Short-Circuit Switches Fault Analysis of Voltage Source Inverter using Spectrogram

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Abstract — The identification of faults in voltage source inverter is highly required to ensure the reliability of the inverter. Early detection of the faults can greatly assist in maintenance of the system by avoiding possibly harmful damage borne out. This paper presents the analysis of short-circuit switches fault of voltage source inverter (VSI) using time frequency distribution (TFD). The TFD which is spectrogram represents current signal of the VSI in time-frequency representation (TFR) that provides temporal and spectral information of the signal. From the TFR, parameters of the signal are estimated such as average current, root mean square (RMS), total harmonic distortion (THD), total waveform distortion (TWD) and total non-harmonic distortion (TnHD). The results shows that the analysis using spectrogram gives information of the current signal of the VSI to identify short-circuit switches and can be implemented for faults detection system.

I. INTRODUCTION

As the backbone of modern industry, voltage source inverter (VSI) plays role in motor drives, power supplies, power quality conditioners, etc. The design and control technique of VSI have matured in commercial products as a result of efforts to enhance their performance. It estimated 82.5 percent of increasing fault in the power drives because of design and control techniques [1]. The VSI faults can cost maintenance increase, power electronics damage and reduces efficiency.

Previously, the majority about 70% of these faults was related to power switches, such as open circuit faults, short-circuit faults and gate-misfiring faults [2]. The faults caused include of transistor failure, pulse width modulation (PWM) and inverter leg open [3]. Typically, short-circuit switches fault occurs in power drives frequently than open-circuit switch. In most previous study, VSI faults are normally analyzed in frequency domains, and the fast Fourier transform (FFT) is used for transformation technique. However, VSI faults signal are usually in non-stationary pattern depend on caused of faults. Thus, this technique is suitable for stationary signals and does not provide temporal information [4]. To overcome these limitations, time frequency distribution (TFD) such spectrogram is used to analyze the condition of VSI faults.

This paper presents the analysis of short-circuit VSI switches faults using spectrogram. Spectrogram is performed to represent VSI fault current in time-frequency representation (TFR) for fault pattern identification of short-circuit fault. From the TFR, parameters of VSI current signal are estimated and then, the characteristic of the signal are calculated to indentify the short-circuit switches faults.

II. SHORT-CIRCUIT FAULTS OF VSI SWITCHES

Short-circuit switch faults of VSI with DC supply of 50V is modeled as presented in Fig. 1. The model consists of a three-phase inverter, equipped with an induction motor, pulse width modulation (PWM) and fault generation. In theoretical, the three phase inverter switches are controlled in pairs (S_{11}, S_{12}), (S_{21}, S_{22}) and (S_{31}, S_{33}). In the operation, only one switch in a pair closed and the other is open. The output voltage can be +Vdc, -Vdc or zero, depending on which switches are closed. The switching of inverter is controlled by comparison of a sinusoidal control and a pulse width modulation (PWM). The sinusoidal control waveform establishes the desired fundamental frequency of the inverter output, while the triangular waveform establishes the switching frequency of the inverter. The most advantages of PWM is reduction in filter requirements to decrease harmonics and easier to control the output voltage amplitude [5].

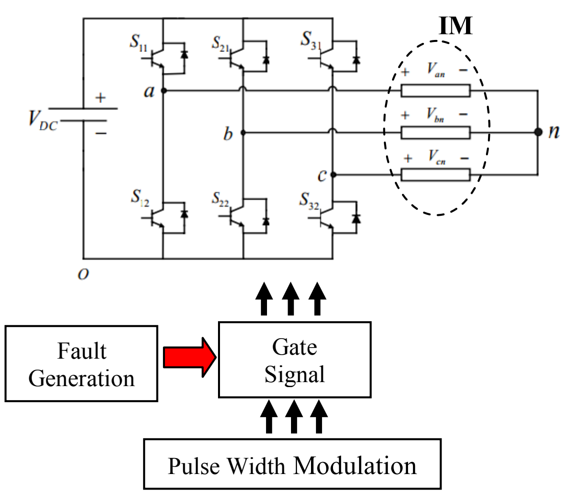

Fig. 1 Short-circuit faults model of VSI switches.

A switching function of the VSI is defined as Fig. 2, where *j* represents the phase, and variable *p* and *n*, respectively, represent the upper and lower component of the phase leg. Where the three-phase VSI is considered, *j*= {a, b, c}. The switching status represent in term of “1” when the switch is closed and “0’ when open [6].

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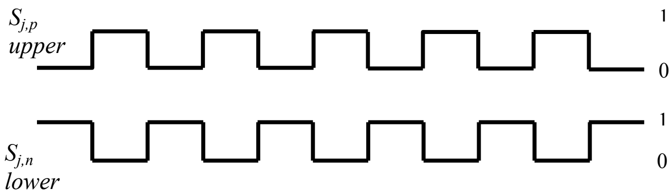


Fig. 2 Gating signal of the inverter in an ideal case.

A. *Short-Circuit Fault of the Upper Switch*

The short-circuit fault of the upper switch is occurred when the upper switch, S_{jp}, is closed while the lower, S_{jn}, is also closed in the same time [7]. As example, the condition S_{jp} normally opened and S_{jn} are closed at certain time and then back to normal operation as shown in Fig. 3.

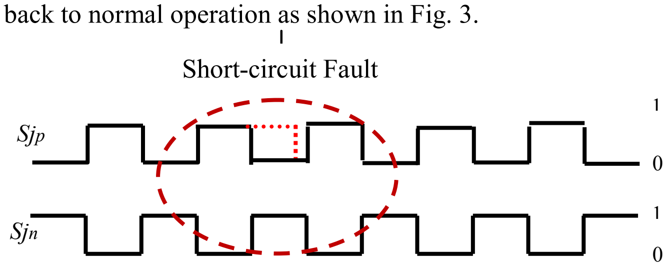


Fig. 3 Switching signals of the inverter in an short-circuit fault (*upper*).

B. *Short-Circuit Fault of Lower Switch*

Similar to the upper switch short-circuit fault, the short-circuit fault of the lower switch is occurred when the S_{jp} normally opened is closed and the S_{jn} is closed in the same time [7]. Fig. 4 shows the switching gate signal consist delay at certain time where the switching at the "1" condition until return to normal for the lower switch.

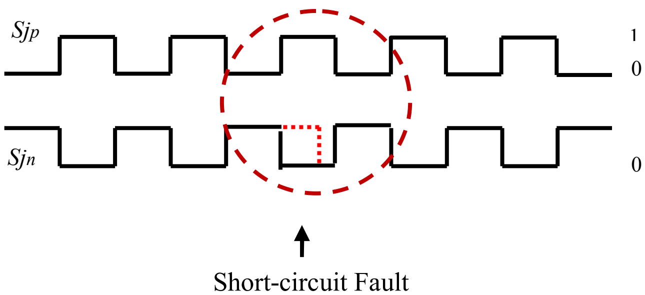


Fig. 4 Switching signals of the inverter in an short-circuit fault (*lower*).

III. Time Frequency Analysis Technique

In this paper, time-frequency analysis technique which is spectrogram is used to analyze the faults signal in time-frequency representation (TFR). The TFR consists of the signal magnitude with respect to time and frequency [8]. Spectrogram is the squared magnitude of the Short Time Fourier Transform (STFT) [9] and can be expressed as below.

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

Where $x(\tau)$ 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.

IV. Parameter Estimation

Parameters of the faults signal are estimated from the TFR to identify the characteristics of the signal. These parameters are instantaneous of root mean square (RMS) current, RMS fundamental current, total waveform distortion (TWD), total harmonics distortion (THD), total non-harmonics distortion (TnHD) and average current.

A. *Instantaneous RMS Current*

The instantaneous RMS current is the square root of the arithmetic mean of squares of the function of continuous waveform [10]. It can define as:

$$I_{rms}(t)=\sqrt{\int_{0}^{f_{\max}} S(t,f)df} \qquad (2)$$

Where $S(t,f)$ is the TFR of signal and f_{max} is the maximum frequency of interest.

B. *Instantaneous RMS Fundamental Current*

Instantaneous RMS fundamental current is defined as the RMS current at power system frequency [11, 12] and can be calculated as:

$$I_{1_{rms}}(t)=\sqrt{2\int_{f_{lo}}^{f_{hi}} S(t,f)df}$$
$$f_{hi}=f_1+\frac{\Delta f}{2},\quad f_{lo}=f_1-\frac{\Delta f}{2} \qquad (3)$$

Where f_1 is the fundamental frequency that corresponds to the power system frequency and Δf is the bandwidth which is set to 60Hz.

C. *Instantaneous Total Waveform Distortion*

TWD consists of harmonic and non-harmonic distortion [11, 12] and can be defined as:

$$I_{TWD}(t)=\frac{\sqrt{I_{rms}(t)^2-I_{1_{rms}}(t)^2}}{I_{1_{rms}}(t)} \qquad (4)$$

D. *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 [11, 12]. Such as, given a fundamental frequency 60 Hz, the harmonics component will be 120 Hz, 180 Hz and 240 Hz.

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

Where $I_{h,RMS}(t)$ is RMS harmonic current and H is the highest measured harmonic component.

E. Instantaneous Total Non-Harmonic Distortion

Non-harmonic signal contains interharmonic component that are not multiple integer of the fundamental frequency [13]. For example, the fundamental frequency given 60 Hz, the interharmonic will be 75Hz or 130 Hz.

$$I_{TnHD}(t) = \frac{\sqrt{I(t)_{rms}{}^2 - \sum_{h=0}^{H} I_{h,rms}(t)^2}}{I_{1rms}(t)} \tag{6}$$

F. Instantaneous Average Current

Instantaneous average voltage is the mean value of a signal that corresponds to a specific time, t. It is the most commonly used parameter to measure DC value of the signal and can be defined as:

$$I_{ave}(t) = \frac{1}{T}\int_{0}^{T} x(\tau)w(\tau - t)d\tau \tag{7}$$

Where $x(\tau)$ is the input signal, $w(t)$ is the window function and T is the period measured.

V. RESULTS

The simulation analysis by using a three-phase induction motor is completed and the parameters used are as follow: input DC voltage, V_{DC}, is 50 V, sampling time, T_s, is 50µs and fundamental frequency, f_1, is 60 Hz.

A. Short-Circuit Fault of Upper Switch

The output current of the three-phase VSI for short-circuit switch fault at S_{11} is shown in Fig 4. Red color represents phase a while green and blue color for phase b and c, respectively. The figure shows that the magnitudes of the fault signals increase from 0.2 to 0.3 s for all phases.

The TFR of the fault signal for phase a is shown in Fig. 5. The highest power of signal in the contour plot is represented in red color, while the lowest in blue color. The TFR indicates that the fundamental frequency of the signal is 60 Hz and has a momentary power increase at DC component (0 Hz) between 0.2 and 0.3s.

Fig. 6 shows the instantaneous of average current, RMS current and fundamental RMS current of the fault signal for all phases that estimated from the TFR in per unit (pu). Fig. 6(a) shows that the average current of phase a is greater while phase b and c, respectively, is lower than zero between 0.2 and 0.3 s. For the RMS value, the magnitude of the phase a is higher but the RMS fundamental value is lower compare to phase b and c as shown in Fig. 6(b) and (c).

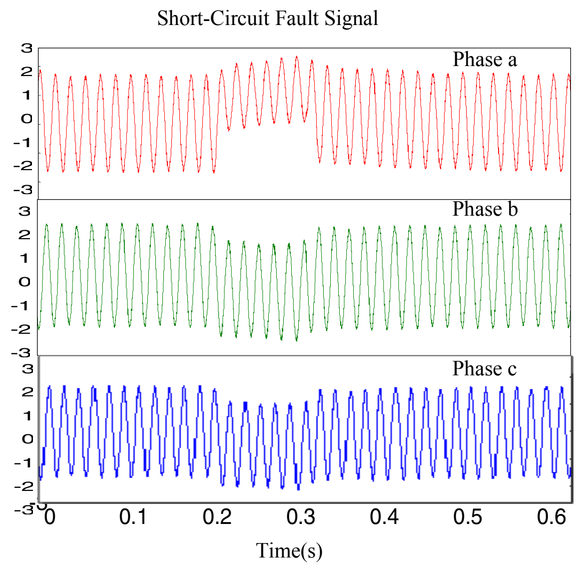


Fig. 4 Short-circuit fault signals of upper switch for phase a, b and c.

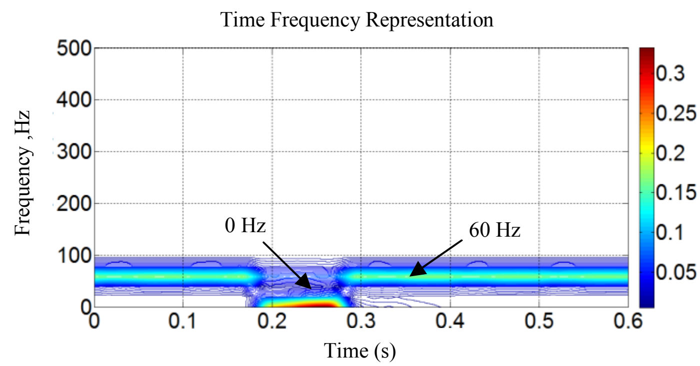
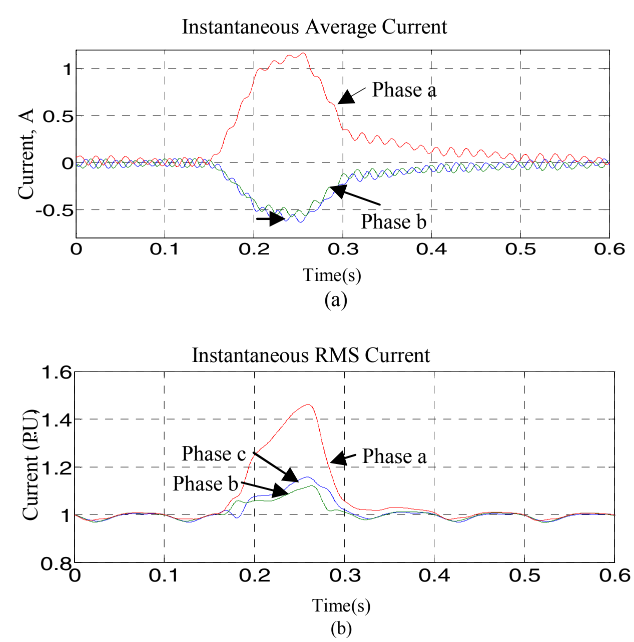
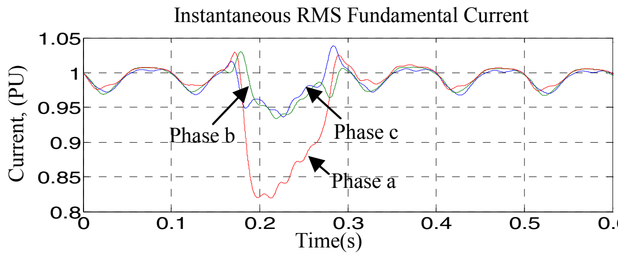


Fig. 5 The TFR of short-circuit fault signal of upper switch for phase a using spectrogram.





(c)

Fig. 6 Signal parameters of the short-circuit fault signals for upper switch: a) Instantaneous average current, b) Instantaneous RMS current (pu) and c) Instantaneous RMS fundamental current (pu).

Besides that, instantaneous of total harmonic distortion, total non-harmonic distortion and total waveform distortion of the fault signals are shown in Fig. 7. Since the fault signals only occur at DC frequency component, there are zero percentage for THD and TnHD but TWD gives 1.43% from 0.2 to 0.3 s as shown, respectively, in Fig. 7(a), (b) and (c).

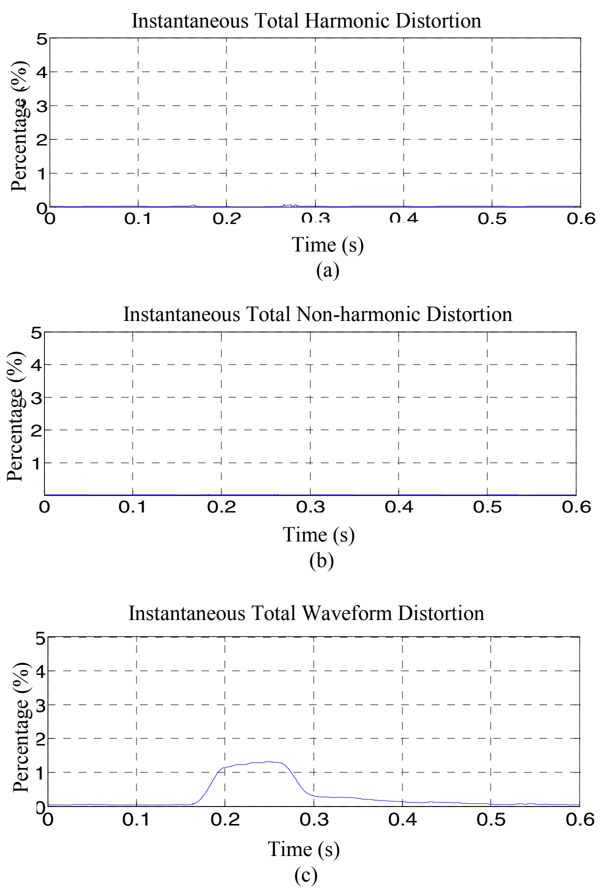


Fig. 7 Signal parameters of the short-circuit fault signals for upper switch: a) Instantaneous Total Harmonic Distortion, b) Instantaneous Total non-harmonic Distortion and c) Instantaneous Total Waveform Distortion.

B. Short-Circuit Fault of Lower Switch

The simulation signals of the three-phase VSI output current for short-circuit switch fault at S_{12} is shown in Fig 8. Similar to short-circuit fault signal for the upper switch, the magnitude of the fault signal increases from 0.2 to 0.3 s for all phases. In addition, the contour plot of the fault signal for phase a also presents that the frequency of the signal is 60 Hz and the magnitude is higher than normal between 0.2 and 0.3 s. The fault signal is occurred at 0 Hz as shown in Fig 9.

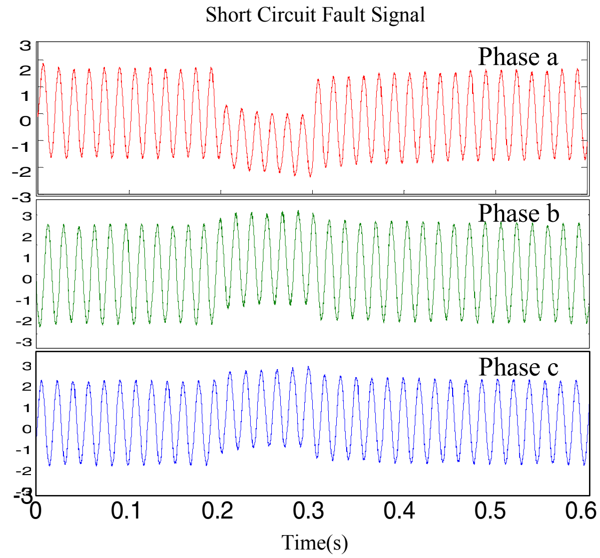


Fig. 8 Short-circuit fault signals of lower switch for phase a, b and c.

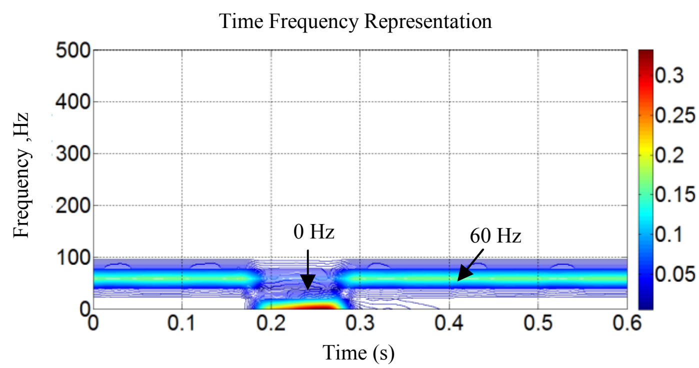


Fig. 9 The TFR of short-circuit fault signal of lower switch for phase a using spectrogram.

The estimated of instantaneous average current, RMS current and fundamental RMS current of the fault signals for all phases are shown in Fig 10. The Fig. 10(a) shows the average current of phase a is lower while phase b and c, respectively, is greater than zero between 0.2 and 0.3 s. Based on the RMS value, the magnitude of the phase a is higher and the RMS fundamental value is lower compare to phase b and c as shown in Fig. 10(b) and (c).

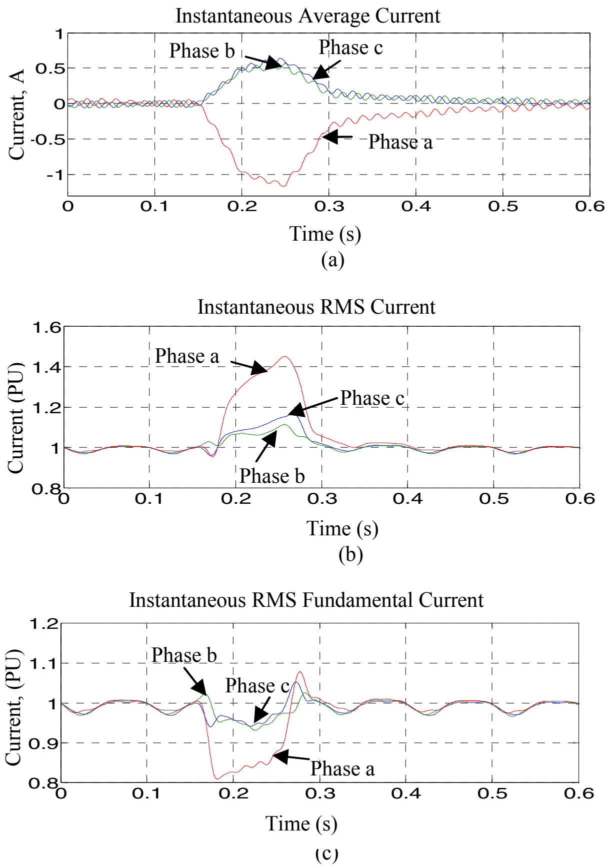
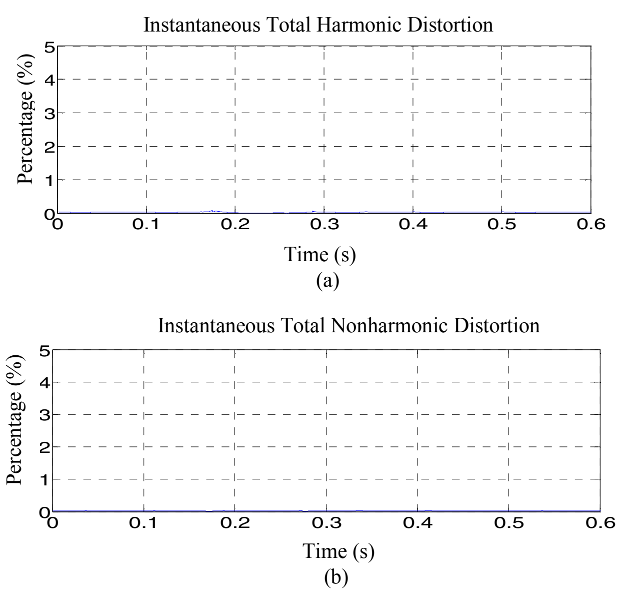


Fig. 10 Signal parameters of the short-circuit fault signals for lower switch: a) Instantaneous average current, b) Instantaneous RMS current (pu) and c) Instantaneous RMS fundamental current (pu).

Fig. 11 shows instantaneous of total harmonic distortion, total non-harmonic distortion and total waveform distortion of the fault signals. Since the fault signals only occur at DC frequency component, there are zero percentage for THD and TnHD, in Fig 11(a) and (b). However, the magnitude of TWD is higher than 1% from 0.2 to 0.3 s as shown in Fig. 11(c).



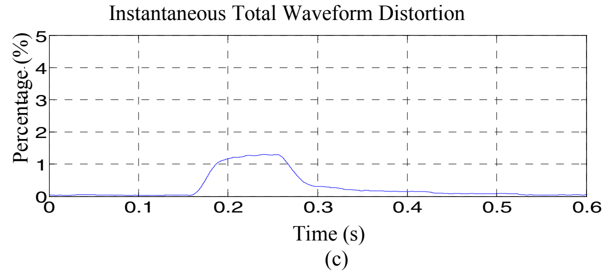


Fig. 11 Signal parameters of the short-circuit fault signals for lower switch: a) Instantaneous Total Harmonic Distortion, b) Instantaneous Total non-harmonic Distortion and c) Instantaneous Total Waveform Distortion.

VI. CONCLUSION

Safety, reliability, efficiency and performance are some of the major issues and concerns for the power electronics drive system applications. With factors such as aging systems, high reliability demands and cost competitiveness, the issues of preventive and condition based maintenance and system fault detection increasing importance. Spectrogram is performed to identify the temporal and spectral information of the fault signals. The signal parameters such as instantaneous average current, instantaneous RMS current and instantaneous fundamental RMS current, THD, TnHD and TWD are estimated from TFR and then characteristics of the signal can be calculated. The results of the upper switch short-circuit faults shows that, the magnitudes of average current, RMS current and TWD is higher while fundamental RMS current is lower for phase a compare to phase b and c. For the lower switch, the magnitudes is lower for average current and fundamental RMS current but RMS current and TWD are, respectively, higher compare to phase b and c. Since, the fault signals only occur at fundamental frequency, there are no values for THD and TnHD. As conclusion, the information of VSI faults signals estimated by using time-frequency analysis technique which is spectrogram can be used to identify the short-circuit switches fault.

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