

# Open Switch Faults Analysis in Voltage Source Inverter using Spectrogram

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**Abstract**—The performance and effects is critical factor in industry, especially usage power inverter such as motor, switching and control circuit. Until now, the statistic of effects still increase in the application. In order to overcome this, the spectrogram technique is used to represent the signals in time frequency representation (TFR). This paper introduces time-frequency distribution (TFD) technique for detecting and identifying the open circuit fault in application of inverter. The condition monitoring is based on time-frequency distribution. Since Fast Fourier Transform (FFT) is one of the techniques to analyze the signal, but it has some limitations in non-stationary signal. From TFR the parameters such as root means square voltage ( $V_{rms}$ ), total waveform distortion (TWD), total harmonic distortion (THD) and total non-harmonics (TnHD) for voltage source inverter (VSI) are used to identify the characteristic of the signals. The result shows that spectrogram technique capable to identify and evaluate the information of voltage source inverter (VSI). The proposed technique is verified as simulation results.

**Index Term**-Voltage Source Inverter; Fast Fourier Transform; Spectrogram

## I. INTRODUCTION

Inverters are widely utilized to drive application of ac motor. Such as in power electronic applications drive motor, air conditioning, uninterruptible power supplies and others. In statistic, about 38% failures that found in the application of power inverter and mostly that come from power switches [1]. Signal condition of voltage source inverter (VSI) and their performance severity can be determined by frequency component of signal current. The time-frequency distribution (TFD) used as a method for several of applications such as power quality because it is appropriate for examining non stationary.

The better electrical apparatus usage in life depends on a design and performance of inverter. If any failure of the system occurs in real application, the main effects to the human life is high cost for maintenance. Regarding this issue, the knowledge and parameter identify about the fault mode behaviour of a inverter a extremely important from the standpoint of improved system design and protection. There could be a quite high chance of failure in the switching devices due to the high electrical [3]. The failure of switching devices can take place in the form of open and short. Therefore, the knowledge and information about the behavior

of inverter is important to improve system design and protection [4].

Several pieces of research use fast Fourier transform (FFT) to analyze the performance of current VSI. But, the FFT not appropriate for non stationary signal. As regards real signals, that consists of harmonics and inter-harmonics components. Meanwhile have several technique used to identify the harmonic and inter-harmonics component and evaluate performance of the signal

. As stated in, advantages of the spectrogram is able to present time-frequency representation and accurate compare using FFT [5]. Smith *et al.* [6] used a technique based on stator current time-domain response. The purpose research to detect intermittent misfiring fault of switched in the inverter. Mohamed Trabelsi *et al.* [7] develop simulation for PWM-Switching pattern either open-circuit fault upper switches and analyze open-circuit fault lower switches. Previous researches familiarize two methods to identify the inverter fault modes. The research is Peugeot *et al.* [8] introduce technique based on analysis of the current vector trajectory and the second technique determines by current vector instantaneous frequency.

This paper presents the performance of the inverter under open circuit power device failures, in voltage source inverter by using simulation. The new approach is achieved by analyzing the switching pattern and the change of the line-to-line voltage levels during the switching times, under both healthy and faulty operating conditions. The spectrogram technique is used to represent the signals in time frequency representation (TFR) to evaluate and present the parameter performance voltage source inverter when open-circuit fault identified. Under these fault conditions time domain and frequency domain analyses are performed to discriminate fault condition.

## II. SWITCHING FUNCTION MODEL FOR VSI

Fig. 1 presents the standard three phase ac drive structure of the VSI. It consists of a classical three-leg inverter. To operate power transistors such as MOSFET, an appropriate gate voltage must be applied in order to drive transistors into the saturation mode for low on-state voltage. The control voltage, which generated by gate drive circuit, should be applied between the gate and source terminal [9].

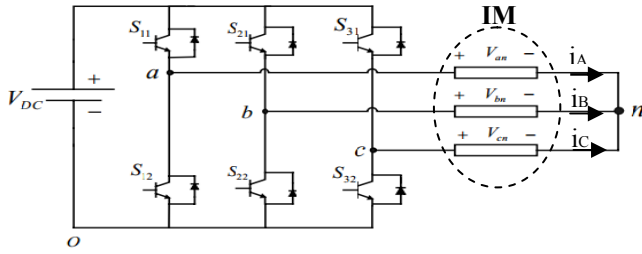


Fig. 1. Standard three-phase ac drive structure

Based on the theory switching function of the voltage source inverter, the relationship between the input and output variables can be obtained. In application inverter, fault occurs in one of the power switches ( $S_{11}$ - $S_{32}$ ), the inverter fault detects the fault occurrence and isolates the faulty leg. If the fault is an open circuit, the isolation is implemented by removing the gate signal from the switches of the faulty leg [10].

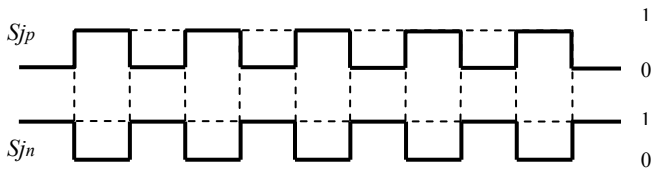


Fig. 2. Gating signals of the inverter in an ideal case

A switching function of the VSI is defined as fig. 2, where  $j$  represents the phase, and variable  $p$  represents the upper and  $n$  represent lower component of the phase. When a three-phase VSI is considered,  $j = \{a, b, c\}$ . The switch  $S_j$  is closed whenever current flow through the IGBT or the anti-parallel diode ( $D_1$ -  $D_6$ ), and otherwise open show the gating signal when in an ideal case. The switching status represent in term of "1" when the switch is closed and "0" when open.

According of the eight switching states as shown in Table 1 two of them produce zero ac line voltage at the output. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states produce no zero ac output line voltages. In order to generate a given voltage waveform, the inverter switches from one state to another. Thus the resulting ac output line voltages consist of discrete values of voltages, which are  $-V_{DC}$ , 0, and  $V_{DC}$ .

 TABLE 1  
 SWITCHING VOLTAGE POSSIBILITIES 3-PHASE VSI

S11	S12	S13	Vab	Vbc	Vca
0	0	0	0	0	0
0	0	1	0	$-V_{DC}$	$V_{DC}$
0	1	0	$-V_{DC}$	$V_{DC}$	0
0	1	1	$-V_{DC}$	0	$-V_{DC}$
1	0	0	$V_{DC}$	0	$-V_{DC}$
1	0	1	$V_{DC}$	$-V_{DC}$	0
1	1	0	0	$V_{DC}$	$-V_{DC}$
1	1	1	0	0	0

### III. DEFINITION OF OPEN-CIRCUIT FAULT

An open-circuit fault in the VSI makes the current in the phase be zero for either the positive or negative half-cycle depending on whether it occur to the upper or lower switch. On the other hand, it was demonstrated here that an open-circuit switch fault will still permit the operation of the motor-drive system, but at a much inferior performance due to the presence of significant torque pulsations. For illustration, consider the one inverter leg a, as they are shown in Fig. 3, which illustrates which semiconductor is conducting, the output phase current and corresponding line-to-line voltage be consider.

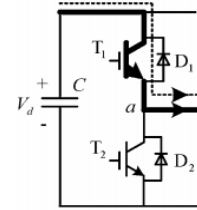
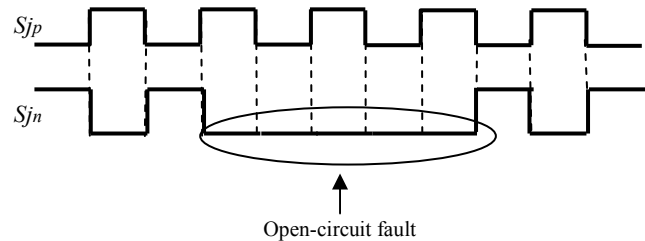


Fig. 3. Gating signals of the inverter in an ideal case

#### A. Open-Circuit Fault of the Lower Switches

The open-circuit fault that considering the switching dead-time and Fig. 4(a) shows the basic configuration of phase  $a$  leg of a three phase PWM VSI. When the system is under the fault condition as can be seen in Fig. 4(a).


 Fig. 4(a) Gating signals of the inverter in an open-circuit fault (*lower*)

The switching gate signal below defined the condition switch voltages under open-circuit fault in lower power switch  $S_{12}$  where  $S_{jp}$  and  $S_{jn}$  represent the upper and lower switching signals of phase  $a$ . In this case, the faults occur and detect at certain time and the back normal operation.

#### B. Open-Circuit Fault of the Upper Switches

Similarly to the open-circuit fault at  $S_{12}$ , the switching voltage at  $S_{jp}$  occurs of the upper switches where  $S_{11}$  open-circuit fault occur. In the case, the upper switching consists delay at certain time then current drop occur at VSI. The normal operation switching, the upper and lower side not similarity, it because only one IGBT function for phase  $a$ .

Fig.4(b) shows the switching gate signal consist delay at certain time. That mean, the switching at the "0" condition until return to normal.

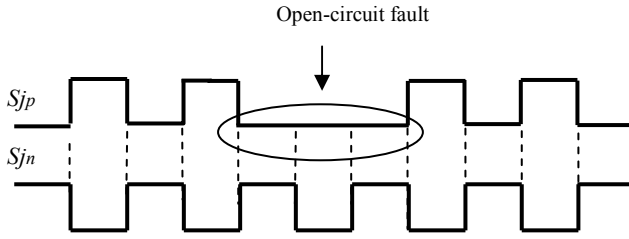


Fig. 4(b) Gating signals of the inverter in an open-circuit fault (upper)

## VI. PERFORMANCE PARAMETER

The performance of parameter in VSI by using time-frequency analysis techniques presents a three-dimensional plot of a signal in terms of the signal energy or magnitude with respect to time and frequency [11].

This study focused on spectrogram to perform time-frequency for evaluate performance of the open-circuit fault VSI signal.

### A. Spectrogram

The spectrogram is the result of calculating the frequency spectrum of windowed frames of a compound signal [9- [10]. The spectrogram time frequency representation is calculated as follows:-

$$S(t, f) = \left| \int_{-\infty}^{\infty} x(\tau) w(\tau - t) e^{-j2\pi f \tau} dt \right|^2 \quad (1)$$

### B. Instantaneous RMS voltage

The instantaneous RMS voltage [17] is :-

$$V_{rms}(t) = \sqrt{\int_0^{f_{max}} S_z(t, f) df} \quad (2)$$

where  $S_z(t, f)$  is the time-frequency distribution and  $f_{max}$  is the maximum frequency of interest.

### C. Instantaneous RMS fundamental voltage

Instantaneous RMS fundamental voltage is defined as the RMS voltage at power system frequency [12]. It can be calculated as

$$V_{1rms}(t) = \sqrt{2 \int_{f_{lo}}^{f_{hi}} S_z(t, f) df} \quad (3)$$

$$f_{hi} = f_1 + \frac{\Delta f}{2}, \quad f_{lo} = f_1 - \frac{\Delta f}{2}$$

where  $f_1$  is the fundamental frequency that corresponds to the power system frequency and  $\Delta f$  is the bandwidth. In this paper, the fundamental frequency that used is 60 Hz.

### D. Instantaneous Total Waveform Distortion

Waveform distortion represents all deviations of the voltage waveform from the ideal sinusoidal waveform in terms of magnitude or frequency the signal [12, 15]. The instantaneous total waveform distortion can be expressed as:-

$$TWD(t) = \frac{\sqrt{V_{rms}(t)^2 - V_{1rms}(t)^2}}{V_{1rms}(t)} \quad (4)$$

where  $V_{1rms}(t)$  is the instantaneous RMS fundamental voltage and  $V_{rms}(t)$  is the instantaneous RMS voltage.

### E. Instantaneous Total Harmonic Distortion

Total harmonic distortion, *THD* is used to measure of how much harmonic content in a signal [13,15]. It and can be defined as

$$THD(t) = \frac{\sqrt{\sum_{h=2}^H V_{h,rms}(t)^2}}{V_{1rms}(t)} \quad (5)$$

where  $V_{h,rms}(t)$  is the RMS harmonic voltage and  $H$  is the highest measured harmonic component.

### F. Instantaneous Total Nonharmonic Distortion

Voltage often contains interharmonic components that are not multiple integer of the power system frequency [14]. It can be written as:-

$$TnHD(t) = \frac{\sqrt{V(t)_{rms}^2 - \sum_{h=0}^H V_{h,rms}(t)^2}}{V_{1rms}(t)} \quad (6)$$

## V. PERFORMANCE EVALUATION RESULT

To evaluate the performance of the proposed method, simulation software has been implemented. The simulations by using an induction motor are completed and the parameters used for the simulation are as follows:  $t_s=50\mu s$ ,  $V=60v$ . The evaluation result as figure below.

A. Analysis Open-Circuit Fault of the Upper Switches

Fig. 5(a) shows the current waveforms three phases VSI consist of normal and fault condition for phase *a* open-circuit fault in the upper power switch. The faults occur at 0.2 to 0.3second. When IGBT switch open fault occurs, the positive current of the phase *a* is rapidly decreased to 0A because the positive voltage is not applied to the terminal. However, negative current flows normally even if the upper switch has

fault. The clearly result shows in Fig. 5(b), where the current negative when fault detection.

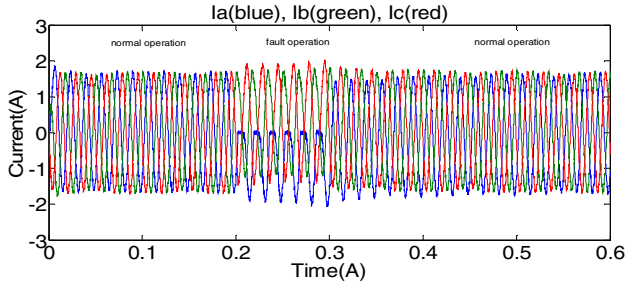


Fig. 5(a) Simulation result for 3phase VSI and fault-detection output when open-circuit fault occur in the upper IGBT

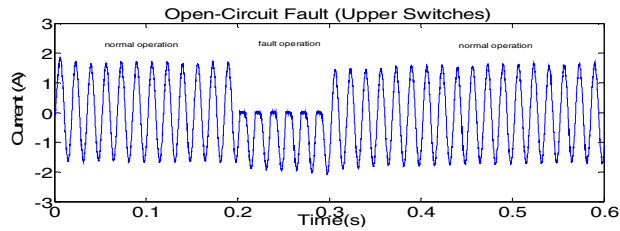


Fig. 5(b) Open-circuit fault condition in phase *a*

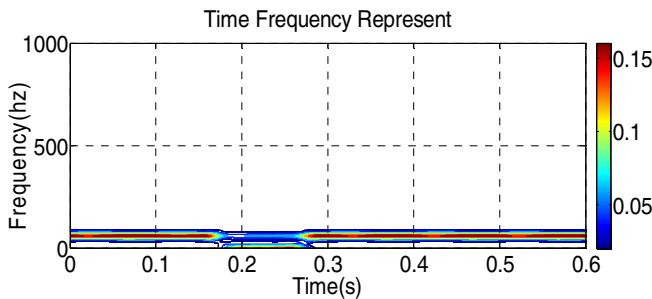


Fig. 6. Time-Frequency Represent of open-circuit fault signal using spectrogram

The open circuit fault current is sinusoidal shape contained the distorted waveform with different amplitude. Fig. 6 shows time and frequency of open circuit fault signal using spectrogram. The signal consists of fundamental frequency 60 Hz and 0 Hz. The highest amplitude represents red color and lowest represent blue color.

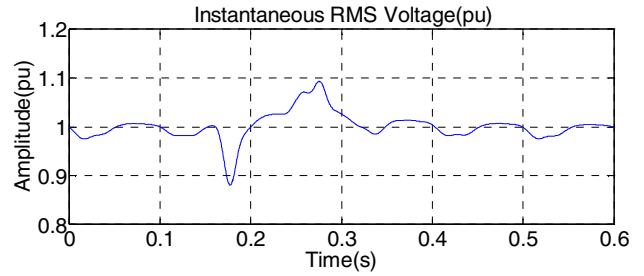


Fig. 7(a) Instantaneous RMS Voltage, Vrms (pu)

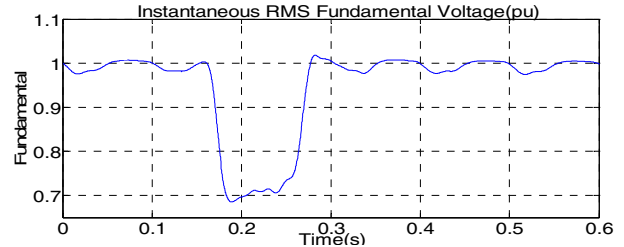


Fig. 7(b) Instantaneous RMS Fundamental Voltage, Vrms(pu)

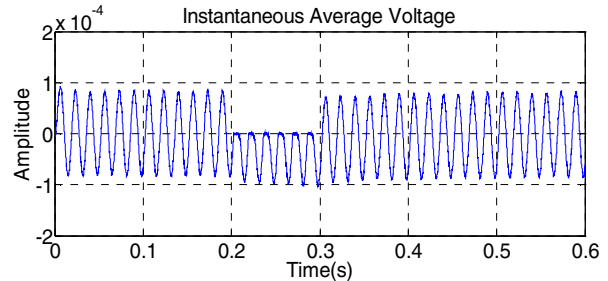


Fig. 7(c) Instantaneous Average Voltage

Fig. 7(a) shows the RMS voltage decrease starting at 0.15 to 0.2 second and increase at 0.2 to 0.3 second. The fig. 7(c) shows the average voltage for open-circuit fault in the upper inverter.

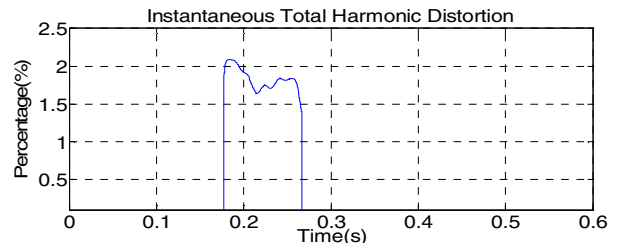


Fig. 8(a) Instantaneous total harmonic distortion

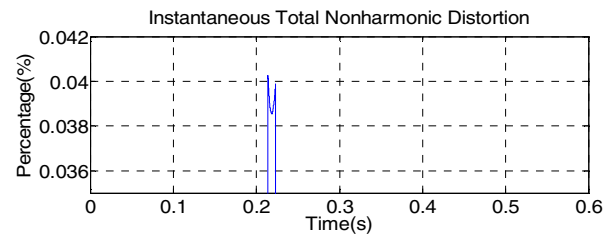


Fig. 8(b) Instantaneous total non harmonic distortion

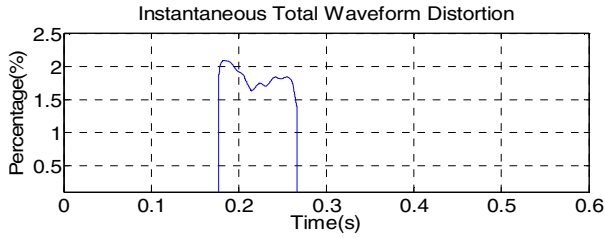


Fig. 8(c) Instantaneous total waveform distortion

Fig.8(a)-(c) shows the parameter estimation from TFR which is THD, TnHD, and TWD. Fig.8a show THD occurs in this signal starting at 0.18 until 0.28second. The TnHD also occur in this signal as per Fig. 8(b).It means this signal consist of multiple integer and non multiple integer frequency. The value of TWD is obtained from the total of THD and TnHD.

*B. Analysis Open-Circuit Fault of the Lower Switches*

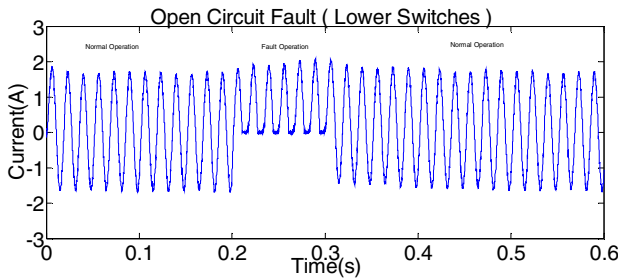


Fig. 9 Open-circuit fault condition in phase a

Similarly, simulation result for S12 open-circuit fault is shown in Fig. 9 and the current is nonnegative. When an open-circuit occurs at 0.2second, current of phase a can be positive, it indicates open-circuit fault lower occurs. The faults detections for the current signal starting with 0.2 to 0.3second.

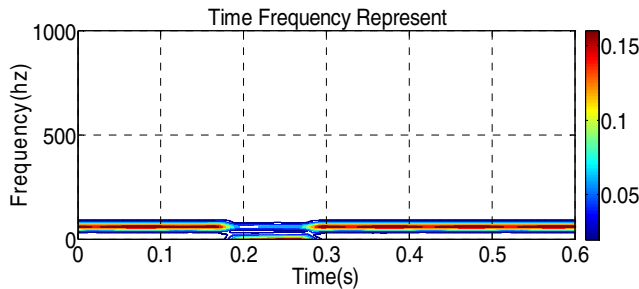


Fig. 10 Time-Frequency Represent of open-circuit fault signal using spectrogram

Fig.10 shows the time-frequency distribution used to analyze the performance of the signal. The TFR shows by using spectrogram where the open-circuit fault signal lower switches consist which is 60 Hz and 0 Hz. The result time-frequency represents in red color for highest amplitude and lowest is represent in blue color. The figure also shows the fault occurs at 0.18 to 0.3second at 0 Hz .This technique is used to analyze the performance of the signal after fault occurs.

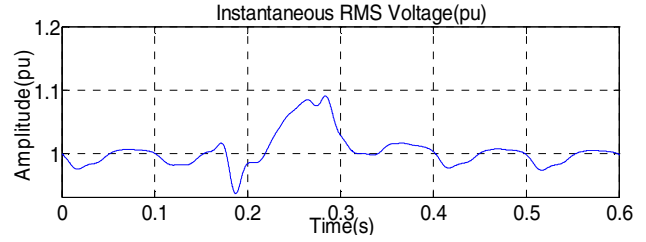


Fig. 11(a) Instantaneous RMS Voltage, Vrms (pu)

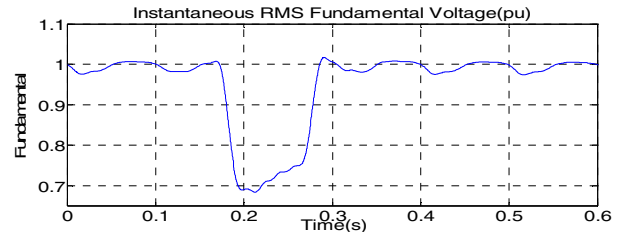


Fig. 11(b) Instantaneous RMS Fundamental Voltage, Vrms (pu)

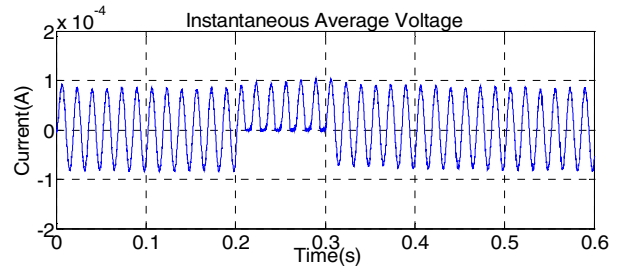


Fig. 11(c) Instantaneous Average Voltage

Fig. 11(a) shows the RMS voltage decrease starting at 0.15 until 0.3second. After 0.3 second voltage operate in normal condition and fig. 11(c) present the average voltage when fault occur at the lower IGBT.

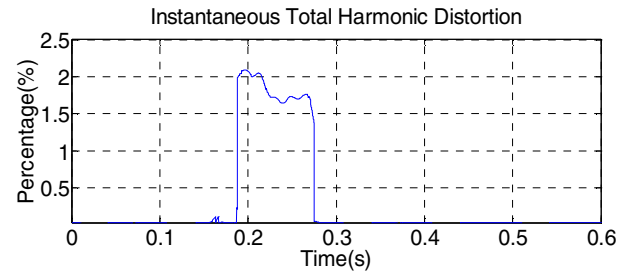


Fig. 12(a) Instantaneous total harmonic distortion

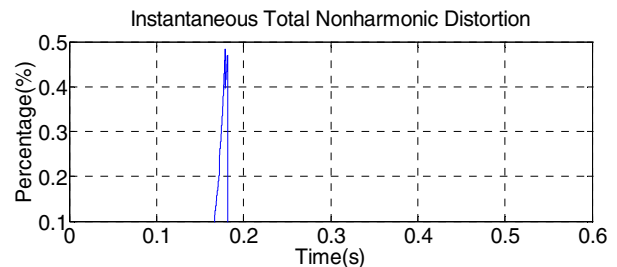


Fig. 12(b) Instantaneous total non-harmonic distortion

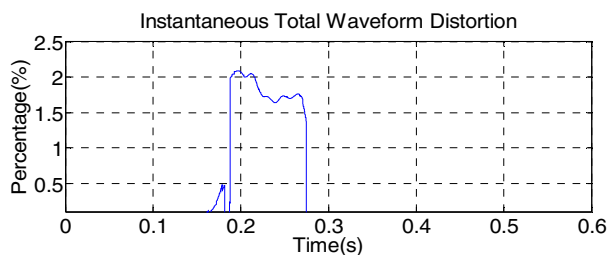


Fig. 12(c) Instantaneous total waveform distortion

Fig. 12(a) - (c) shows the parameter estimation from TFR which is total harmonic distortion (THD), total non harmonics distortion (TnHD), and total waveform distortion (TWD). Fig.12(c) show THD two distortion occurs in this signal at 0.5% and 2% compare with open circuit fault upper. That consist one distortion. The result of TWD is obtained from the total of THD and TnHD. The TnHD occur in this signal as per Fig. 12(b).It means this signal consist of multiple integer and non-multiple integer frequency.

TABLE 2  
COMPARISON PERFORMANCES OF PARAMETER BETWEEN FAULT CIRCUIT UPPER & FAULT CIRCUIT LOWER

Parameter measures	Normal operation	Upper fault	Lower fault
Vrms(pu)	1.0075	1.0939	1.0918
Vaverage	-61.878 $\mu$	-61.964 $\mu$	-62.096 $\mu$
THD	0.0354	2.0916	2.0902
TnHD	0.0312	0.0403	0.4839
TWD	0.0415	2.0916	2.0903

The performance of normal operation, upper fault and lower fault operation are shown in Table 2. The results show that the comparison maximum values of parameter measures in term of RMS voltage, average voltage, THD, TnHD and TWD.

## VI. CONCLUSION

As a conclusion, this paper has showed the estimated parameter such as Vrms, THD, TnHD and TWD to identify performance of open-circuit fault detection of VSI. The results are extremely important for monitoring and analysis fault condition and simulation for the open fault of switches in VSI. That also can be classified the upper and lower switches fault in open-circuit switches. The spectrogram technique has advantage of the VSI for gives the better information in term of time and frequency component. Therefore, faults can be detected early through information of performance. Moreover, the presented technique can be easily to reduce the cost maintenance.

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