION

To evaluate the proposed scheme, the healthy operating mode and the faulty one are tested.

C. *Healthy case*

In the case of healthy operation, the three residuals (Fig.10.) are approximately nulls. They don't exceed respectively 1.10^{-13} for r1, 2.10^{-13} for r2 and 1.10^{-13} for r3. Thus, they remain in the threshold range which is equal to [-0.1, 0.1]. As a result, the three Flags F1, F2 and F3 (Fig.11) are nulls. According to the signature table, it is the healthy mode operation.

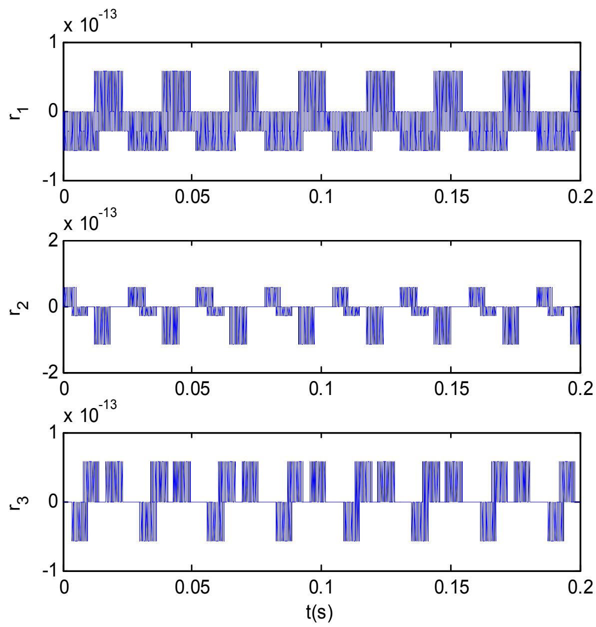

Fig. 10 Residuals under healthy function.

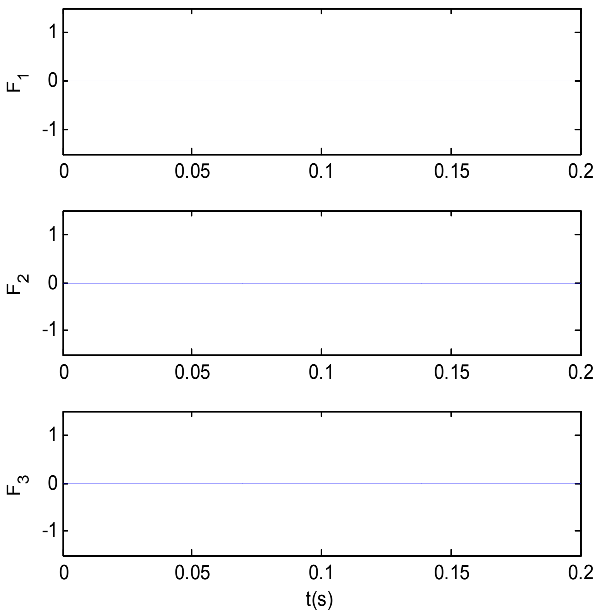

Fig. 11 Flags under healthy function..

D. *Single fault in T1*

To evaluate the faulty case, an open circuit fault is injected in T1: the upper IGBT in the first leg. As shown in Fig.12. the first residual r1 is null until t_d. After that, it becomes equal to f_a which represents the fault quantity added to the nominal voltage v_{as}. The two other residuals r2 and r3 are set within the range. From t_d, the Flags [F1 F2 F3], illustrated in Fig.13, are equal to [1 0 0]. That means, it is an open circuit fault occurred in the upper IGBT of the first leg: T1.

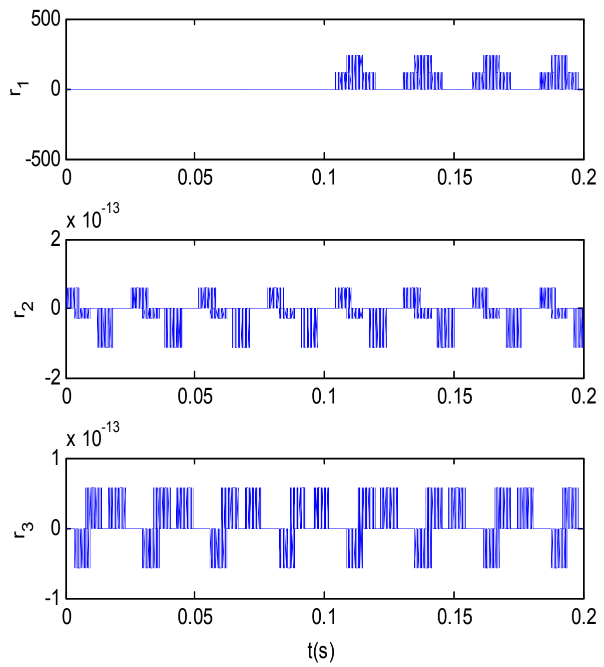

Fig. 12 Residuals when an open circuit occurred in T1.

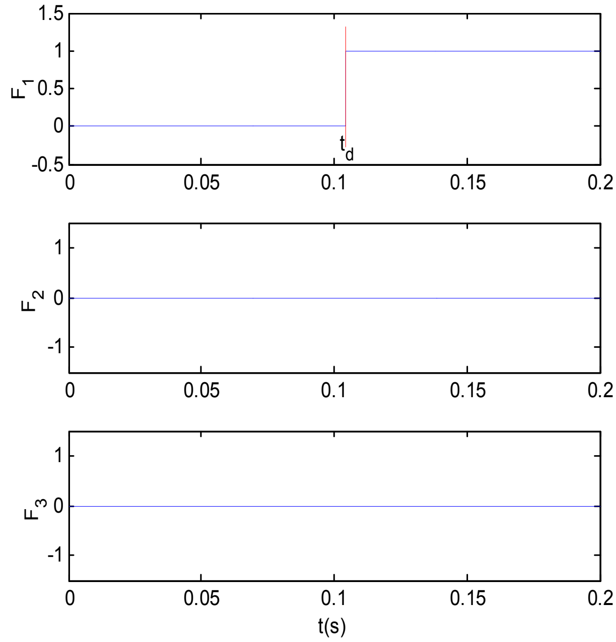

Fig. 13 Indicators when open circuit occurred in T1.

E. *Single fault in T5*

Now we consider an open circuit fault affected the lower IGBT of the second leg: T5. The fault is injected at 0.11s. Until t_d=0.1s, all the residuals don't exceeded the threshold bounds as it mentioned in Fig 14. Hence, all the Flags are nulls. But from t_d, only the second residual deviates and becomes equals to f_b which represents the fault quantity in case of lower IGBT open circuit. As a result, the Flag F2 sets to -1 and the two other Flags are nulls (Fig.14). Referring to signature table, the fault corresponds to an open circuit in T5.

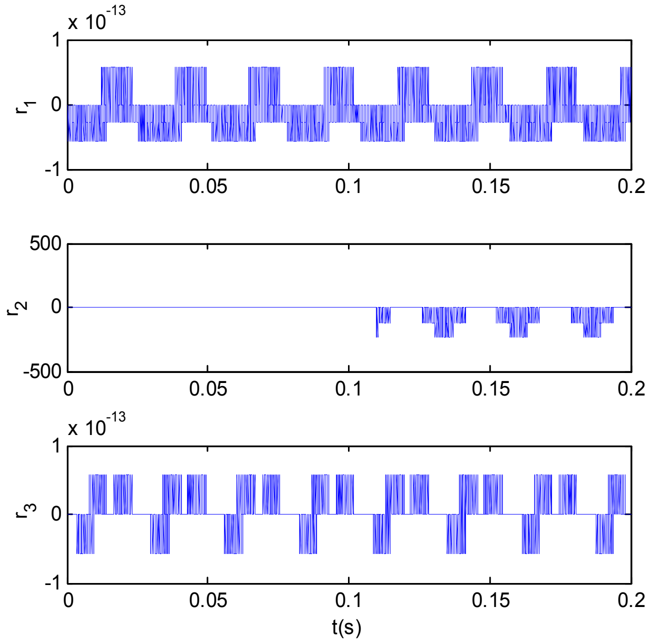

Fig. 11 Residuals evolutions open circuit occurred in T5.

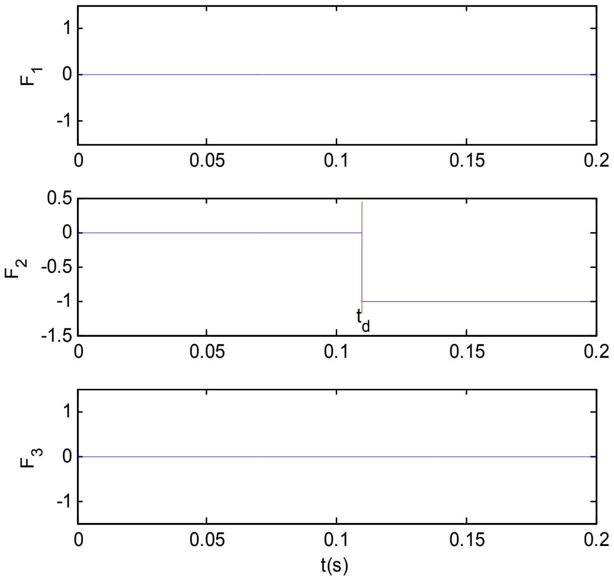

Fig. 12 Indicators evolutions open circuit occurred in T5.

VI. Conclusion

In this research work, a robust FDI of a single open circuit fault is developed. It based on ANN. Many advantages are obtained: 1) the FDI scheme is simple; 2) it is applicable to open-loop and closed-loop current control of induction motors since it depends only on voltages; 3) the detection time is minimized because it is based on ANN; 4) it could detect and isolate a single fault in steady and transient state.

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