Three-Phase Induction Motor Short Circuits Fault Diagnosis using MCSA and NSC

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***Abstract*— In this paper, a comparative study between two methods used to detect inter-turn short circuits in only one winding of the motor stator has been carried out. The first method is based on the Motor Current Signature Analysis (MCSA), while the second method is based on the Negative Sequence Component (NSC) analysis of stator current. The study showed the advantages and disadvantages of each method, and it also showed the change in the fault indicator for each method under different operating loads and in the presence of an inter-turn short circuit in only one winding of the motor stator. Experimental results proved that MCSA is more efficient to detect inter-turn short circuits in the stator winding.**

Keywords—Fault detection, Induction motor, Inter-turn, Motor Current Signature Analysis, Negative Sequence Component analysis.

I. INTRODUCTION

Currently, the asynchronous motor is becoming the key element in industry and is increasingly used in driving industrial equipment due to its robustness, ease of operation, low cost, etc. Induction machines make up more than 80% of the electrical machines used in the industrial and commercial sectors, [1]. Although it is reputed to be the most robust of electrical machines, a certain number of constraints of a very different nature (electrical, thermal, mechanical, and environmental) can restrict its lifespan, and lead to faults in the stator, rotor, or even both, which leads to unscheduled shutdowns leading to production losses and costly repairs. Monitoring industrial systems requires diagnostics of defects. Diagnostics consists of detecting changes in the state or behavior of the system, and in determining the cause of these changes. The general principle of diagnostics is based on the use of information from the system under consideration, as well as on the knowledge that we have about its operation in the absence and presence of a malfunction. Diagnosis of defects can be precisely defined as, [2]: "Determination of the possible cause of a defect using logical research based on a set of information obtained as a result of examination or test." This definition summarizes two main diagnostic tasks: monitoring the indicators of a malfunction or defect, and determining the cause of the defect through logical processing of a set of observations. Failures in the induction motor can be of mechanical origin (eccentricity of the rotor, fault in the couplings, wear of the bearings, etc.), electrical or magnetic (short circuit of the stator winding, breakage of the bar or ring, etc.). Imperfections can also be due to other elements of the drive, such as power supply faults from the power source (network or power converter). Fig. 1 shows the percentage of faults occurring in induction machines, [3].

Based on the statistical study, described in Fig. 1, it can be noticed that the short circuit in the stator windings is one of the main causes of electrical failure of electrical machines. Gradual deterioration of winding insulation can be caused by overheating, transient over voltages, coil movement, or contamination. This fault produces high currents and generates an overheating in the winding that can quickly result in severe faults between windings of different phases or between the windings and ground, producing irreversible damage to them or to the core, [4]. For this reason, early detection of short circuit faults between turns during motor operation is very important.

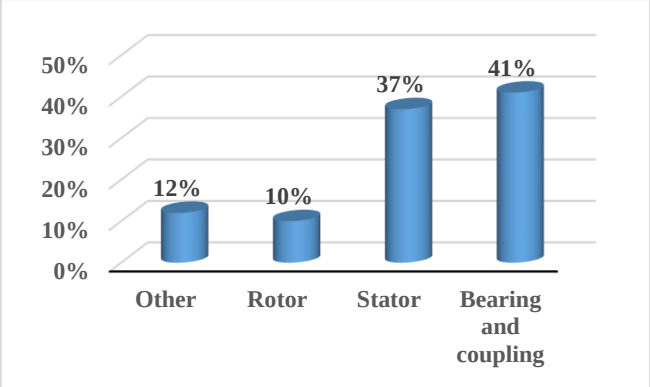

Fig. 1. Percentages of defects that occur in an induction machine.

There are several methods for fault diagnosis in the stator winding of induction motors (IM). Signal processing methods are now widely used in diagnosis due to their efficiency, simplicity, and lack of the need for mathematical modelling of the machine [5]. This approach depends on knowing the system's behavior in the absence of defects and then comparing it to the measured signals. Diagnostic techniques that depend on signal processing can generally be classified into two groups: spectral analysis and temporal analysis as shown in Table I [6].

The appearance of the inter-turn short circuits leads to an increase in the asymmetry of the stator winding currents, thus the negative-sequence component of current changes when a fault occurs [7-8]. For this reason, some short circuit detection techniques rely on detecting changes in the negative-sequence component of current. Also, due to symmetry in electrical machines, any defect that occurs in the machine will lead to a distortion in the distribution of the magnetic field in the air gap of the machine, which leads to the appearance of harmonics in the measured signals such as the stator current, through which

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we can distinguish between these faults. Monitoring the stator current spectral components of the motor allows us to monitor its operation. In this paper, a comparative study between two methods used to detect inter-turn short circuits in only one winding of the motor stator has been carried out. The first method is based on motor current signature analysis (MCSA), while the second method is based on the negative sequence component analysis of stator current (NSC).

TABLE I. CLASSIFICATION OF DIAGNOSTIC TECHNIQUES BASED ON SIGNAL PROCESSING

Diagnostic techniques based on signal processing	
Temporal analysis	Spectral analysis
• Negative-Sequence Current • Sequence Impedances • Zero-Sequence Voltage	• Axial Leakage Flux • Current • Electromagnetic Torque • Vibration

II. DIAGNOSIS OF INTER-TURN SHORT CIRCUITS BY SPECTRAL ANALYSIS OF THE STATOR CURRENT

Stator current spectral analysis is a powerful tool for detecting the presence of mechanical or electrical anomalies in motors, and also in their loads. The signals of the currents have the advantage of being easily measurable using a lower-cost sensor [9-10].

In the presence of a defect in the insulation between the stator windings, this will lead to a modification of the magnetic flux density in the air gap. Inter-turn short circuits in the stator winding of the motor can be compared to deleting some turns in the winding. The electromotive force (EMF) inside the shorted turns, creates a current that flows only through the equivalent impedance of the shorted circuits. This current creates a magnetomotive force (MMF) whose frequency content is added to the frequency content of the main magnetic flux [11].

It has been established that the frequencies related to the occurrence of an inter-turn short circuit in the winding of a low-voltage electric motor can be expressed in the following relation, [12]:

$$f_{st} = f_s \cdot \left[\left(h_t \pm \frac{n(1-s)}{p} \right) \right] \begin{matrix} n=1,2,3,.. \\ h_t=1,3,5 \end{matrix} \quad (1)$$

$$f_{st} = h_t f_s \pm n f_{2s}; n \neq 2p; p = 2 \quad (2)$$

where f_s is the power frequency in Hz, p is the number of pole pairs, s is the motor slip.

III. ANALYSIS OF SYMMETRICAL COMPONENTS OF CURRENT

The presence of electrical damage, in particular a short circuit between the turns, leads to an imbalance in the phase currents, which, in turn, leads to the appearance of a reverse current component. Symmetrical components are increasingly used to detect asymmetric systems due to electrical stator faults. There is a simple method for converting a three-phase system of initial stator currents into a single number of components with equivalent complex values. An effective way to concentrate the information contained in a three-phase system is to calculate its "space vector". This quantity with complex and time-dependent values is obtained from the symmetrical components originally proposed by Fortescue for the analysis of three-phase sinusoidal quantities.

This transformation, applied to the three-phase system of currents $I_a(t)$, $I_b(t)$, and $I_c(t)$ is expressed in the following reversible matrix form [13, 14]:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} = \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} * \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}, \alpha = e^{j\frac{2\pi}{3}} \quad (3)$$

The method of symmetrical components is widely used to calculate asymmetric modes of a three-phase network, for example, short circuits. The specific nature of the electrical quantities analyzed for this application allows for several simplifications of Eq. (3). First, since stator currents are real-valued quantities, the instantaneous forward and reverse components (positive $I_{a1}(t)$, and negative $I_2(t)$ sequences) are complex and conjugate to each other and are therefore completely equivalent. Furthermore, the sum of the three stator currents is zero and the instantaneous zero sequence component $I_{a0}(t)$ is zero for all (t). Under these assumptions, all the information carried by the original three-phase system is contained in the single instantaneous reverse component $I_{a2}(t)$.

The reverse current I_{a2} is calculated by the following relationship that extracted from Eq. (3):

$$\mathrm{I_{a2}} = \frac{1}{3}(\mathrm{I_a} + \alpha^2 \mathrm{I_b} + \alpha \mathrm{I_c}) \; ; \alpha = e^{j\frac{2\pi}{3}} \quad (4)$$

Finally, we can notice that according to the previous hypotheses, Eq. (4) transforms (I_a (t), I_b (t), and I_c (t)) into (I_{a2} (t)), through which the severity and location of the fault can be known.

IV. EXPERIMENTAL SETUP OF THE PRESENT WORK

A set of laboratory equipment is represented in Fig. 2, which consists of a three-phase squirrel cage induction motor having the specifications shown in Table II, three voltage sensors, and three current sensors. The tests were performed on an induction motor whose specifications are:(11kW, 220V/400 V, I_n = 22.5A, COS θ = 0.83, n = 1460 rpm, T_n = 72 N.M). The signals - coming out of the sensors are converted into digital signals through an electronic collection card with a maximum frequency of 200 kHz and a resolution of 12 bits, which will be analyzed using the MATLAB program.

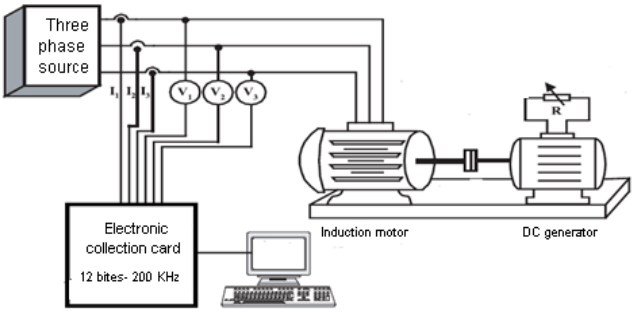


Fig. 2. Elements of the experimental procedure

One of the stator windings has been modified so that we can simulate the electrical short circuit between the turns.

Short circuit is accomplished outside the motor by connecting the ends of the winding that has been modified to an external terminal box and via a resistor R_{st} that allows reducing the fault current.

TABLE II. PARAMETERS OF THE MOTOR UNDER EXPERIMENT

Parameter	Data
Power	11 KW
Frequency	50 Hz
No. of phases	3
Speed	1460 rpm
Voltage	230/400 V
No. of pole pair	2

Two turns of the stator winding of the motor can generate high current (greater than the nominal current) within these short turns which may cause severe damage to the winding insulation. Therefore, we had to maintain the integrity of the machine by limiting this current using a resistance. From here it can be assumed that the fault that we simulated is less in intensity than the real fault, and therefore, if the two methods under study were able to detect this fault, they are able to detect the true short circuit where the resistance is non-existent. Voltage and currents were measured by three voltage sensors and three current sensors.

V. MCSA FOR INTER-TURN SHORT CIRCUITS WITH (0 - 100%) COUPLED LOAD

The MCSA principle is based on the presence of certain frequency components that reflect the behavior of the induction machine in normal operation and the behavior of the induction machine in the event of a fault. The first step in this method is to receive signals from current sensors. Then their spectral content and its change are determined. Since this fault detection scheme is dependent on the frequency components of the current, an appropriate spectral algorithm must be used to determine the fault signatures. A Welch spectrum applied in MATLAB is used in this study. This technology provides significant noise reduction, making it easier to identify the frequency components associated with the fault. This experiment is performed under normal operation and operation with a short circuit between stator turns. Where the percentage of shorted turns is only (2-6) % under different loading conditions (without load and nominal load). Fig. 3 shows the fundamental harmonic of the stator current spectrum of an induction motor operating under no-load for a bandwidth of 0 to 500 Hz. On the one hand, we can notice that the spectral components at the frequencies $f_s - f_{2s}$, $f_s + f_{2s}$, are already present in the current spectrum of the healthy machine, and this can be explained by the natural dynamic eccentricity of the machine.

Fig. 3 shows the increase in amplitudes of the same components presented by the Eq. (1) due to the presence of short turns in the stator winding of the motor.

Fig. 4 shows the frequency spectrum of the stator current at 100% of the nominal load. This test is used to demonstrate that the inter-turn short circuits can be detected under higher loading conditions. As expected, the frequency spectral amplitude $f_s - f_{2s}$, $f_s + f_{2s}$ exhibits a constant behavior under this load condition, as the amplitude of the frequency components increases with increasing the percentage of shorted turns in the stator of the motor.

It can be seen that the frequency components that have been adopted as indicators of failure (spectrum signatures) are less sensitive in the non-load operation compared to the operating condition at the nominal load, and this is due to the fact that the phenomena affecting the machine in the case of no-load current are less than the nominal load current. The most important of these phenomena is the magnetic flux. Nevertheless, we see that the studied fault is detectable in the case of no-load operation as in the case of nominal operation even for the ratio of shorted turns only 2%. Frequencies and amplitudes of the components introduced by the short-circuit, for different load conditions, are shown in Tables III and IV.

Tables V and VI show the comparison of theoretical and experimental fault frequencies under no load and full load conditions along with the error percentage.

TABLE III. THE AMPLITUDES OF THE SPECTRAL COMPONENTS DUE TO SHORT CIRCUIT- NO LOAD ($S \approx 0$).

No Load				
Formula (around the fundamental harmonic)	Freq. (Hz)	Amplitude (dB)		
		Healthy	Fault	
			2%	6%
$h_t f_s - n f_{2s} = f_s - f_{2s}$; $h_t=1$; $n=1$	25	-40.25	-37.16	-34.57
$h_t f_s + n f_{2s} = f_s + f_{2s}$; $h_t=1$; $n=1$	75	-40.84	-37.87	-34.5

TABLE IV. THE AMPLITUDES OF THE SPECTRAL COMPONENTS DUE TO SHORT CIRCUIT- FULL LOAD($S \approx 0.0268$)

full Load				
Formula (around the fundamental harmonic)	Freq. (Hz)	Amplitude (dB)		
		Healthy	Fault	
			2%	6%
$h_t f_s - n f_{2s} = f_s - f_{2s}$; $h_t=1$, $n=1$	25.66	-39.36	-32.83	-28.89
$h_t f_s + n f_{2s} = f_s + f_{2s}$; $h_t=1$, $n=1$	74.33	-39.64	-34.14	-29.98

TABLE V. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL FAULT FREQUENCIES AND % ERROR (NO-LOAD).

Formula	Freq- Eq(1) Hz	Freq-real (Hz)			error %
		fault severity %			
		0%	2%	6%	
$f_s + f_{2s}$	75	74.8	74.8	74.8	0.27
$f_s - f_{2s}$	25	25.2	25.2	25.2	0.8

TABLE VI. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL FAULT FREQUENCIES AND % ERROR (FULL LOAD).

Formula	Freq- Eq. (1) Hz	Freq-real (Hz)			error %
		fault severity %			
		0%	2%	6%	
$f_s + f_{2s}$	74.33	74.4	74.8	74	0.1
$f_s - f_{2s}$	25.66	26	25.6	26	0.81

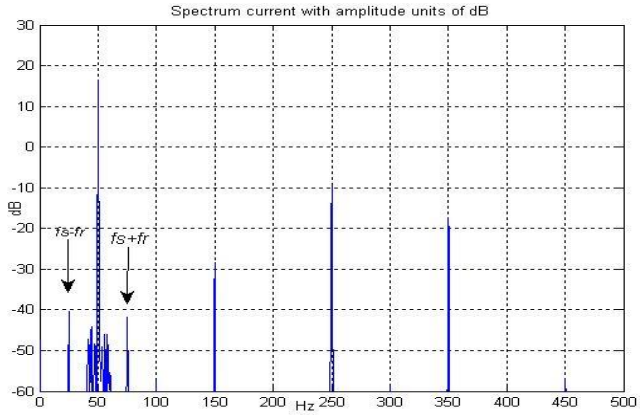
The experimental results show that both experimental and theoretical fault frequencies are close together, so the effect of the load is negligible compared to the change occurring between a healthy and a faulty motor.

VI. NCS FOR INTER-TURN SHORT CIRCUITS WITH (0 - 100%) COUPLED LOAD

NSC is implemented by reprogramming Eq. (4) in MATLAB software environment. The results of the experiments are presented in Fig. 5 and Fig. 6 under different operating conditions (no-load - full load) with three fault severities (0 %, 2 %, and 6% of shorted winding). Data from the three phases are used to obtain I_{a2}. The results are set out in Table VII which shows the amplitude of negative sequence component (NCS) for different loading conditions and with different percentages of shorted turns. As shown in Fig. 5, the method that has been implemented is poorly sensitive to distinguish between healthy and defective conditions when the motor is not loaded with 2% of shorted turns, but this sensitivity increases clearly for the percentage of shorted turns 6%. Hence, we can say that there is a clear relationship between the fault severity and the size of the negative series current indicator. As shown in Fig. 6, in the case of operating under the full load, with inter-turn short circuits (0%, 2%, and 6%) it can be seen that the amplitude of the Negative Sequence Component of the current (I_{a2}) increases even in the case of the healthy machine, and therefore this requires us to establish a relationship between the load level and the fault indicator in order to avoid false alarms during operation. This complicates the application of this approach for inter-turn short circuits detection.

TABLE VII. NSC AMPLITUDE FOR DIFFERENT LEVELS OF LOAD AND FAULT SEVERITY

Percentage inter-turn short circuits %	The amplitude of the Negative Sequence (pu)	
	No-load	nominal load
0%	0.02	0.0791
2%	0.0215	0.081
6%	0.031	0.0978



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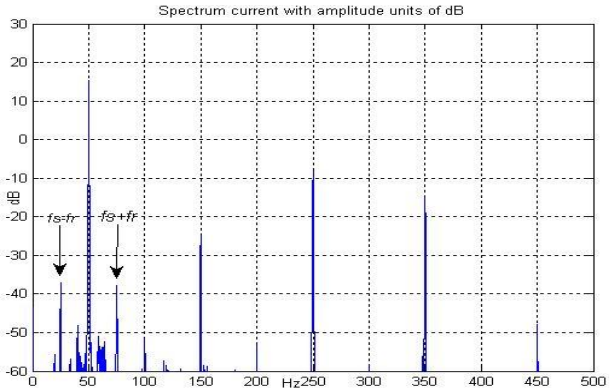

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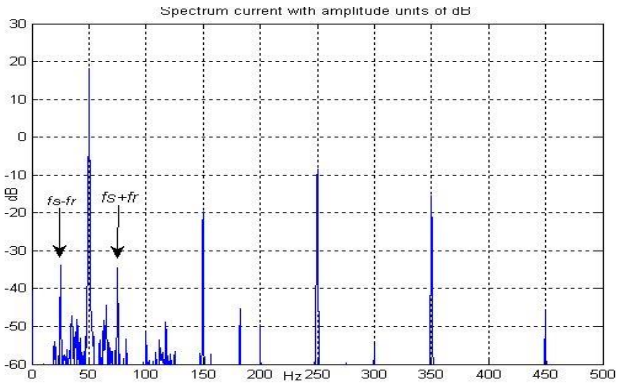

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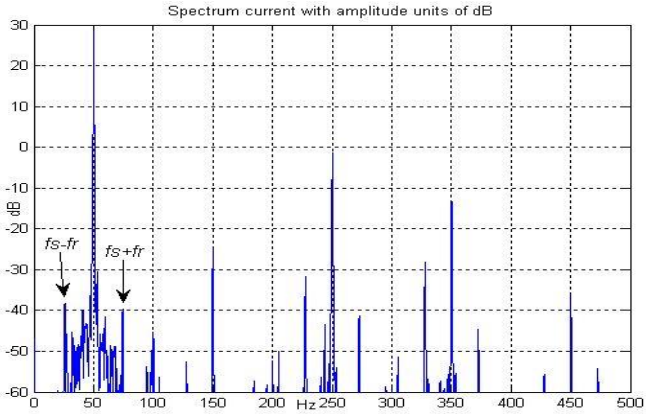
Fig. 3. Spectrum of current without load: a) healthy machine, b) machine with short-circuit 2%, c) machine with short-circuit 6%.



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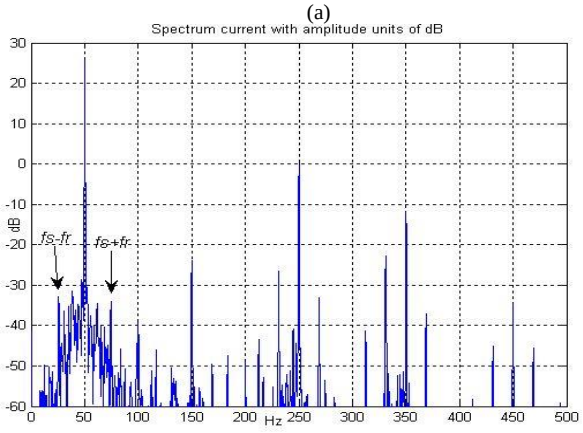

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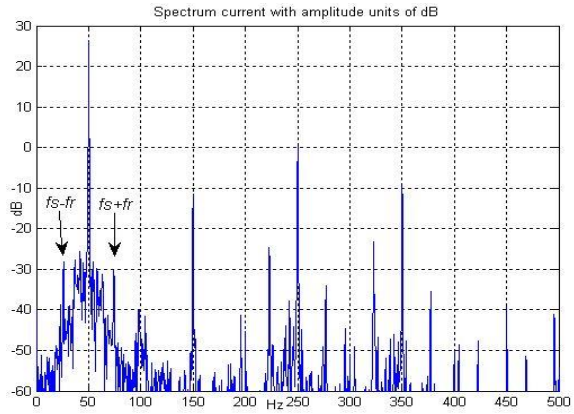

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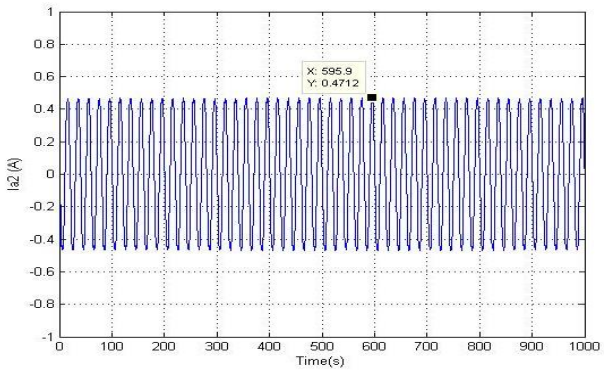
Fig. 4. Spectrum of current with nominal load: a) healthy machine; b) machine With short-circuit 2% c) machine With short-circuit 6%.



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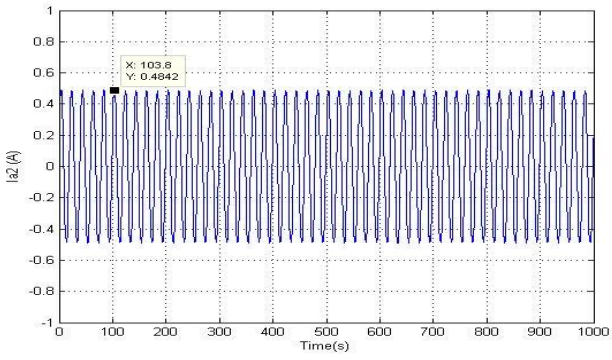

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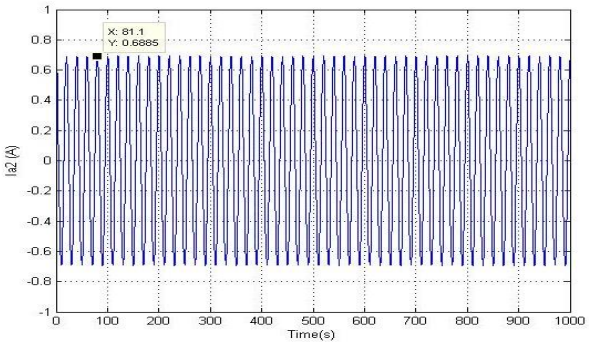

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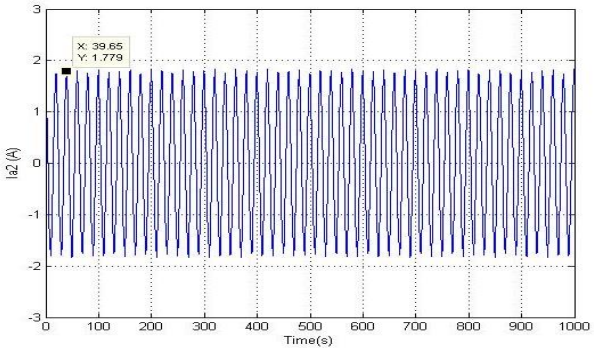
Fig. 5. Negative sequence current without load : a) healthy machine; b) machine With short-circuit 2% c) machine With short-circuit 6%.



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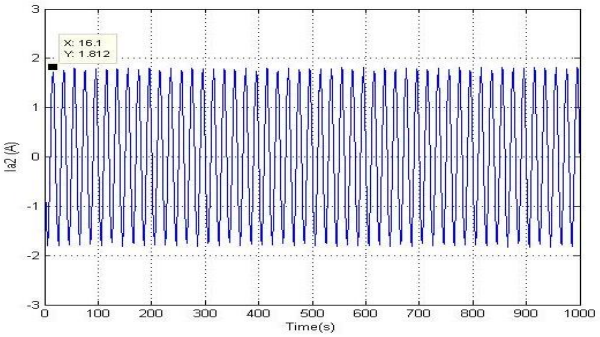

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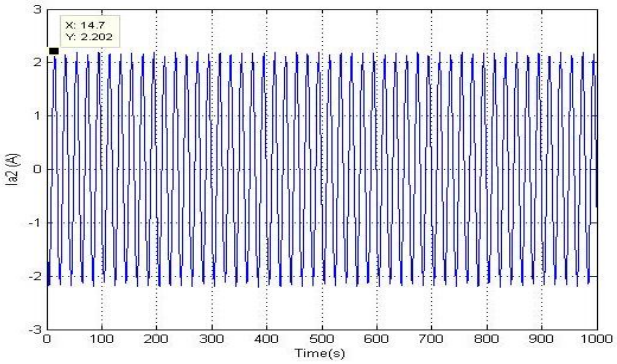

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Fig. 6. Negative sequence current with nominal load: a) healthy machine; b) machine With short-circuit 2% c) machine With short-circuit 6%.

I. CONCLUSION

In this paper, a comparative study between two methods MCSA and NSC for detecting inter-turn short circuits in one winding of the motor stator with different loading conditions and fault severities has been carried out.

MCSA: The experimental results show an increase in the frequency components presented by Eq. (1) when (h_t = 1, n = 1) in different fault conditions and at different loads, where the behavior of this frequency component is consistent with the expected results in most of the studied malfunctions. The frequency component is less sensitive in the conditions of operation without load compared with the operation under full load, however, it is noticed that the considered fault remains detectable even with the severity of the failure not exceeding 2%. Moreover, the experimental results show that both experimental and theoretical fault frequencies closely, so the effect of the load is negligible compared to the change

occurring between a healthy and a faulty motor, but it is important to know the slip precisely to avoid false alarms.

NSC: The experimental study shows that the NSC technology is able to detect the malfunction and determine its severity under different loading conditions and different levels of failure severity if the relationship between the negative component and the loading conditions is known in advance. Another disadvantage of this method is that the electrical supply provided to the motor must be balanced because the negative component reflects the state of imbalance, which arises not only from the short circuit between the stator windings but also from the unbalanced electrical supply, as it can affect the behavior of the negative component and leads to false alarms.

From the above, it can be said that there is no general method of diagnosis that has all the advantages and does not have any disadvantages, but MCSA can be considered the most appropriate way to reach the goal of diagnosis because it presented a greater ability to detect the inter-turn short circuits (even for the percentage of shorted turns only 2%) and with different loading conditions. In addition, in MCSA condition monitoring is performed by monitoring only one phase current not three-phase currents as in the case of the NSC method.

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