OPEN SWITCH FAULTS DETECTION AND LOCALIZATION IN THREE PHASES SHUNT ACTIVE POWER FILTER

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Key words: Shunt active power filter, Fault detection, Two level voltage source inverter, Current mean value, Zero harmonic component, Combinatory logic.

This paper proposes an open switch faults detection and localization algorithm for shunt three phase active filter topology. It mainly details converter configuration and examines a simple and reliable optimised fault diagnosis method. The converter topology is based on classical three-leg active power filter topology. A new fault diagnosis method is proposed, based on classical currents measurements. It includes combinatory logic to analyse and validate error signals. A Hysteresis Control is applied before and after fault detection, which avoids any controller reconfiguration. Simulation results obtained with Matlab/Simulink/Plecs tools prove the effectiveness of this method.

1. INTRODUCTION

The reliability of power electronic equipments becomes extremely important in general in industrial applications. The fault mode behaviour of static converters, protection and fault tolerant control of voltage source inverter systems has been covered in a large number of papers. Most of them are focused on induction motor drive applications.

D. Kastha and B. K. Bose considered various fault modes of a voltage source PWM inverter system for induction motor drive [1]. They have studied rectifier diode short circuit, inverter transistor base driver open and inverter transistor short-circuit conditions. However, they do not propose to reconfig the inverter topology.

C. Thybo was interested in fault tolerant control of induction motor drive applications using analytical redundancy, providing solutions to most frequent occurring faults [2].

E. R. C. Da Silva *et al.*, investigated fault detection of open-switch damage in voltage source PWM motor drive systems [3]. They mainly focused on detection and identification of the power switch in which the fault has occurred. In another paper, they investigated the utilization of a two-leg based topology when one of the

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inverter legs is lost. Then the machine operates with only two stator windings [4]. They proposed to modify PWM control to allow continuous free operation of the drive.

More recently, E. R. C. Da Silva *et al.*, have studied fault tolerant active power filter system [5, 6]. They proposed to reconfig power converter and PWM control and examined a fault identification algorithm.

This present paper deals with open switch faults detection and localization in shunt active three-phase filter based on two level voltage source inverter controlled by current Hysteresis controllers. The proposed method is simple and reliable. It needs no more than active filter current sensors and display interface indicating the open faulty power switch.

First, an inverter based on standard three-phase power structure is presented. Fault diagnosis is detailed. Then, shunt active filter hysteresis control is presented for three-leg structures. Finally, simulation results illustrating fault diagnosis and localization developed in the present paper are presented.

2. SYSTEM DESCRIPTION

Figure 1 presents a classical three-leg shunt active power system. It is composed of a grid (e_{si} for i = {1, 2, 3}), a non-linear load, a voltage source converter. The load is a three phase diode rectifier feeding a series (R, L) load. The grid is supposed to be balanced with equal series resistance R_{cc} and inductance L_{cc} for each phase. The static converter is a voltage source inverter with equal series inductance L_f for each phase.

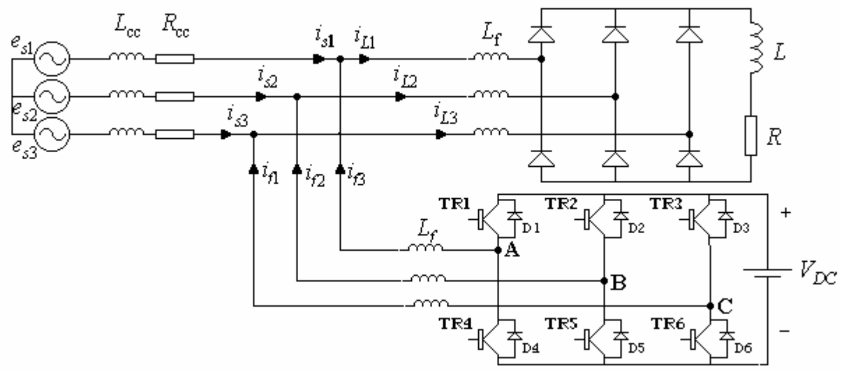


Fig. 1 – Classical three-leg shunt active filter topology.

The output currents of the shunt active filter are controlled by hysteresis controllers to provide reactive power and harmonic currents generated by the non-linear load to ensure filtering.

Several faulty cases can occur: power switch or power switch driver can be faulty. In each case, it results in the following models:

– A switch is closed instead of being normally open. It results in a short-circuit of the DC voltage source, increasing i_{s123} current. To isolate the faulty switch as fast as possible, one can use fuses.

– A switch is open instead of being normally closed. It results in an open phase. The filter may continue injecting currents to the power supply. These currents don't cause any prompt risk because they are at the same range level as the case of no-fault condition. However, the filter in this case is polluting more the power supply instead of elimination of harmonic currents of non-linear load. This case is considered in this paper.

3. ACTIVE FILTER CONTROL

Figure 2 presents a block diagram of the proposed control system. The major advantage of this control principle is its simplicity and easiness to be implemented. The task of this control is to determine the current harmonic references to be generated by the active filter.

They are defined using classical active and reactive power method proposed by Akagi [7].

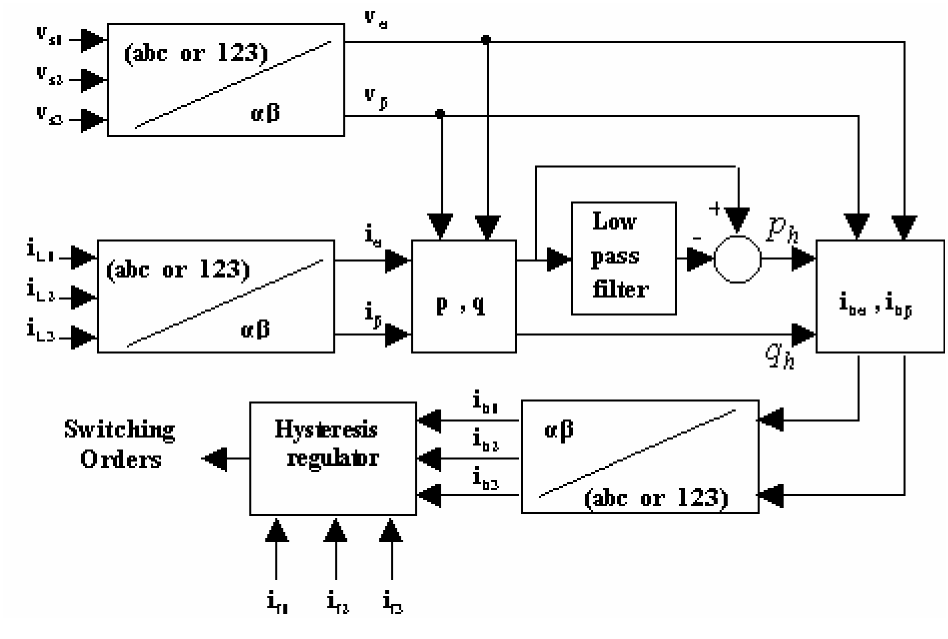


Fig. 2 – Block diagram of the control system.

By supposing that the main power supply voltages are sinusoidal, current harmonic references will be calculated like indicated in [8].

(α, β) voltage components at connexion point of active filter (v_α, v_β) and currents (i_α, i_β) are defined by the classical Concordia transformation:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix}; \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix}. \tag{2}$$

The instantaneous real and imaginary powers, noted by p and q, are calculated by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \tag{3}$$

These powers are then filtered by high-pass filters, which gives p_h and q_h and the harmonic components of the currents will be:

$$\begin{bmatrix} i_{h1} \\ i_{h2} \\ i_{h3} \end{bmatrix} = \frac{\sqrt{3}}{2} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_h \\ q_h \end{bmatrix}. \tag{4}$$

4. **FAULT DIAGNOSTIC METHOD**

This section presents theoretical analysis of open switch fault condition impact on phases current of active filter as well as simulation results obtained with Matlab simulator for the proposed fault detection algorithm. Basing on this analysis, an algorithm of open switch fault detectionand location will be conceived.

General simulation parameters are given in the appendix. These parameters are chosen to reduce THD of main source currents below 5%.

When the transistor TR1 has an open-circuit fault, the phase A of the three phase active filter outputs is connected to the positive dc rail through the diode D1, as presented in Fig. 1. When transistor TR4 is conducting (switch on), the phase voltage (V_A) will be clamped to the negative rail, current i_{f1} will negatively increase. When TR4 stops conducting (switch off), current i_{f1} will flow throughout diode D1 if it is negative and throughout diode D4 if it is positive. Thus, the only path for positive part of phase 1 filter current (i_{f1}) is diode D4. Thus, the positive part of current i_{f1} (surface limited by the curve i_{f1} and the axis of time) will decrease. By the other hand the negative part of currents i_{f2} and i_{f3} will decrease as well (Fig. 4d). Therefore, a negative DC component will be noticed on current if1 and positive DC components will be observed on currents i_{f2} and i_{f3} (Fig. 5).

It must be noted that periodicity of currents i_{f1}, i_{f2} and i_{f3} will not change after TR1 open switch fault happening (Fig. 4d). This same periodicity will be based to calculate DC components of filter currents i_{f1}, i_{f2} and i_{f3} in both cases of before and after TR1 open switch fault condition.

Fault detection is based on the calculation of zero harmonic component (mean value, DC offset) included in the active filter currents. A change in active filter 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 active filter current DC offset component of the current exceeds or falls below a given band (Figs. 4, 5, 6, 7).

If the open circuit faulty transistor is one of the upper transistors of the inverter based active filter, 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 (Fig. 5, Fig. 7).

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 (Fig. 6).

On detecting fault, the system will calculate the value of DC offset in the currents values. The currents DC offset values are then fed to the diagnosis classifier to determine the faults. Diagnosis classification rules for this proposed VSI fault diagnosis algorithm are resumed in Table 1.

Table 1

DC current offset polarity corresponding to faulty open circuit transistor

Faulty Device	DC current offset polarity		
	Phase 1	Phase 2	Phase 3
TR1	negative	positive	positive
TR2	positive	negative	positive
TR3	positive	positive	negative
TR4	positive	negative	negative
TR5	negative	positive	negative
TR6	negative	negative	positive

To identify the faults is not always straightforward case, particularly when in practice, the signal always containing noise and disturbance. For instance, a slight load unbalance during normal operation may introduce a low level DC offset on one of the phase currents. Measurement and sensor errors may also give misleading information. To exclude such cases from faulty operation category, more insight into the data is required, and to improve reliability of diagnosis algorithm a hysteresis band was considered (± 0.25 A). In this project, if the dc offset magnitude is less than 0.5 A, it will be considered as a healthy condition.

Currents DC offsets are calculated by using the discrete variable-frequency FFT calculation block in Simulink/Matlab with sample time of 0.0001 s where input signal (phase current) frequency is 50 Hz before and after open switch fault.

Figure 3 shows the flowchart of the fault detection scheme proposed.

The identification algorithm of open-circuit transistor fault is based on classification rules of Table 1.

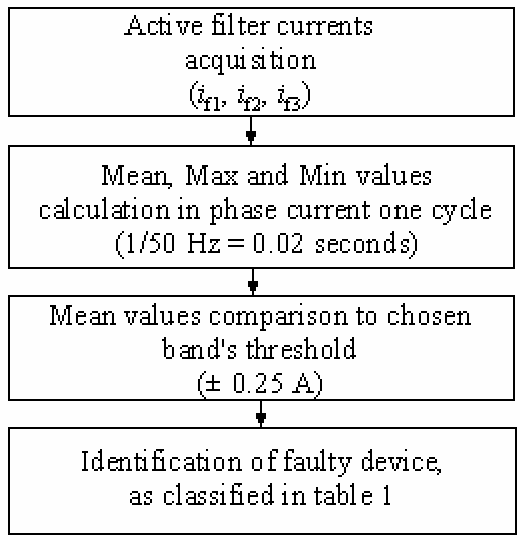
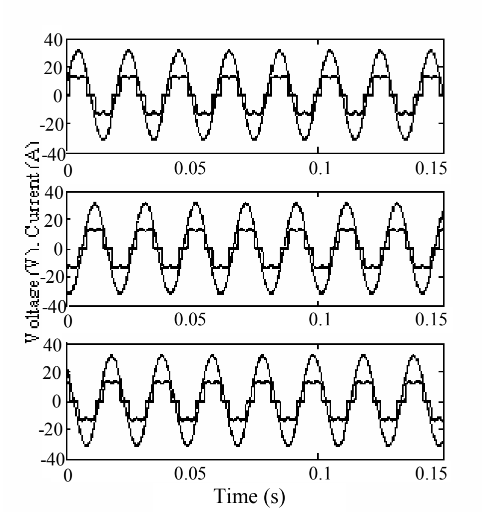
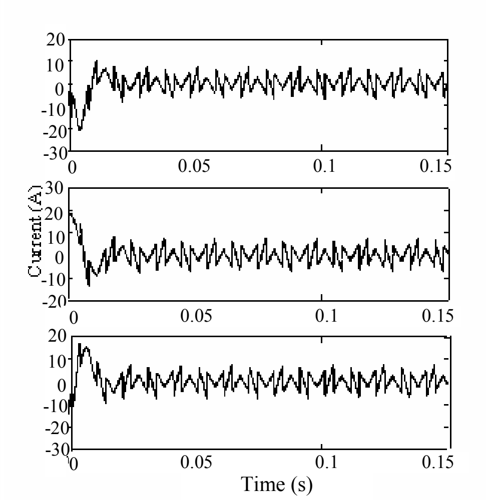


Fig. 3 – Flowchart of fault detection process.

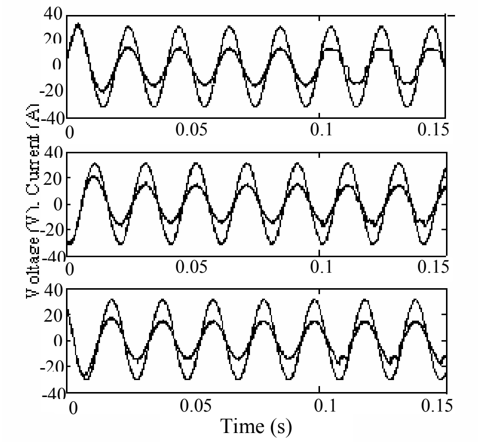
Figures 4, 5, 6 and 7 present the results in an open switch fault cases (fault of respectively TR1, TR4 and TR2), introduced at t = 0.1 s. Besides the delay time due to the transfer from safe operating steady state to fault operating steady state of active filter, it present a systematic delay time between 0 en T ($T = 1/f$, T – one cycle period of active filter currents, f – frequency of active filter currents). Even that, these results show that the proposed fault detection algorithm is reliable and efficient.



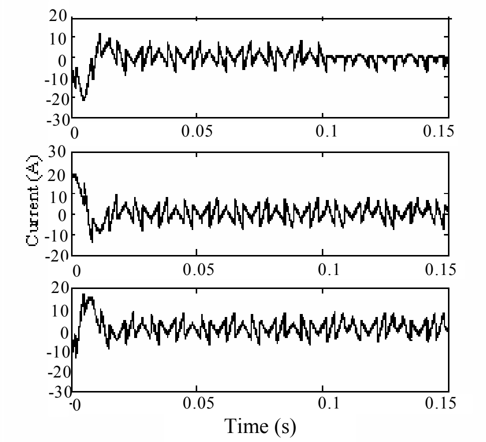
a) main phases voltage instantaneous values / 10, rectifier phases currents instantaneous values;



c) harmonic identified currents instantaneous values;

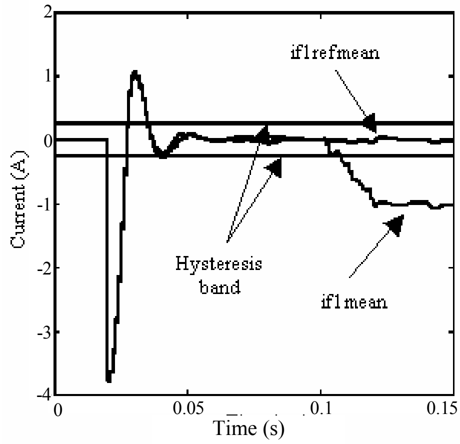


b) main phases voltage instantaneous values / 10, main source phases currents instantaneous values before and after TR1 open fault condition;

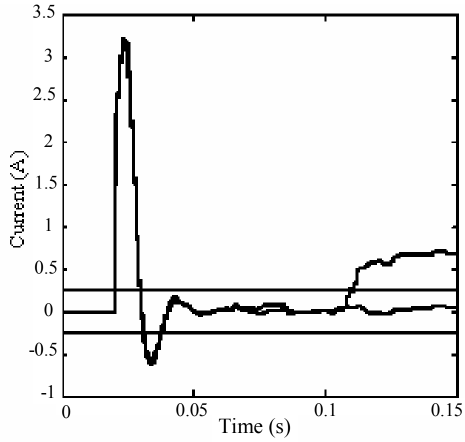


d) active filter currents instantaneous values before and after TR1 open fault condition from the top to the bottom i_{f1}, i_{f2}, i_{f3};

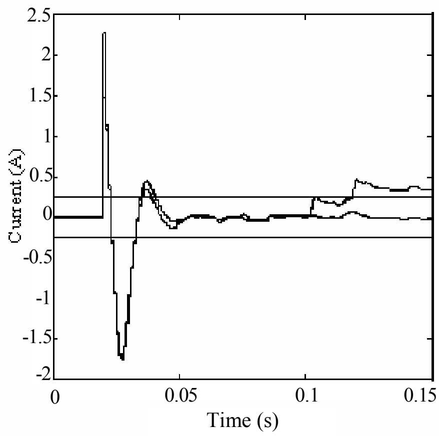
Fig. 4 – Simulation results of active power filtering before and after TR1 open fault condition (instantaneous main source phase voltages and currents, non linear load currents and active filter currents with their references).



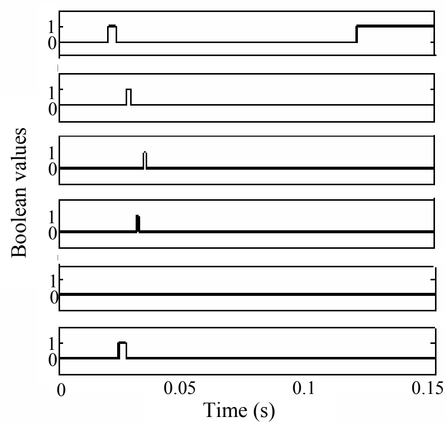
a) phase 1 active filter current with its reference mean values (i_{f1}refmean, i_{f1}mean) with DC Hysteresis band +/– 0.25 (A) before and after TR1 open fault condition;



c) phase 3 active filter current with its reference mean values with DC hysteresis band +/– 0.25 (A) before and after TR1 open fault condition;

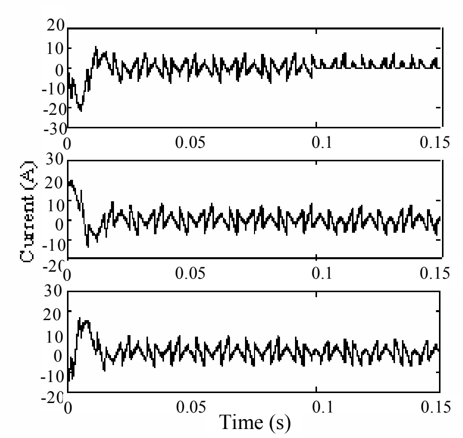


b) phase 2 active filter current with its reference mean values with DC hysteresis band +/- 0.25 (A) before and after TR1 open fault condition;

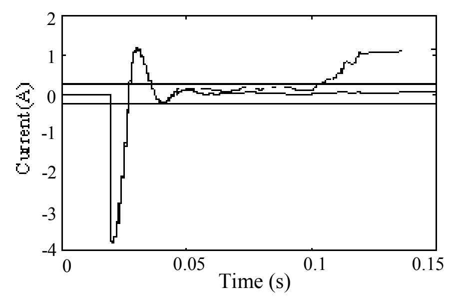


d) Boolean outputs of open switch fault detection algorithm before and after TR1 open switch fault (from the top to the bottom TR1, TR2, TR3, TR4, TR5, TR6);

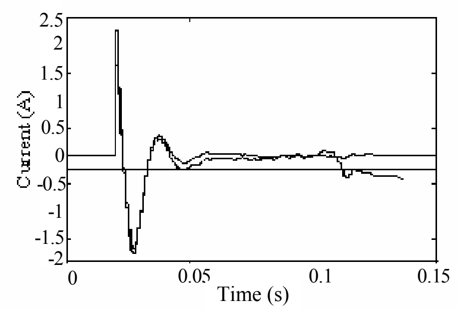
Fig. 5 – Simulation results of open switch fault identification system before and after TR1 open fault condition (active filter currents mean values with their references mean values, Boolean outputs of diagnostic system).



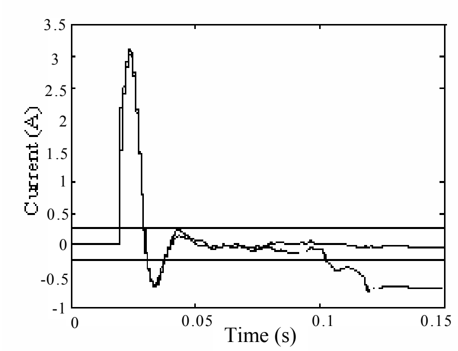
a) active filter currents instantaneous values (from the top to the bottom i_{f1}, i_{f2}, i_{f3});



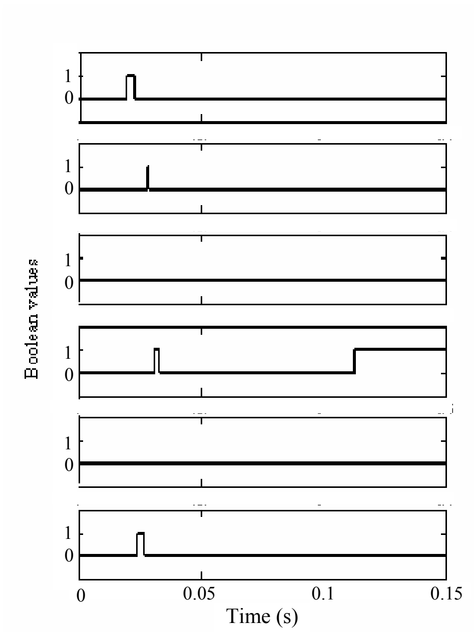
b) phase 1 active filter current with its reference mean values with DC hysteresis band;



c) phase 2 active filter current with its reference mean values with DC hysteresis band;

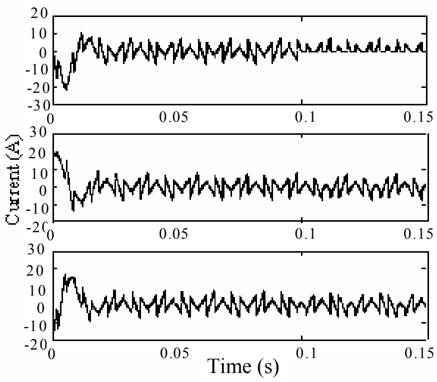


d) phase 3 active filter current with its reference mean values with DC hysteresis band;

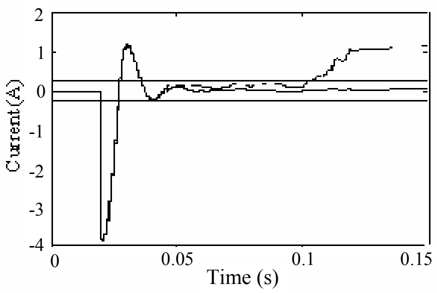


e) Boolean outputs of open switch fault detection algorithm before and after TR2 open switch fault (from the top to the bottom TR1, TR2, TR3, TR4, TR5, TR6);

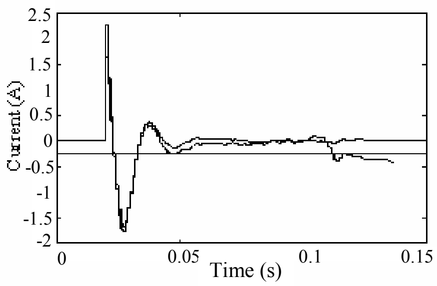
Fig. 6 – Simulation results of open switch fault identification system before and after TR4 open fault condition (active filter currents mean values with their references mean values, Boolean outputs of diagnostic system).



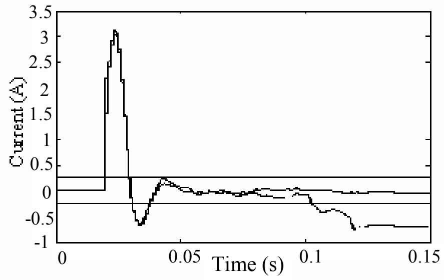
a) active filter currents instantaneous values (from the top to the bottom i_{f1}, i_{f2}, i_{f3});



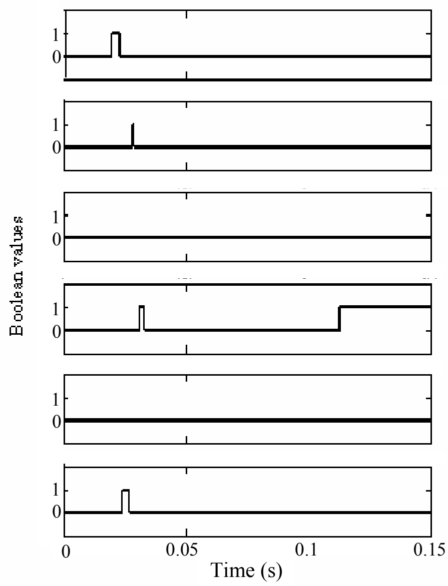
b) phase 1 active filter current with its reference mean values with DC hysteresis band;



c) phase 2 active filter current with its reference mean values with DC hysteresis band;



d) phase 3 active filter current with its reference mean values with DC hysteresis band;



e) Boolean outputs of open switch fault detection algorithm before and after TR2 open switch fault (from the top to the bottom TR1, TR2, TR3, TR4, TR5, TR6);

Fig. 7 – Simulation results of open switch fault identification system before and after TR2 open fault condition (active filter currents mean values with their references mean values, Boolean outputs of diagnostic system).

5. **CONCLUSION**

In this paper, it is presented a simple, reliable and efficient open switch faults detection and localization in shunt active three-phase filter based on two level voltage source inverter controlled by current Hysteresis controllers. The semiconductor open fault detection method is robust to semiconductors switching and includes combinatory logic to perform reliability. Simulation results demonstrate that when optimising active filter parameters, the zero harmonic component strategy can be used with robustness to detect and localize the open faulty switch in active filter inverter.

APPENDIX 1. SIMULTION PARAMETERS

Main source grid: 220V, R_{cc} = 0.0148 Ω, L_{cc} = 0.175 mH, 50 Hz.

Non-linear load: R = 40 Ω, L = 2 mH, L_s = 0.2 mH.

Active filter: V_{dc} = 700 V, L_f = 5 mH,

Currents regulators hysteresis band = +/– 0.5 A.

Mean value calculator computes the mean value of input signal over running window of one cycle of the specified fundamental frequency (50 Hz).

For the first cycle of simulation, the output is held constant to the value specified by the parameter initial input (DC Component = 0 A).

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