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"Detection of a Two-Level Inverter Open-Circuit Fault Using the Continuous Wavelet Transforms Technique"

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Detection of a Two-Level Inverter Open-Circuit Fault Using the Continuous Wavelet Transforms Technique

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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 diagnosis technique based on the continuous wavelet transforms *(CWT)* 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 voltage inverter fed induction motor. The inverter is controlled by the *SVM* control strategy.**

Keywords- Inverter, diagnostic, detection, open-circuit, continuous wavelet, spectrum

I. Introduction

The wavelet transform technique has perhaps been the most persistent development in recent decades. It has drawn the attention of several researchers in various fields, such as signal processing, image processing, communication, computer science and mathematics. Numerous works describing the advancement in wavelet theory and its applications in various fields have been published. Among others, it is one of the most attractive techniques in the field of rotary machines and static converter for fault diagnosis and it particularly matches well for the non-stationary signals [1, 2]. The main disadvantage of this technique is that the length of the range (scale) is fixed. Therefore, it is necessary to be able to keep the time-frequency representation and carry out an analysis based on a concept somewhat different from the concept of frequency: the scale concept [3]. In 1982, J. Morlet opens the way to the solution by constructing the wavelet analysis, based on the concept of scale. By manipulating the scale factor, one can zoom in and out a portion of the signal [3, 4]. Unlike the short-term Fourier transform, the wavelet transform uses the notion of time-scale involving dynamic length analysis windows.

Several researchers have carried out their investigation in relation to the field of detection and location of faults in static converters and more particularly those related to three phase power inverters [5]. The treated fault is mainly concerned with the open-circuit fault of an inverter IGBT switch [6]. Most published papers are based on Park's current vectors approach [7]. 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 [8]. 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 [7, 9], 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 [10]. Some detection techniques mentioned above are briefly discussed in reference [11, 12].

Others researchers used stator current as key parameter for fault diagnosis purpose because it does not require costly sensors. This technique widely termed as Motor Current Signature Analysis (*MCSA*) technique. [13, 14 and 15]. For steady state constant load conditions, the Fast Fourier Transform (*FFT*) algorithm has been used for different induction motor fault diagnosis purpose. The *FFT* algorithm is able to diagnose bearing fault for full load conditions but not for the no-load or light load condition [13]. Therefore, some researchers proposed Short Term Fourier Transform (*STFT*) and Wavelet Transform (*WT*) methods for different fault diagnosis purpose of the induction motor by taking into consideration the quantity of time (that is for non-stationary applications). However, the *STFT* method faces a big dis-advantage; it gives poor frequency resolution because it shows constant window size for all frequencies. Therefore, there is a strong need to develop health monitoring techniques (*WT* for our case) to address these issues to allow earlier detection of faults. Because the continuous wavelet transform is very sensitive to noise, the discrete wavelet transforms is preferred and used in our paper.

The work proposed in this paper addresses an open-circuit fault detection of an *IGBT* switch of an inverter controlled by a *DSPACE 1104* card based on the *SVM* control strategy feeding an induction motor. The analysis tools and fault diagnosis are based on the use of the continuous wavelet transforms. The paper work focuses on the investigation of the harmonics which may appear in the scale spectrum due to the open-circuit inverter switch faults.

II. EXPERIMENTAL TEST-RIG

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. The acquisition time is taken as $T_{acq} = 5s$ and the sampling frequency $F_e = 1500Hz$.

III. CONTINUOUS WAVELET TRANSFORM

Fig. 1 shows the structure of a three-phase inverter with two levels

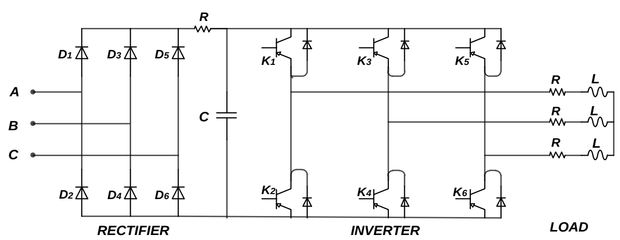

Figure. 1: Structure of the three-phase inverter at two levels.

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.

- ***Continuous wavelet***

Basically, the wavelet transform is computed in the same way as the windowed Fourier transform: we consider the correlation, in the sense of the scalar product on $L^2(R)$, between the signal to be analyzed and a family of functions $\{\Psi_{a,b}, a\epsilon R_+^*, b\epsilon R\}$, well localized in time and frequency:

$$C_x(a,b) = \langle x, \Psi_{a,b} \rangle = \int x(t)\Psi_{a,b}^*(t)dt \quad (1)$$

$$x(t) = \sum_a \sum_b C_x(a,b)\Psi_a, b(t) \quad (2)$$

The coefficients $C_x(a,b)$ are interpreted as the projection of the signal *x (t)* on the family $\{\Psi_{a,b}(t)\}$ of the functions obtained by dilation and translation of b of the mother wavelet.

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{a}}\Psi(\frac{t-b}{a}) \quad (3)$$

A wavelet Ψ (t) is a function of zero mean:

$$\int_{-\infty}^{+\infty} \Psi(t)dt = 0 \quad (4)$$

The scaling factor ***a*** is related to the notion of frequency *(a = 1 / f)* and the shift ***b*** is related to the notion of temporal position. The larger, the more the wavelet is dilated. Consequently the large values of ***a*** will logically be associated with the low frequencies, the smallest with the high frequencies therefore:

- Scales a> 1 dilate the signals (low frequencies).
- Scales a <1 compresses the signal (high frequencies).

Application conditions Finite-energy function:

$$C_\Psi = \int_0^{+\infty} \frac{|\hat{\Psi}(f)|^2}{|f|} df < +\infty \quad (5)$$

To ensure the existence of finite, C_Ψ must ensure the convergence of the integral terminals. At infinity, must the specter of the mother wavelet is a decrease at least in $|f|^{-1/2}$ By cons, about the origin, the spectrum should cancel to ensure convergence of the integral to zero:

$$\hat{\Psi}(0) = \int_{-\infty}^{+\infty} \Psi(t)dt = 0 \quad (6)$$

This condition forces the wavelet to be zero mean. Thus, its amplitude necessarily passes through zero and therefore presents some oscillations; this is why it is called the wavelet. Finally, the frequency approach allows the rewriting of equation (4) in the form [16]:

$$C_x(a,b) \int x(t) \frac{1}{\sqrt{a}} \Psi^* \left(\frac{t-b}{a}\right) dt = \int_{-\infty}^{+\infty} x(f)\Psi^*(af)e^{2j\pi fb}\sqrt{a}.df \quad (7)$$

In this paper, the Coiflet wavelets are to be applied for the detection of the IGBT open-circuit. The Coiflet wavelets are defined in the time domain by the following equation:

$$\int_{-\infty}^{\infty} f(t)dt = 1 \quad (8)$$

For numerical analysis applications, the Coiflet wavelets are expressed by the following equations:

$$\sum_j^{L-1} (-1)^j j^k h_j = 0 \quad for\ 0 \le k < m \quad (9)$$

$$\sum_j^{L-1} j^k h_j = \alpha^k \quad for\ 0 \le k < n \quad (10)$$

$$3m > L-1 \quad and\ 3n \ge L-1 \quad (11)$$

The equations above can be taken as some requirement about vanishing moments of the scaling function. The resulting Coiflets have a support of size *6n-1*. Fig.2 depicts a graphical Coiflet wavelet family's representation.

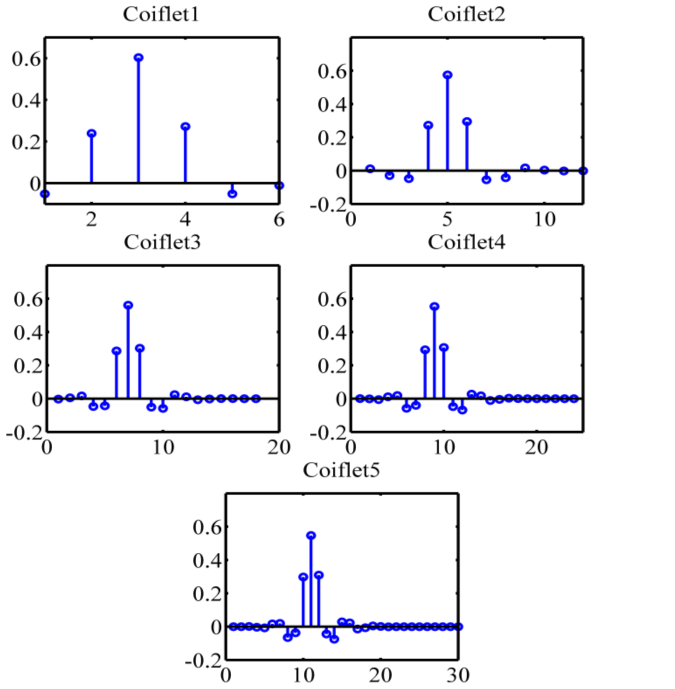

Figure.2. Coiflet wavelet families [17]

IV. RESULTS

Fig.3, presented the stator currents healthy case and open-circuit faulty case of an *IGBT* K_1.

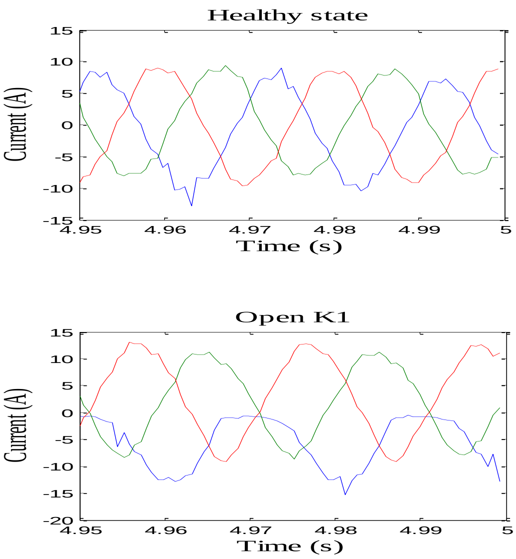

Figure.3. Stator current state healthy state and open-circuit K_1 (Experimental results)

Fig. 4 shows the coefficients of *(CWT)*, the stator current for scales between 0 and 70, respectively. In the healthy case and the open-circuit case of K_1.

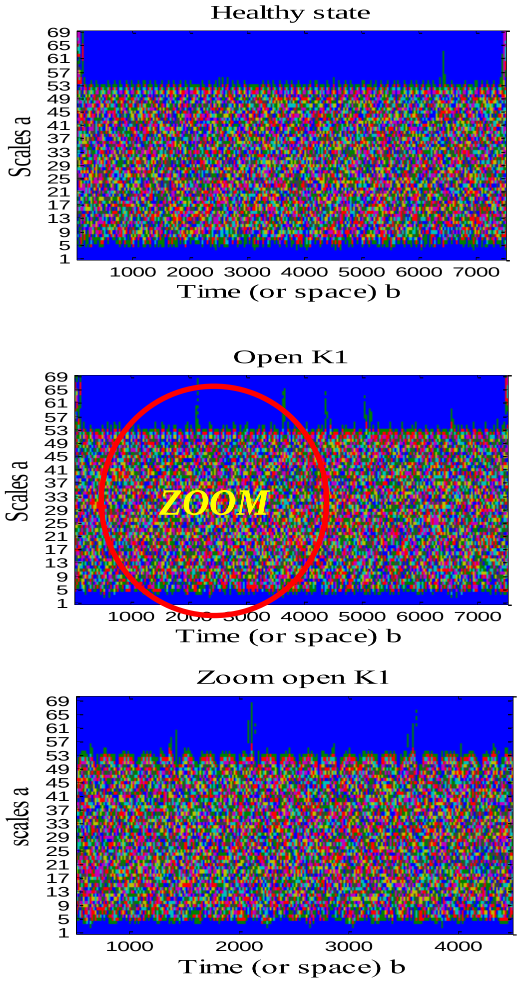

Figure. 4: Wavelet 'coiflet' case healthy and case of an open circuit fault K_1.

The experimental results obtained above by the application of the continuous wavelet transform (time-scale representation) to the current of a stator phase show that the coefficients $Cx(a, b)$ are stable in the interval *[0 7500]* In the case of operation in a healthy state, whereas in the case of open circuit of a switch, the coefficients begin to change their peak presence regimes (Fig. 5), this is an early index indicating that The arm A of the inverter will suffer from defects. In the case of an open circuit fault, there is a significant change in the localization of the *CWT* coefficients in the range *[950, 4500]* which indicates the presence of harmonics in the frequency interval *[95 Hz, 450 Hz]*.

Fig. 5 presents the spectra of the frequency ranges *[95Hz, 450Hz]*, for the healthy and the faulty cases. Fig. 5 shows the signal spectrum up to 450 Hz. As is evident with spectral analysis and for fault detection purposes, a peak is expected to occur around 100 Hz, 200 Hz, 300 Hz and 400 Hz, on the spectrum.

The spectrum in this case shows a peak around 100 Hz. A slightly higher spectral energy can also be observed from spectrum at approximately the same frequency. The latter coincides well with the frequency which characterizes the open circuit fault of an *IGBT*.

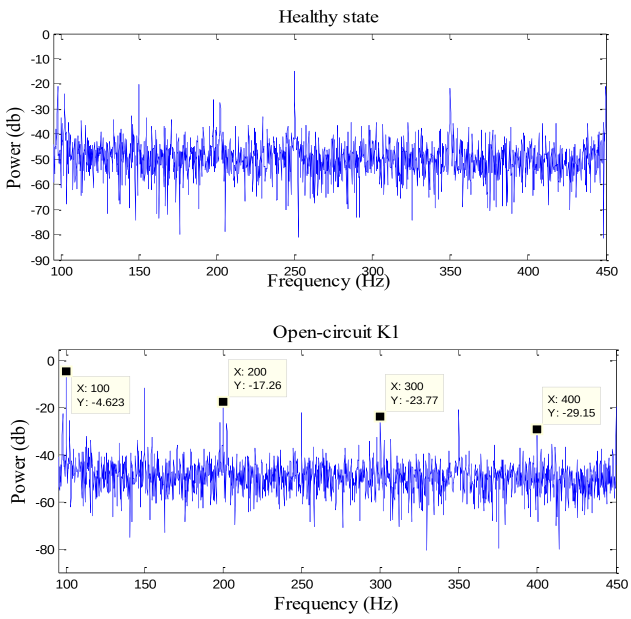

Figure.5. Harmonic spectrum corresponding of the frequency ranges [95Hz, 450Hz], for healthy case and open-circuit fault

The 100Hz harmonic is the harmonic that characterizes the open circuit fault of an *IGBT* we can summarize the open circuit fault signature synthesis of an *IGBT*.

Table.I presents the characteristics of an open-circuit fault.

TABLE I. FAULT SIGNING SYNTHESIS

TYPE FAULT	**OPEN-CIRCUIT IGBT**
SYMBOL	$F_{C\text{-}O}$
CURRENT	$F_S(1+K)$, *SI* $K=1,3,5,7$
VARIATION OF PARAMETER	phase current decrease $i_{open\text{-}circuit}=1/2\ i_{nominal}$
OBSERVATION	Presence of the harmonic 100Hz,200Hz, 300Hz,400Hz
HARMONIC CHARACTERIZES THE OPEN CIRCUIT FAULT	100Hz

V. CONCLUSION

This paper tackles a research dealing with the technique of diagnosis and detection of open-circuit fault in a three-phase two-level inverter fed induction motor controlled by the *SVM* strategy.

First, the *IGBT* open-circuit fault impact on the inverter-induction motor set is investigated. From the experimental results depicting the currents waveforms of the motor, it is impossible to ensure for long term the continuity of service of the motor in the presence of an open-circuit fault on one of the *IGBT* switches.

The paper also proposes a diagnostic technique based on the continuous wavelet transform *(CWT)* for the detection of an inverter *IGBT* open-circuit switch fault. The study focuses on the investigation of the harmonics (related to the obtained scale) which may appear in the spectrum due to the faults.

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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