Fuzzy-Wavelet for Detection of Eccentricity in Induction Motors

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Abstract: In this paper, we try to detect mechanical faults of induction motors. For this goal, the stator line current of motor is considered. Wavelet Packet Decomposition of this signal can provide good information about the occurrence, type and size of the fault. But it is better to have more understandable concept for an operator to find fault.
Hence, fuzzy system is applied to wavelet features. Eccentricity between rotor and stator is considered for testing proposed method.

1. Introduction

Because of the increasing demands on reliability and control of processes are getting an increasing interest. This holds as well for advanced processes with highest demands on reliability and safety.
Induction motor especially squirrel cage has a very important role in the industry, that depend to their usage, face in the various faulty modes. So it is necessary to detect this faulty condition and avoid increasing them before they can result catastrophic failure [1].
Machine eccentricity is the condition of unequal air-gap that exists between the stator and rotor. Approximately 80% of mechanical faults result to this condition [2].
One of the simplest methods traditionally is used, for motor fault detection is Motor Current Signature Analysis (MCSA) [1]. Since the stator line current consists many of the motor harmonics, a Fast Fourier Transforming (FFT) of the stator line current, can show these harmonics [3]. Also inequality between rotor and stator of induction motors lead to change in magnetic fields, and these changes produce some harmonics in the stator current, so an FFT can easily shows this problem.
The Wavelet Packet Transform (WPT) [4] is a modification of classic wavelet can provide high resolution in the both frequency and time domain. So in the recent works has tried to detect induction motor faults using WPT [5-6].
A fuzzy logic approach may help to diagnose induction motors faults [7]. In fact a reminiscent of human thinking processes and natural language enabling decisions to be made based on vague information [8].
When conducting fault diagnosis, there several situations in which an object is not obviously "good" or "bad", but may fall into some interior range. A major difficulty is the lack of a well processing of fuzzy input data.
This paper applies fuzzy logic, to the diagnosis of induction motor conditions, based on the features of WPT energies of the current stator.

2. Wavelet Packet Decomposition (WPD) for fault detection in induction motor

In induction motors, inequality between rotor and stator lead to change in magnetic fields and these changes produce some harmonics in the stator currents. The equation, which describes such frequency components for eccentricity, is given by [1]:

$$f_{har} = \left[\left(kR \pm n_d \right) \frac{1-s}{p} \pm \eta \right] f_s \tag{1}$$

Where $n_d = 0$ in case of static eccentricity, $n_d = 1,2,3,\cdots$ in case of dynamic eccentricity, f_s is the fundamental supply frequency, R is the number of rotor slots, s is the slip, p is the number of pole pairs, and k is integer and η is the order of the stator time harmonics.
When $n_d = 0, \eta = 1, k = 1$, The Principal Slot Harmonics (PSH s) are given.

$$f_{psh} = \left(\frac{1-s}{p} R \pm 1 \right) f_s \tag{2}$$

In the presence of mixed form of eccentricity, certain low-frequency components given by:

$$f_{ecc0} = \left(1 \pm \frac{1-s}{p} \right) f_s \tag{3}$$

Will be presence in the stator current spectrum, also high-frequency components given by:

$$f_{ecc1} = \left(\frac{R \pm 1}{p} (1-s) \pm 1 \right) f_s$$

Low frequency components is very useful for the detection of the eccentricity, while the load torque variation and broken rotor bar also affect on these harmonics, so they may be mistaken, Hence low frequency and high frequency components together can provide a good information about the eccentricity in induction motors, but computing the high frequency harmonics need to be known rotor slot numbers and pole pairs, so the method limits for individual motor.

In WPD, the energy of signal in the above harmonics is very useful device for detection of the faults may occur [6], for example in Depth (*j*) and Node (*i*), the energy of signal is given by [4]:

$$E_{j,i} = \sqrt{\frac{\sum_{n=1...N} {d_j^i}^2}{N}} \quad (4)$$

Where *N* is the number of coefficients in each Node of J^{th} Depth, which it can easily given by $N = D2^{-J}$, where D is the length of original signal. In this case, by substituting simulated motor information, the harmonics related to the mixed eccentricity condition will be given such: f_{ecc0} =*30 Hz* and *90 Hz,* f_{ecc1}=*720Hz* and *840 Hz* and *960Hz.* The stator current, has *16384* samples and the sample time is *0.0001*, so for applying the WPD the best Depth should be selected, is *10*, Hence, each Node of 10th Depth consists energy of $\frac{fs/2}{2^J} = 4.8828\,Hz$ of the original signal in frequency domain.

Via Coifman, Wickerhauser lemma can be found that the Node No. 5 is related 29.29Hz to 34.17Hz frequency domain and the Node No. 7 is related 24.4Hz to 29.29Hz frequency domain also the rest are shown in Table 1.

We can see in Table 1, the energy of related Nodes, can provide good information about the size of eccentricity. Hence, one can detect and identify this mechanical fault well.

Fault harmonics / Condition	f_{ecc0} 1 (30Hz)	f_{ecc0} 2 (90 Hz)	f_{ecc1} 1 (720Hz)	f_{ecc1} 2 (840Hz)	f_{ecc1} 3 (960Hz)
Energies in Healthy	0.1647	0.0452	0.0038	0.0169	0.0126
Energies in 15% Eccentricity	0.1662	0.0494	0.0053	0.0152	0.0141
Energies in 25% Eccentricity	0.1815	0.0505	0.0078	0.0264	0.0158
Energies in 35% Eccentricity	0.2512	0.0770	0.0148	0.0266	0.0250
Energies in 40% Eccentricity	0.3029	0.1404	0.0265	0.0434	0.0348
Node Number	5+7	25	218	250+254	166+167
Frequency Domains (*Hz*) that energies are computed in them	[24.4 29.3] & [29.3 34.17]	[87.89 92.78]	[717.8 722.7]	[834.9 839.8] & [839.8 844.7]	[957 961.9] & [961.9 966.8]

Table 1 the energy of the stator current in Depth 10

3. Fuzzy system for fault detection in induction motor

In the proposed method input features to fuzzy system are the residuals, which are generated by different between stator current in healthy condition and current condition.

Now in which frequency, energies should be computed and the residual signal will be calculated? Surely, its answer is frequencies related to especial fault which one wants to detect it. In this paper, eccentricity condition of motor was simulated, so we calculate their frequencies and test our algorithm on this fault. We saw that 30Hz and 90Hz can show the eccentricity occurrence, but since we want to isolate each fault, so 720Hz, 840HZ and 960Hz should be considered.

Evaluation on low component harmonic around the fundamental and PSH frequency would be enough for detection of this condition, because they can represent occurrence and size of this fault well (30Hz and 720Hz).

After simulation of induction motor in different eccentricity conditions, the residual signal that is difference between the energies of stator line current in faulty and healthy condition. They have been computed and shown. R_1 is residual signal related to 30Hz and R_2 related to 720Hz.

Eccentricity condition can identify certainly by the R_1 and R_2, but this method of fault detection is not user friendly. These residuals in our procedure are used as input features to fuzzy system, also the state of induction motor uses as output of the fuzzy set.

Inputs and output of the fuzzy system are defined in terms of fuzzy sets as follows:

$$R_1 = \left\langle \mu_{R_1}(r_{1j}) \;\middle|\; r_{1j} \in R_1 \right\rangle \quad (5)$$

$$R_2 = \left\langle \mu_{R_2}(r_{2j}) \;\middle|\; r_{2j} \in R_2 \right\rangle \quad (6)$$

$$State = \left\langle \mu_{State}\left(state_j\right) \ \middle|\ state_j \in State \right\rangle \qquad (7)$$

The energies of the stator current in frequencies, related to individual fault, are compared with healthy condition. After generating their residuals, by a fuzzy system diagnostic is completed.

Where r_1, r_2 and state are the elements of the universe of the discourse respectively of R_1, R_2 and State; μ_{R_1}, μ_{R_2} and μ_{State} are the corresponding membership functions.

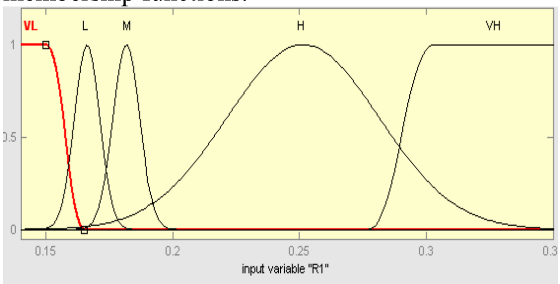

Figure 1 Membership function of variable R_1

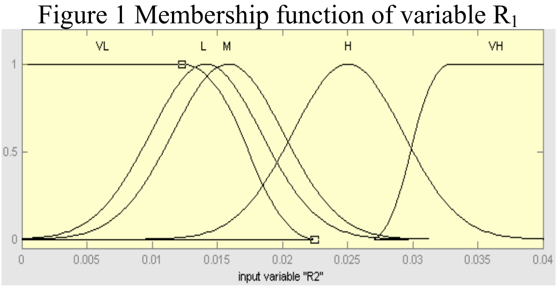

Figure 2 Membership function of variable R_2

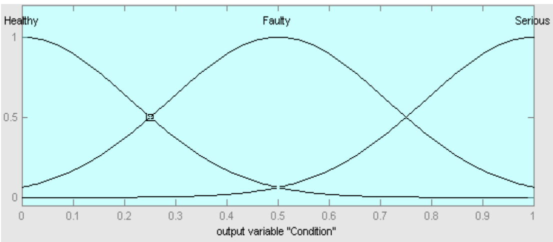

Figure 3 Membership function of variable State

In Figures 1, 2 and 3 the membership functions of the inputs and output have been drawn.

The inputs signal to fuzzy system has been defined by VS=Very Low, L=Low, M=Medium, H= High, VH=Very High, and the output signal from fuzzy system, State, has been defined by Healthy, corresponding to an mixed eccentricity less than 15%, FAULTY, corresponding to an mixed eccentricity between 15% and 30% and SERIOUS, corresponding to an mixed eccentricity more than 30%.

Also in figure 4, fuzzy inference rules and rule surface in Figure 5, have been shown.

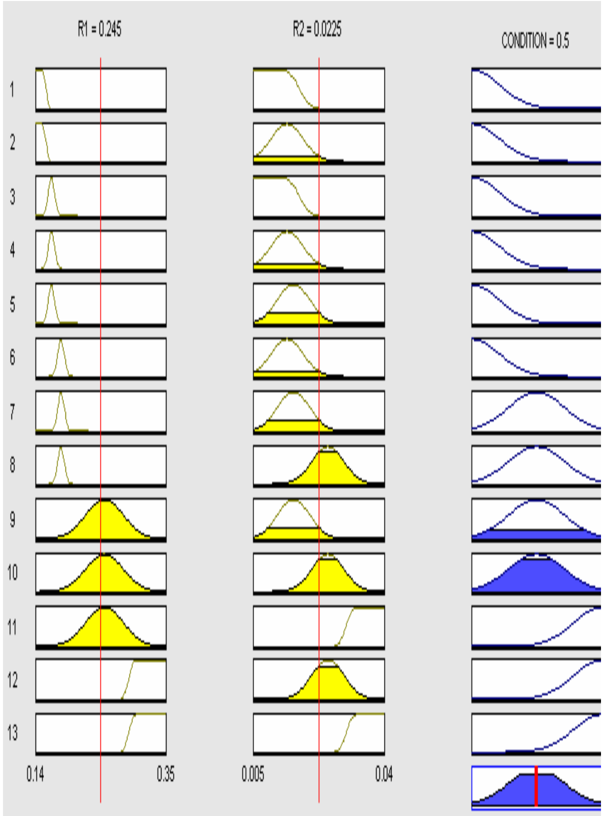

Figure 4 Fuzzy inference diagrams

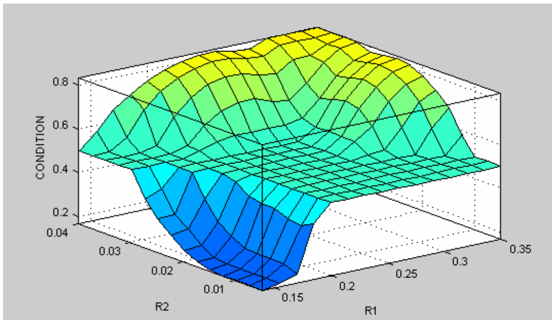

Figure 5 Rule Surface

4. Fault diagnosis results

Using the system depicted by Figure 6, the stator line current was measured and its wavelet relation derived.

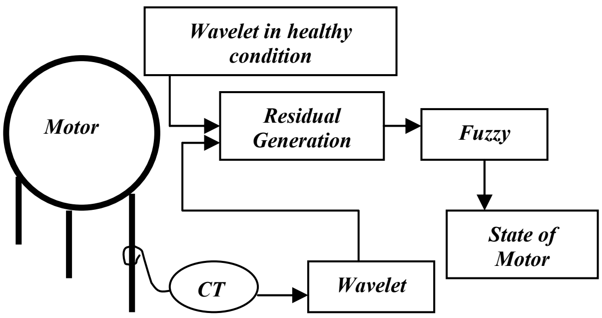

Figure 6 Block diagram of fault detection in induction motor

The power spectrum of the stator current in frequencies, related to individual fault, is compared with power spectrum of these frequencies in healthy condition. After generating their residuals, by a fuzzy system diagnostic is completed.
To detection of other faults, this procedure can be completed by adding the frequencies related to all of them, generation of their residuals. Therefore, the inputs/outputs of the fuzzy system are increased.
The fuzzy system evaluates the residuals, using the knowledge base and then diagnoses the motor condition.
According to this method, first each affected output membership function is cut at the strength indicated by the previous max-rule, next the gravity center of possible distribution is computed and it becomes the crisp output value.
To detection of other faults, this procedure can be completed by adding the frequencies related to all of them, generation of their residuals. Therefore, the inputs/outputs of the fuzzy system are increased.

5. Conclusion

WPD may be proposed as a proper method for detection of any fault occurs in three-phase induction motor such as mixed eccentricity. The expert system, was designed in this paper, is fuzzy system. Correctly processing these power spectrum signals and inputting them to a fuzzy decision system achieved high accuracy.

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