A New Method to Detect Inter-Turn Short-Circuit in Induction Motors

M. Sahraoui, S. E. Zouzou, A. Ghoggal, and S. Guedidi.

Abstract -- **It is well known that stator winding faults such the inter-turn short circuit are the most frequent source of breakdowns in induction motors. Early detection of any small inter-turn short circuit during motor operation would eliminate some subsequent damage to adjacent coils and stator core, reducing then the repair cost. To achieve this purpose, the present paper proposes a new method, called Park-Hilbert (P-H), to detect stator faults in induction motors using a combination between the Hilbert transform and the Extended Park's Vector Approach. The P-H approach is based on the spectral analysis, via the FFT, of the $PSVM_{P-H}$ that represents the Park's Square Vector Modulus computed starting from the amplitudes of the three-phase current's analytical signals obtained by Hilbert Transform. The theoretical bases of the P-H method are presented, and the experimental tests which are carried out on a special 3kW three-phase induction motor confirm the efficiency of the proposed method and corroborate that this fault doesn't have new specific spectral signatures, but it causes important increases on the amplitudes of all harmonics that were present in the $PSVM_{P-H}$ spectrum, even those related to other faults.**

Index Terms--**Diagnosis, induction motors, inter-turn short circuit, Hilbert transform, Park's Vector Approach.**

I. INTRODUCTION

THE three-phase squirrel cage induction motors are the most common prime machines in industrial processes. Usually, the induction motors work under many stresses from various natures (thermal, electrical, mechanical and environmental) which can affect their lifespan by involving the occurrence of stator and/or rotor faults [1], [2]. The need for on-line condition monitoring of large induction motors has increased because a sudden failure of critical motor can cause great economical losses. Therefore, the main goal is to reduce the maintenance costs and to prevent unscheduled downtime of these machines.

Failure surveys [3] have reported that 40% of the motor failures were caused by bearing related failures, 38% by stator winding failures, 10% by rotor related failures and 12% by mixed failures which affect other parts of the machine. It is obvious that stator winding faults are the most frequent source of breakdowns in induction motors. Also, it should be noted that the majority of stator winding failures result from crash of turn-to-turn insulation; this produces thermal hotspots causing progressive degradation that eventually can grow to a complete winding failure. This kind of defects is usually due to an electrical, thermal, mechanical and environmental stress. Usually, a short circuit of a small number of turns doesn't have great physical signs, but it can lead to a catastrophic insulation failure in a short time. Early detection of inter-turn short circuit during motor operation would eliminate some subsequent damage to adjacent coils and stator core, reducing then the repair cost and motor outage time.

There are a great number of papers presenting many techniques used to detect winding faults such inter-turn short-circuit [1], [2]. For example, Penman et al [4] have used the axial leakage flux monitoring as a method for detecting the occurrence of an inter-turn short circuit by means of a large coil fixed concentrically around the machine shaft whilst the motor was operating. Also, they state that the fault position could be located by monitoring four coils placed symmetrically in the four quadrant of the motor at a radius of about half the distance from the shaft to the stator end winding. In [3] and [5] Thomson et al. proved, through a lot of experimental results on industrial motors, that inter-turn short circuit fault can be detected accurately in low voltage stator windings of induction motors by using the motor current signature analysis (MCSA) based on the monitoring of the frequency components expressed by:

$$f_{sc} = f_s \left\{ \frac{n}{p}(1-s) \pm k \right\} \tag{1}$$

where f_s is the fundamental supply frequency, n is any integer and $k = 1,3,5,\ldots$. In [6], Nandi *et al.* proposed a novel method based on the monitoring of certain rotor-slots-related harmonics at the terminal voltage of the machine, once it is switched off. Unlike negative sequence current or impedance measurement, this technique is insensitive to supply voltage unbalance. In [7], it was reported that the observation of the air-gap torque could be used as a method to diagnose some faults on both stator and rotor sides. The Extended Park's Vector Approach (EPVA) has also been successfully applied for the diagnosis of stator winding faults in three-phase induction motors by monitoring the behavior of a spectral component at twice the fundamental supply frequency [8]. It was shown that the amplitude of this spectral component is directly related to the severity of this fault.

Among all these techniques, the EPVA has presented many advantages during detection of all kinds of faults in induction motors [8], [9], [11]. In addition, this method uses the three-phase currents which are easily to acquire and they give good information about the machine state.

On the other hand, one can observe a growing interest on the use of Hilbert Transform (HT) in the condition-monitoring

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field [12]–[14]. This is mainly due to the fact that HT enables to follow, separately, the changes that appeared on both modulus and phase of any acquired signal.

In order to improve the diagnosis of stator winding faults in induction motors, the authors propose a new method, called Park-Hilbert (P-H), that combines between the EPVA and the HT and profits, then, from their advantages.

II. Theoretical Background

A. The Inter-Turn Short-Circuit

The effect of the inter-turn short-circuit fault is to remove some turns from stator windings, and create then a shorted turns [16]. This changes the stator MMF and consequently causes small but finite effect on the stator flux density. More information about the analytical study of the induction motors at healthy state and with such fault can be found in [10], [15], [22].

B. The Extended Park's Vector Approach

The EPVA is a simple and efficient diagnosis method; it is based on the spectral analysis of Park's Vector Modulus (PVM) that is computed as:

$$PVM = \sqrt{\left(i_d^2 + i_q^2\right)} \qquad (2)$$

where i_d and i_q are the Park's vector components which are computed using the three-phase currents as follows:

$$\begin{cases} i_d(t) = \sqrt{\frac{2}{3}} i_A(t) - \sqrt{\frac{1}{6}} i_B(t) - \sqrt{\frac{1}{6}} i_C(t) \\ i_q(t) = \sqrt{\frac{1}{2}} i_B(t) - \sqrt{\frac{1}{2}} i_C(t) \end{cases} \qquad (3)$$

The analysis of the PVM has been, successfully, used to detect stator winding faults [8], by only the identification of a spectral component at twice the fundamental supply frequency.

C. The Hilbert Transform

The Hilbert Transform is a signal analysis method that is frequently used in different scientific fields. Mathematically, the HT of a real signal $x(t)$ such as the phase current is defined as the time-domain convolution of $x(t)$ with $1/t$ and can emphasise the local properties of the real signal as follows:

$$y(t) = HT\{x(t)\} = \frac{1}{\pi t} * x(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (4)$$

The so-called analytical signal $\bar{x}(t)$ is obtained by coupling $x(t)$ with its HT, as follows:

$$\bar{x}(t) = x(t) + jy(t) = a(t)e^{j\theta(t)} \qquad (5)$$

with

$$a(t) = \sqrt{\left[x^2(t) + y^2(t)\right]} \qquad (6)$$

$$\theta(t) = \arctan\left(\frac{x(t)}{y(t)}\right) \qquad (7)$$

Where $a(t)$ is the instantaneous amplitude of the $\bar{x}(t)$, and $\theta(t)$ is the instantaneous phase of the $\bar{x}(t)$.

This means that HT enables to study, independently, the changes that happen on both amplitude and phase of any signal acquired from the machine. This represents an important application of the Hilbert Transform, since the occurrence of faults in induction motors cause amplitude and phase modulations in the supply currents [13], [14].

D. The Park-Hilbert Approach (P-H)

Using the HT, one can compute the Instantaneous Amplitude (IA) of a single phase current (6); its spectrum has been successfully used to detect broken rotor bars in induction motors [12], [14]. However, the three-phase induction motors have three-phase currents which can be considered as three sources of information. Hence, one can calculate the IA corresponding to each phase current; and in order to gather the information provided by these signals, the authors propose to apply the EPVA on these three IA. Consequently, the proposed approach will be based on the following steps:

1) Acquisition of the three-phase currents(i_A, i_B, i_C);
2) Computation of the three analytical signals ($\bar{i}_A, \bar{i}_B, \bar{i}_C$) corresponding to the three-phase currents using (4);
3) Determination of the IA of each analytical signal ($|\bar{i}_A|, |\bar{i}_B|, |\bar{i}_C|$) using (5);
4) Calculation of the Park's vector components ($i_{d.P-H}, i_{q.P-H}$) using:

$$\begin{cases} i_{dP-H}(t) = \sqrt{\frac{2}{3}} \left|\bar{i}_A(t)\right| - \sqrt{\frac{1}{6}} \left|\bar{i}_B(t)\right| - \sqrt{\frac{1}{6}} \left|\bar{i}_C(t)\right| \\ i_{qP-H}(t) = \sqrt{\frac{1}{2}} \left|\bar{i}_B(t)\right| - \sqrt{\frac{1}{2}} \left|\bar{i}_C(t)\right| \end{cases} \qquad (7)$$

5) Computation of the $PSVM_{P-H}$ corresponding to (7), as follows:

$$PSVM_{P-H} = i_{d.P-H}^2 + i_{q.P-H}^2 \qquad (8)$$

6) Analysis, via the FFT, of the $PSVM_{P-H}$.

These steps show that the proposed approach combines the efficiency of the EPVA and the improvements given by HT, and it profits from the simplicity of spectral analysis via the FFT. Moreover, the consideration of three-phase currents provides a more meaningful spectrum than the one obtained by the conventional MCSA.

III. Experimental Results

The test bench used in the experimental investigation is available at the LGEB in university of Biskra-Algeria. The motor exploited to study the occurrence of inter-turn short-circuit faults was a three-phase 50-Hz, Y connection, 4-pole, 3kW *Leroy Somer* squirrel-cage induction machine. The stator winding was modified by the addition of five tappings connected to the stator coils of the phase ***W1-W2*** (Fig.1). The other ends of these external wires are connected to a motor terminal box that allows introducing inter-turn short circuits with different number of turns (Fig.2).

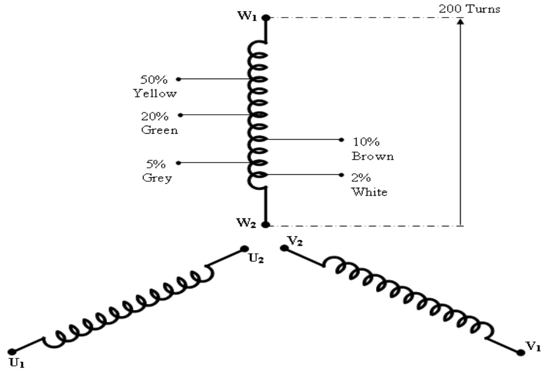

Fig. 1. The five tappings connected to the stator coils of the phase W1-W2.

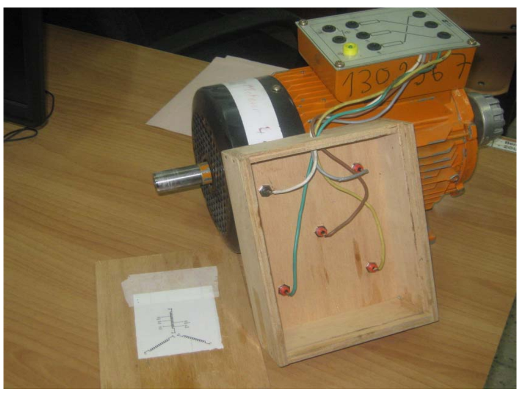

Fig. 2. The external wires connected to the motor terminal box.

The motor was tested initially at healthy state then with 10 short-circuited turns under medium load ($s = 0.022$). In both cases, 10s of the three-phase currents were sampled at 10 kHz. After acquisition, the six steps of the proposed approach were applied to calculate the $PSVM_{P-H}$. Then, all data were processed using the MATLAB software package to compute the fast Fourier transform (FFT). The spectrums obtained from both proposed method and conventional MCSA are shown in Fig.4 and Fig.5.

According to Fig.4, it is obvious that single phase current spectrum contains all harmonic types, with relatively small amplitudes, even in healthy state. Consequently, and since the $PSVM_{P-H}$ is computed starting from three-phase currents, its spectrum will comprise all these harmonic types but shifted by f_s as shown in Table1. (Where ν the order of the time harmonics and k an integer). As can be clearly seen, the occurrence of inter-turn short circuit doesn't induce new spectral components in the phase current's spectrum but, it causes modifications on the amplitudes of all harmonics that were present. These corroborate some previous results [10], [15], [16].

Fig.5 shows the $PSVM_{P-H}$ spectrum at healthy state and with 10 turns short-circuited. Note that linear scale, instead of logarithmic scale has been used for the vertical axis, greatly improving the legibility of the graph. In order to observe the changes which happen on all component amplitudes, the $PSVM_{P-H}$ spectrums are visualized in different frequency ranges.

It is obvious that all spectral components (shown in Table1) are present in the $PSVM_{P-H}$ spectrum (in particular the TH and RSH harmonics), even in normal conditions, but relatively with small amplitudes; this is directly related to the existence of residual asymmetries in both stator and rotor.

When a short-circuit of 10 turns is introduced, great changes can be observed on the $PSVM_{P-H}$ spectrum.

Analyzing Fig.5, one can observe that :

1) All TH raise significantly due to inter-turn short-circuit (look at $2f_s$, $4f_s$, $6f_s$, $8f_s$, ..);
2) This fault increased considerably the majority of the RSH, especially the $|10f_s - N_r f_r|$, $|12f_s - N_r f_r|$, $|14f_s - N_r f_r|$ and $|18f_s - N_r f_r|$);
3) The RBFH, which represent the theoretical signatures of broken rotor bars, are also increased notably due to the inter-turn short circuit (look at $(2 \pm 2s)f_s$, $(4 \pm 2s)f_s$, $(4-4s)f_s$, $(6-4s)f_s$ and $(6-8s)f_s$);
4) All EFH which represent the theoretical signatures of the air-gap eccentricity, are augmented greatly especially the f_r , $11f_r$, $13f_r$, $|2f_s \pm f_r|$ and $|4f_s \pm f_r|$.

According to Fig.4 and Fig.5, it is obvious that $PSVM_{P-H}$ harmonics are extremely sensitive to the presence of inter-turn short circuit than those of one phase current; this confirms the superiority of the proposed method comparing to the conventional MCSA.

IV. Conclusion

This paper has introduced a new method for detecting inter-turn short circuit in induction motors. The proposed method was based on the spectral analysis, via the FFT, of the Park's Square Vector Modulus computed starting from the amplitudes of three-phase current's analytical signals obtained by Hilbert Transform. It was shown that the proposed method combined and profited from the advantages given by both EPVA and HT; thus, it was called *Park-Hilbert (P-H)*. The theoretical bases of this method and the steps constituting its algorithm were also presented.

Several experimental tests have shown that the occurrence of inter-turn short circuit in stator windings increased, significantly, all harmonics that were present in spectrum of the $PSVM_{P-H}$, even those related to other defects such as the broken rotor bars (RBFH) or the air gap eccentricity (EFH). In addition, a comparison with the conventional MCSA has proved the superiority of the proposed method.

Comparative studies, in different operating conditions, with other methods such as the EPVA are currently in progress, in order to evaluate the competences of the proposed method.

TABLE1. GENERAL EXPRESSION OF DIFFERENT SPECTRAL COMPONENTS APPEARING IN THE SPECTRUM OF STATOR CURRENTS AND $PSVM_{P-H}$.

Harmonic Types	The general expression of their frequencies in :		Their causes
	Current Spectrum	$PSVM_{P-H}$ Spectrum	
Time Harmonics (TH)	νf_s	$(\nu - 1) f_s$	Imposed by the supply source or residual asymmetry in stator windings [10], [16]
Rotor Slot Harmonics (RSH)	$\lvert \nu f_s \pm N_r f_r \rvert$	$\lvert (\nu - 1) f_s \pm N_r f_r \rvert$	Imposed by the rotor structure (discrete distribution of the rotor bars in rotor slots) [19], [20]
Rotor Bar Fault Harmonics (RBFH)	$\lvert (\nu \pm 2ks) f_s \rvert$	$\lvert [(\nu - 1) \pm 2ks] f_s \rvert$	Due to the inherent rotor cage asymmetries[18], [21]
Eccentricity Fault Harmonics (EFH)	$\lvert \nu f_s \pm k f_r \rvert$	$\lvert (\nu - 1) f_s \pm k f_r \rvert$	Due to the inherent level of mixed eccentricity [17], [19], [20]

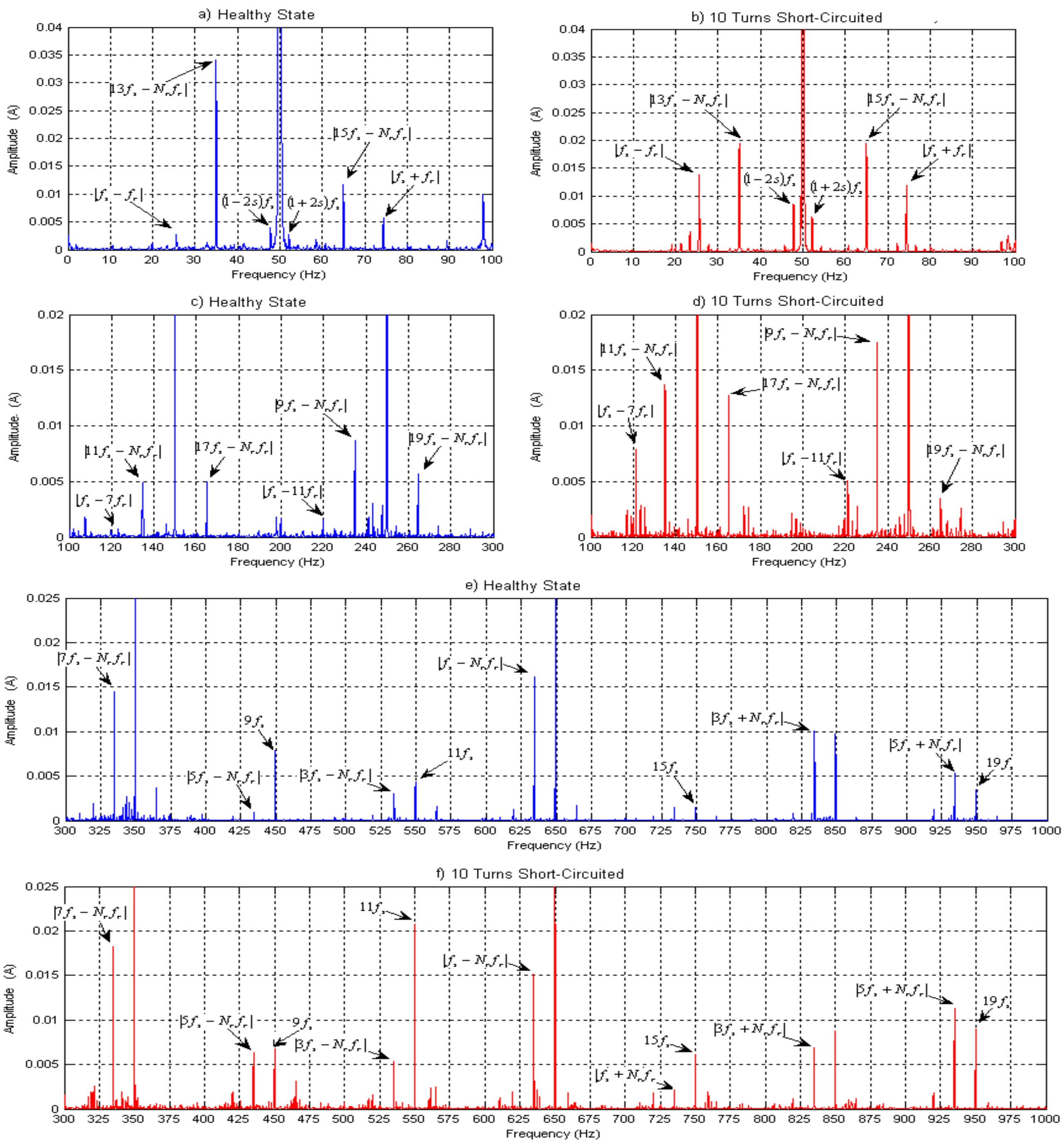

Fig. 4. Spectrum of a phase current for healthy motor and with 10 turns short-circuited under medium load.

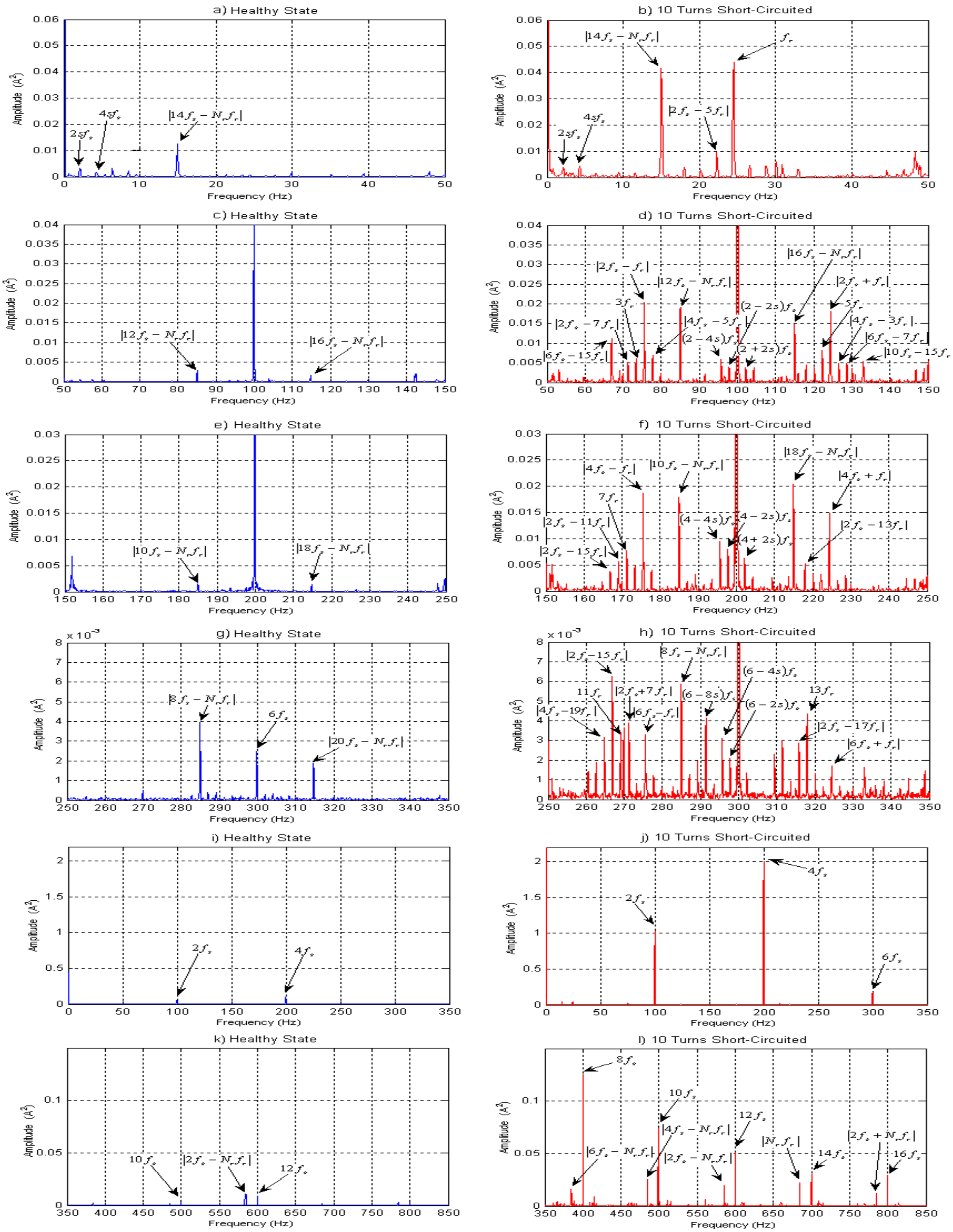

Fig. 5. Spectrum of the $PSVM_{P-H}$ for healthy motor (all left figures) and with 10 turns short-circuited (all right figures) under medium load.

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V. Biographies

Mohamed Sahraoui was born in Biskra, Algeria in 1978. He received the Engineer and the "Magistère" degrees in electrical engineering both from the University of Med Khider of Biskra, Algeria in 2001 and 2003 respectively. He is interested in the modelling, condition monitoring and faults diagnosis of electrical machines and working toward the Ph. D degree on the same axis. He has authored or co-authored many national and international scientific conferences and journal papers. Mr. Sahraoui is an assistant professor with the University of Constantine, Algeria since 2005 and he is a member in the "Laboratoire de Génie Electrique de Biskra".

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Adel Ghoggal was born in Biskra – Algeria in 1972. He became Electrical Engineer from the University of Biskra, Algeria, in 1996. In 2005, he received the "Magistère" degree in electrical engineering from the University of Batna, Algeria. Between 1999 and 2003, he worked for the national company of electricity and gas SONELGAZ–Algeria, where he has been interested by the diagnostic and faults detection of electrical machines. Mr. Ghoggal is an assistant professor with the University of Constantine, Algeria since 2005 and currently, he is a member in the "Laboratoire de Génie Electrique de Biskra".

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