Fault Detection in Induction Machine by Application of Hilbert Transform to Neutral Voltage

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Abstract

To detect the presence of a rotor fault of an asynchronous machine, diagnostic methods are typically based on frequency analysis of signals revealing. It is common to use the modulus of the Fourier transform of the current absorbed by the machine to detect the presence of this type of failure, and also the voltage between neutrals. In this article and as a first step, special attention is given to the contents of the phase spectrum of the stator current and neutral voltage, because the phase of the analyzed signal contains more relevant information than the module.

However, we show that the information given by the phase spectrum of signal (current, voltage) allows us to conclude the presence of a fault in the machine rotor. In the following study, we show that it is possible to improve the diagnosis of the machine using the information given by the Hilbert transform applied to the module spectrum signal analyzed.

These two approaches will be validated through various experimental tests performed on a wound rotor induction machine.

Key words: Monitoring; Diagnosis; Hilbert; Asynchronous machine; Rotor fault; MCSA; Neutral voltage

1 Introduction

Nowadays, the greatest concern of the industry is the performance, and therefore it is imperative to ensure proper functioning, the safety and security of goods and devices. To do this, the industrial and scientific communities are seeking solutions to make these systems more competitive, more efficient, and safer. One of the routes on which research works is oriented is the conditional preventive maintenance which is carried out works on the diagnosis for fault detection. There are a number of research papers on technical monitoring of electrical machines which are most relevant are [1] : [6].

The fault detection is seen more and more in the electrical machines using induction machine because of its strength, power and low cost.

Fault diagnostics requires measures sensitive to the change greatness of the machine and an appropriate method to obtain a diagnostic index and a threshold indicating the limit between the healthy state and the defective one.

Generally, MCSA "Motor Current Signal Analysis" [7] [8] [9]. (Widely known in the literature) is the most commonly used technique and well established. In fact, *MCSA* is simple and effective in appropriate operating conditions. However, this technique has significant limitations due to the increasing complexity of electrical machines and drives [1]:

- It is influenced by the operating conditions (*eg* low load conditions, load oscillations);
- The fault diagnosis is difficult or impossible if the system operates under time-varying conditions or the machine is supplied by a power converter;
- The diagnosis is difficult or impossible in machines with special magnetic structure (*eg* machines with double cage in which there are a strong influence of interbar currents or only the outer cage has a fault).

To reduce these limitations, the proposed work focuses on the use of voltage between neutrals NV "Neutral Voltage" [12] : [17]. The method that has performance comparable to *MCSA* or better is based on the analysis of the potential difference between the neutral of star-connected stator and the neutral network in the case of a direct feed or artificial neutral in the case of a supply voltage by inverter in order to detect a rotor fault in induction machine.

Thereafter, an analysis of phase spectra by the Hilbert transform is made, this transform is usually used in image processing, where the phase contains more relevant information than its module, its advantage is that the

Hilbert transform calculated from the amplitude spectrum of the signal to analyze, which allows to conclude on the nature of default.

2 Phase spectrum analysis

In order to verify experimentally the impact of the presence or absence of fault on the machine, we developed a test bench including a wound rotor induction machine.

2.1 Presentation of the test bench

A specific experimental set-up has been designed in the laboratory of CPS2I ENIM-Rabat-(*National School of Mineral Industry*) in order to perform measurements on a Wound Rotor Induction Machine *WRIM* ; 3*kW*, 50*Hz*, 220V/380V, 4-poles (Figure 1). Two voltage sensors and two current sensors with galvanic insulation are used to monitor the induction machine operation. The induction machine voltages and currents are measured by means of the four sensors. These four signals are used as inputs of the signal conditioning and the data acquisition board integrated into a personal computer.

For those two variables, the sampling frequency was *2kHz* and each data length was equal to 2^{14} values. 3 tests were performed on this machine. Table 1 shows the testing carried out on the bench for the study of voltage between neutral and notations used in this article.

It is important to note that the rotor fault is taken into account by an additional resistance of one of the rotor phases.

Figure 1 : Test bench laboratory (CPS2I)

	Description	Load level (%)	Rotor state	Notation	Addi resi	s (%)
Test 1	Non loaded	0	Healthy	HNL	-	-
			defective	DNL		
Test 2	75% loaded	75	Healthy	HL-75	42 Ω	5.2
			defective	DL-75		
Test 3			Healthy	HIL-75	72 Ω	5.2
			defective	DIL-75		
Test 4	Full load	100	defective	DL-100	42 Ω	5.8

Table 1 : Measurements

2.2 Influence of rotor fault on phase stator current

Recall the mathematical equation of the Fourier transform of a finite sequence *{ps (0),. . . , Ps (N - 1)}*, we have

$$F(k) = \frac{1}{N}\sum_{n=0}^{N-1} p_s(n) e^{-j\frac{2\pi nk}{N}} \tag{1}$$

Applying this relationship, the result is a complex signal with a real part and an imaginary that allows writing the previous equation as:

$$F(k) = \Re(F(k)) + j\Im(F(k)) \tag{2}$$

In our work we are interested in the shape of the phase of the diagnosis measurable magnitudes such as current and voltage between neutral. The phase of the Fourier transform is given by:

$$\varphi_{FT}(k) = \arctan\left(\frac{F_{\mathrm{Im}(k)}}{F_{\mathrm{Re}(k)}}\right) \tag{3}$$

We present in Figure 2 the module (a) and phase spectrum (b) of the stator current in the case where the rotor is defect, it appears frequency components (*1 ± 2.k.s*) *fs* on the modulus of the spectrum of current characterizing the defect rotor [7]. The phase spectrum of the current, in turn brings up the frequencies (*1 ± 2.k.s*) *fs* phase variations brute. We analyze the phase spectrum when the machine works with a healthy rotor figure 2 (c) in order to show that the phase jumps frequency (*1±2.k.s*) *fs* present in this phase are due to a fault on the rotor Figure 2 (d).

According to Figure 2 (c and d) we see a clear change in the value of the phase at 50Hz.

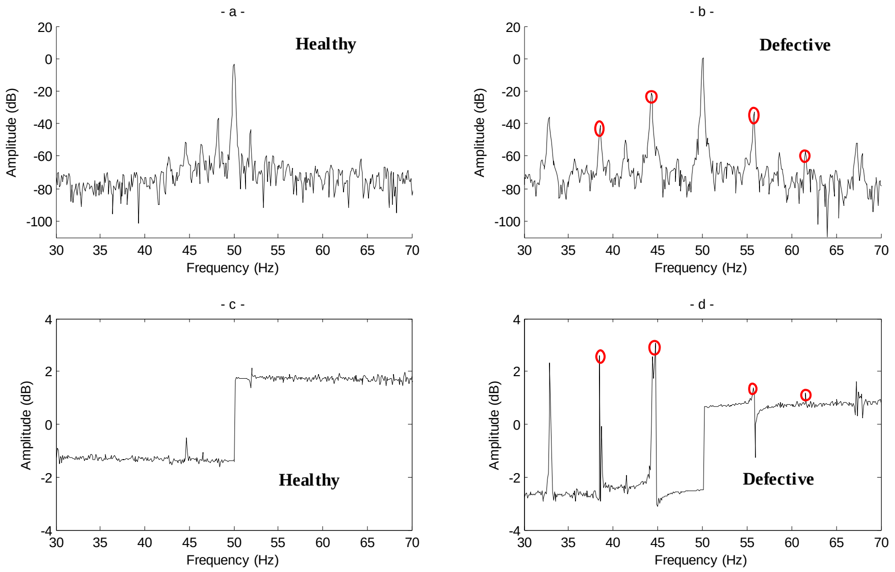

Figure 2 : Spectrum of the stator current: healthy (a) and the defective cases (b) and the corresponding phase in the healthy case (c) the defective one (d)

Stator current analysis is best suited to diagnose faults in electrical induction machine. However, analysis by the voltage between neutral, little known in the literature, can have performance comparable to or even better than the current, where the study of the usefulness of the neutral voltage for diagnosis.

2.3 Neutral Voltage Signal Analysis (NVSA)

2.3.1 NVSA frequency

1998, *M.A.Cash* [12] used the voltage between the neutral of the supply voltage and the neutral of induction machines (Fig. 1) to detect short circuits between spiral in stator coils. A similar analysis was carried out by [14] [15] in order to detect rotor fault in induction machines.

The presence of a fault rotor reveals additional components in the spectrum of *NV*. Indeed, *M.E.K. OUMAMMAR* [17] demonstrated by a complex analysis, that the appearance of a rotor fault induces additional components in the frequency spectrum of the *NV* at frequencies given by the relation:

$$f_h = \left[3h - (3h \pm 1)s\right] f_s \tag{4}$$

s: slip, *fs*: supply frequency, *h* = 1,3,5, ...

The speed ripple induced additional harmonic components around the previous frequency, and the frequencies of all components can be expressed as follows:

$$f_h = \left[3h(1-s) \pm s(1+2k)\right] f_s \tag{5}$$

We present in Figure 3 the power spectral density of NV for a faulty rotor. We note the presence of the main frequency component (4) and additional components around these main components.

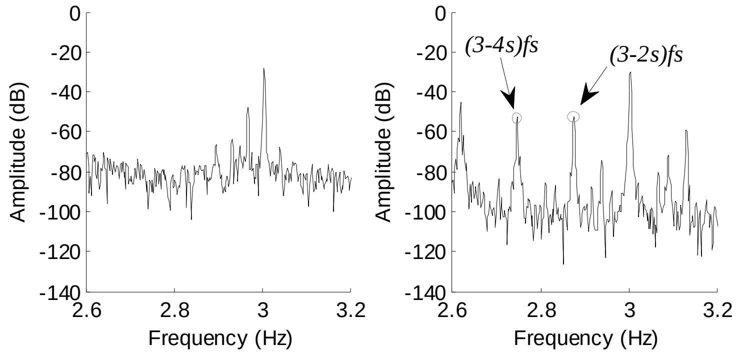

Figure 3 : Power spectral density of the NV

2.3.2 Phase Fourier transform analysis

As the *MCSA*, around the 3rd harmonic [11], it appears frequency components *(3-2s).fs* and *(3-4s).fs* characterizing the rotor fault on the amplitude spectrum. The phase spectrum brings up the frequencies of these abrupt changes phase.

A comparative analysis of the phase spectrum when the machine operates with a healthy rotor (Fig.4a) and defective case, shows that the phase jumps frequency *(3-2s).fs* and (*3-4s) fs* in this phase are due to a rotor fault in induction machine (Fig.4b and 4c)

From these figures we can see a clear change in the value of the phase 150Hz. As a first conclusion for both (*MCSA* and *NVSA*) , the detection of the phase jump at frequencies *(3-2s).fs* and *(3-4s) fs* around the 3rd harmonic [15] due to the rotor fault in the phase spectrum of the *NV* is simpler than detecting the component of the same frequency in the spectrum of the spectral density.

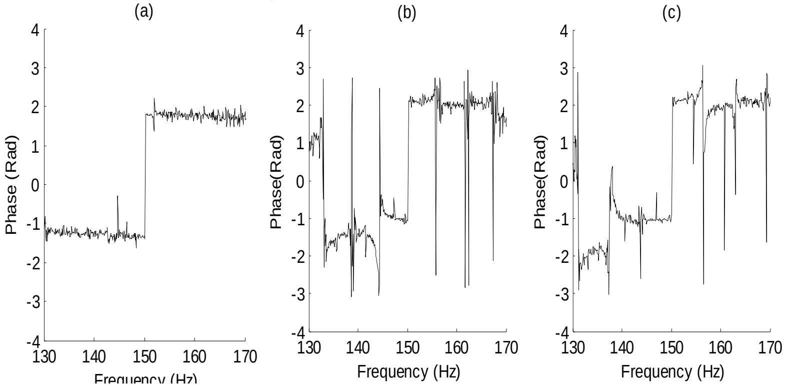

Figure 4 : Spectrum phase of NV. (a) HNL, (b) HL-75 and (c) HIL-75

From Figure 4, the first problem for this approach is the significant noise in the frequency range studied. The second problem is the bad detection of the phase jump at frequencies located characterizing the fault rotor analysis of the neutral voltage. Indeed, the presence of random phase shifts in the frequency range does not allow a good detection of phase jump required to calculate the slip [9].

3 Hilbert transform to diagnose rotor fault:

We have already seen that even the good results that phase spectrum analysis compared to the module spectrum analysis, this method has two drawbacks.

- The noise level is high, which makes detection difficult.
- The second is that the form of the phase is not fixed. Indeed, the real and imaginary parts can take random values.

To stabilize the form of phase, we must find a solution to control the values of the real and imaginary parts of the spectrum, the idea is to obtain a phase always equal to[-*π/2*] to the left of f_s and equal to [*π/2*] right f_s, the real part must be zero at frequencies ± f_{def} and f_s.

These problems can be circumvented with the use of the Hilbert transform, as we will see below.

The Hilbert transform of a real signal dimensional $v_n(t)$ can be calculated using the relationship:

$$H\left[v_n(t)\right] = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{v_n(t)}{t-\tau}d\tau = \frac{1}{\pi}v_n(t) * \frac{1}{t} \qquad (6)$$

Where t is time, $v_n(t)$ is the time signal of the voltage between neutrals and $H[v_n(t)]$ is the Hilbert transform of the signal $v_n(t)$.

The Hilbert transform [10][18][19] does not change the domain of the variable $v_n(t)$. Indeed, the Hilbert transform of a signal dependent on the variable t is also a function of this variable.

The amplitude of the analytical signal [$a(t)$] is the instantaneous amplitude or envelope signal, while the signal $\varphi(t)$ is the instantaneous phase, where formulas are given by:

$$\begin{aligned} a(t) &= \sqrt{v_n{}^2(t) + H^2\left[v_n(t)\right]} \\ \varphi(t) &= \arctan\frac{H\left[v_n(t)\right]}{v_n(t)} \end{aligned} \tag{7}$$

The analytic signal $A[v_n(t)]$ is calculated using different methods. One of these methods uses the Fourier transform. Indeed, the Fourier transform of the signal $H[v_n(t)]$ is given by the following equation:

$$A\left[v_n(t)\right] \xrightarrow{F} V_n(f) + j(-j\,\mathrm{sgn}(f)V_n(f)) = (1+\mathrm{sgn}(f))V_n(f) \tag{8}$$

Where the function $V_n(f)$ is the Fourier transform of $v_n(t)$ and $sgn(f)$ the function of the sign.

The use of Hilbert phase analysis is applied to the module of Fourier transformation frequency of the signal $v_n(t)$. Indeed, the analytic signal and the corresponding phase are given by:

$$A\left[V_n(f)\right] = \left|V_n(f)\right| + jH\left(\left|V_n(f)\right|\right) \tag{9}$$

$$\varphi(f) = \arctan\frac{H\left[\left|V_n(f)\right|\right]}{\left|V_n(f)\right|} \tag{10}$$

To perform fault diagnosis without introducing comparison with the healthy functioning, we will treated the $\varphi_{TH}(f)$ phase, it is identical to that applied to the $\varphi_{TF}(f)$ phase, ie we will analyze the phase jump at the frequency located at $(3-2s)fs$ in the module of the frequency spectrum of *NV*, the absence of this frequency component in the spectrum of the *NV* is reflected in the absence of the phase jump at the same frequency in the $\varphi_{TH}(f)$ phase.

In conclusion, the Hilbert transform applied to the module spectrum gives a phase limited to the interval [$-\pi/2$, $\pi/2$]. In addition, knowledge of the imaginary part can predict the exact form of the phase of the analytic signal.

With noise reduction, phase jumps are more pronounced than in Figure 4, which allows easier detection. The noise level is lower than $\varphi_{TF}(f)$ due to the redefinition of the signal and using the Hilbert transform.

Before starting the analysis phase of the analytical spectrum of the Hilbert transform, it is important to note that when we are in the case of a no fault simulation, the voltage spectrum V_{nn} contains no component-specific default what is normal in theory. This is not the case in the experiments. Indeed, we know that the construction of the machine is not perfect and there is a slight asymmetry called natural at the rotor. This asymmetry results in the appearance of fault frequency components in power spectrum.

After an analysis of figures for a load of 75%, and with different levels of fault (partial and important default). We note an increase of the amplitude of the lines having the frequency (11) Figure 5b and a large increase D in the case of an important defect in Figure 5c:

$$f_h = \left[3(1-s) \pm s\right] f_s \tag{11}$$

If we analyze these results, we see that the amplitude of the frequency components of default increases significantly with the increase of the additional resistance representing the rotor fault,

We note that the rotor fault detection can be performed with a load higher than or equal to 50% if we base ourselves on the evolution of the amplitude of specific components in rotor fault.

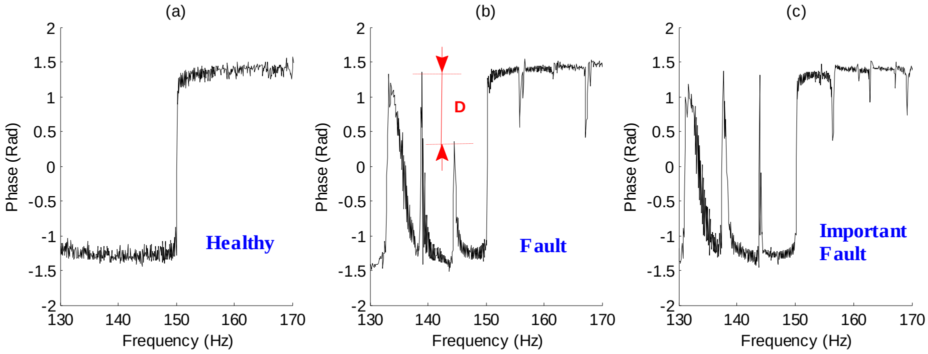

Figure 5 : Phase of the Hilbert transform to different state level of the rotor [DE] (a) [DL-75] (b) and [DIL-75] (c)

A simple comparison between the three approaches (Fig. 6) (module of the Fourier spectrum of the neutral voltage (a) phase of its spectrum (b) and the phase of its Hilbert transform (c)) shows the effectiveness and good detection for the third approach.

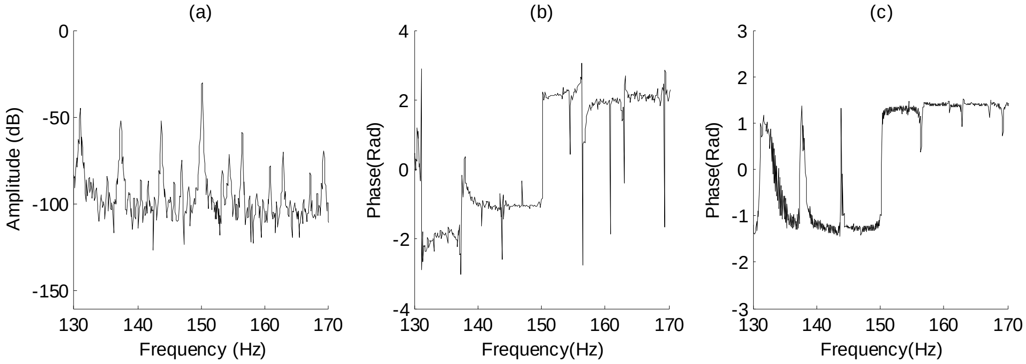

Figure 6 : module of the Fourier spectrum of neutral voltage (a) phase (b) and the phase of Hilbert transform (c)

4 Conclusion

Two approaches have been proposed to diagnose rotor fault. The first approach is based on the calculation of Fourier transform phase of Neutral Voltage. This phase contained relevant information on the status of the asynchronous machine. The results are relatively interesting.

To improve fault diagnosis, a second approach has been proposed. This method uses the same approach as described above, the only difference lies in the fact that this is not the phase of the Fourier transform of the Neutral Voltage which is analyzed by the program decision, but the phases of the analytic signal obtained by Hilbert transform of the amplitude spectrum of Neutral Voltage. This analysis helped to detect other defects that were not detected by the first approach.

It remains to note that the instrumentation necessary to analyze this voltage stays simple and inexpensive and only access to the motor neutral and neutral supply network is needed.

References

[1] F.Filippetti, A.Bellini and G.A. Capolino " *Condition Monitoring and Diagnosis of Rotor Faults in Induction Machines: State of Art and Future Perspectives*" Electrical Machines Design Control and Diagnosis (WEMDCD), IEEE Workshop on pp. 196 – 209, 2013

[2] Bellini, F. Filippetti, C. Tassoni, and G. Capolino, "*Advances in diagnostic techniques for induction machines*," Industrial Electronics, IEEE Transactions on, vol. 55, no. 12, pp. 4109–4126, 2008.

[3] Mohamed El Hachemi Benbouzid, "*A Review of Induction Motors Signature Analysis as a Medium for Faults Detection*" IEEE Transactions on industrial electronics, vol. 47, no. 5, pp. 984-993 , october 2000

[4] S. Nandi, H. Toliyat, and X. Li, "*Condition monitoring and fault diagnosis of electrical motorsa review*," IEEE Transactions on Energy Conversion, vol. 20, no. 4, pp. 719–729, Dec. 2005.

[5] P. Zhang, Y. Du, T. G. Habetler, and B. Lu, “*A survey of condition monitoring and protection methods for medium-voltage induction motors*,” IEEE Transactions on Industry Applications, vol. 47, no. 1, pp. 34–46, 2011.

[6] Y. Gritli, L. Zarri, C. Rossi, F. Filippetti, G. Capolino, and D. Casadei, “*Advanced diagnosis of electrical faults in wound rotor induction machines*,” IEEE Transactions on Industrial Electronics, , p. 1, 2013.

[7] J. H. Jung, J. J. Lee, and B. H. Kwon, “*Online diagnosis of induction motors using MCSA*,” IEEE Transactions on Industrial Electronics, vol. 53, no. 6, pp. 1842–1852, Dec. 2006.

[8] A. Espinosa, J. Rosero, J. Cusido, L. Romeral, and J. Ortega, “*Fault detection by means of hilbert-huang transform of the stator current in a pmsm with demagnetization*,” Energy Conversion, IEEE Transactions on, vol. 25, no. 2, pp. 312 –318, june 2010.

[9] G. Didier, E. Ternisien, O. Caspary, H. Razik “*A new approach to detect broken rotor bars in induction machines by current spectrum analysis*” Mechanical Systems and Signal Processing 21 pp. 1127–1142 , 2007

[10] M. E. K. Oumaamar, H. Razik, A. Rezzoug, A. Khezzar “*Line Current Analysis for Bearing Fault Detection Induction Motors Using Hilbert Transform Phase*” acemp, Electromotion 2011, pp. 289-294, 8-10 Sept 2011, Istanbul (Turkey).

[11] Yuefeng Liao, Thomas A. Lipo , “*Effect of saturation third harmonic on the performance of squirrel-cage induction machines*” Electric Machines & Power Systems, vol. 22, no2, pp. 155-171, 1994

[12] M. A. Cash, T. G. Habetler, G. B. Kliman, “*Insulation Failure Prediction in AC Machines Using Line-Neutral Voltages*”, in IEEE Transactions on Industry Applications, Vol. 34, No 6, pp. 1234–1239,November/December 1998.

[13] H. Razik and G. Didier, “*A novel method of induction motor diagnosis using the line-neutral voltage*,” in Proc. EPE-PEMC, Riga, Latvia, Sep. 2004.

[14] M.E.K. OUMAAMAR « *Surveillance et diagnostic des défauts rotoriques et mécaniques de la machine asynchrone avec alimentation équilibrée ou déséquilibrée* » PhD thesis (Groupe de Recherche en Electrotechnique et Electronique de Nancy GREEN-UdL Faculté des Sciences et Technologies) March 2012

[15] Khezzar, A.; Oumaamar, M. E. K.; Hadjami, M.; Boucherma, M.; Razik, H.; “*Induction Motor Diagnosis Using Line Neutral Voltage Signatures*”, Industrial Electronics, IEEE Transactions on, Volume 56, Issue 11, Nov. 2009 Page(s):4581 – 4591.

[16] M.E.K. Oumaamar, F. Babaa, A. Khezzar and M. Boucherma, “*Diagnostics of Broken Rotor Bars in Induction Machines Using the Neutral Voltage*”, ICEM’2006 Conference. Chania. Greece, 2- 5 September 2006.

[17] M.E.K. Oumaamar, A. Khezzar, M. Boucherma, H. Razik, R. Andriamalala, L. Baghli, "*Neutral Voltage Analysis for Broken Rotor Bars Detection in Induction Motors Using Hilbert Transform Phase*" , IAS 2007,43rd Annual meeting, New Orleans (USA),23-27 pp. 1940 - 1947 september.2007

[18] J. Antonino-Daviu, M. Riera-Guasp, M. Pineda-Sanchez, and R. Perez, *“A critical comparison between dwt and hilbert huang-based methods for the diagnosis of rotor bar failures in induction machine”* Industry Applications, IEEE Transactions on, vol. 45, no. 5, pp. 1794 –1803, sept.-oct. 2009.

[19] Liru Han *“ Gear fault detection and diagnosis based on Hilbert-Huang transform”* Image and Signal Processing (CISP), 3rd International Congress on , Vol. 7 pp 3323 – 3326 , 2010