International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 6, No. 3, September 2015, pp. 576~585
ISSN: 2088-8694

Faults Diagnosis in Five-Level Three-Phase Shunt Active Power Filter

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Article Info

Article history:

Received Jan 12, 2015
Revised Jul 10, 2015
Accepted Jul 25, 2015

Keyword:

Diagnostic
Mean Values
Multilevel inverter
Open transistor fault

ABSTRACT

In this paper, characteristics of open transistor faults in cascaded H-bridge five-level three-phase PWM controlled shunt active power filter are determined. Phase currents can't be trusted as fault indicator since their waveforms are slightly changed in the presence of open transistor fault. The proposed method uses H bridges output voltages to determine the faulty phase, the faulty bridge and more precisely, the open fault transistor.

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1. INTRODUCTION

Multilevel inverter offers interesting advantages such as possibility of operation in medium, high voltage and high power applications, providing a better voltage waveform with low total harmonic distortion for electric machines applications, output filter elimination, dv/dt transient reduction during commutation, low EMI emissions by overvoltages and power loss reduction [1]. Diode-clamped, cascaded-bridges and flying capacitors are the most used multilevel inverters in industry [2], [3]. However, the number of switches needed in the topology increases with the number of levels and, although the switches may be highly reliable, a system's fault probability will become increased [4], [5]). An unbalanced voltage is generated when a fault occurs which can produce permanent damage to the load or complete system failure [6], [7].

Studies about fault detection in multilevel inverter and even fault-tolerant multilevel inverter have been focused on power systems' fault analysis ([8], [9] and [10]) as first step to conceive different techniques for obtaining a three-phase balanced output voltage ([4], [5], [11] and [12]). Xiaomin analyzed a flying capacitor-based four-level inverter using the material redundancy technique (using extra components) [13]. A cascaded H-bridge multilevel inverter with an additional leg and redundancy technique regarding change of pulse width modulation (PWM) when a fault occurs has also been described [7]. Others ([4], [5] and [6]) have shown tolerant control for an asymmetric cascade multilevel inverter using material redundancy. Other works have analyzed a three-level diode clamped multilevel inverter and also used extra components to tolerate faults [14]. Some of these studies used protection functions [15], e.g. passive protection could become activated according to fault time duration [16]. Several papers ([17] and [18]) have presented a cascade multilevel inverter and fault-tolerant technique used to change PWM modulation in semiconductor power devices. Others works ([19]) have dealt with a fault-tolerant system for electrical machines, such as

induction motor [20], besides focusing on Aerospatiale applications and electric vehicle applications [21]. Others considered the most common faults in static converters (short and open circuit transistors) [22]. In the same direction, D. Kastha and B. K. Bose considered various fault modes of a two level voltage source PWM inverter system for induction motor drive [23]. 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.

De Araujo Ribeiro R. L. et al. investigated fault detection of open-switch damage in two level voltage source PWM motor drive systems [24]. 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 [25]. They proposed to modify PWM control to allow continuous free operation of the drive. E. R. C. Da Silva et al. have studied fault tolerant active power filter system [26]. They proposed to reconfigure power converter and PWM control and examined a fault identification algorithm. T. Benslimane used active filter output currents mean values polarities to detect and localize open switch faults in shunt active three-phase filter based on two level voltage source inverter controlled by current Hysteresis controllers [27]. Surin Khomfoi used artificial neural networks for the diagnostic of open loop PWM controlled cascaded h-bridge multilevel inverter drives. He used inverter output voltages FFT analysis to extract principle component as fault indicators for simultaneous transistor and diode open switch fault [28]. Karimi S. and Pourea P. et al. put into practice an FPGA (Field Programmable Gate Array)-based online fault tolerant control technique of parallel active power filter based on two level three-phase voltage source inverter with redundant leg [29], [30].

Most of mentioned works about multilevel inverter faults detection are related to electrical machine drives applications. The few of them, which are related to static applications such as active power filters, considered only two-level voltage source inverter.

This present paper deals with open transistor faults characterization in cascaded H-bridge five-level three-phase PWM controlled shunt active power filter. Phase currents can't be trusted as fault indicator since their waveforms are slightly changed in the presence of open transistor fault. The proposed method uses H-bridges output voltages to determine the faulty phase, the faulty bridge and more precisely, the open faulty transistor.

2. ACTIVE POWER FILTER DESCRIPTION

Figure 1 presents the cascaded H-bridge five-level three-phase shunt active power filter connected to balanced power grid (vsi for i = {1, 2, 3}) powering a three phase parallel-connected two diode rectifiers feeding variable series (R, L) loads. The active filter is composed, in each phase, of two voltage source H-bridge inverters (Hij, i = 1, 2, 3, j = 1, 2) with 4 bidirectional switches (transistor + diode) for each one. The filter is connected to the power grid through inductive filter L_f for each phase. The output currents of shunt active filter are controlled to provide a similar waveform of identified reactive and harmonic currents generated by the non-linear load (diode rectifiers).

3. HARMONIC CURRENT IDENTIFICATION

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 [31].

They are defined using classical active and reactive power method proposed by Akagi [32]. By supposing that the main power supply voltages are sinusoidal, current harmonic references will be calculated like indicated in [33], [34]. The (α, β) voltage components at connexion point of active filter (vα, vβ) and currents (iα, iβ) are defined by the classical Concordia transformation:

$$\begin{bmatrix} x\alpha \\ x\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ x3 \end{bmatrix} \quad (1)$$

Where x = {v, vs, i, i_L}

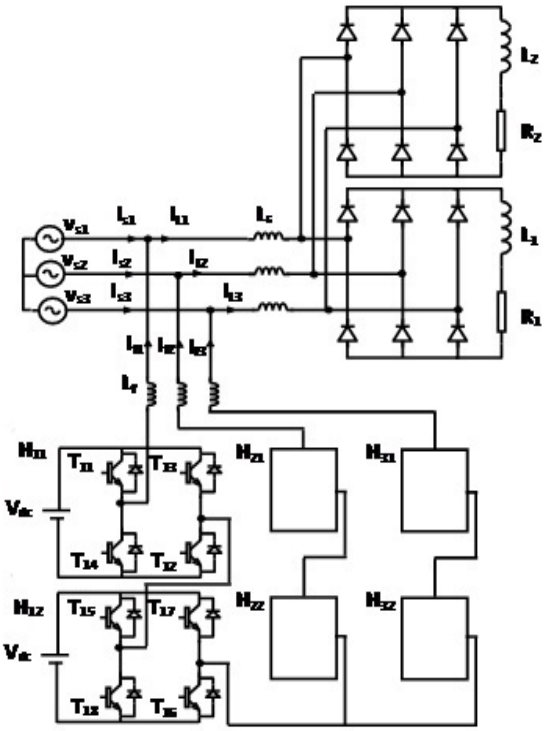


Figure 1. Cascaded H-bridge Five-level three-phase shunt active power filter topology

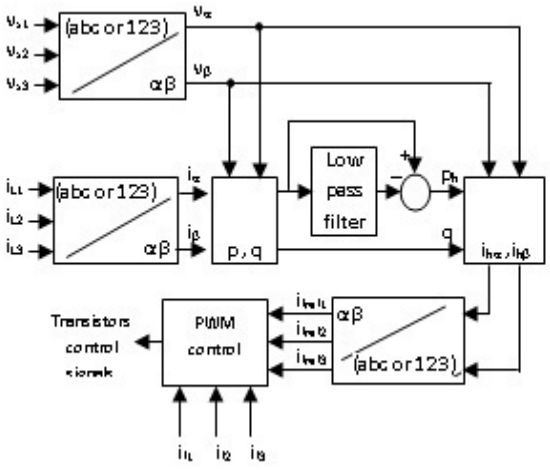


Figure 2. Block diagram of the harmonic currents identification

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

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (2)$$

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

$$\begin{bmatrix} i_{h1} \\ i_{h2} \\ i_{h3} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} 1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_h \\ q_h \end{bmatrix} \quad (3)$$

4. COMPARISON OF FAULT DETECTION IN STATIC CONVERTERS

Recently, static converters behavior during an occurence of faults in a static power switch or in drivers as well as in topologies known as fault tolerant have been subject to numerous works and publications. Early in 1994, Kastha et Bose have presented a systematic study on the consequences of voltage source invertrs defaults feeding an induction motor [35]. However they did not present a method allowin the detection of these faults. Peuget et al have presented a method allowing fault detection based on the trajectory path of the phase current vector [35]. Actually, in normal condition (without faults), phase current vector in $\alpha\beta$ frame has a circle trajectory path. When an open circuit fault occurs, caused by the failure of a static power switch remaining in open state, whithin one leg of the inverter, the trajectory path becomes a semi-circle. The position of the semi-circle in $\alpha\beta$ frame can be informative on the faulty power switch. Mendes et Cardosohave prposed to use the phase current mean value in the stationary park frame in order to identify

faults of open circuit type [36]. The methods proposed above have been only applied to inverters feeding induction motors and require at least one period of the phase current fundamental to detect faulty operation.
Also, more recently, reduction of the required time to detect malfunction (delay between fault apprition and its detection) has been investigated in several research papers. Ribeiro et al. Have proposed to use supplementary voltage sensors to detect open circuit and short circuit faults [37] and [38]. They have shown that using the measurement of the three voltages between each inverter's phase and the voltage at midpoint of teh capacitors divider of the DC source and their comparison with the estimated voltages, fault can then be detected in quarte of the period of the phase currents. Yu et al., Shamsi-Nejhad et al. Have used voltage measurements of the switch terminals at the bottom of each leg to detect faults, [39] and [40]. They also showed that from these measured voltages and their comparison with a threshold, the fault can be detected in a period of the fundamental phase currents. Table 1 compares the methods mentioned previously in terms of limits of application, detection time and the number of additional required sensors.

Table 1. Comparison of defect detection methods at the power semiconductors (fundamental frequency of 50 Hz)

Method Principle	Application Limit	Detection Time	Number. sensors additional
Tracking the trajectory of the phase current vector [35]	machines Power	> 20 ms	-
Average value of the phase currents in the reference frame Park [36]	machines Power	> 20 ms	-
Voltage measurement "pole voltage" converter [37]	-	> 5 ms	3
Measuring the voltages across the switches [39]	-	> 5 ms	3

In the present work, a novel fast fault detection method of power switches or drivers used in a three phase voltage source inverter. The prposed method allows a considerable reduction of detection time. We show that a fault can be detected less than 10us by using an algorithm based on temprel criterium and voltage criturium. Thus, it is allowed from one hand to detect faults rapidly (voltage test), and on the hand avoiding erroneous detection that follow state change of power switches (temporal test)

5. ACTIVE FILTER FAULT DIAGNOSIS METHOD

Several faulty cases can occur: power transistor or power transistor driver can be faulty. In each case, it results in the following models:
- A transistor is closed instead of being normally open. It results in a short-circuit of the DC voltage source. To isolate the faulty switch as fast as possible, one can use fuses.
- A transistor is open instead of being normally closed. 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, may pollute more the power supply instead of elimination of harmonic currents of non-linear load. This case is considered in this paper.

This section presents simulation results obtained with PSIM simulator for PWM controlled cascaded H-bridge five-level three-phase shunt active power filter. Horizontally shifted carriers PWM control technique is considered where reference signals are compared to 4 carriers shifted by 90° one to another to generate transistors control signal. Simulation parameters are:

- Main source grid: 220V, 50 Hz;
- Non-linear load: R1 = 10 Ohm for t ϵ [0,0.7sec], R1 = 5 Ohm for t ϵ [0.7,1.5sec], L1 = 0.005 H, R2 = 1000 Ohm for t ϵ [0,1.1sec], R2 = 5 Ohm for t ϵ [1.1, 1.5sec], L2 = 0.01 H, Ls = 0.0015 H;
- Active filter: Vdc = 300 V, Lf = 0.004 H, fp = 5000 Hz (PWM carriers frequency), Proportional-integral (PI) regulators: Gain kp = 0.5, time constant Ti = 0.001.

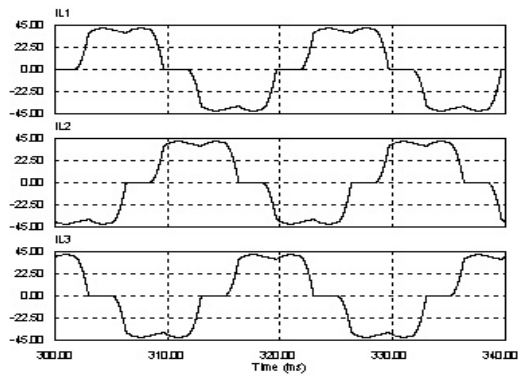
These parameters are chosen to reduce THD of main source currents below 5%. It is noticed that filter output currents are superimposed to their harmonic identified reference currents and that grid source currents are almost sinusoidal (Figure 3.b, Figure 3.c). It is also remarked that PI output signals (PWM reference signals: Vref1, Vref2, Vref3) are symmetric (Figure 4.d) which produce symmetric output voltages Va1 and Va2 (Vb1, Vb2, Vc1, Vc2 with a,b et c as phase indicators) with small mean values Va1mean, Va2mean, Vb1mean, Vba2mean, Vc1mean, Vc2mean (Figure 4.e, Figure 4.f).

Faulty phase, faulty bridge and more precisely, open faulty transistor detection is based on the calculation of zero harmonic component (mean value, dc offset) included in H bridges output voltages. This is done by using a second-order low-pass filter with cut-off frequency of 5 Hz and damping ratio of 0.7.

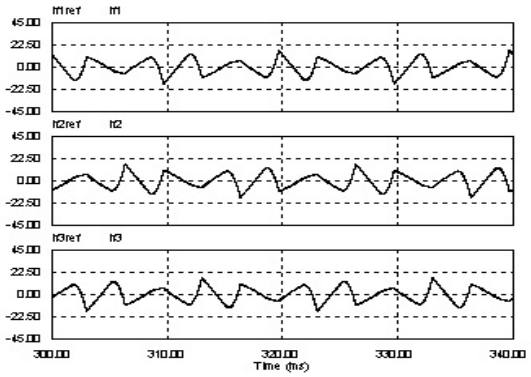
When a transistor is in open fault condition, the PI regulators will output a PWM reference signal in a way to compensate the error due to that faulty transistor. In this case, PWM reference signals will be asymmetric making H bridges output voltages asymmetric too with significant mean values specific to each faulty transistor (Figure 5).

A change in H bridges output voltages waveforms is defined as the instant at which a sudden increase or decrease is observed in the DC offset component of these voltages. A change is considered to have occurred in the H bridges output voltages mean values when they exceeds or falls below a given band (Figure 5.c).

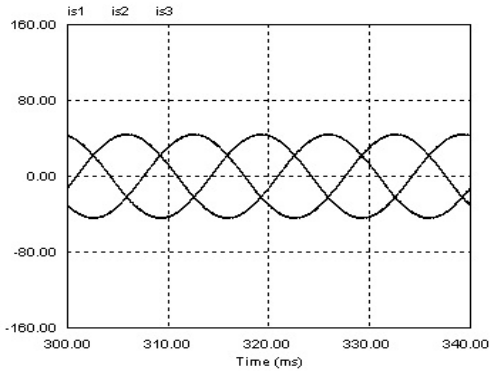
Phase 1 is linked to the first leg of inverter which is composed of upper bridge H11 and lower bridge H12. If the open circuit faulty transistor belongs to leg 1, one of its bridges output voltages will have the maximum mean value (Va1mean = ± 60 V or Va2mean = ± 60 V). If the faulty transistor belongs to the upper bridge H11 (T11, T12, T13, T14), this latter's output voltage will have the maximum mean value (Va1mean = ± 60 V) (figure 4). If the faulty transistor belongs to the lower bridge H12 (T15, T16, T17, T18), this latter's output voltage will have the maximum mean value (Va2mean = ± 60 V) (Figure 6). If one of the transistors T11 and T12 of the upper bridge H11 is the faulty one, this bridge's output voltage will have the maximum mean value with negative polarity (Va1mean = - 60 V) (figure 4.c). If one of the transistors T13 and T14 of the upper bridge H11 is the faulty one, this bridge's output voltage will have the maximum mean value with positive polarity (Va1mean = + 60 V). If one of the transistors T15 and T16 of the lower bridge H12 is the faulty one, this bridge's output voltage will have the maximum mean value with negative polarity (Va2mean = - 60 V) (Figure 6).



a. Non linear load phase currents

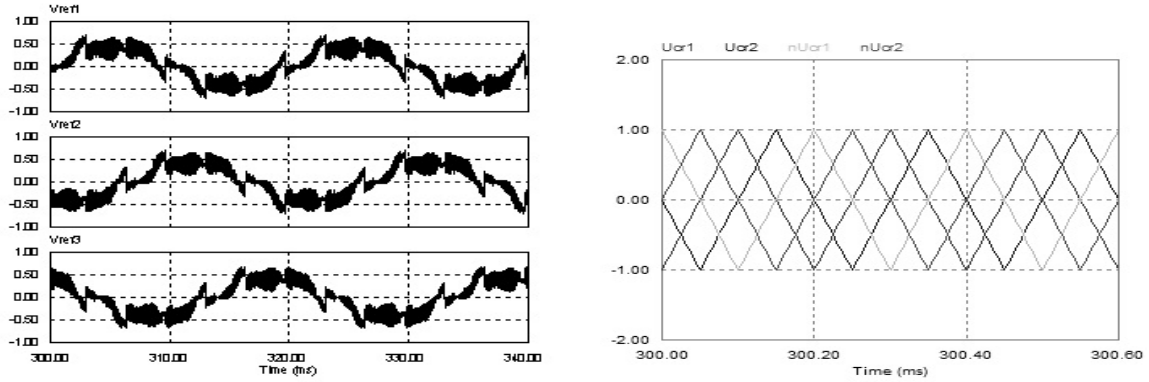


b. Active filter phase currents and their references

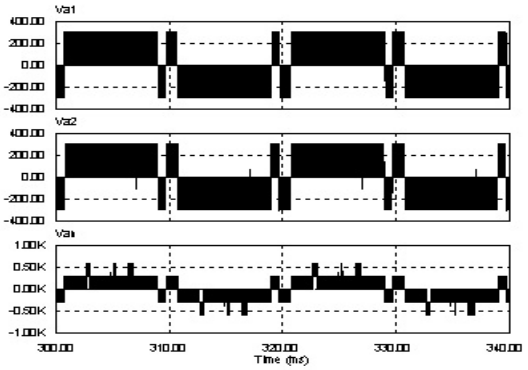


c. Power grid phase currents

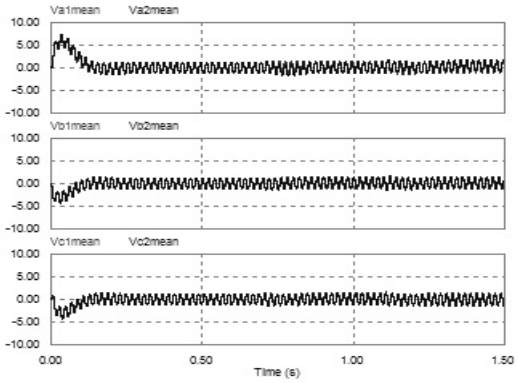
Figure 3. Simulation results of H-bridge five-level three-phase shunt active power filter in normal operating condition (results 1)



a. PWM reference signals and carriers



b. Bridge H11 and phase 1 output voltages



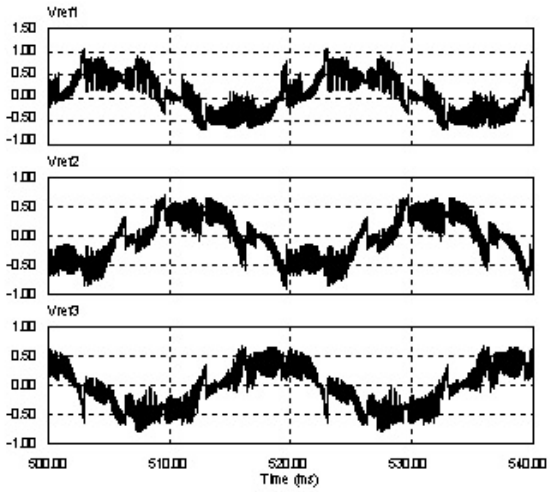
c. Bridges output voltages mean values

Figure 4. Simulation results of H-bridge five-level three-phase shunt active power filter in normal operating condition (results 2)

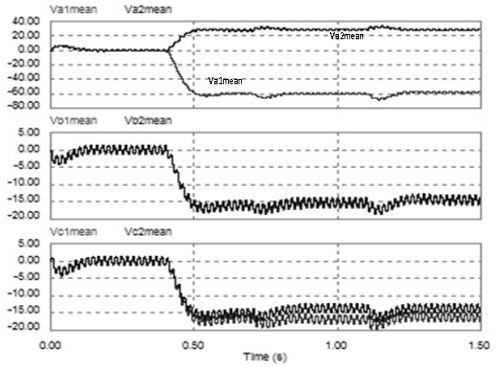
The first phase three bridges open transistor faults characteristics are classified in Table 2. This table could be implemented practically using simple comparators with predefined threshold of H Bridges output voltages mean values.

Table 2. H Bridges output voltages mean values corresponding to faulty open circuit transistors of phase 1

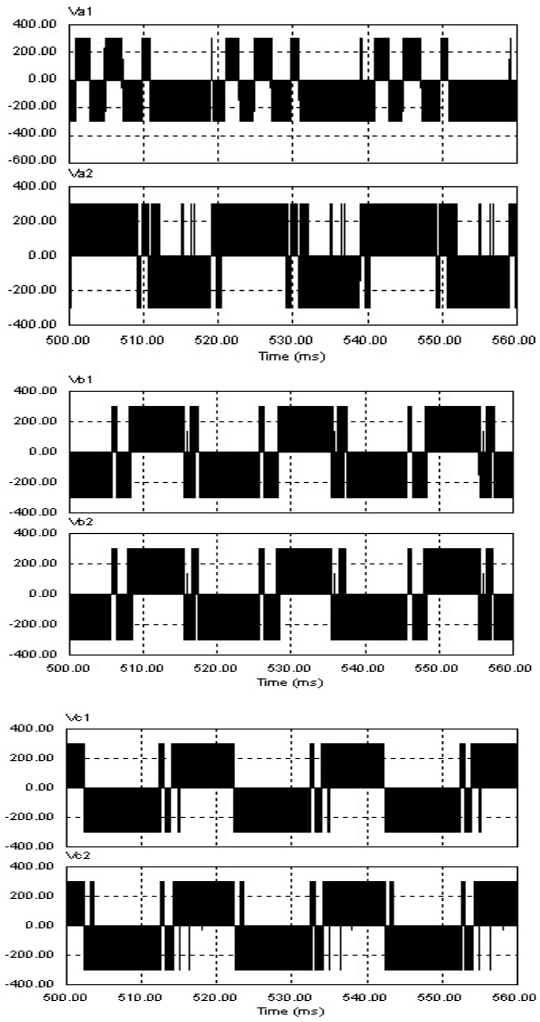
Faulty bridge	Open faulty transistor	Faulty phase 1, 2, 3 or (a, b, c)	H Bridges output voltages mean values					
			Va1mean (V)	Va2mean (V)	Vb1mean (V)	Vb2mean (V)	Vc1mean (V)	Vc2mean (V)
H11	T11 or T12	1 or (a)	-60	+30	-15	-15	-16	-14
	T13 or T14	1 or (a)	+60	-30	+15	+15	+16	+14
H12	T15 or T16	1 or (a)	+30	-60	-15	-15	-14	-16
	T17 or T18	1 or (a)	-30	+60	+15	+15	+14	+16



a. PWM reference signals



c. Bridges output voltages mean values



b. Bridges output voltages

Figure 5. Simulation results of H-bridge five-level three-phase shunt active power filter in T11 open fault condition

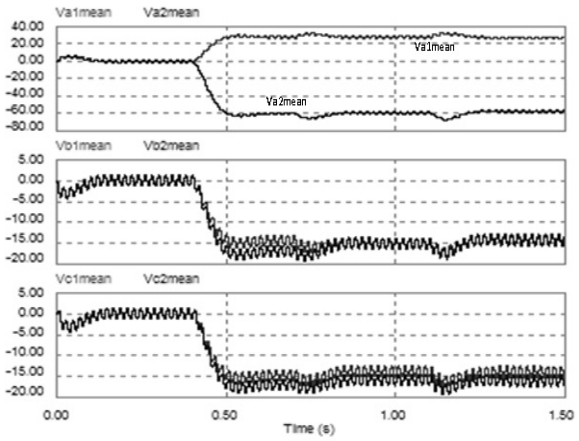


Figure 6. Simulation results of H-bridge five-level three-phase shunt active power filter in T15 open fault condition

6. CONCLUSION

This paper presents a simple, reliable and efficient open transistor faults detection and localization technique in shunt active three-phase filter based on H-bridge five-level three-phase PWM-controlled shunt active power filter. H bridges output voltages mean values are used to characterize different open transistor faults leading to the conception of diagnostic technique permetting the determination of faulty phase, faulty bridge and more precisely the faulty transistor.

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 power filter.

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