

## Open and Short Circuit Switches Fault Detection of Voltage Source Inverter Using Spectrogram

N. S. Ahmad \*, A. R. Abdullah\*\* and N. Bahari \*\*\*

**Abstract** –In the last years, fault problem in power electronics has been more and more investigated both from theoretical and practical point of view. The fault problem can cause equipment failure, data and economical losses. And the analyze system require to ensure fault problem and also rectify failures. The current errors on these faults are applied for identified type of faults. This paper presents technique to detection and identification faults in three-phase voltage source inverter (VSI) by using time-frequency distribution (TFD). TFD capable represent time frequency representation (TFR) in temporal and spectral information. Based on TFR, signal parameters are calculated such as instantaneous average current, instantaneous root mean square current, instantaneous fundamental root mean square current and, instantaneous total current waveform distortion. From on results, the detection of VSI faults could be determined based on characteristic of parameter estimation. And also concluded that the fault detection is capable of identifying the type of inverter fault and can reduce cost maintenance.

**Keywords:** Voltage Source Inverter (VSI), Spectrogram, Time-Frequency Distribution (TFD), Fast Fourier Transform (FFT), Open-circuit fault, Short-circuit fault.

### 1. Introduction

In general of industrial drives and its applications, voltage source inverter (VSI) is commonly used in wide variety, including a number of critical application in which very high levels of reliability are required because of loss at VSI operation can have serious consequences. Cause of VSI faults, the effect of motor drive will stop drive running or at least it affects the drive performances. For example, in conveyor applications the drives motor has collapsed due to VSI failure. As mentioned [1], the VSI faults have several fault can appear as open-circuit faults, short-circuit faults, and intermittent gate-misfiring faults. However, a VSI fault has certain limitations such as difficulty in detecting type of faults.

The recent research shows that the fault occurred in the power electronic are about 82.5 percent of faults occur in the VSI motor drives by Ricardo *et al.* [2, 3]. Also has been estimated by Diqi Zhu *et al.* and Shenlin *et al.* [2, 3] about 38 percent the fault in inverter driven industrial induction motors are due to malfunctioning of power

devices in the drive module. Then a survey was done by Thorsen and Dalva on the reliability of VSI for industrial drives. According to results of their survey, 50 percent of all failures are in the control circuit, 7.7 percent in the cooling fans, and 37.9 percent are in the power circuits. So from recent research and survey, faults in power electronics are large percentage of the VSI faults [4]. Due VSI faults is higher issues, analyze of faults is important in industrial drives, thus fault can identified early.

Different methods and analytical techniques were used to detection and identification the VSI faults. As an example, B. Raison *et al* [2] used Fast Fourier Transform (FFT) to analyzed current spectrum for detecting the characteristics of an open transistor [2, 5]. L. Zhang *et al.* [6] used time domain for analyze fault modes with characterized the patterns of the current waveform While F. Charfi *et al.*[7] examined information about the fault signatures for detection and classification fault using wavelet transform. But each technique has limitations and disadvantages for analyze the performance. For the FFT technique is does not appropriate for non-stationary signal and not provide temporal information [8].

Due to VSI faults signal in non-stationary pattern, this paper present time frequency distribution (TFD) which is spectrogram for analyze VSI faults. Spectrogram technique capable to represent parameter estimated in time frequency

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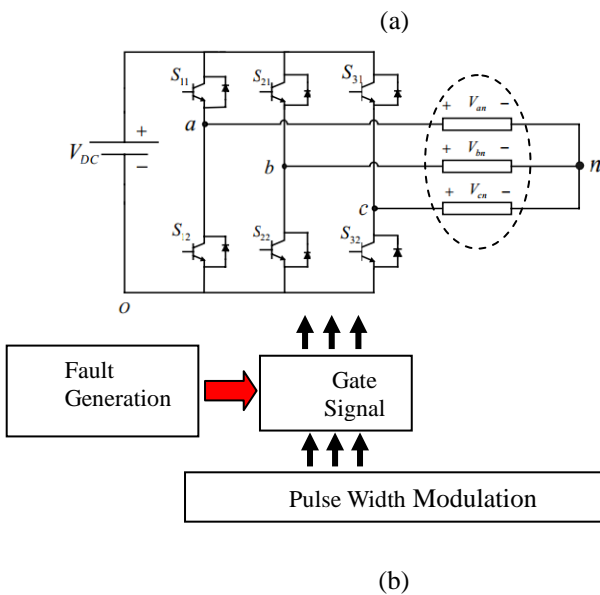
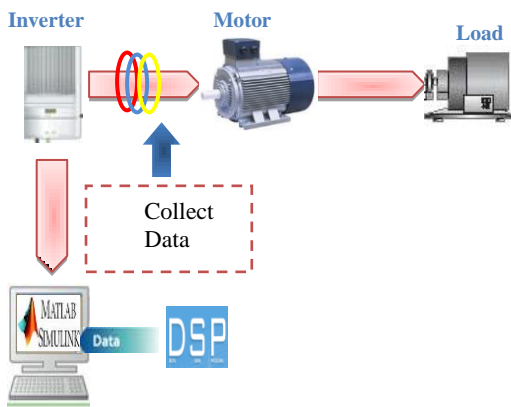
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representation (TFR). Based on TFR, parameters of VSI current signal are estimated and used to identify open and short circuit switches fault based on current pattern then characteristic of VSI are calculated.

### 2. Voltage Source Inverter System

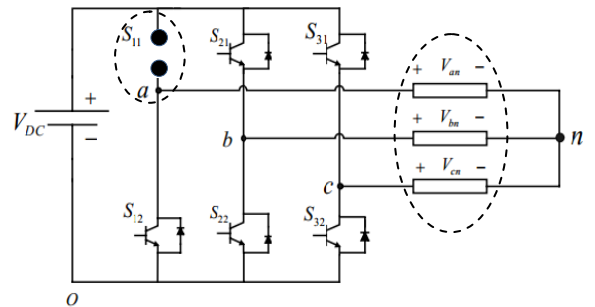
Voltage source inverter (VSI) is an electronic device which convert direct current (DC) to Alternating current (AC). VSI has advantages like higher efficiencies, minimizing installation timing, elimination interconnect power cabling costs and reducing building floor space. Fig.1 (a) shows the diagram of general system for this research and Fig.1 (b) shows the modeling of three-phase VSI with the fault generation. In the model  $S_{11}$  to  $S_{32}$  are Insulated Gate Bipolar Transistors (IGBTs) which can be on or off pulse width modulation (PWM) is a common technique for controlling the switches.



**Fig. 1.** (a) Diagram general of system  
(b) The model of Voltage Source Inverter (VSI)

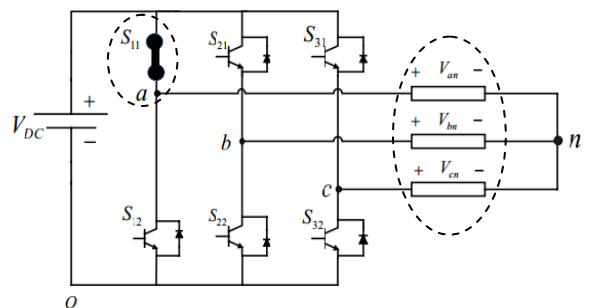
Commonly, intersective method is simplest way to generate a PWM signal, which requires a triangle waveform and a comparator. When the value of the references signal is more than the modulation waveform, the PWM signal is in the high state, otherwise it is in low state. Besides that, the module of fault generation that used for give pulse at switching gate signal means give disturbance at gate signal

The switches fault VSI for open circuit fault condition, IGBT falls in the off state and remains in this situation regardless of the gate voltage value. Open circuit fault generally do not cause system shutdown, but degrade its performance. Fig. 2 show the model of circuit when VSI switches open circuit fault.



**Fig. 2.** The model of Voltage Source Inverter when Switches Open Circuit Fault

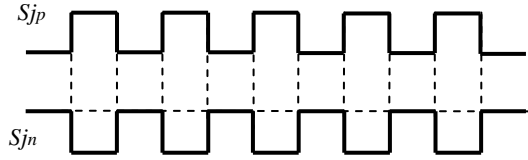
The short-circuit fault where this faults leads to catastrophic failure of the inverter if the other transistor of the same inverter leg is turned-on, this resulting in a direct short-circuit as show Fig.3



**Fig. 3.** The model of Voltage Source Inverter when Switches Short Circuit Fault

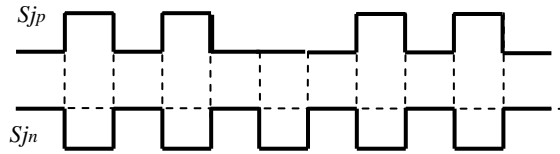
Based on modeling of three-phase VSI with the fault generation, the transistors are  $S_{11} - S_{32}$  and the output stage is considered as a general R load. To control this VSI it was used the pulse width modulation (PWM) as switching to control the transistor. A switching function of the VSI is defined as Fig. 4, where  $j$  represents the phase, and variable  $p$  and  $n$ , respectively, represent the upper and lower

component of the phase leg. The switching status represent in term of “1” when the switch is closed and “0” when open. The cause of fault in VSI for this paper depends on pulse width modulation (PWM). Such the fault is open circuit fault upper, open circuit fault lower, short circuit fault upper and short circuit fault lower [9-11].

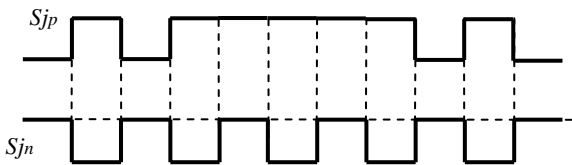


**Fig. 4.** Gating signals of the inverter in an ideal case

The gate switching fault is one of cause open circuit and short circuit VSI. Based on Fig.5 and 6, gate pulse switching is one of causes fault VSI. Open circuit fault causes by gate pulse switching “0” then short circuit fault causes by gate pulse switching “1”.



**Fig. 5.** Gating signals of the inverter in an open-circuit fault



**Fig. 6.** Gating signals of the inverter in short-circuit fault

### 3. Result Time-Frequency Distribution

Spectrogram is one of the time-frequency representations (TFR) that represents a three-dimensional of the signal energy with respect to time and frequency. Time-frequency representations are used to analyze or characterize signals whose energy distribution varies in time and frequency. They map the one-dimensional time-domain signal into a two-dimensional function of time and frequency [12-14]. A time-frequency representation presents the variation of spectral energy over time [8-10]. In this paper, time-frequency analysis technique which is spectrogram is used to analyze the faults signal. Spectrogram is the squared magnitude of the Short Time

Fourier Transform (STFT) and can be expressed as below. Where  $h(t)$  is the input signal while  $w(t)$  is the window function. This technique depends on window size since it results better time resolution and lower frequency resolution by using smaller window size and vice versa[12, 13, 15, 16].

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

## 4. Parameter Estimation

Parameters of the faults signal are estimated from the TFR to identify the characteristics of VSI faults.

### 4.1 Instantaneous Average Current

$$I_{rms,ave} = \frac{1}{T} \int_0^T I_{rms}(t) dt \quad (2)$$

### 4.2 Instantaneous Root Mean Square [17]

The equation below from,  $S_x(t, f)$  is the distribution and  $f_{max}$  is the maximum frequency of interest.

$$I_{rms}(t) = \sqrt{\int_0^{f_{max}} S_x(t, f) df} \quad (3)$$

### 4.3 Instantaneous RMS Fundamental Current

The instantaneous RMS fundamental current is as the RMS current at power system frequency [12, 15, 18] can be calculated as

$$I_{1rms}(t) = \sqrt{2 \int_{f_{lo}}^{f_{hi}} S_x(t, f) df} \quad (4)$$

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

### 4.4 Instantaneous Total Waveform Distortion

The total waveform distortion consists of harmonic and non-harmonic distortion. The TWD can be defined

$$TWD(t) = \frac{\sqrt{V_{rms}(t)^2 - V_{1rms}(t)^2}}{V_{1rms}(t)} \quad (5)$$

**4.4 Instantaneous Total Harmonic Distortion**

THD is commonly used to measure harmonic distortion in signal. Harmonics have frequency that are integer multiples of the waveform’s fundamental frequency [18]Such as, given a fundamental frequency 60 Hz, the harmonics component will be 120 Hz, 180 Hz and 240 Hz.

$$THD(t) = \frac{\sqrt{\sum_{h=2}^H V_{h,rms}(t)^2}}{V_{1,rms}(t)} \tag{6}$$

**4.4 Instantaneous Total Non-Harmonic**

Total non-harmonic represents total non-harmonic distortion. Non-harmonic refer are signal not integers multiples of the fundamental frequency [1212, 14, 19]. For example, the fundamental frequency given 60 Hz, the interharmonic will be 70 Hz, 85 Hz.

$$TnHD(t) = \frac{\sqrt{V(t)_{rms}^2 - \sum_{h=0}^H V_{h,rms}(t)^2}}{V_{1,rms}(t)} \tag{7}$$

**5. Results**

The results of analysis the VSI switches open and short fault are represented from Fig. 7 to Fig. 14. That signal consists of three-phase which is phase A, phase B and phase C. The red color represent phase A, green color represent phase B and blue color represent phase C.

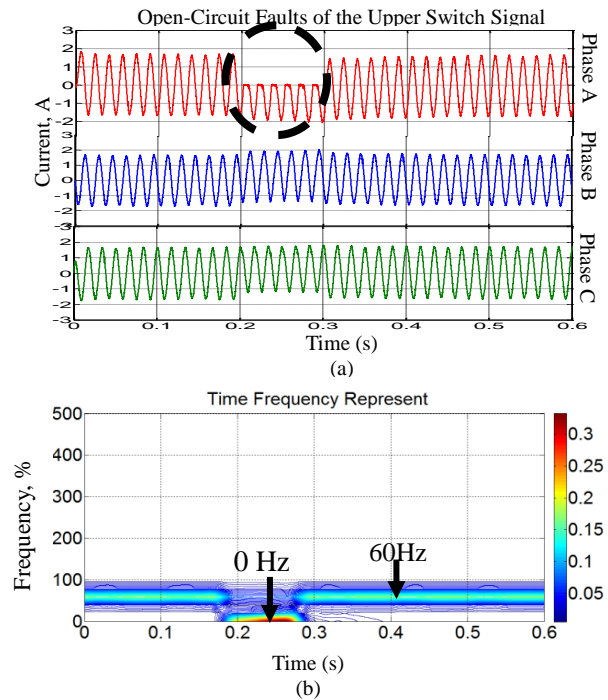
Based on the shown Table 1, that considers dc supply, carrier frequency (Hz), IGBT and fundamental frequency (Hz). From simulation, the result of open-circuit and short-circuit faults for upper and lower switches has been analyze and calculate all characteristic of parameter

**Table 1.** Voltage source inverter specifications

Parameter, unit	Value
DC supply, V	50
Carrier frequency, Hz	5kHz
Snubber resistance	1 x 10 <sup>5</sup>
Internal resistance	1 x 10 <sup>6</sup>
Fundamental frequency	60Hz

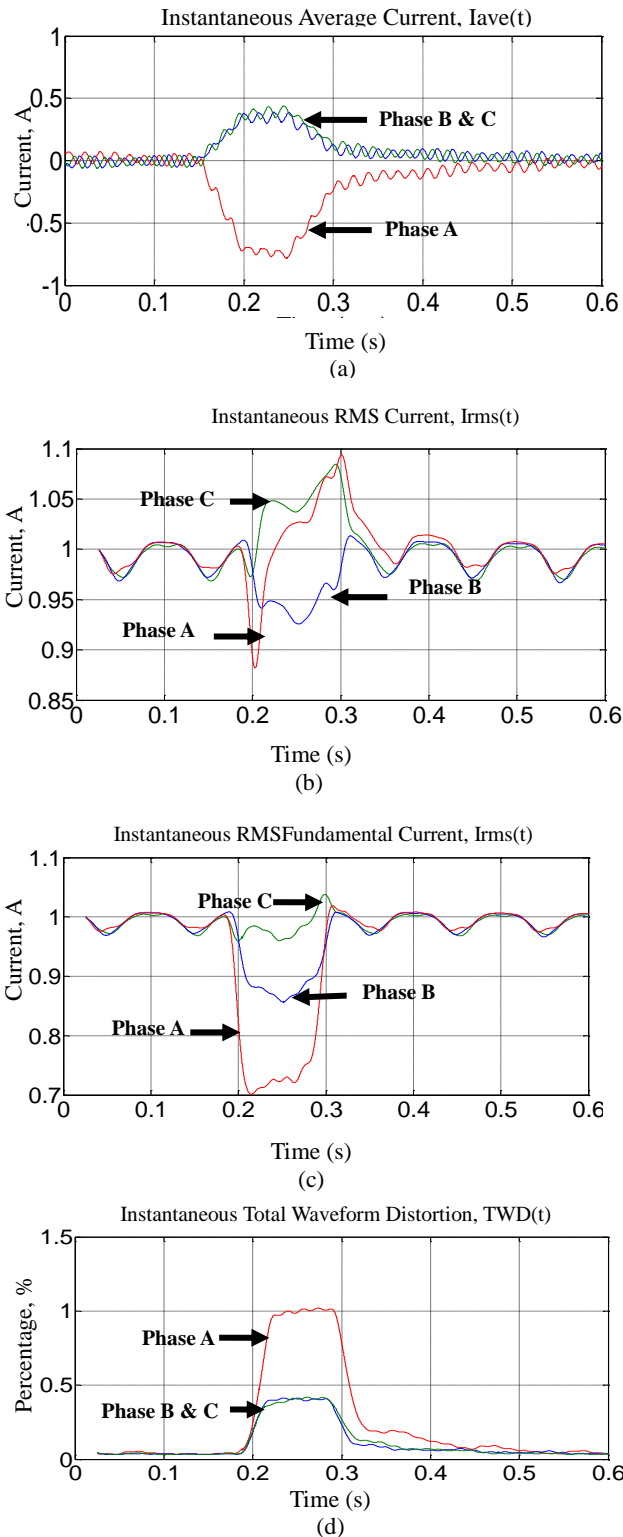
**5.1 Open Circuit Switches Fault in VSI (Upper Fault)**

The fault analysis done by using spectrogram technique, we can see observe from Fig.7 (a) for the fault in phase A there is discontinuity in the signal and the severity of the fault can be clearly understood by spectrogram analysis. According on signal, fault current occur at 0.2 – 0.3 s where current at phase A lower compare phase B and C. From the TFR that display time, frequency and amplitude on the same graph and as can be seen two frequency detected. Fig. 7(b) the higher power of signal in the contour plot is represented in red color, while the lowest in blue color. Based on result, TFR shows the 60 Hz for fundamental frequency and frequency of VSI fault at DC component is 0 Hz



**Fig.7.** (a) Signal of Open-Circuit Fault Upper (b) Spectrogram open-circuit fault upper

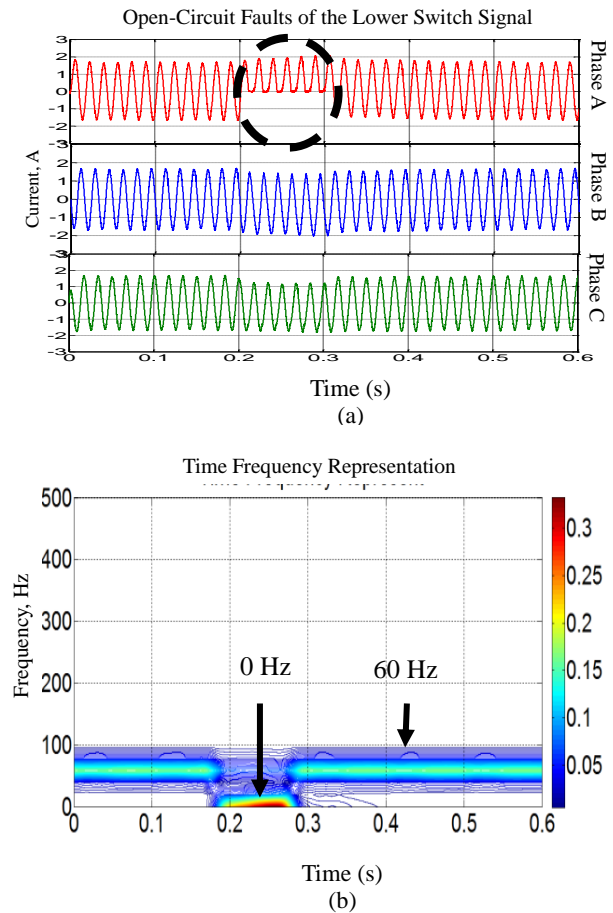
From the TFR, the parameters are estimated for all phase in per unit (pu). For Fig. 8(a), the instantaneous average current phase A is greater while phase B and C, respectively is lower than zero between 0.2 and 0.3 s. From the observed on Fig. 8(b), the RMS value of magnitude of the phase A momentary decrease at 0.2 – 0.3 s compare with phase B and C. The RMS fundamental value for phase A is lower but phase B and C is higher show as Fig. 8(c). Lastly, the value of THD is 1 percent for phase A but phase B and C is below than 0.5 percent shown in Fig.8(d) respectively.



**Fig.8.** Parameter Estimation for open-circuit fault upper  
 (a) Instantaneous Average Current,  $I_{ave}(t)$   
 (b) Instantaneous RMS Current,  $I_{rms}(t)$   
 (c) Instantaneous RMS Fundamental Current,  $I_{rms}(t)$   
 (d) Instantaneous Total Waveform Distortion,  $TWD(t)$

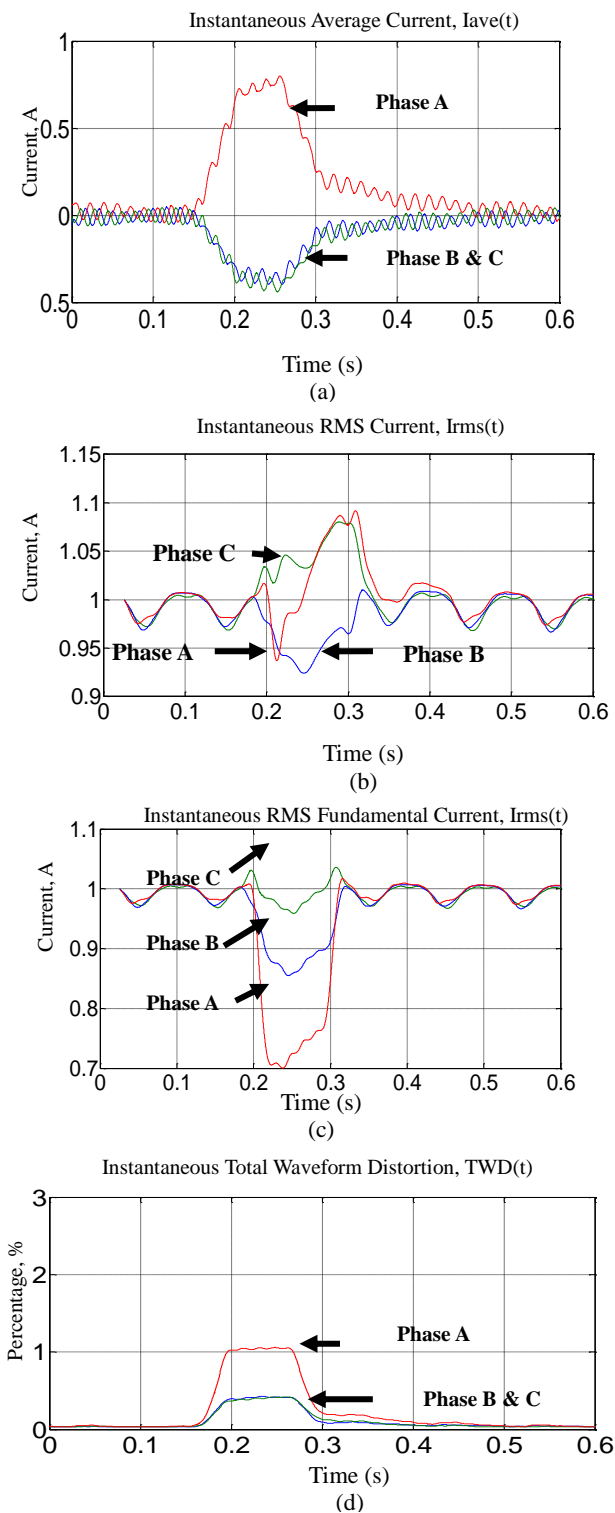
**5.2 Open Circuit Switches Fault in VSI (Lower Fault)**

Fig. 9(a) shows the three-phase VSI for fault at lower switches. We can see, observation from the open-circuit fault lower signal where current phase A higher than phase B and C. The current phase A increase starting from 0.2 – 0.3 s but phase B and C respectively.



**Fig. 9.** (a) Signal of Open-Circuit Fault Lower  
 (b) Spectrogram Open-Circuit Fault Lower

Based on result, the contour of TFR detect 60 Hz for fundamental frequency and fault current at DC component (0 Hz) at phase A. Based on TFR, the instantaneous average current, instantaneous RMS current, instantaneous RMS fundamental are estimated as shown in Fig. 10(a) – (d). Fig. 10(a) show the average current for phase A is higher while phase B and C is lower. The current is higher at phase A when RMS value result compares than phase B and C. Besides that, the RMS fundamental value is lower compare at phase A and higher current at phase B and C, respectively. From all parameter, the percentage of THD for the open circuit at lower fault is higher than 1 percent while both of phase B and C is lower 1 percent

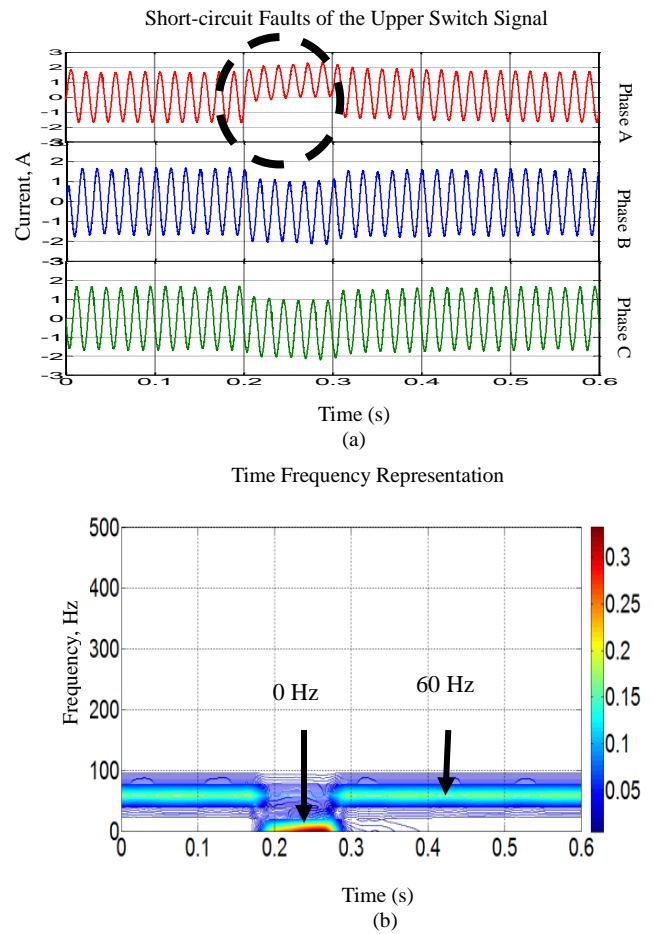


**Fig.10.** Parameter Estimation for open-circuit fault upper

- (a) Instantaneous Average Current,  $I_{ave}(t)$
- (b) Instantaneous RMS Current,  $I_{rms}(t)$
- (c) Instantaneous RMS Fundamental Current,  $I_{rms}(t)$
- (d) Instantaneous Total Waveform Distortion,  $TWD(t)$

**5.3 Short Circuit Switches Fault in VSI (Upper Fault)**

Fig. 11(a) shows signal short circuit switches fault where three-phase current indicate the fault also occur at phase A where current signal is increase at 0.2 – 0.3 s. At current signal at phase B and C is decrease when fault occur. Based on Fig. 11(b), the TFR detect two frequency at faults signal, where fundamental and fault frequency. From the contour, the spectrogram is show three-axis where the detect fault at DC component is 0 Hz and 60 Hz for fundamental frequency.

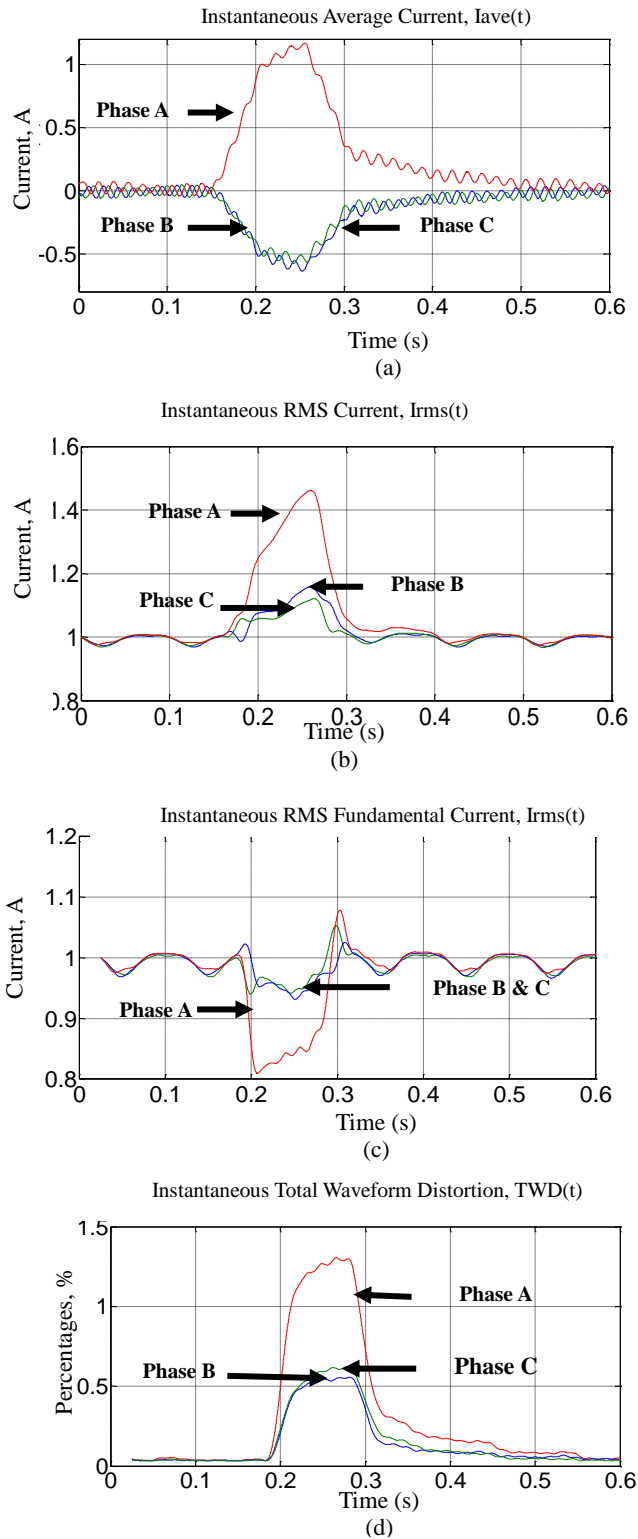


**Fig.11.** (a) Signal of Short-Circuit Fault Upper  
(b) Spectrogram Short-Circuit Fault Upper

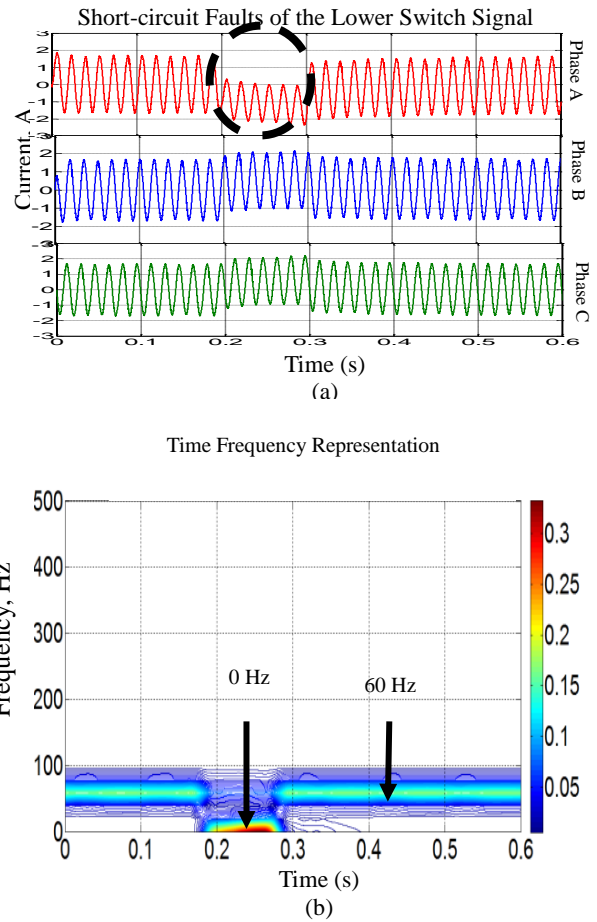
Fig. 12 (a) shows the average current, phase A is higher compare phase B and C at 0.2 – 0.3 s. During the RMS current, the phase A is phase faults occur where the value of current is higher compare with phase B and C as shows Fig. 12(b). According Fig.12 (c), the RMS fundamental for phase A is momentary decrease but other phase is higher than phase fault occurring. While, value of TWD gives 1.4 percent and phase B and C is below than 1 percent as show Fig. 12 (d).

5.4 Short Circuit Switches Fault in VSI (Lower Fault)

Fig. 13(a) shows the signal short-circuit faults of the lower switch where switch at phase A fault at 0.2-0.3s. The current momentarily decrease and for phase B and C have certain distortion. According TFR shows harmonics and interharmonics that occurred as represented Fig. 13(b). As previous results, faults occurred at dc component and at 60 Hz.



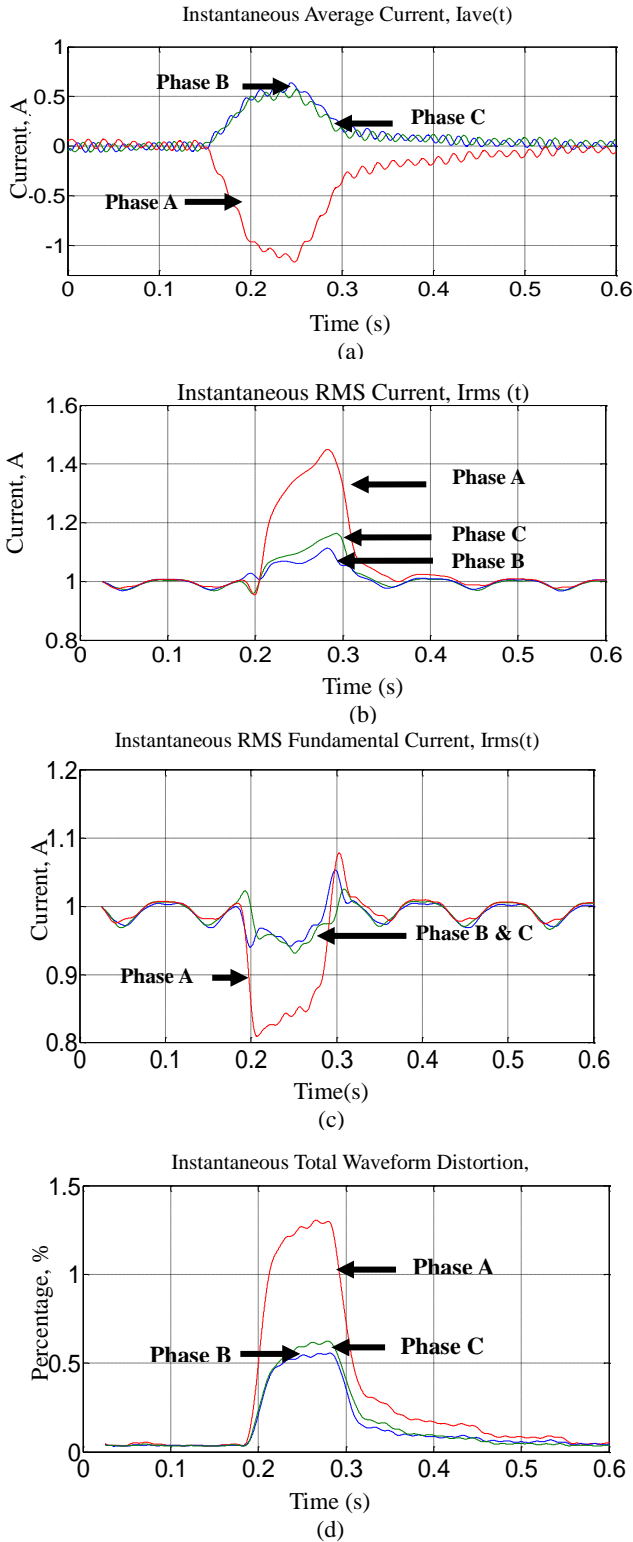
**Fig.12.** Parameter Estimation for short-circuit fault Upper  
 (a) Instantaneous Average Current,  $I_{ave}(t)$   
 (b) Instantaneous RMS Current,  $I_{rms}(t)$   
 (c) Instantaneous RMS Fundamental Current,  $I_{rms}(t)$   
 (d) Instantaneous Total Waveform Distortion, TWD(t)



**Fig.13.** (a) Signal of Short-Circuit Fault Lower (b) Spectrogram Short-Circuit Fault Lower

The parameter that estimated from TFR with the instantaneous average current for phase A is lower than phase B and C as shows Fig. 14(a). But for the RMS current value, phase A is higher while phase B and C is lower, respectively as Fig. 14(b). For the instantaneous RMS fundamental current in Fig. 14(c), phase A is lower than phase B and C. Besides that, instantaneous waveform distortion as shows in Fig. 10(d), where faults signal occur at DC component, there TWD gives 1.42 percent but phase B and C is below then 1 percent.





**Fig. 14.** Parameter Estimation for short-circuit fault lower

- (a) Instantaneous Average Current,  $I_{ave}(t)$
- (b) Instantaneous RMS Current,  $I_{rms}(t)$
- (c) Instantaneous RMS Fundamental Current,  $I_{rms}(t)$
- (d) Instantaneous Total Waveform Distortion

According all results that shows four patterns which is open circuit fault upper, open circuit fault lower, short circuit fault upper and short circuit fault lower, the parameter that estimate gives information for detect type of fault. Fig. 15 shows the bar graph indicates that error of current detection for VSI faults can be known from the parameter estimation by applying TFD. The condition of each fault can be identifying according to the result as a bar graph below. The details of each fault are shows in table 1 and 2

In order to find out the relation between parameter to detect condition of the VSI faults have been conducted. Analysis results were made based on current parameter estimation from spectrogram. Table 1 shows general of current error during fault detected. Next, Table 2 shows overall observation of current error from parameter estimation. From the observation of average current, that found the value of  $I_B$  is equal  $I_C$  but less than 0.5 and other of current is  $I_B$  equal with  $I_C$ . Both of current is greater than 0.5 and less than zero. Next, the open-circuit lower can be detect with  $I_A$  below than 1, respectively is greater than zero. For this condition  $I_A$  is greater than 1 but  $I_A$  less than zero. higher than zero for open circuit fault upper. Besides that, the current error at phase A is greater than 1 when short circuit fault upper detected. But other  $I_A$  is less than 1. When short-circuit lower,  $I_A$  less than -1 and other  $I_A$  is greater than -1. On the other hand, the error of rms current when open circuit fault either upper and lower, value  $I_A$  is equal  $I_C$  but for short-circuit is  $I_A$  different  $I_C$ . During short circuit fault upper detected, value of  $I_B$  is greater than  $I_C$  and other fault  $I_B$  is greater than  $I_C$ . Then, open circuit fault can be detected during RMS fundamental current  $I_A$  is greater than  $I_B$  and  $I_C$ , where both of current are equal. But, short circuit fault can be detected  $I_A$  is greater than  $I_C$  and greater then  $I_B$ . Lastly, table 2 give summaries of characteristic for each fault cased on error current where average current is important used to detect type of faults. The rules based on error current detection during fault are used to detection the faults event instantaneously are summaries in Table 1.

**Table 1.** General of current error during fault

Switch	Type of fault	Current	Observation
Upper	Open	Average	$I_A < (I_B = I_C)$
		RMS	$(I_A = I_C) > I_B$
	Short	Average	$I_A > (I_B = I_C)$
		RMS	$(I_A = I_C) > I_B$
Lower	Open	Average	$I_A > (I_B = I_C)$
		RMS	$I_A > I_B > I_C$
	Short	Average	$I_A < (I_B = I_C)$
		RMS	$I_A > I_C > I_B$



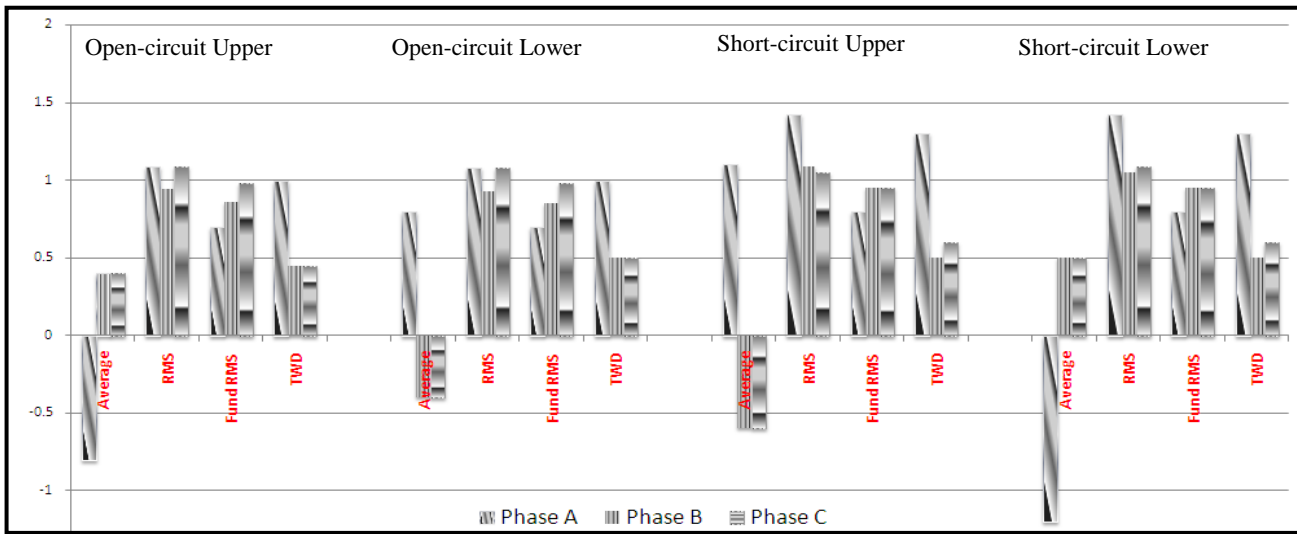


Fig. 15. The bar graph for error of current detection

Table 2. Characteristic for each fault detection based on parameter estimation

Parameter	Type of fault	Observation
Average Current	Open Upper	$(I_B = I_C) < 0.5$
	Others	$(I_B = I_C) > 0.5$ $(I_B = I_C) < 0$
	Open Lower	$I_A < 1$ but $I_A > 0$
	Others	$I_A > 1$ & $I_A < 0$
Short Upper	Others	$I_A > 1$
	Others	$I_A < 1$
Short Lower	Others	$I_A < -1$
	Others	$I_A > -1$
RMS Current	Open	$(I_A = I_C)$
	Other	$(I_A = I_C)$
	Short Upper	$(I_B > I_C)$
	Other	$(I_B = I_C)$
Short Lower	Other	$(I_C > I_B)$
	Other	$(I_C = I_B)$
RMS Current	Open	$I_A > (I_B = I_C)$
	Short	$I_A > I_C > I_B$

6. Conclusion

The analysis and detection system of type VSI faults is presented using TFD. From the parameter calculation, the TFR is estimated to identify fault signal parameter and then, from the parameters, fault signal characteristic can be calculated. Next, the characteristic for each fault detection can be identifying based on current error. The performance of the faults system is verified by the value current error which is average current and fundamental current. It shows the VSI faults can be identified depends on value parameter

estimation. So, the detection faults can be early and fault in VSI will be decrease.

Acknowledgment

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