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(RESEARCH ARTICLE)

Fault-tolerant cascaded H-bridge inverter connected to power grid

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Abstract

Nowadays, the use of inverters is increasingly required in domestic and industrial installations, electrical energy production plants, and in several other areas for the conversion from the DC form to the AC form of the electrical energy such as aviation, maritime and especially in the field of Parallel Active Filtering where it constitutes the capital element for the injection of harmonic compensating energy into the electrical network. In the interest of ensuring its reliability and especially its availability, it is therefore important to design its fault-tolerant model. In this paper, we propose a new model of cascaded H-bridge inverter which could even in the presence of faults, continue to deliver a voltage of value equal to that in normal operating mode. The results of simulations carried out using the Matlab/Simulink software show good performance of the proposed inverter.

Keywords: Availability of electrical energy; Cascaded H-bridge inverter; Fault tolerant; Reliability

1. Introduction

Nonlinear loads such as diode and thyristor rectifiers, dimmers, computers and their peripherals, air conditioning and lighting devices based on fluorescent tubes, draw non-sinusoidal currents, even if they are powered by a sinusoidal voltage, and therefore introduce harmonic pollution on the currents and voltages of electrical distribution networks [4, 9, 13]. As consequences, we have malfunction, reduction in lifespan, destruction of these electrical devices, overheating, or even explosion of transformers. Thus, relying on the quality of electrical energy, the use of power switches in the field of electronics is increasingly demanded for the manufacture of static converters such as the multi-level inverter which is a crucial element for the reduction of harmonics [2, 7]. According to references [4] and [7], the intervention of the Parallel Active Filter remains today the most appropriate solution for the attenuation of current harmonics. Previous work [1, 3, 10, 11] raised a major drawback the degradation of multilevel inverters when the latter are confronted with difficulties such as short circuits, open circuits, which result from overcurrent/overvoltage phenomena, or environmental phenomena such as temperature variations, humidity and/or dust which can affect the power switches (IGBT). The simulation results under the matlab/simulink interface proved that the waveform degradation is a function of the defect size. In order to solve the problem of reliability and continuity of electric power, the present work aims to design a fault-tolerant cascaded H-bridge inverter model which could even in the presence of a fault, operate as in mode normal. The proposed system consists of: a three-phase alternating energy source, a non-linear load including an uncontrolled three-phase dual-wave rectifier intended to power a resistive load, and a 4-H-bridge inverter in tolerant cascade to faults with sinusoidal PWM control and the chosen field of application is the Parallel Active Filter.

This paper is structured as follows: the cascaded H-bridge inverter and the principle of FAP are presented in part 2, the working principle of the H-bridge inverter in part 3. Section 4 is devoted to present the types of defects that can occur

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in IGBTs as well as their origins. In section 5 we present the H-bridge tolerant inverter model as well as its operating principle. Section 6 is devoted to the results and the conclusion is presented in section 7.

2. Cascaded H-Bridge inverter

2.1. Cascaded H-Bridge Inverter

An H-bridge is an electronic circuit that reverses the voltage/current at both ends of the load or output to which it is connected. The advantages of cascaded H-bridge inverter are the following: it requires less number of components and hence the weight and cost of this inverter is less. Soft switching can achieved easily. The inverter is the device that will convert DC voltage into AC voltage by switching the DC input voltage in a preset sequence so that generates AC voltage. The disadvantages of half-bridge inverter it is in simple words, the main drawback is source utilization factor when compared to full bridge inverter. You don't use the total source voltage at a time. Let Vs be the total voltage of source. In every half cycle, voltage across the load is only half of source voltage i.e., Vs/2.

2.2. Principle of the FAP

The parallel active filter is most often controlled as a current generator; it generates harmonic currents, in phase opposition with the network, so that the sum with these is zero. It therefore makes it possible to eliminate all the current harmonics of the nonlinear load at the connection point. In practice, we cannot obtain a purely sinusoidal line current as in the ideal case, but the goal is to have a current which will be as close as possible to the sinusoid.

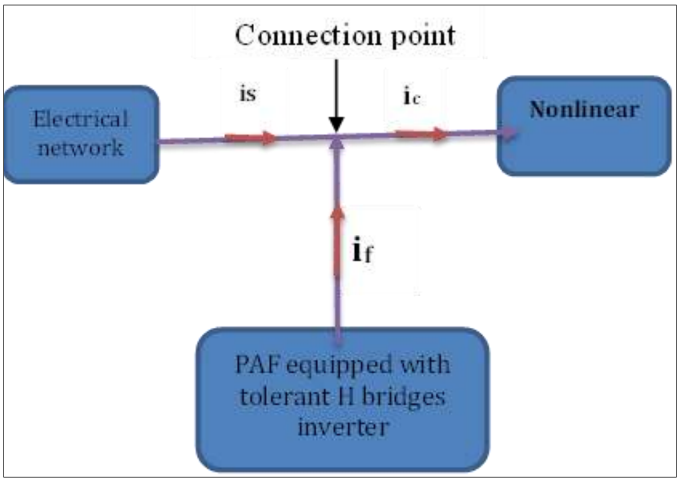

Figure 1 Principle of parallel active filtering

By applying Kirchhoff's law to the connection point, we have:

$$i_{ch} = i_f + i_s \text{ ……………………… } (1)$$

With i_s the source current, i_{ch} the current absorbed by the load and i_f the current injected by the filter. In general, the current absorbed by the load includes; an active component i_{cha}, a reactive component i_{chr} and a harmonic component $\sum_{n=2}^{\infty}(i_{chn})$

$$i_{ch} = i_{cha} + i_{chr} + \sum_{n=2}^{\infty}(i_{chn}) \text{ ……………………… } (2)$$

The parallel active filter provides reactive power and distorting power in phase opposition;

$$i_f = i_{chr} + \sum_{n=2}^{\infty}(i_{chn}) \text{ ……………………… } (3)$$

(2) and (3) in (1) gives:

$$i_{cha} + i_{chr} + \sum_{n=2}^{\infty}(i_{chn}) = i_s + i_{chr} + \sum_{n=2}^{\infty}(i_{chn}) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (4)$$

$$i_{ch} = i_{cha} = i_s \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5)$$

Relation (5) gives us the expression of the filtered current. However, in the presence of a fault, the filter current is affected; and can be written in the form:

$$i_{fd} = d \times i_f \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (6)$$

With d the failure coefficient; and can be expressed by:

$$d = \frac{i_{fd}}{i_f} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (7)$$

The value d is between $]0, 1[$; when $d \approx 1$, we say that the inverter operates in tolerant mode.

3. Principle of operation of a cascaded H-bridge inverter

Assuming that the inverter is in healthy operating mode, and that it is powered by a direct voltage E; the possible switching states are as follows:

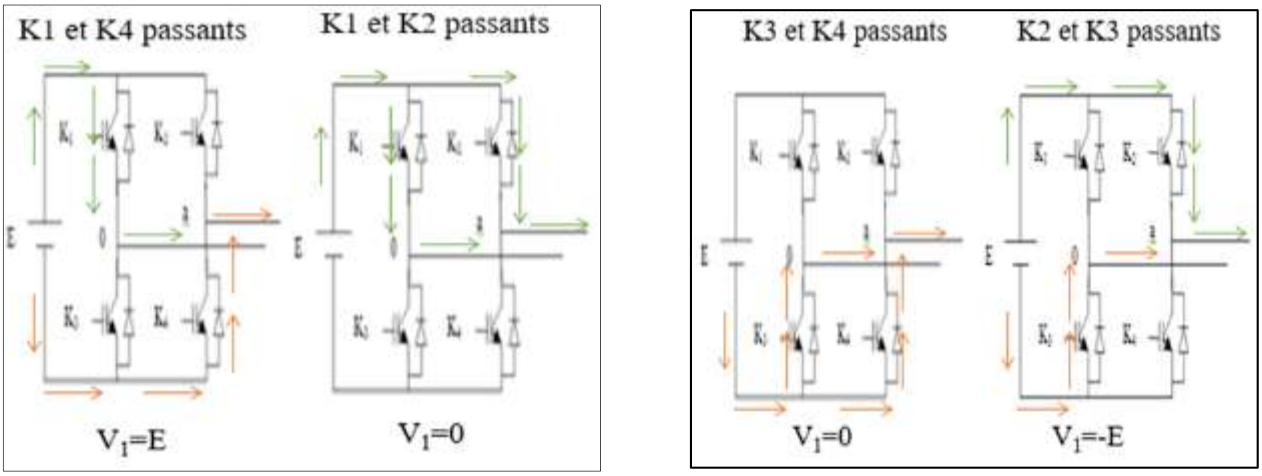

Figure 2 Possible switching states of an H-bridge inverter

When we have several bridges connected in series as shown in Figure 3, the output voltage V_{A0} is the sum of the output voltages of all the bridges constituting the phase (phase A in our case). Let **n** be the number of levels, **N** be the number of bridges; we have:

$$n = 2N + 1 \ or\ N = \frac{1}{2}(n - 1)$$

$$V_{A0} = V_1 + V_2 + V_3 + \cdots + V_N$$

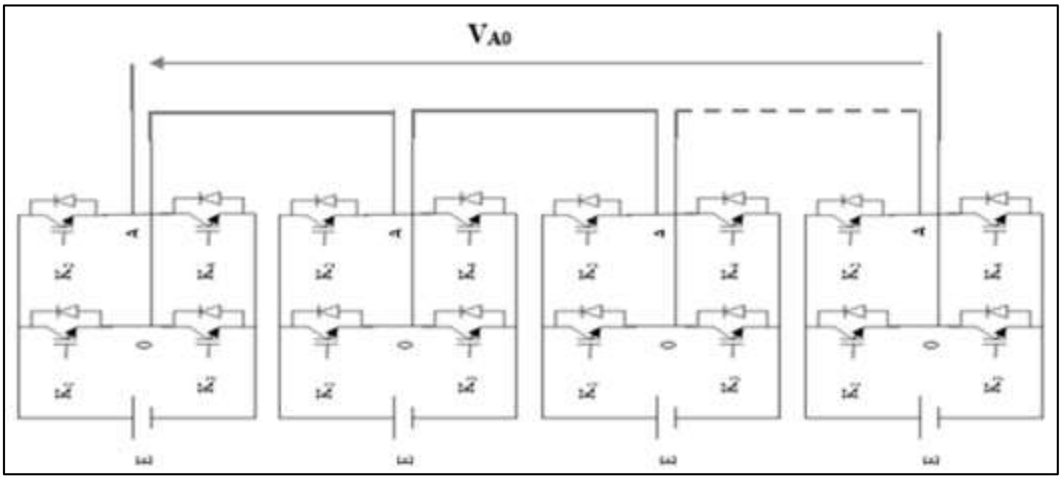

Figure 3 n - level cascaded H-bridge inverter

In the presence of a fault, the value of the output voltage of the bridge concerned deteriorates, which automatically affects the voltage V_{A0} of the phase, as well as that of the inverter; and the level of degradation is a function of the size of the defect.

4. Types of defects and their origins

Faults inverter is a big concern. There are mainly two kinds of faults which need to be identified

- Switch faults and
- Phase faults

The former is based on faults like open circuit and short circuit faults in IGBTs. The first one is to connect the voltage or current sensor in each IGBT and the second one is to observe the output waveform and classify the faults by taking its THD values.

In this paper, only two types of fault have been taken into account in semiconductor power devices.

- Short circuit fault (SCF)
- Open circuit fault (OCF)

Open circuit fault and short circuit fault of IGBTs or antiparallel diodes are the basic cause for the faults in IGBTs modules. Under the OCF conditions, the current cannot flow from the switch to the load. Likewise, the SCF conditions will force the high current to flow from the IGBT to the load. The number of switching faults occurring at a specific time will decide different open circuit fault types in any inverter. The devices faults $(n-1)$ may occur for n number of switches, such as single device, double device, and $(n-1)$ device faults.

5. Fault-tolerant cascaded H-bridge inverter and working principle

In order to overcome these difficulties, it would be important to design a new inverter model that can tolerate failures occurring on the power switches. In [13], the authors proposed the integration of chemical storage batteries into an H-bridge inverter. The author in [14], proposes the addition of an additional $4th.\ arm$ of FC type to a three phase inverter NPC type, and in [15], the authors propose the addition of an additional arm to a three-phase inverter. In this paper, we propose to mount a thyristor in parallel with each IGBT (i.e. antiparallel with each diode); and a fuse at each input of each phase as shown in the Figure 4.

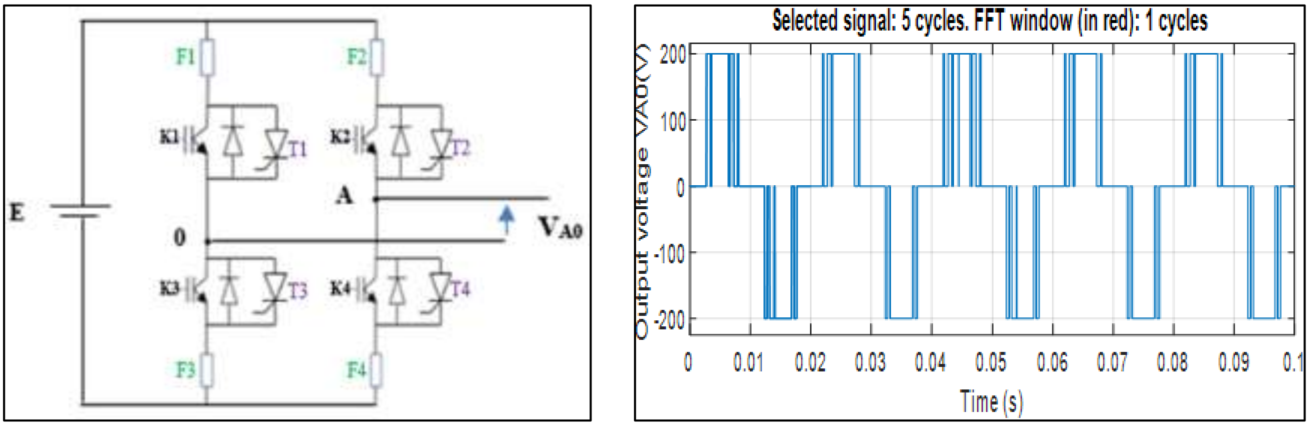

Figure 4 Proposed fault-tolerant H-bridge inverter and output voltage shape

In a healthy operating mode, the inverter operates like a conventional inverter [16].

In the presence of a defect; for example, in the case where K_1 is kept open as shown in Figure 5, the thyristor T_1 automatically takes over and conducts. The output value is not affected and is equal to the value in a normal operating mode.

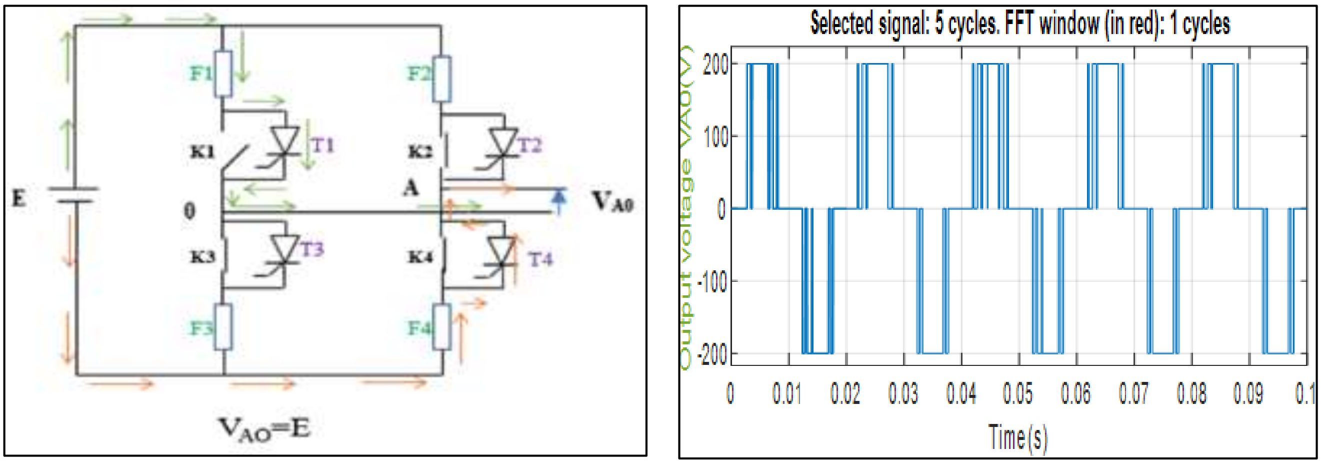

Figure 5 Fault-tolerant H-bridge inverter with K_1 open and output voltage shape

6. Simulation results

Above all, a comparative study on the evolution of the number of levels was carried out; and the values are mentioned in the table 1. The aim of this study is to see the behavior of the output voltage of the two inverter models as the number of levels increases. We see that for each level studied, the value of the output voltage is more important for the tolerant model. Subsequently, the simulation parameters are mentioned in table 2. And the results presented are those of the first phase.

6.1. Parallel Active Filtering: operation in healthy mode

In this first part, we assume that there is no defect; the system is therefore assumed to operate normally.

6.1.1. Case using the classic 9-level inverter model

Here, we apply to the Parallel Active Filter, a classic H-bridge inverter, with 9 levels; ie with 4 complete H bridges. The simulation results are shown in Figure 6 to Figure 10.

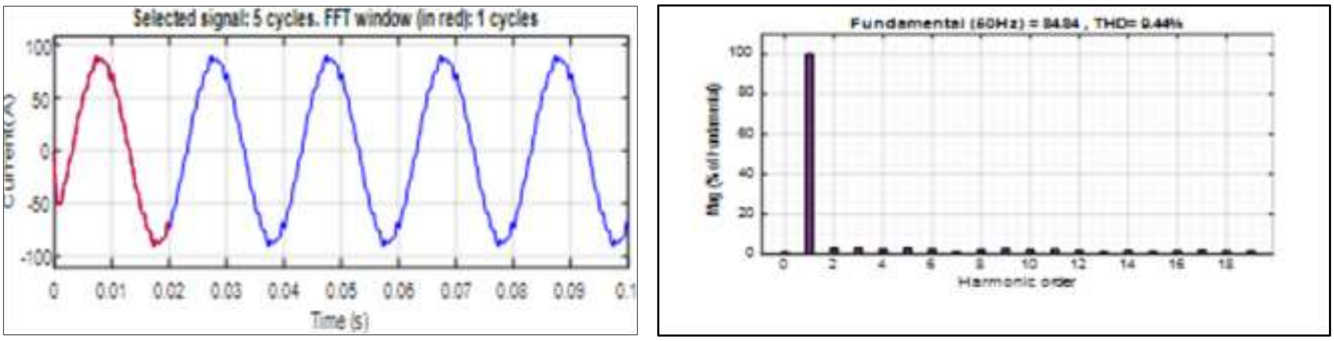

Figure 6 Source current ($\boldsymbol{i_s}$) and Total Harmonic Distortion

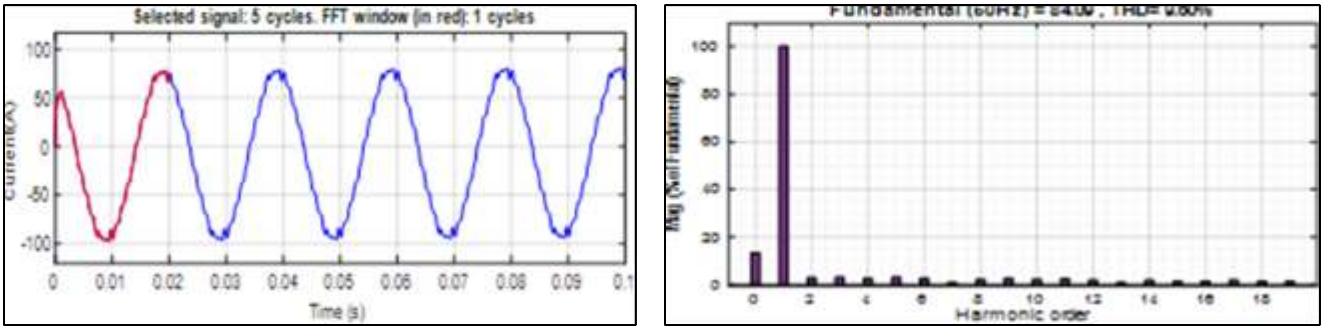

Figure 7 Filter current ($\boldsymbol{i_f}$) and Total Harmonic Distortion

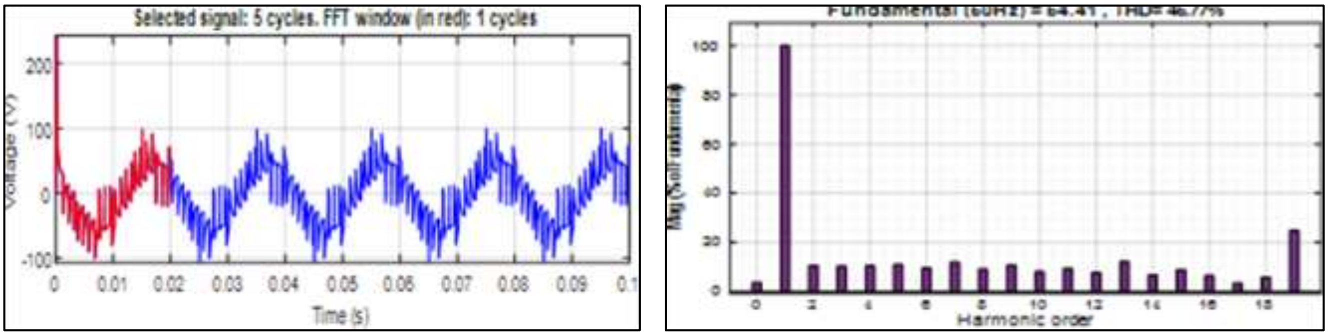

Figure 8 Voltage ($\boldsymbol{V_f}$) across the filter side connection load and Total Harmonic Distortion

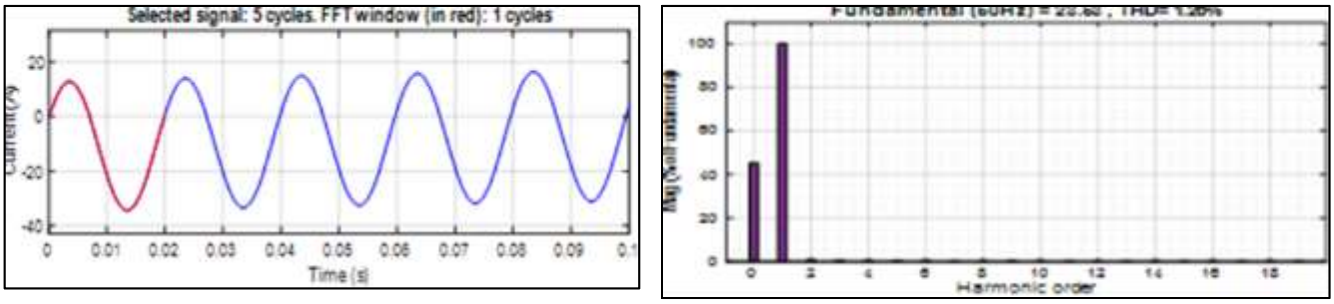

Figure 9 Load current ($\boldsymbol{i_{ch}}$) and Total Harmonic Distortion

Table 1 Summary of average values of voltages Total Harmonic Distortion at 60Hz

	Level	**3**	**5**	**7**	**9**	**11**	**13**	**21**	**25**	**31**	**35**
Model classic	Voltage(V)	165.3	405.6	603.7	689.1	881.9	1103	1927	2320	2934	3336
	TDH	49.05	27.54	24.57	24.54	23.66	21.86	21.91	22.30	22.35	22.53
Model tolerant	**Voltage(V)**	**171.2**	**407.6**	**603.8**	**805.3**	**982.8**	**1198**	**1996**	**2379**	**2993**	**3347**
	THD	**46.14**	**26.07**	**25.10**	**25.17**	**24.94**	**25.93**	**30.27**	**30.76**	**31.54**	**32.36**

Table 2 Simulation parameters

Settings	Features
Source	V_S=220V, $R_s = 10\Omega$, $L_S = 0.002H$, $f = 50Hz$
Parallel Active Filter	E=200V, $R_f = 0.5\Omega$, $L_f = 0.001H$, C=10^{-6} F, $f_p = 1000Hz$
Nonlinear load	Connection resistance and inductance: $R_{ch} = 0.1\Omega$, $L_{ch} = 0.1H$ Load connected following the rectifier: $R_d = 0.1\Omega$

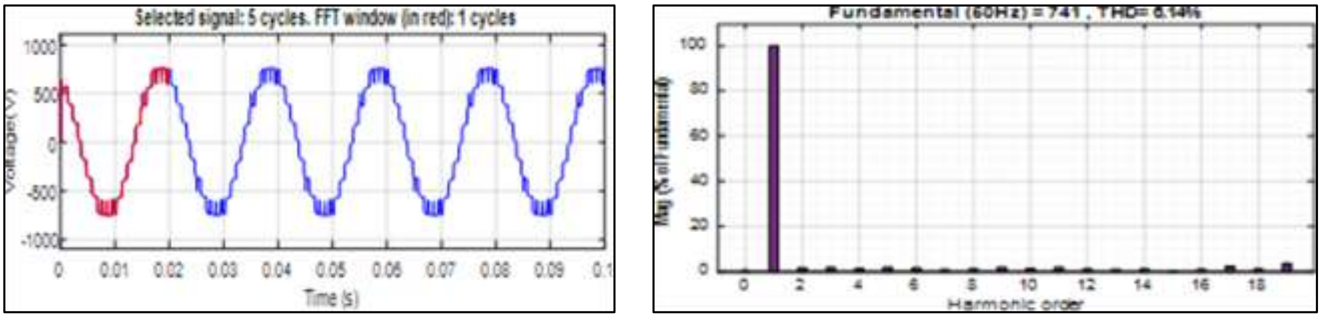

Figure 10 Voltage ($\boldsymbol{V_{ch}}$) across the connection load and Total Harmonic Distortion

6.1.2. Example of the 9-level tolerant inverter model

This time, we apply our new 9-level fault-tolerant inverter model to the Parallel Active Filter as well. The simulation results are reported in Figure 11 to Figure 15.

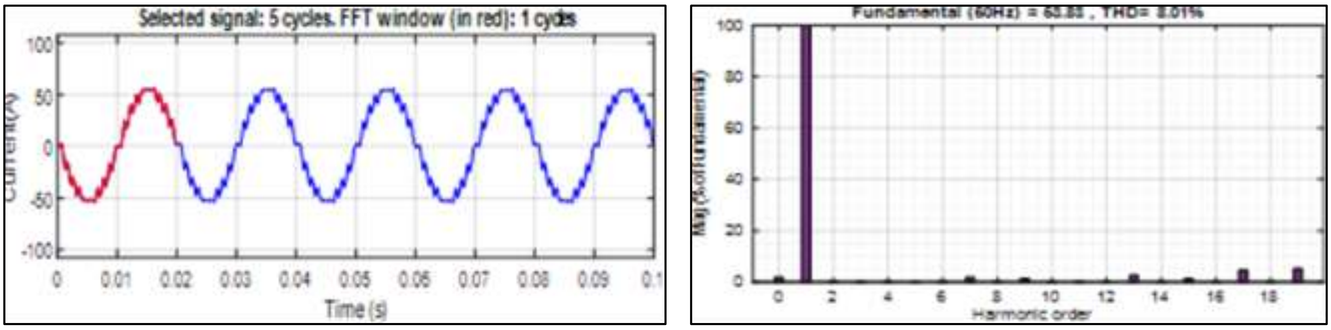

Figure 11 Source current ($\boldsymbol{i_s}$) and Total Harmonic Distortion

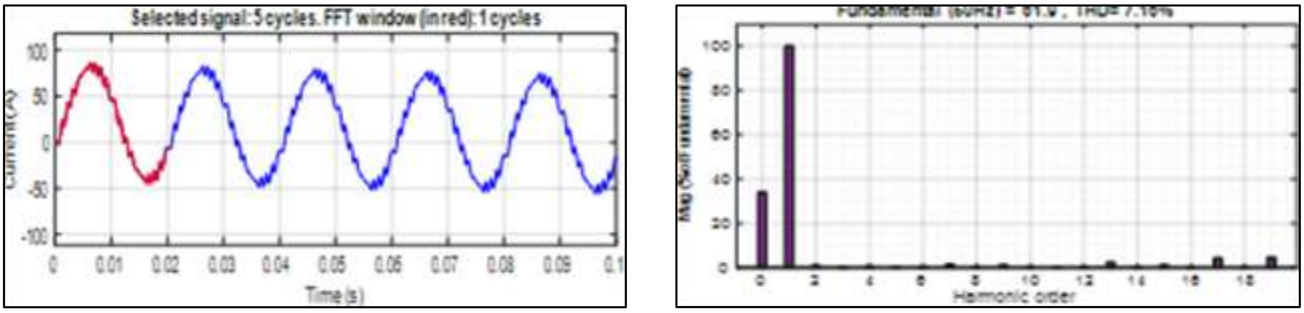

Figure 12 Filter current ($\boldsymbol{i_f}$) and Total Harmonic Distortion

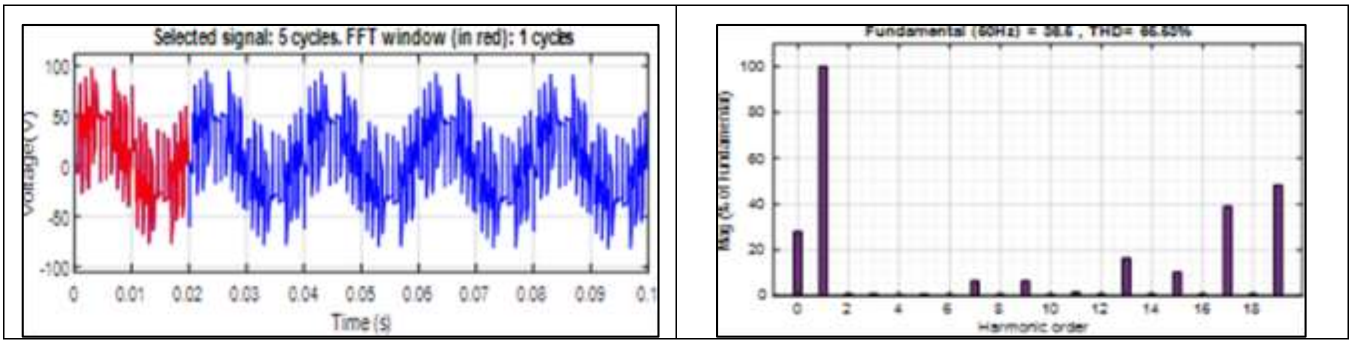

Figure 13 Voltage ($\boldsymbol{V_f}$) across the filter side connection load and Total Harmonic Distortion

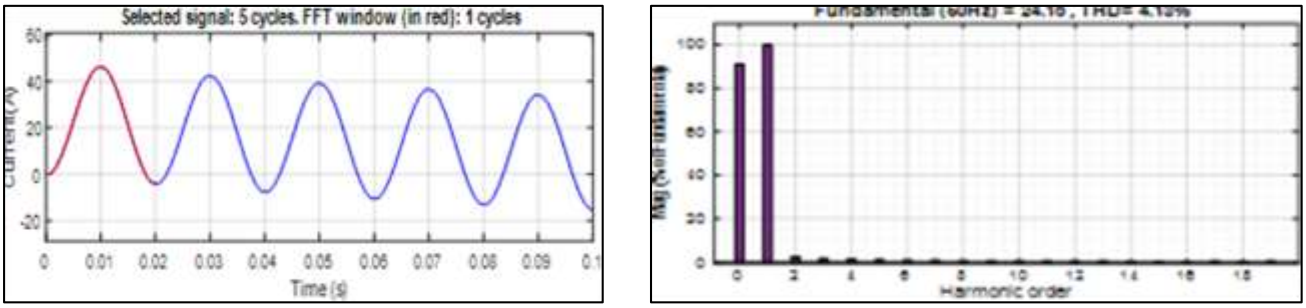

Figure 14 Load current ($\boldsymbol{i_{ch}}$) and Total Harmonic Distortion

Table 3 Summary of the values and Total Harmonic Distortion of source currents ($\boldsymbol{i_s}$), filter ($\boldsymbol{i_f}$) and load ($\boldsymbol{i_{ch}}$)

Switch(es) Kept open	**None**	**K1**	**K2**	**K3**	**K4**	**K1,K3**	**K2,K4**	**K1,K4**	**K2,K3**	**K1,K2**	**K3,K4**	**K1, K2, K3, K4**
$i_s\ (A)$	84.84	80.11	79.66	73.11	74.65	68.41	69.32	69.97	67.93	74.94	62.15	52.30
THD (%)	9.44	12.03	11.78	11.93	11.08	13.23	11.05	14.95	13.64	12.95	16.50	14.62
$i_f\ (A)$	84.09	78.51	79.18	73.79	71.65	68.20	66.48	66.08	69.14	73.58	60.21	49.81
THD (%)	9.60	12.93	12.71	15.26	11.29	14.14	10.51	18.36	18.78	13.51	17.51	15.71
$i_{ch}\ (A)$	23.63	23.43	20.36	15.08	24.18	14.87	21.05	24.13	12.15	20.24	15.67	12.50
THD (%)	1.26	4.56	7.53	28.46	13.37	22.10	10.97	18.05	43.66	3.73	6.57	4.95

Table 4 Summary of the values and Total Harmonic Distortion of source, filter and load currents

Switch(es) Kept open	**None**	**K1**	**K2**	**K3**	**K4**	**K1,K3**	**K2,K4**	**K1,K4**	**K2,K3**	**K1,K2**	**K3,K4**	**K1, K2, K3, K4**
i_{ch} (A)	53.83	53.81	53.81	53.79	53.79	53.77	53.77	53.76	53.77	53.79	53.75	53.71
THD (%)	8.01	8.01	8.01	8.01	8.02	8.01	8.01	8.01	8.01	8.01	8.02	8.01
i_f (A)	61.90	61.89	61.88	61.85	61.88	61.83	61.85	61.86	61.82	61.86	61.82	61.78
THD (%)	7.16	7.16	7.16	7.15	7.16	7.16	7.16	7.17	7.15	7.16	7.16	7.16
i_{ch} (A)	24.16	24.15	24.15	24.15	24.15	24.14	24.14	24.14	24.14	24.15	24.14	24.12
THD (%)	4.13	4.16	4.10	4.07	4.22	4.10	4.19	4.24	4.05	4.13	4.16	4.16

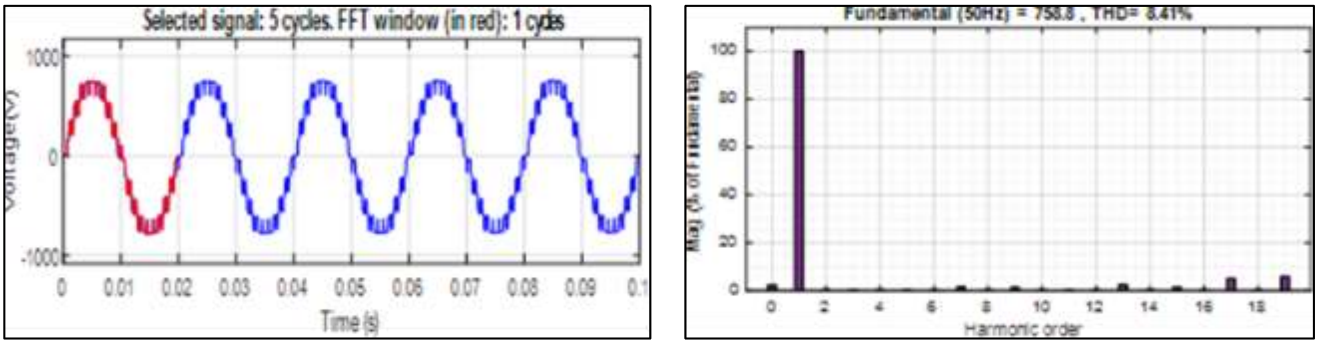

Figure 15 Voltage ($\boldsymbol{V_{ch}}$) across the connection load and Total Harmonic Distortion

6.2. Parallel Active Filtering: operation in degraded mode

Here we create imbalances by introducing breakdowns. We therefore begin by keeping a few power switches open.

6.2.1. Case of the classic 9-level inverter model

For switch K_1 kept open, we have the following results: (Fig. 16 to Fig. 20).

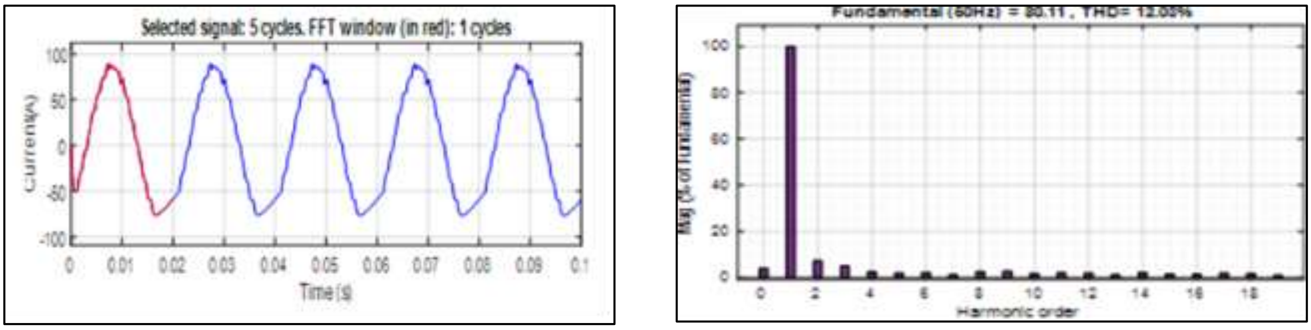

Figure 16 Source current ($\boldsymbol{i_s}$) and Total Harmonic Distortion

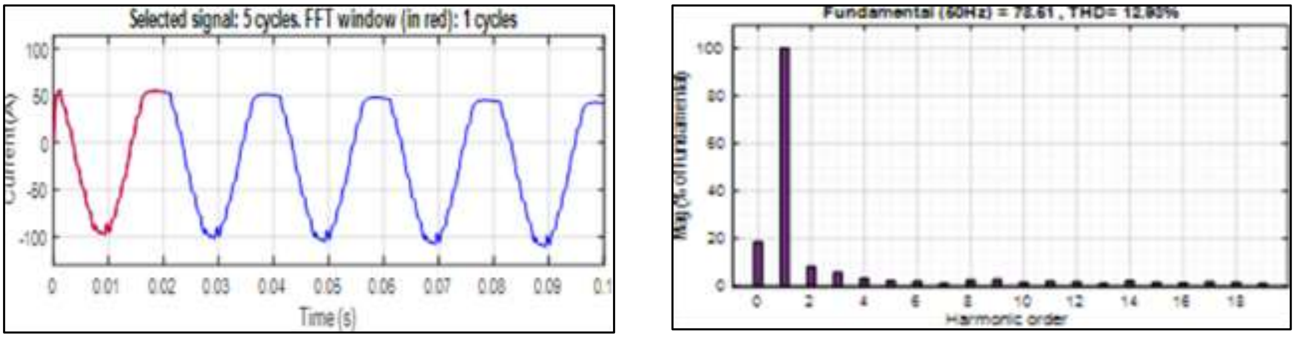

Figure 17 Filter current (i_f) and Total Harmonic Distortion

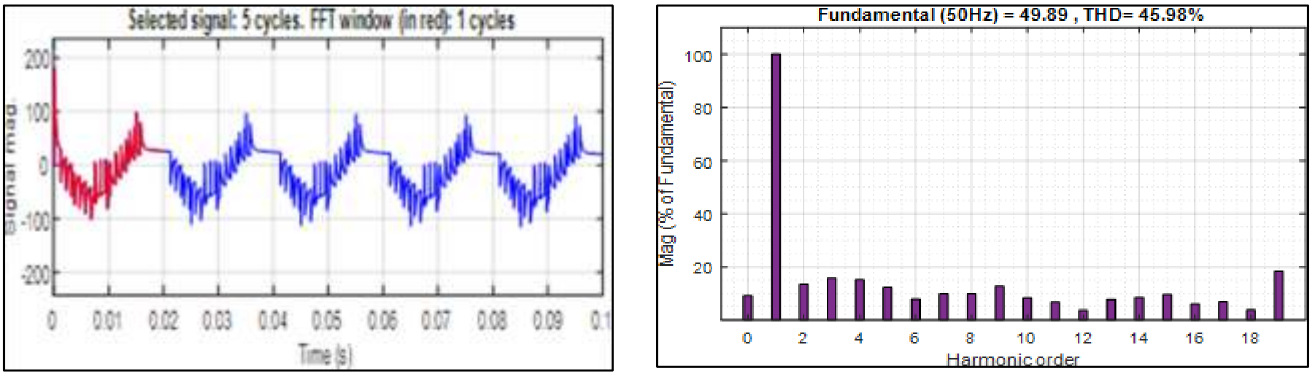

Figure 18 Voltage (V_f) across the filter side connection load and Total Harmonic Distortion

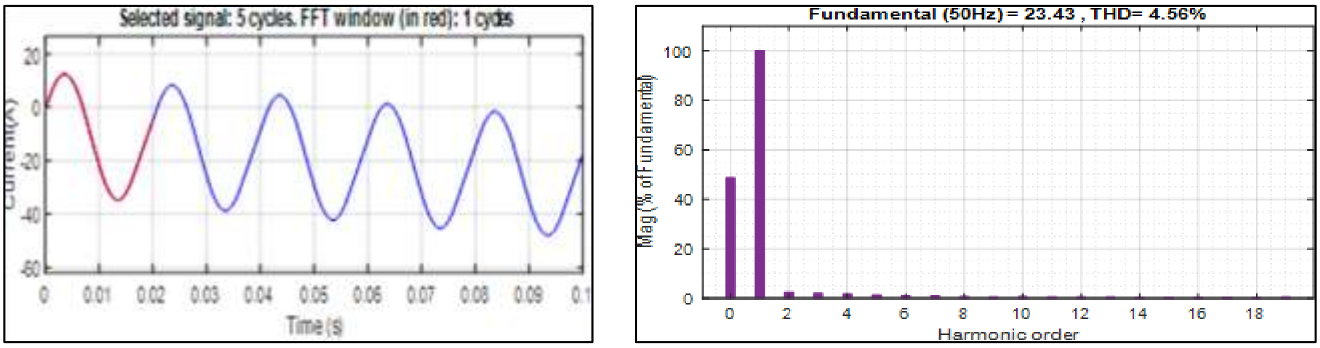

Figure 19 Load current (i_{ch}) and Total Harmonic Distortion

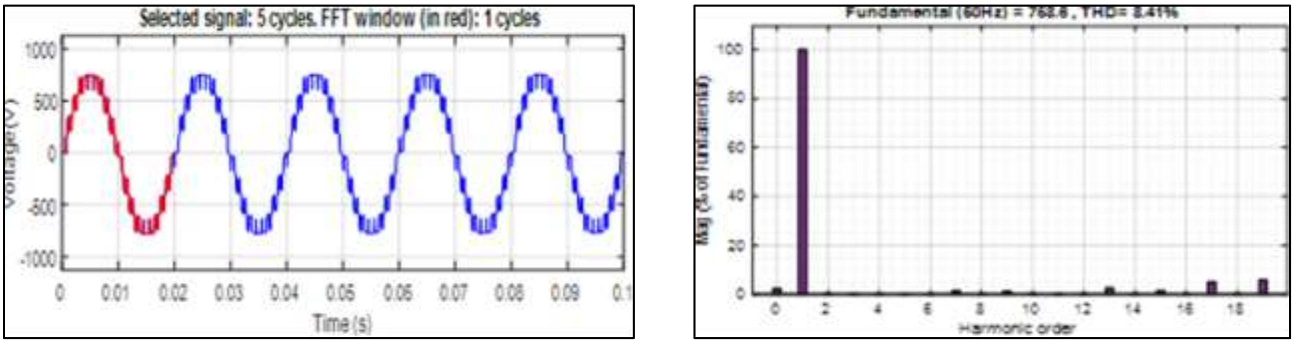

Figure 20 Voltage (V_{ch}) across the connection load and Total Harmonic Distortion

As in the previous case, the same study is carried out on the other power switches of the 1^{st} bridge of the 1st phase, and the results are mentioned in the table 4.

We see that the values of the currents and the Total Harmonic Distortion remain almost unchanged in all cases; which verifies the following hypotheses: “In faulty mode, the fault-tolerant inverter continues to deliver a voltage of value equal to the value in normal operating mode”, “the THD of the filtered current remains unchanged during the tolerance time.”

7. Conclusion

The problem of reliability and availability of electrical energy in static converters, especially in multilevel inverters is one of the major concerns in the field of scientific research in power electronics. In this paper, our study focuses on the fault-tolerant cascaded H-bridge inverter connected to the power grid for parallel active filtering. The results of simulations in MATLAB/SIMULINK have proven that: the tolerant inverter model presented makes it possible to overcome breakdowns linked to power switches.

Subsequently, we first applied the classic 9-level inverter, i.e. 4 complete bridges to the Parallel Active Filter; and the results obtained showed that: the average values of voltages and currents, as well as the Total Harmonic Distortion are reliable indicators for the detection and location of faults since they vary depending on the fault. Secondly, we applied to the same PAF the fault-tolerant inverter model designed at 9 levels and the results obtained also show the effectiveness of the latter in tolerating faults linked to power switches, and even when faults act on several switches simultaneously. In perspective to this work, we recommend powering the proposed inverter model with a photovoltaic generator for good availability of galvanically isolated continuous energy.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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