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Use of asymmetrical currents waveforms to detect and localize open switch faults for two level voltage source inverter three-phase shunt active power filter

TARAK BENSLIMANE, BOUKHEMIS CHETATE and THAMEUR ABDELKRIM

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 optimized fault diagnosis method. The converter topology is based on classical three-leg active power filter topology. New fault diagnosis method is proposed, based on classical currents measurements. It includes combinatory logic to analyze and validate error signals. 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.

Key words: active power filter, fault detection, two level there phase voltage source inverter, current mean value

1. Introduction

The shape and the phase of line current are determined by the load, while grid voltage remains relatively stable. Hence most power quality problems appear as harmonic currents and reactive currents arising from the load side, because of a large amount of non-linear, inductive load are used nowadays. Current quality problems not only deteriorate the performance of electric equipment such as strong heating, sudden stopping of the revolving machines or even the total destruction of the equipment, but also impair power generation [1].

Several solutions for reducing harmonic current in electrical power supply networks were proposed. Active compensators such as shunt active filter, series active filter and combined shunt-series active filters satisfy the industrial constraints better than passive compensators because they ensure a continuous control of the harmonic distortion in an active way by compensating these harmonics [1]. These filters as many other power

T. Benslimane and B. Chetate are with Laboratory of Automation and Electrification of Industrial Enterprises, University of Boumerdes University of Msila, Algeria, e-mail: bens082002@yahoo.fr. T. Abdelkrim is with Applied Research Unit on Renewable Energies, Industrial zone, B.P. 88 Ghardaia, Algeria, e-mail: tameur2@yahoo.fr.

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electronic equipments may be exposed to incident due to components malfunction as a result of their ageing, overload and control faults. Therefore, the continuous surveillance of these equipments becomes indispensable to guarantee a good reliability.

The fault mode behavior 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 [2]. They have studied rectifier diode short circuit, inverter transistor base driver open and inverter transistor short-circuit conditions. However, they do not propose to reconfigure 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 [3]. In [4] fault detection of open-switch damage in voltage source PWM (Pulse Width Modulation) motor drive systems was investigated by De Araujo Ribeiro R.L., Jacobina C.B., Da Silva E.R.C. and Lima A.M.N.. 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 inverter legs is lost. Then the machine operates with only two stator windings [5]. They proposed to modify PWM control to allow continuous free operation of the drive. More recently, Jacobina C.B., Correa M.B.R., Pinheiro R.F., Lima A.M.N. and Da Silva have studied fault tolerant active power filter system [6], [7]. They proposed to reconfigure power converter and PWM control and examined a fault identification algorithm.

This 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

Fig. 1 shows how a classical three-leg shunt active power is connected. The system is composed of a grid (for $i = \{1,2,3\}$), a non-linear load (rectifier), a voltage source converter (active filter). The load is a three phase balanced inductance L_s with three phase thyristor (or diode) rectifier feeding a series (R, L) DC load. The grid is supposed to be balanced with the same series resistance R_{cc} and inductance L_{cc} for each phase. The static converter is a three phase voltage source inverter with the same series inductance L_f for each phase. Every leg has two bi-directional switches TR_k $(k = 1$ to $6)$. Every switch is composed of a transistor and a diode in anti-parallel. This inverter is fed by a battery of voltage V_{dc}. The mathematically model of the inverter is like as follows:

$$\begin{bmatrix} v_{f1} \\ v_{f2} \\ v_{f3} \end{bmatrix} = \frac{V_{dc}}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 - S_4 \\ S_2 - S_5 \\ S_3 - S_6 \end{bmatrix} \tag{1}$$

where the switch connection function S_k $(k = 1$ to $6)$ indicates the opened or closed state of the switch TR_k $(k = 1$ to $6)$ and v_{fi} $(i = 1, 2, 3)$ is the output phase voltage vectors of the inverter.

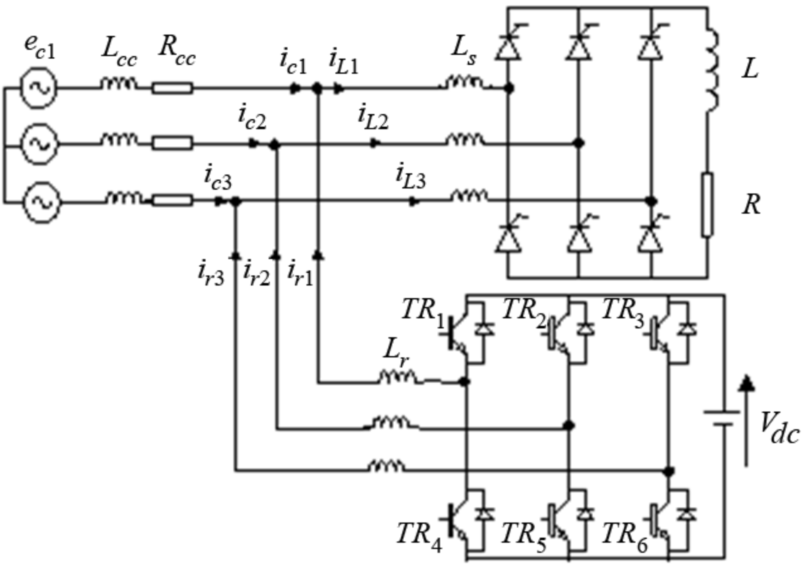

Figure 1. Classical three-leg shunt active power filter topology.

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 e.g. power switch or power switch driver can be faulty. In each case, it results in the following models:

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

Fig. 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 [8].

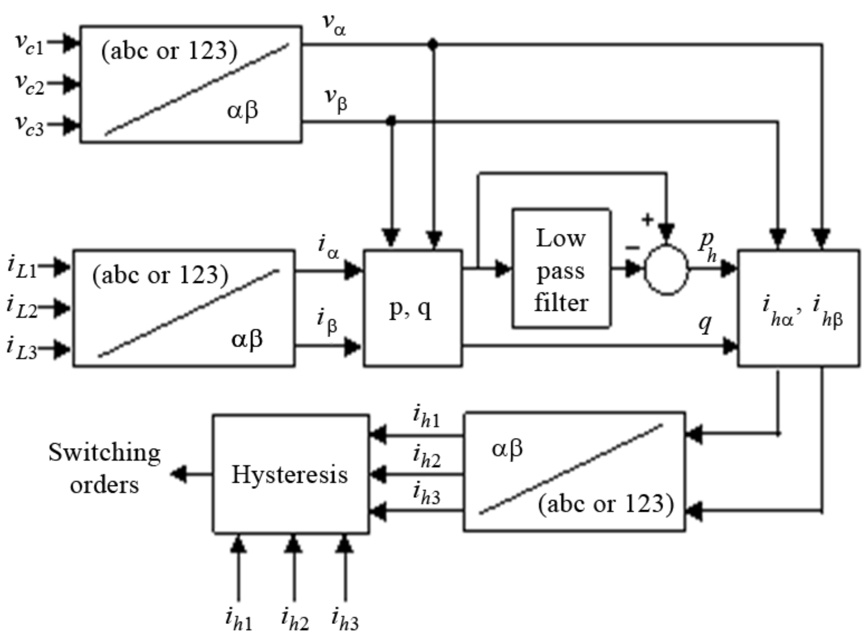

Figure 2. Block diagram of the control system.

By supposing that the main source power supply voltages are sinusoidal, current harmonic references will be calculated like indicated in [9]. (α, β) voltage components at connection point of active filter (v_α, v_β) and currents (i_α, i_β) are defined by the classical Concordia transformation:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{s1} \\ v_{s2} \\ v_{s3} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \end{bmatrix} \tag{3}$$

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

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{4}$$

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:

$$\begin{bmatrix} i_{h1} \\ i_{h2} \\ i_{h3} \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} \left[\frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_h \\ q_h \end{bmatrix} \right] \tag{5}$$

The identified harmonic currents $(i_{h1}, i_{h2}$ and $i_{h3})$ are used as reference to control the switches of the inverter in order to apply the appropriate output phase voltage vectors v_{fi} $(i = 1,2,3)$ to keep the injected filter current within the hysteresis band around the reference current according to the following equation for the phase 1:

$$\begin{aligned} &\text{If } [(i_{h1} - i_{f1} < -h) \to (i_{f1} > i_{h1} + h)] \text{ than } S_1 = 0 \text{ and } S_4 = 1, \\ &\text{If } [(i_{h1} - i_{f1} > +h) \to (i_{f1} < i_{h1} - h)] \text{ than } S_1 = 1 \text{ and } S_4 = 0, \\ &L_f \frac{di_{f1}}{dt} = v_{f1} - v_{s1}, \end{aligned} \tag{6}$$

where v_{f1} and v_{s1} denote respectively the first phase output filter voltage and power network voltage, i_{h1} and i_{f1} refer to respectively the first phase identified harmonic current and active filter injected current, $2h$ is the width of hysteresis band of current regulator. Remaining two phase's currents are similarly controlled.

Fault diagnostic method

This section presents simulation results obtained with Matlab simulator for the proposed fault detection algorithm. General simulation parameters are given in the appendix. These parameters are chosen to reduce THD (Total Harmonic Distortion) of main source currents below 5%. 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 (Fig. 3-6.).

Table 4. DC current component polarity corresponding to faulty open circuit transistor.

Faulty device	Zero harmonic component 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

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. 4, Fig. 6).

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. 5).

The open switch fault detection algorithm is developed to identify the faulty device as classified in Tab. 1.

Mean value calculator computes the mean value of input signal (filter current) over running window of one cycle of the specified lowest harmonic component. Even if the filter current contains a small fundamental component as the lowest harmonic component, its frequency will define the filter currents mean value calculating window. In this case of constant grid frequency, 50 Hz was considered. For the first cycle of simulation, the output is held constant to the value specified by the parameter initial input (DC component = 0 A).

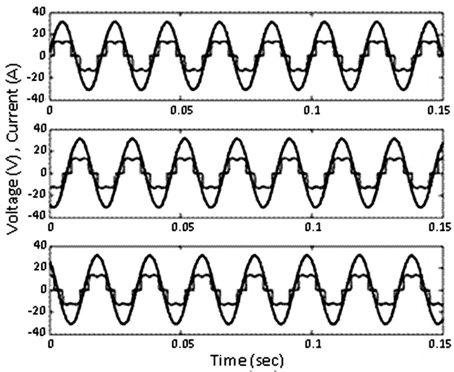

Figure 3. a) Main source phases voltage instantaneous values / 10, rectifier phases currents instantaneous values.

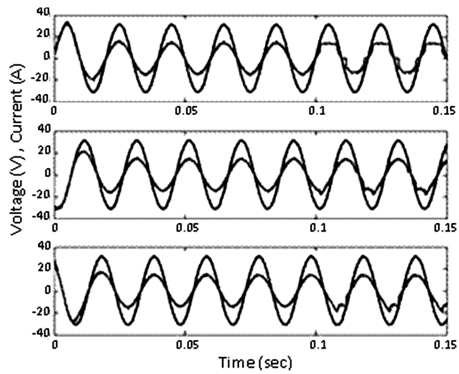

Figure 3. b) Main source phases voltage instantaneous values / 10, main source phases currents instantaneous values before and after TR1 open fault condition.

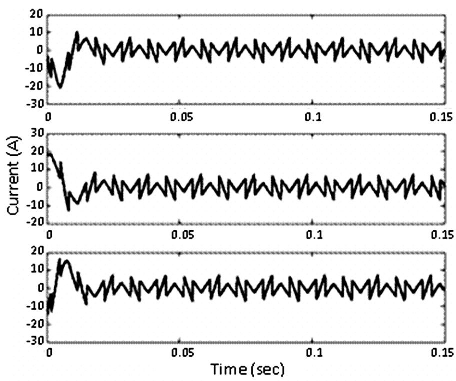

Figure 3. c) Harmonic identified currents instantaneous values.

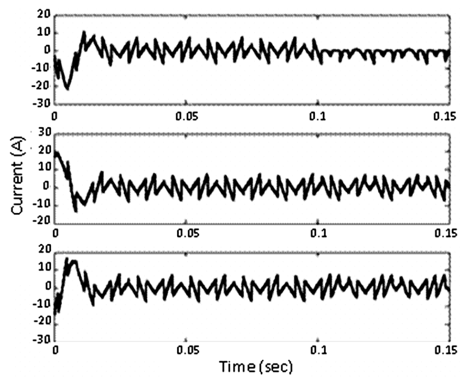

Figure 3. d) Active filter currents instantaneous values before and after TR1 open fault condition (from the top to the bottom i_{f1}, i_{f2}, i_{f3}).

Figure 3. 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).

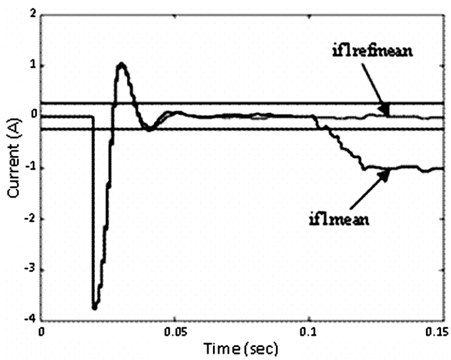

Figure 4. a) Phase 1 active filter current with its reference mean values $i_{f1refmean}$, i_{f1mean} with DC band $\pm$ 0.25A before and after TR1 open fault condition.

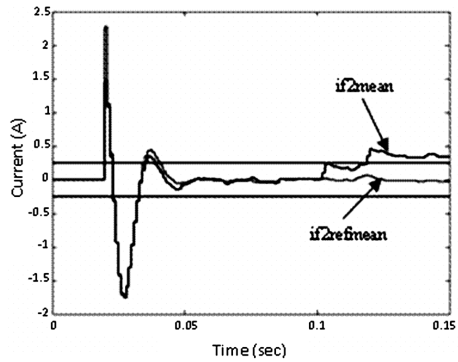

Figure 4. b) Phase 2 active filter current with its reference mean values $i_{f2refmean}$, i_{f2mean} with DC band $\pm$ 0.25A before and after TR1 open fault condition.

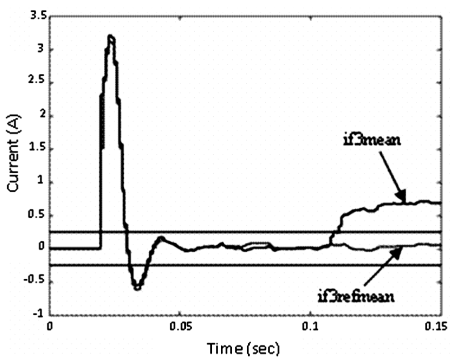

Figure 4. c) Phase 3 active filter current with its reference mean values $i_{f3refmean}$, i_{f3mean} with DC band $\pm$ 0.25A before and after TR1 open fault condition.

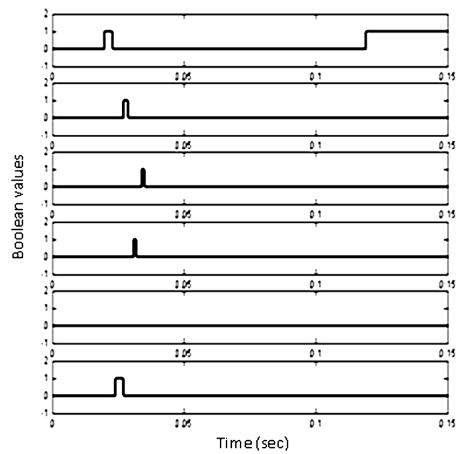

Figure 4. d) Boolean outputs of open switch fault detection algorithm before and after TR1 open switch fault from the top to the bottom TR1, TR2, TR3, TR4, TR5, TR6.

Figure 4. 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).

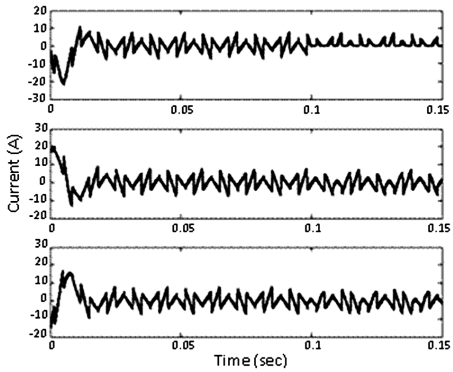

Figure 5. a) Active filter currents instantaneous values from the top to the bottom i_{f1}, i_{f2}, i_{f3}.

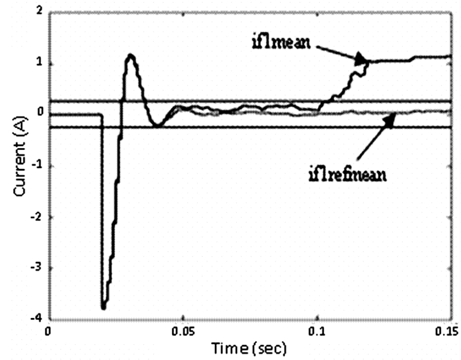

Figure 5. b) Phase 1 active filter current with its reference mean values $i_{f1refmean}$, i_{f1mean} with DC band $\pm$ 0.25A.

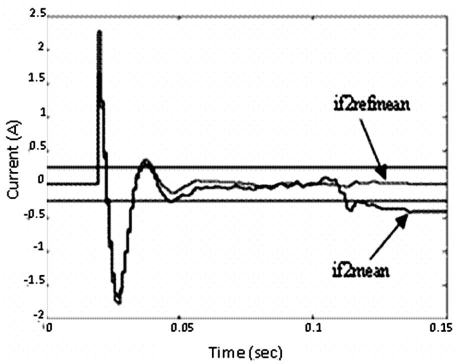

Figure 5. c) Phase 2 active filter current with its reference mean values $i_{f2refmean}$, i_{f2mean} with DC band $\pm$ 0.25A.

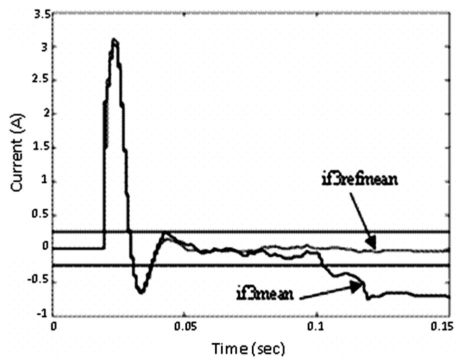

Figure 5. d) Phase 3 active filter current with its reference mean values $i_{f3refmean}$, i_{f3mean} with DC band $\pm$ 0.25A.

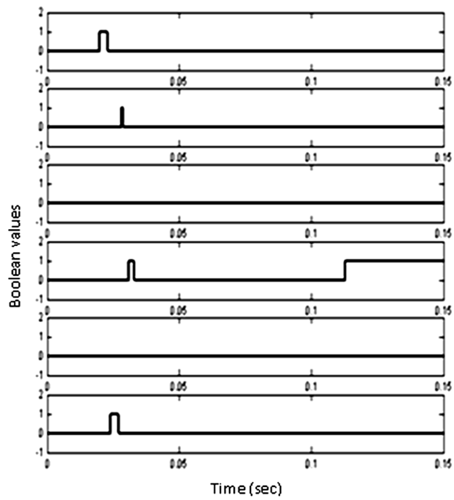

Figure 5. e) Boolean outputs of open switch fault detection algorithm before and after TR4 open switch fault (from the top to the bottom TR1, TR2, TR3, TR4, TR5, TR6).

Figure 5. Simulation results of open switch fault identification system before and after TR4 open fault condition (active filter currents with their mean values and their references mean values, boolean outputs of diagnostic system).

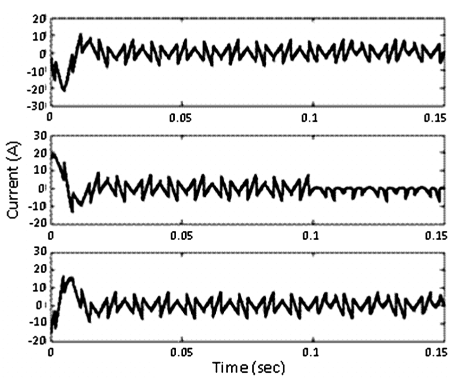

Figure 6. a) Active filter currents instantaneous values from the top to the bottom i_{f1}, i_{f2}, i_{f3}.

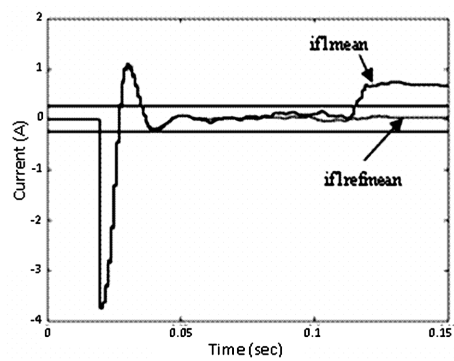

Figure 6. b) Phase 1 active filter current with its reference mean values $i_{f1refmean}$, i_{f1mean} with DC band $\pm$ 0.25A.

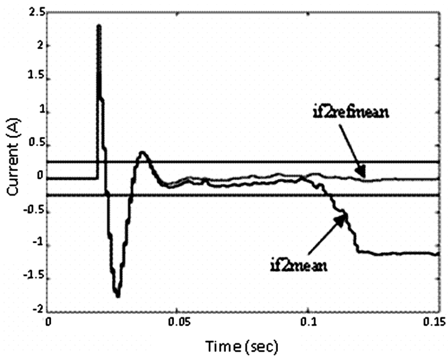

Figure 6. c) Phase 2 active filter current with its reference mean values $i_{f2refmean}$, i_{f2mean} with DC band $\pm$ 0.25A.

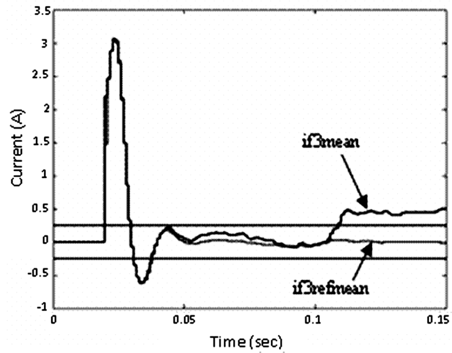

Figure 6. d) Phase 3 active filter current with its reference mean values $i_{f3refmean}$, i_{f3mean} with DC band $\pm$ 0.25A.

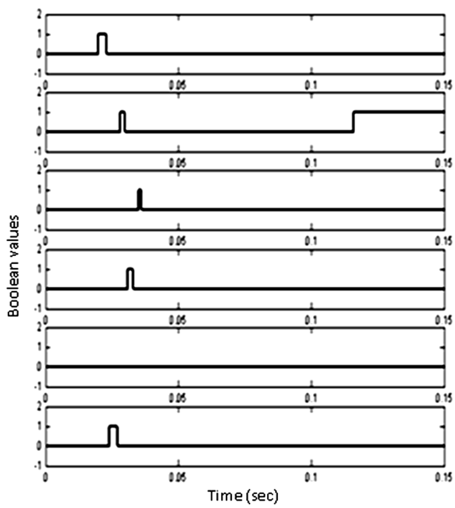

Figure 6. e) Boolean outputs of open switch fault detection algorithm before and after TR2 open switch fault (from the top to the bottom TR1, TR2, TR3, TR4, TR5, TR6).

Figure 6. Simulation results of open switch fault identification system before and after TR2 open fault condition (active filter currents with their mean values and their references mean values, boolean outputs of diagnostic system).

4. 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. Simulation results demonstrate that when optimizing active filter parameters, the zero harmonic component strategy can be used with robustness to detect and localize the open switch faulty transistor in active power filter.

Appendix

Simulation parameters are as follows:

- Power network:
  Root mean square of power network phase voltage 220V,
  Frequency of power network phase voltage 50 Hz,
  Equivalent short circuit resistance and inductance at the point of coupling of the filter $R_{cc} = 0.0148$ Ohm, $L_{cc} = 0.175$ mH.

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

- Active filter:

  Direct Current source voltage: $V_{dc} = 700$ V,
  Coupling inductance of active power filter: $L_f = 5$ mH,
  Currents regulators Hysteresis band ± 0.5 A.

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