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# Experimental Study of Inverter Open-Circuit Fault Diagnosis using Stator Current Spectrogram

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*Abstract*— **Three-phase static converters with voltage structure are widely used in many industrial systems. In order to prevent the propagation of the fault to other components of the system and ensure continuity of service in the event of a failure of the converter, efficient and rapid methods of detection and localization must be implemented. This paper work addresses a diagnostic technique based on the time-frequency representation called Short Time Fourier Transform or Spectrogram (STFT), for the detection of an inverter IGBT open-circuit switch fault. To illustrate the merits of the technique and validate the results, experimental tests are conducted using a built three-phase voltage inverter fed induction motor.**

***Keywords*— Inverter, diagnostic, detection, open-circuit, STFT, spectrum**

## I. INTRODUCTION

Three-phase static converters voltage structures are widely used in many power applications. Continuity of service of these systems and their safety, reliability and performance are of major concerns today. Indeed, the failure of the inverter can lead to loss of control of the phase currents resulting in serious system malfunction or even a complete stop. To prevent the spread of the fault to other system components and ensure continuity of service in all circumstances, upon failure of the inverter, the converter topologies fault tolerant associated with effective and rapid methods of detection and localization failure must be implemented.

Several researchers have carried out their investigation in relation to the field of detection and localization of faults in static converters and more particularly those related to three phase power inverters [1]. The treated fault is mainly concerned with the open-circuit fault of an inverter IGBT switch [2]. Most published papers are based on Park's current vectors approach [3]. This approach is based on the trajectory tracking of the phase current vector. In fact, for the case of a healthy state condition of the inverter, the trajectory of these current vectors in the (d-q) frame is a circle. It was found that the circle becomes a semicircle under an open-circuit IGBT switch fault in one of the legs of the inverter. The position of this semicircle in the (d-q) frame makes it possible to identify the faulty IGBT switch [4]. Another paper used the mean value of the phase currents in Park's frame for the extraction of the open-circuit fault angle of each IGBT switch [3], [4], unfortunately this method presents an inconvenient as it depends on the load. To overcome the problem some authors suggested the normalized DC current method which is fundamentally based on the dc component of the current and the first order harmonic coefficients of the ac-currents [5]. Some detection techniques mentioned above are briefly discussed in reference [6], [7].To overcome this constraint, it is necessary to use a time-frequency representation. Indeed, the Gabor works in the 40s have led to the foundations of a new type of analysis called Short Time Fourier Transform (STFT) or spectrogram. He was the first to imagine a local Fourier transform based on a windowing signal analysis to observe changes in frequency with time. This transformation requires the division of the signal in consecutive short segments and then calculates the Fourier transform of each segment. The idea is to introduce the local frequency parameter so that the Fourier transform is applied to the signal through a sliding window on which the signal is approximately stationary. This method represents the results into three dimensions; the description of the signal is carried out in the time-frequency plan composed of spectral characteristics as a function of time [8].

This paper presents an approach using the technique based on the spectral analysis (STFT) to investigate the detection of the harmonic characterizing the IGBT switch open-circuit fault and localization. This approach addresses the STFT technique to extract the information related to the harmonic characterizing the open-circuit IGBT switch and presents the various experimental results and their interpretations.

## II. VOLTAGE SOURCE INVERTER STRUCTURE

Fig 1 shows the structure of a three-phase two-level voltage source inverter feeding an induction motor.

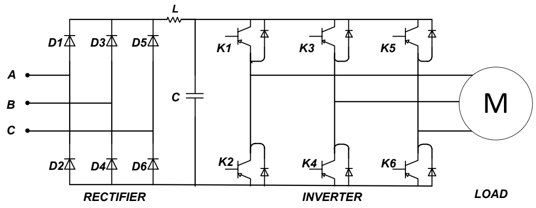

Fig. 1. Structure of a three-phase two-level inverter

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Experimental tests are conducted to study the effect of the inverter open-circuit faults on the induction motor behavior. The experimental test-rig used, includes a three-phase induction squirrel-cage motor fed by a three-phase two-level voltage source inverter. The detailed characteristics of the motor are given in the appendix. Furthermore, the motor is mechanically coupled to a dc generator supplying resistors, which allows varying the load torque. In addition, the measuring system includes three current Hall Effect sensors and three voltage sensors and a DSPACE 1104 acquisition card to generate pulses for triggering the *IGBTs* gates. The whole set is connected to a computer for visualizing the processed sensed signal as shown in the photo of Fig. 2.The acquisition time is taken as $T_{acq} = 5s$ and the sampling frequency $F_e = 1500Hz$.

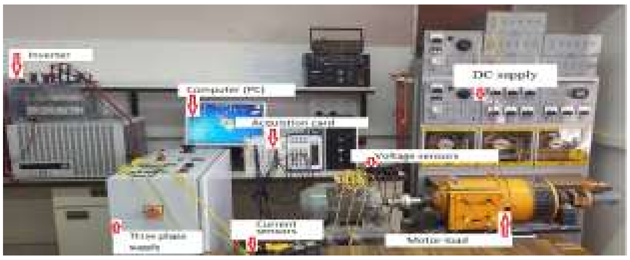

Fig.2. Photo of the experimental test-rig

At this stage, it should be noted that all the experimental results which are obtained and presented in this paper work are carried out using the test-rig below built by the 'Diagnostic Group' at the LDEE laboratory University of Sciences and Technology of Oran (USTO-MB).

The following Fig. 3 depicts the phase current waveforms of the induction motor for both a healthy state and an *IGBT* open-circuit faulty inverter.

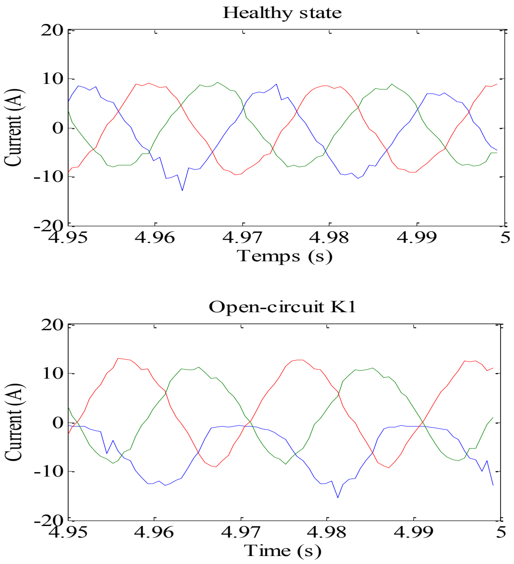

Fig.3 Currents waveforms of an induction motor for healthy case and open-circuit switch at $K_1$

Induction motor is controlled in speed. Following an IGBT open-circuit fault $K_1$ of the inverter leg, the phase current connected to this leg can no longer be controlled as it can only be negative or zero. The sum of the currents of the other two healthy phases is zero which may make it impossible to start the motor.

## III. TIME FREQUENCY ANALYSIS

The Fourier transform is expressed by the following equation:

$$FT_X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \tag{1}$$

We define the power spectral density or PSD as the square modulus of the Fourier transform, which is thus independent of the signal phase. Therefore, any information on the frequency changes with time variation is lost in the PSD. The time-frequency distribution, known as Short Time Fourier Transform or STFT is defined by:

$$STFT_X(t,f) = \int_{-\infty}^{+\infty} x(\tau)h(\tau - t)e^{-j2\pi f\tau}d\tau \tag{2}$$

$$STFT_X(t,f) = \int X(\theta + f)H(\theta)e^{-j2\pi\theta t}d\theta_R \tag{3}$$

The second expression of the STFT xi s obtained from the classical properties of the FT: conservation of the scalar product, shift properties and transformation of a normal product into a convolution one.

The STFT is constituted by the FT of $x(\tau)h(\tau - t)$obtained by weighting $x(\tau)$by the window $h(\tau - t)$which is a short time analysis window localized around t and that shifts by varying the parameter *t*. Join to $h(\tau)$, the family of functions depending on two parameters *t* and *f*, defined by [8]:

$$h_{t,f}(\tau) = h(\tau - t)e^{j2\pi f\tau} \quad , (t,f)\epsilon\Re^2 \tag{4}$$

The numbers $STFT_X(t,f)$are commonly called projections of $x(\tau)$on the function's system $h_{t,f}$. If *h* is the rectangle window of T support, the STFT consists in taking the FT of a sequence of signals equal to x on the support and zero elsewhere. We begin by the discrete-time signal $[x_n = x(nT)]$, $T>0$. Let $h_n = h(nT)$ and *N* is the number of samples in the analysis window. Finally, a discretisation of the frequency variable *f* is introduced. The STFT is then defined by the entire numbers $X_{k,n}$ calculated as follows [8]:

$$X_{k,n} = \sum_{\ell}^{N-1} x_{\ell+k}h_\ell e^{-j2\pi\ell T\frac{n}{N}}, \;\; k \in n = 1,2, \dots. \tag{5}$$

As for the FT, the zero-padding technique allows the improvement of the frequency resolution. The principle of this method is to complete by M zeros a set of *N* samples so that M+ N is a power of 2 and thereafter can perform calculations using the Fast FT algorithm using the N + M points. When M= N, the method use the Discrete FT

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algorithms that are being made to calculate 2N points from the spectrum, from only N points of the signal.

### *A. Heisenberg-gabor uncertainty principle*

The uncertainty principle, also called time-frequency inequality is based on the uncertainty relationships established by Werner Heisenberg in quantum mechanics. The analogy with the work of Heisenberg for the Fourier transform was made by Dennis Gabor in 1946. Let us consider the finite energy signal $x(t)$ centered in time and frequency around zero. Gabor defines the duration $\Delta t$ and the spectral band $\Delta f$ as follows:

$$\Delta t = \frac{1}{E_x}\int_{-\infty}^{+\infty}|x(t)|^2 dt \tag{6}$$

$$\Delta f = \frac{1}{E_x}\int_{-\infty}^{+\infty} f^2|X(f)|^2 df \tag{7}$$

Where $Ex$ is the energy of the signal given by the Parceval relationship:

$$E_x = \int_{-\infty}^{+\infty}|x(t)|^2 dt = \int_{-\infty}^{+\infty}|X(f)|^2 df \tag{8}$$

Therefore, the time-frequency inequality is defined by [9]:

$$\Delta t.\Delta f \geq \frac{1}{4\pi} \tag{9}$$

It expresses the fact that the duration-band product of a signal is lower bounded for a $\Delta t$ duration and a $\Delta f$ spectral band. In other words, the greater the accuracy in frequency localization is, the lower the accuracy in time localization and vice versa. The spectrogram is subject to the uncertainty principle due to the use of Fourier transform. This issue requires the search for the right time-frequency compromise suitable to the case considered in determining the correct window width. Gaussian window has the best time-frequency localization. Indeed, it verifies the following equality [10]:

$$\Delta t.\Delta f = \frac{1}{4\pi} \tag{10}$$

Finally, the choice of the window is important because it represents another compromise (comparable to the time-frequency compromise) between the main lobe width and the amplitude of the sideband in the frequency domain.

### *B. Experimental results and discussion*

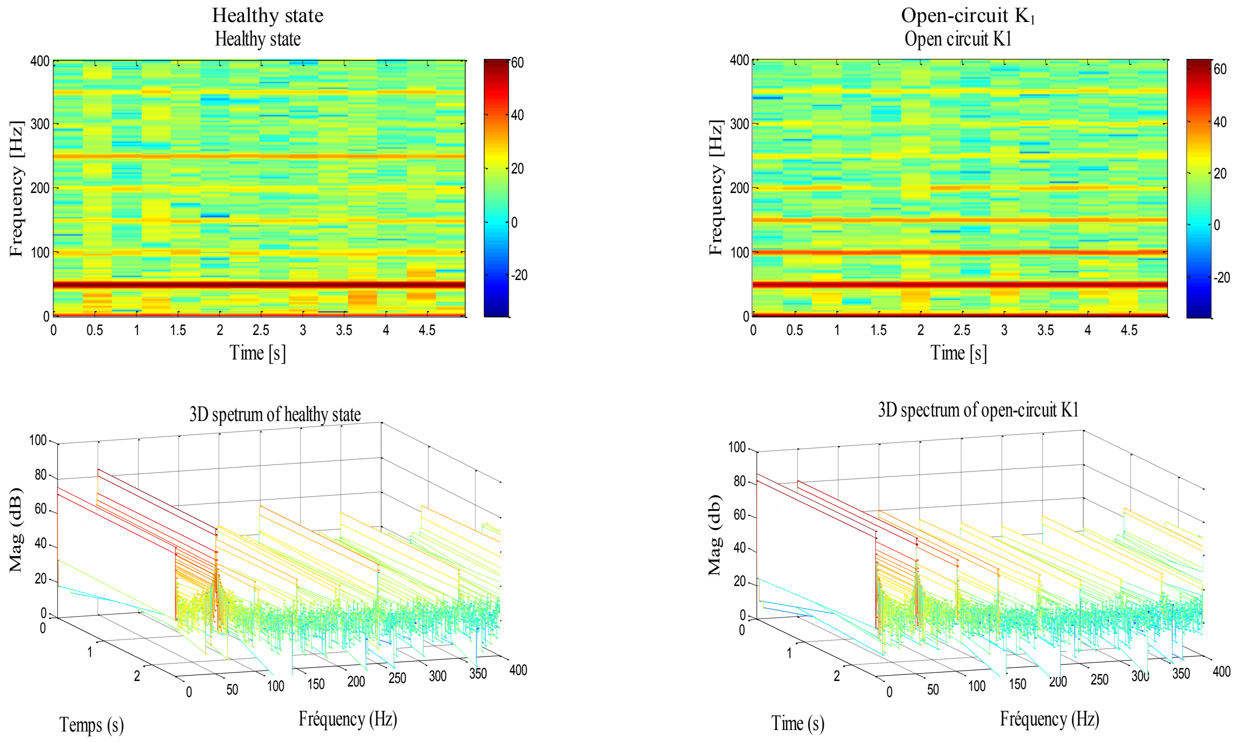

Fig.4 Spectrogram of stator current case healthy state and case open-circuit fault

By comparing the spectrogram of the stator current $i_{as}$ of the healthy state and faulty case open-circuit IGBT, it is noted the presence of a red band at the level frequency *0Hz* and *100Hz*.

In the presence of an open-circuit switch fault at $K_1$, the experimental result in Fig. 4 depicts in addition to the fundamental harmonic, a DC component for each phase. It can be noted that the dc component in the faulty phase A is *h* lower than the fundamental harmonic but it is higher compared to the two other DC components in phases B and C. One can also notice that the two healthy phases *B* and *C* have the same dc component value.

Open circuit fault detection based on the presence of the harmonic *100Hz*:

$$f_{o-c} = 2f_s \tag{11}$$

The following Table I, summarizes the calculation of the various fault angles related to the various corresponding faulty switches. The fault angle computation is obtained based on the following equation:

$$\varphi_{h0} = \arccos\left(\frac{h_0}{h_{50}}\right) \tag{12}$$

TABLE I
OPEN-CIRCUIT FAULT CHARACTERISTICS OF THE INVERTER

| | The zero-order harmonic of the three phases | | |
|---|---|---|---|
| Faults Types | Phase A | Phase B | Phase C |
| Healthy case | $\|h_0\|=\varepsilon_{h0}$ | $\|h_0\|=\varepsilon_{h0}$ | $\|h_0\|=\varepsilon_{h0}$ |
| Open-circuit *K₁* | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ |
| Open-circuit *K₂* | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ |
| Open-circuit *K₃* | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ |
| Open-circuit *K₄* | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ |
| Open-circuit *K₅* | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ |
| Open-circuit *K₆* | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=270°$ | $\varepsilon_{h0}<\|h_0\|<\|h_{50}\|$<br>$\varphi_{h0}=90°$ |

The analysis of the first tow harmonics shows that the difference between the healthy state and the case of open-circuit fault state lies at the zero-order harmonics which means the presence of the DC component in the signal. The argument of zero harmonic relative to the fundamental enables us to know the type of fault. On the other hand, the argument of this harmonic enables us also to know the faulty switch either the upper one or the lower one.

From the result of Table I below, we note that the phase which contains the open-circuit fault has its dc component equals to the sum of the dc component of the two other phases and is expressed by the following relations as:

- If the fault is at *phase A*, then: $h_{0A}=h_{0B}+h_{0C}$
- If the fault is at *phase B*, then: $h_{0B}=h_{0A}+h_{0C}$
- If the fault is at *phase C*, then: $h_{0C}=h_{0A}+h_{0B}$

Where $h_{0A}$ is the zero-order harmonic of phase A, $h_{0B}$ the zero-order harmonic of phase B and $h_{0C}$the zero-order harmonic of phase C. From the three above relations, we conclude that: one can detect if there is an open-circuit fault or not in the inverter and from this detection, one can localize which is the faulty switch.

## IV. CONCLUSIONS

In this paper, first, the inverter IGBT switch open-circuit fault impact on the induction motor is presented. Thereafter, a technique is presented and discussed in order to detect and localize voltage inverter switch faults. The proposed technique uses the stator current spectrum analysis of the short time Fourier transforms (STFT). To illustrate the merits of the proposed technique and validate the results, experimental tests are conducted using a built three-phase voltage inverter fed induction motor.

## APPENDIX

| | |
|---|---|
| Rated Power | 3 KW |
| Supply frequency | 50 Hz |
| Rated voltage | 380 V |
| Rated current | 7A |
| Rotor speed | 1440 rev/min |
| Number of rotor bars | 28 |
| Number of stator slots | 36 |
| Power factor | 0.83 |
| Number of pair of poles | 2 |

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