Novel Approach for Diagnosis and Detection of Broken Bar in Induction Motor at Low Slip Using Fuzzy Logic

W. Laala. , S. Guedidi, S. Zouzou

Abstract -- **This paper presents a new automated practical implementation for noncontiguous broken bars diagnosis and detection in electrical induction machine. In this work, a method for detection and diagnosis based on spectral analysis via fast Fourier transform (FFT) of the stator current envelope (SCE) is used. According to the fault diagnosis objective, two features are selected from the (SCE) spectrum: the amplitude of the harmonic representing the broken bars defect 2sf (s is the slip and f the fundamental harmonic) and the dc value. These features will be used as inputs for fuzzy logic bloc, where the decision about the state of rotor is made. The results obtained are astonishing and it is capable to detect the correct number of broken bars.**

Index Terms-- **Fuzzy logic, Diagnosis, Induction Motor, Hilbert transform.**

I. INTRODUCTION

Three-phase induction motors are widely used in industrial application due to their simple and robust design as well as their construction. It is indeed, omnipresent in the industrial sectors like aeronautics, the nuclear power, chemistry. In spite of these qualities, stresses of various natures (thermal, electrical, mechanical or environment) can affect the life span of this one by involving the occurrence of stator and/or rotor faults [1]. Failure surveys have reported that percentage failure by components in induction motors is typically [2]:

- Stator related (38%)
- Rotor related (10%)
- Bearing related (40%)
- Others (12%)

Precisely, the cast aluminium bars of the squirrel-cage rotor may be subject to faults as a result of internal mechanical stresses. A single broken rotor bar may cause its neighbours to fail dues to increased currents in adjacent bars and consequently increased thermal and mechanical stresses. These faults cause considerable economic losses. However, to obtain a high level of reliability for an electric drive with induction motors, a diagnostic system is necessary [1].
Traditionally, the monitoring and diagnostic of rotor broken bars based on motor current signature analysis (MCSA) [3]-[5] used as non invasive method to detect sidebands harmonics around the fundamental supply frequency expressed by:

$$f_{rbb} = (1 \pm 2s)f \qquad (1)$$

where f_{rbb} is the related broken bar frequency. However, at low slip these components $(1 \pm 2s)f$ are relatively close to the fundamental component, which makes their detection much more difficult. To avoid this problem, the amplitude modulation (AM) of stator current induced by rotor asymmetry is exploited in aid of diagnostic. In fact, the rotor fault effect can be localized in the stator current envelope spectrum at frequency expressed by [6]:

$$f_0 = 2ksf \qquad (2)$$

As shown in fig. (3, 4 and 5), the most important components amplitudes are localized in the low frequency bandwidth. In this range the important components amplitudes are related to the dc term and rotor broken bars $(2sf)$.

In this paper, the Hilbert transform is used to extract the stator current envelope. Then this signal is processed via fast Fourier transform (FFT). To extract the fault frequency component (2*sf*) from the stator current envelope spectrum, the frequency bandwidth affected by broken bar can be easily limited at frequency $[f_m \ f_M]$, where $f_m \ et \ f_M$ are selected according to type of the machine. In our case, f_m , f_M are fixed respectively at 0.33 Hz and 6.2 Hz. However, the dependence of the component (2sf) amplitude, at the same time, to the load and to the defect severity, returns the detection of the broken bars number very difficult. For this reason, in order to make an efficient diagnosis at various loads, it is important to introduce a discernment criterion. This is presented by the dc component amplitude which reflects the slip image fig. (7). These two previous amplitudes combined with fuzzy logic technique, as artificial intelligence diagnostic tool already used in [9]-[15], can be defined as a new broken bar fault detection method.

This paper is organized as follows. Section II gives a brief description of the Hilbert transform (HT) and its application for the phase stator current. Section III presents the experimental verification of this method and section IV the use of fuzzy logic for diagnosis and decision. Finally, section V presents the conclusion.

II. STATOR PHASE CURRENT ENVELOPE

Theoretically, in the case of rotor asymmetry created by broken bars, the stator current can be written as [6]:

W. Laala S. Guedidi and S. E. Zouzou are with Laboratoire de Génie Electrique de Biskra (LGEB), Med Khider University, Biskra 07000,Algeria (email:laala.wid@hotmail.fr,guedidi.salim@hotmail.fr,zouzou_s@Hotmail.com).

978-1-4244-9303-6/11/$26.00 ©2011 IEEE

$$i_A(t) = I_f \cos(2\pi f t - \varphi\ \ ) + \sum_k I_{RBB1}^{k} \cos\left(2\pi(f - 2ksf)t - \varphi_{RBB1}^{k}\right) + \sum_k I_{RBB2}^{k} \cos\left(2\pi(f + 2ksf)t - \varphi_{RBB2}^{k}\right) \quad (3)$$

where:

- I_f The fundamental value of the phase stator current.
- φ The main phase shift angle of the phase stator current.
- I_{RBB1}^{k} The left magnitude for the harmonic component f_{Rbb}.
- I_{RBB2}^{k} The right magnitude for the harmonic component f_{Rbb}.
- φ_{RBB1}^{k} The left phase shift angle of component f_{Rbb}.
- φ_{RBB2}^{k} The right phase shift angle of component f_{Rbb}

Expression (3) can be rewritten as:

$$i_A(t) = A(t)\cos(2\pi f t) + B(t)\sin(2\pi f t) \quad (4)$$

(4) Can take the following form:

$$i_A(t) = A_m(t)\sin(2\pi f t + \theta(t)) \quad (5)$$

With:

$$A_m(t) = \sqrt{A(t)^2 + B(t)^2} \quad (6)$$

$$\theta(t) = \arctan\left(\frac{A(t)}{B(t)}\right) \quad (7)$$

$$A(t) = I_f\cos(\varphi) + \sum_k \left((I_{RBB1}^{k}\cos\varphi_{RBB1}^{k} + I_{RBB2}^{k}\cos\ \varphi_{RBB2}^{k})\cos(2\pi(2ksf)t) + (I_{RBB2}^{k}\sin\varphi_{RBB2}^{k} - I_{RBB1}^{k}\sin\varphi_{RBB1}^{k})\sin(2\pi(2ksf)t)\right) \quad (8)$$

$$B(t) = I_f\sin(\varphi) + \sum_k \left((I_{RBB1}^{k}\sin\varphi_{RBB1}^{k} + I_{RBB2}^{k}\sin\ \varphi_{RBB2}^{k})\cos(2\pi(2ksf)t) + (I_{RBB1}^{k}\cos\varphi_{RBB1}^{k} - I_{RBB2}^{k}\sin\varphi_{RBB2}^{k})\sin(2\pi(2ksf)t)\right) \quad (9)$$

As shown in previous relation, the rotor faults in induction motor as rotor asymmetry, induced by the broken bar, modulate the amplitude of stator current at frequency $2ksf$, by exploiting this fact; the stator current envelope can be used as a diagnostic signal.

A. Extraction of the Stator Phase Current Envelope

Typically, the stator current envelope can be extracted via different methods as Hilbert transform, filter demodulation and others.

Hilbert transform (HT) is a well known signal analysis method, used in different scientific fields such as faults diagnosis [12]-[15], and others.

The HT of a real signal $i_A(t)$ is defined as [2]:

$$HT(i_A(t)) = y(t) = \frac{1}{\pi t} * i_A(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{i_A(\tau)}{(t-\tau)} d\tau \quad (10)$$

The combination of the real signal with its HT, the so called analytic signal $\tilde{\imath}(t)$ is formed:

$$\tilde{\imath}(t) = i_A(t) + jy(t) = a(t)e^{j\theta(t)} \quad (11)$$

where:

$$a(t) = \sqrt{i_A(t)^2 + y(t)^2} \quad (13)$$

$$\theta(t) = \arctan\left(\frac{y(t)}{i_A(t)}\right) \quad (14)$$

a(t) is the instantaneous amplitude of $\tilde{\imath}(t)$ known as envelope of $i_A(t)$ and $\theta(t)$ is the instantaneous phase of $\tilde{\imath}(t)$. The stator current of a 3 kW squirrel cage induction motor with two broken bars at 50 % of rated load was processed using the HT. Fig. (1) shows stator current and its envelope.

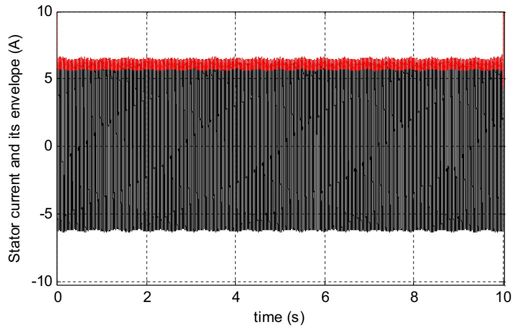

Fig. 1. Stator current and its envelope for two broken bars at 50 % of the rated load

III. Application to Induction Machine Broken Bar Faults Detection

A. Experimental Setup Description

A scheme of the experimental set-up is shown in fig.2. The motor under test is 3 kW, Y connection, 50 Hz, 4 pole, Squirrel-cage induction motor with 28 rotor bars, a DC generator acts as a load. In the experiments, only one stator current signal was collected and interfaced to a PC by a Data acquisition card. The sample frequency used for the measurement is about 10 kHz. The measurements are taken, at three different conditions (healthy rotor and two rotors with one and two broken bars) and under different levels starting from 20% to 100% of rated load.

Fig. 2. View of the experimental test bench.

B. Spectrum of Stator Current Envelope

Several tests, under different loads, for healthy and faulty rotor were carried out. In each case, after acquisition of one phase stator current and extraction of its envelope via Hilbert transform, the FFT is applied to obtain the envelope spectrum. Then, the dc and 2sf amplitude are extracted.

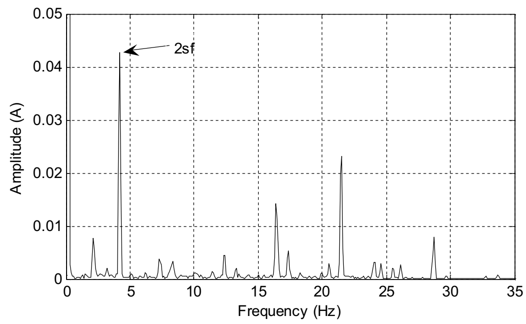

Fig. 3. Spectrum of stator current envelope for two broken bars at 100% of the rated load

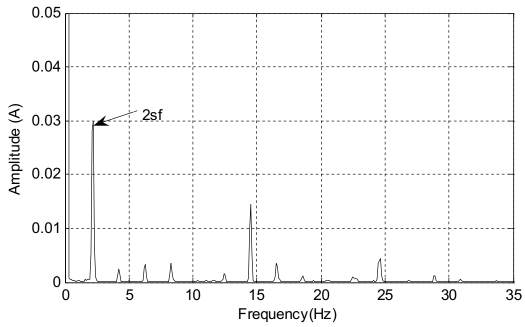

Fig. 4. Spectrum of stator current envelope for two broken bars at 50% of the rated load

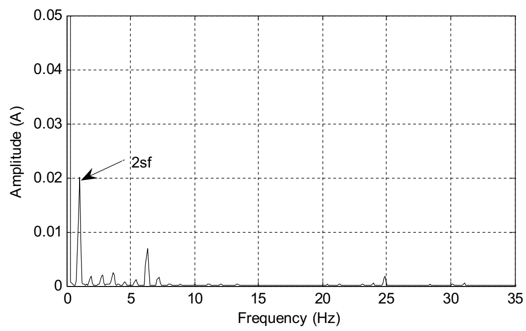

Fig. 5. Spectrum of stator current envelope for two broken bars at 20% of the rated load

Fig. (6, 7) show the evolution of these amplitudes according to the defects severity and the load. It is obvious that the amplitude of a dc component is extremely sensitive to the load. On the other hand, the amplitude of the harmonic 2sf is sensitive at the same time to the defect severity (number of broken bars) and to the load variation. Thus, by the observation of this amplitude, the rotor state can be deduced.

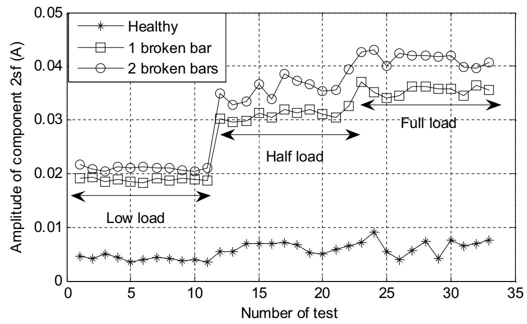

Fig. 6. Amplitude of component 2sf under different load and state (Healthy, 1 broken bar, 2broken bar,

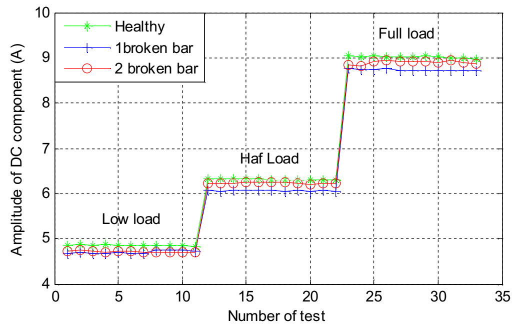

Fig. 7. Amplitude of dc component under different load and state (Healthy, 1 broken bar, 2broken bar,

IV FUZZY LOGIC APPROACH FOR ROTOR FAULTS DIAGNOSIS

A. *Fuzzy System Input-Output Variables*

Our objective is to conceive an effective expert system for the diagnosis with the less input possible. In accordance to the practical, the selection is related at the harmonic amplitude 2sf, unfortunately, this harmonic is sensitive to the load which leads to interference between data. For example, some amplitude extracted during functioning at, full load with one broken bar and the half load with two broken bars, is interfered. For the distinction, another entry sensitive to the load proves to be indispensable. The amplitude of the dc component accomplished this task. Thus, the amplitudes of dc and 2sf components called respectively $\mathbf{A}_{dc}$ and $\mathbf{A}_{fbb}$, will be used as input for the fuzzy system fig. 8. The numerical inputs data are normalized fig (9, 10) and converted as linguistic information. By fuzzy inference, using a knowledge base, compressing a rule and data base, the state of the rotor, is then obtained as output. The rotor condition, CM, is chosen as the output variable. The output provides three decision outputs ∈ {0,1}.

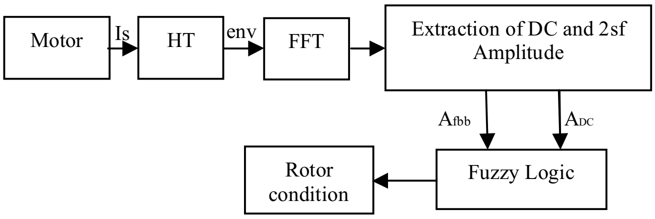

Fig. 8. Motor fault diagnosis using fuzzy logic.

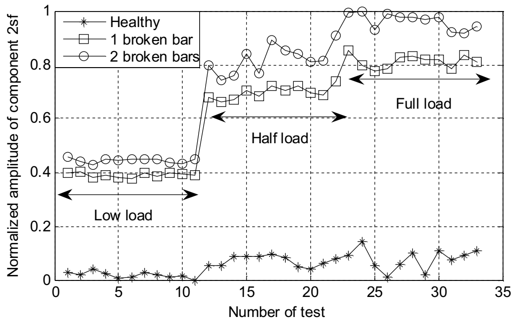

Fig. 9. Normalized amplitude of component 2sf under different load and state
(Healthy, 1 broken bar, 2broken bar,

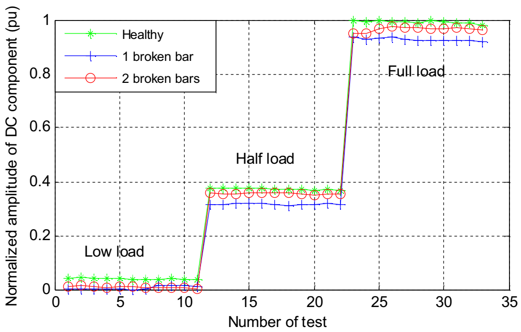

Fig. 10. Normalized amplitude of dc component under different load and state
(Healthy, 1 broken bar, 2broken bar,

B Construction of Membership Function and Fuzzy Inference

Fuzzy rules and membership function are constructed by observing the data set. The available human knowledge and skills on fault diagnosis of induction motors as interpreted as a set of linguistic rules, used to build a knowledge base, comprising a data base and a rule base. The shape of membership functions for input variables is illustrated in fig. 11 and fig. 12. There are six linguistic values for input A_{fbb} which "Very Small" (VS), "Small1" (S1), "Small2" (S2), "Medium1" (M1), "Medium2" (M2), and "Big" (B), three linguistic values for A_{dc}, which are respectively "Low load" (LL), "Half load" (HL) and "Full load" (FL).

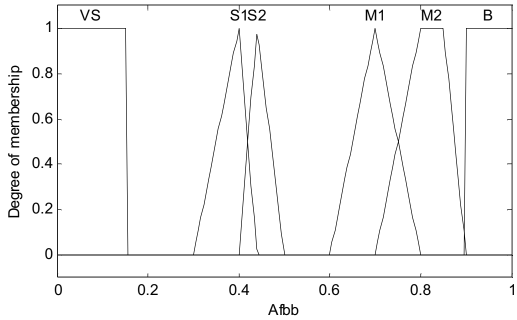

Fig. 11. Member ship Functions for A_{fbb},

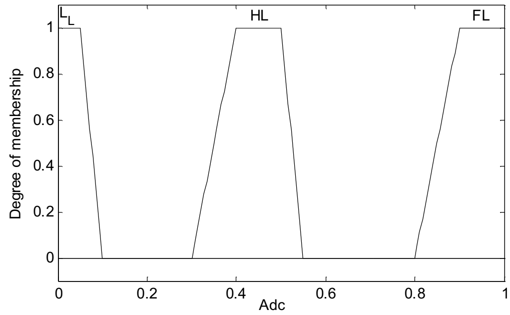

Fig. 12. Member ship Functions for A_{dc},

The shape of the output CM is chosen as singletons, which have three linguistic values "H" (healthy), "D" (defect), "SD" (severe defect). Table I described the output range for this variable.

TABLE I
Range of Output

Range	Rotor Condition	Number of Broken Bar
0≤output≤0.1	Healthy (H)	0
0.4≤output≤0.7	Defect (D)	1
0.7 < output≤ 1	Severe Defect (SD)	2

C. Rules base

The rule base is set up as follows:

Rule 1: if (A_{fbb} is VS) then (CM is H)
Rule 2 : if (A_{fbb} is S1) and (A_{dc} is LL) then (CM is D)
Rule 3 : if (A_{fbb} is S2) and (A_{dc} is LL) then (CM is SD)
Rule 4 : if (A_{fbb} is M1) and (A_{dc} is HL) then (CM is D)
Rule 5 : if (A_{fbb} is M2) and (A_{dc} is HL) then (CM is SD)
Rule 6 : if (A_{fbb} is M2) and (A_{dc} is FL) then (CM is D)
Rule 7 : if (A_{fbb} is B) then (CM is SD)

The implementation inference system is of Sugeno type and the centroid method has been used for defuzzification process.

To verify the efficiency of the fuzzy logic system, several tests were carried out. These tests were made under different loads, for the healthy and faulty rotors. In each case, the stator current envelope is transformed to the frequency domain using a fast Fourier Transform algorithm (FFT). After, the amplitude of dc and 2fs components are extracted and transferred into the corresponding universes of discourse as the inputs. The fuzzy logic system evaluates the inputs and diagnosis the rotor condition. For instance, for a rotor without faults, the diagnosis obtained should be "H", for healthy, "D" for one broken bar and "SD" for two broken bars. The fuzzy technique was realised by Matlab fuzzy toolbox and the results are presented in Table II, III et IV.

Table II
Diagnostic Results of Healthy Motor

	Normalized Afbb	Normalized Adc	Output CM
Full load	0.0588 0.0997 0.0181	0.9924 0.9908 0.9934	00 00 00
Half load	0.0873 0.0828 0.0953	0.3761 0.3732 0.737	00 00 00
Low load	0.0289 0.0183 0.0401	0.0428 0.0437 0.0429	00 00 00

Table III
Diagnostic Results of Motor with 1Broken Bar

	Normalized Afbb	Normalized Adc	Output CM
Full load	0.8279 0.8309 0.8177	0.9264 0.9252 0.936	0.5000 0.5000 0.5000
Half load	0.7037 0.6973 0.7227	0.3207 0.3152 0.3165	0.5184 0.500 0.6100
Low load	0.3975 0.3790 0.3868	0.0024 0.0032 0.0032	0.5100 0.5000 0.5000

Table IV
Diagnostic Results of Motor with 2Broken Bar

	Normalized Afbb	Normalized Adc	Output CM
Full load	0.9219 0.9150 0.9415	0.9736 0.9671 0.9615	01 01 01
Half load	0.7675 0.8546 0.8394	0.3600 0.3574 0.3136	0.8377 01 01
Low load	0.4594 0.4410 0.4359	0.0094 0.0140 0.0050	01 01 0.9485

V. CONCLUSION

A diagnosis method using fuzzy logic to determine the state condition of the induction motor was presented. In order to make an efficient diagnosis at low slip, the stator current envelope obtained via Hilbert transform has been used as diagnostic signal. The amplitude of the dc and 2sf components of the spectrum stator current envelope are intended as inputs to the fuzzy system which are converted to variables linguistic by fuzzy subsets and their corresponding membership functions. The output of this system represents the rotor condition. The system was tested under different load and for different number of broken bars. The results obtained with this system are good and is capable to detect the correct number of broken bar.

VI. REFERENCES

[1] S. E. Zouzou, W. Laala, S. Guedidi and M. Sahraoui, "A Fuzzy Logic Approach for Diagnosis of Rotor Faults in squirrel Cage Induction Motors," in Proc. 2009 IEEE Computer and electrical Engineering Conf., pp. 173-177.

[2] R. P. Panadero, M. P. Sanchez, M. R. Guasp, "Improved Resolution of the MCSA Method Via Hilbert Transform, Enabling the Diagnosis of Rotor Asymetries at Very Low Slip," IEEE Trans. Energy Convers. ,vol 24 n°1 March 2009.

[3] M. E. H. Benbouzid, A review of induction motors signature analysis as a medium for faults detection, *IEEE Transactions on Industrial Electronics, vol. 47, n°.5, pp. 984-993*, October 2000.

[4] W. T. Thomson, M. Fenger, Current Signature Analysis to Detect Induction Motor Faults, *IEEE Industry Application Magazine, pp. 26-34,* July/August 2001

[5] G. B. Kliman, J. Stein,"Methods of Motor Current Signature Analysis," *Electric Machines and Power Systems, vol. 20, no. 3, pp. 463-474*, September 1992.

[6] S. H. Kia, H. Henao and G.A.Capolino, "Diagnosis of Broken Bar Fault in Induction Machines Using Discrete Wavelet Transform Without Slip Estimation," IEEE trans. Application, Vol 45 n°4 July/August 2009.

[7] F. Zidani, D. Dialo, M. E. Benbouzid, R. Nait-Said, A fuzzy-based approach for the diagnosis of fault modes in a voltage-fed PWM inverter induction motor drive, *IEEE Transactions on Industrial Electronics, vol. 55, no.2, pp. 586-93*, February 2008.

[8] M. E. H. Benbouzid, H. Nejjari, A Simple Fuzzy Logic Approach for Induction Motors Stator Condition Monitoring, *Proceeding of International Electric Machines and Drives Conference, (IEMDC 2001), pp. 634-639*, Cambridge USA 2001.

[9] M. K. Mishra, S. G. Tarnekar, D. P. Kothari, A. Ghosh, Detection of incipient faults in single phase induction motors using fuzzy logic, *Proceeding of the Power Quality Conference, pp. 117-121*, 1998, India.

[10] F. Filippetti, G. Franceschini, C. Tassoni, P. Vas, A fuzzy logic approach to on-line induction motor diagnostics based on stator current monitoring, *Proceedings of the Power Tech International Symposium on Electric Power Engineering, vol. 3, pp. 156-161,* Stockholm Sweden , 1995.

[11] E. Ritchie, D. Xialan, T. Jokinen, Diagnosis of Rotor Faults in Squirrel Cage Induction Motors Using Fuzzy Logic Appoach, *Proceeding of International Conference on Electrical Machines (ICEM '94), vol.2, pp.348-352*, Paris France,1994.

[12] Z.Liu, X. Zhang, X.Yin and Z. Zhang," Rotor cage fault diagnosis in induction motors based on spectral analysis of current Hilbert modulus," in Proc. IEEE Power Eng. Soc. Gen. Meeting, Jun 3-10, 2004, Vol. 2, pp. 1500-1503.

[13] M. Blodt, M. Chabert, J. Rgnier, and J.Faucher, "Mechanical load fault detection in induction motor by stator current time-frequency analysis," IEEE Trans. Ind. App., Vol. 42, n°6, pp 1454-1463, Nov/Dec.2006.

[14] A. H. Nuttal and E. Bedrosian, “on the quadrature approximation to the Hilbert transform of modulated signals,” Proc. IEEE, Vol.54,n°10, pp.1458-1459, Oct.1966.
[15] Z. K. Peng, P. W. Tse and F. L. Chu,” A comparison study of improved Hilbert-Huang Transform and wavelet transform: Application to fault diagnosis forrolling bearing,” Metch. Syst. Signal Process, Vol. 19, pp. 974-988, 2005.

VII. Biographies

Wided Laala was born in Biskra Algeria. She received the Engineer and the “Magistère” degrees in electrical engineering both from the University of Med Khider of Biskra, Algeria in 1993 and 2001 respectively. She is interested in the modeling, condition monitoring and faults diagnosis of electrical machines and working toward the Ph. D degree on the same axis. She is author or coauthor of several national and international papers. Ms. Laala is an assistant professor with the University of Biskra

Salim Guedidi was born in Biskra, He received the D.E.S from the university of Batna and the “Magistère” degrees in electrical engineering from the University of Med Khider of Biskra, Algeria. He is interested in the modeling, condition monitoring and faults diagnosis of electrical machines and working toward the Ph. D degree on the same axis. He is the author or coauthor of some national and international papers. Mr. Guedidi is an assistant professor with the University of Biskra and he is a member in the “Laboratoire de Génie Electrique de Biskra”.

Salah Eddine Zouzou was born in Biskra, Algeria. He received the B.S degree from the “Ecole Nationale Polytechnique d’Alger”, Algeria in 1987 and the M.S and Ph.D degrees from the “École Nationale Polytechnique de Grenoble” France, in 1988 and 1991 respectively. His fields of research interests deal with the design and condition monitoring of electrical machines. He has authored or co-authored more than 40 scientific papers in national and international conferences and journals. Prof. Zouzou is a Professor at the University of Biskra, Algeria and he is the director of the “Laboratoire de Génie Electrique de Biskra” since 2003.