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ZSV Spectrum-Based Detection of IM Rotor Dissymmetry Immunity to False Alarms

***Abstract**. This paper presents a comprehensive study of new tool used to detect rotor asymmetries in induction motors, which operate in different types of operating conditions and different loads. The proposed approach is performed by tracking the amplitude of the most sensitive harmonics in the spectrum of the line neutral voltage called also the Zero Sequence Voltage (potential difference between the null point of the supply voltage system and the neutral of the star connection of IM stator winding), using a dynamic acquisition rate based on machine frequency supply. To assess detection accuracy under the various severity levels of the faults, two supply conditions are investigated: (i) Motor supplied by network fed and (ii) Motor supplied by inverter fed. Results obtained from experimental tests are presented to validate the study.*

Streszczenie.** W artykule opisano nowe narzędzie do wykrywania asymetrii wirnika w silniku indukcyjnym. W opisanej metodzie śledzone są wartości harmonicznych w napięciu Zero Sequence Voltage (różnicy między punktem zerowym zasilania I punktem zerowym uzwojenia stojana połączonego w gwiazdę. **Wykrywanie asymetrii wirnika w silniku indukcyjnym na podstawie analizy napięcie ZSV

Keywords: diagnosis; broken rotor fault; Zero Sequence Voltage; MCSA; Rotor Fault indicator.
Słowa kluczowe: silnik indukcyjny, asymetria wirnika

Introduction

Induction motors (IM) are used in many industrial processes and are frequently integrated in commercially available equipment. Robustness, cost advantage, high power capabilities, and performance are the major concerns of IM applications. Although IM are reliable, they are subjected to some failures. Therefore, monitoring and diagnosing faults in IMs is a scientific and economic issue which is motivated by objectives for reliability and serviceability in electrical machines drives. There has been substantial amount of research to provide new condition monitoring techniques for induction motors mostly based on analysing vibration signals, or other signals such as current, and hence several commercial tools are available in this area.

Studies in the area of diagnosis and monitoring of electrical machines have shown that stator and rotor faults are assumed equal. However, the vast majority of articles dealing mainly with rotor fault ([11]) first and then with stator faults and finally bearing faults. [1][2]

Knowing that the topic is so important, this paper deals on rotor fault detection in IMs, this fault that physically result either by short/open circuits or by increasing of the rotor resistance. Among the rotor fault accrued in this type of machines we can cite the broken rotor bars (BRB) in in case of machines with squirrel cage.

There are various methods that have been developed to detect BRB in IMs such us vibration analysis, temperature analysis, acoustic measurement, neuronal and artificial intelligence based methods. However, the most used techniques are based on the monitoring of the stator current spectrum (known by Motor Current Signature Analysis [MCSA]). MCSA is simple and effective in appropriate operating conditions. [3]

Even the advantages that represent this method, this technique has some significant practical limitations such us:

1) Operating conditions can influence the MCSA. In case of rotor asymmetries faults in motors working at a very low load, the main frequency component may hide the fault harmonics because their frequencies are close to the main frequency of the power supply.

2) The diagnosis is difficult if the IM is supplied by a power converter or if the IM operates in a system under time-varying conditions;

3) Recently, the IMs are frequently installed with inverters which provide some advantages but makes the stator current inaccessible to diagnosis.

To overcome some of these limitations, the use of zero sequence voltage (or Line neutral voltage which is the potential difference between the null point of the supply voltage system and the neutral of the star connection of IM stator winding) is proposed and analysed. [4-9]

Because no direct fault detection criterion is provided, the mentioned methods requires the knowledge of the healthy state to take a decision about the rotor. Instead, the proposed harmonic tracking approach is developed using the zero-sequence voltage as electrical indicator to detect of BRBs without the knowledge of a primary state of the motor. This approach is based on standard deviation calculations taken on two frequency ranges, the first standard deviation will be calculated on the first frequency range, this range identifies where the phase jump whose frequency $(3-4s)f_s$. The second standard deviation represent the picture of measurement noise present between jumps being located at frequencies $(3-4s)f_s$ and $(3-6s)f_s$ that is going to be mentioned in this paper as f_{tar1} and f_{tar2} respectively. Finally, using this approach, we can generate a decision about the rotor fault which is presented in the end of the proposed method section. It is important to note that the method is valid both for line connected as well as for inverter-fed machines.

Proposed method

The presence of a fault rotor reveals additional components in the spectrum of NV. Indeed, M.E.K. OUMAMMAR 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:

$$f_{asym} = \left[3h - \left(3h \pm 1\right)s\right] f_s \quad (1)$$

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

The information given by the spectrum of the voltage at the third harmonic [10], i.e., nears the spectral line having the frequency 150 Hz can be used for WRIM fault diagnosis.

This section provides an analysis of the tracking harmonics module, the threshold performance and the decision making method.

As already seen in introduction, The proposed method is based on the analysis of the jump *(3-4s)f_s* which is function of the motor slip *s*. This is why it is necessary to calculate the slip of the IM, the easiest way to do it is the using of a speed sensor in case of experiment test. In this paper we focus on some harmonics to estimate the slip.

From the equation given the principal RSH found on the spectrum of the line neutral voltage:

$$f_{sh} = f_s\left[\lambda \frac{N_r}{p}(1-s) \pm 1 \pm 2ks\right] \tag{2}$$

Where: λ is a positive integer; *p*: Number of pole pairs; and N_r: Number of rotor bars

We can express the slip as:

$$s = 1 - \frac{p}{N_r}\left[\frac{f_{RSH}}{f_s} \pm 1\right] \tag{3}$$

Practically, all IM have a slight asymmetry of construction induced, in the spectrum of Line neutral voltage, the appearance of the frequency component whose frequency equal to *(3 -2s)f_s* , Therefore, the slip can be expressed from:

$$s = \frac{1}{2}\left[3 - \frac{f_{RSH}}{f_s}\right] \tag{4}$$

where: f_{RSH} is the frequency of rotor slot harmonic.

A searching interval is defined because the frequency of the component (*3 -2s*)f_s changes according to the load motor; their boundaries depend on the max and min values of the slip s_{min} and s_{max} ; these correspond to unloaded machine and full load machine respectively.

Consequently, the searching frequency f_{SR} belongs to the following interval:

$$f_{SR} \in \left[(3-2s_{\max})\,fs...(3-2s_{\min})\,fs\right] \tag{5}$$

In our case, given that we know the fundamental frequency f_s, and as our machine is operating with a nominal speed of *2800 rpm* which gives a minimum frequency f_{RS} equal to *143,6* Hz, therefore the range selected our detection of this jump will be [*140,150*] Hz

The next step is to identify the value of the (*3-2s*)f_s component and its amplitude in the spectrum of the line neutral voltage, the best way to do this is define a frequency range corresponding to the wanted harmonic, this component which has the highest magnitude nearest the 3rd harmonic in the interval defined as :

$$R = \left[f_{tar} - i\Delta f \quad ; \quad f_{tar} + j\Delta f\right] \tag{6}$$

Where: f_{tar} is target harmonic obtained via the estimated slip, Δf is the frequency resolution ($\Delta f = f_s/N$), *i* and *j* are integers. Once the slip is determined.

Next, the idea is to compare the standard deviation around the f_{tar1} and f_{tar2} frequencies. Indeed, the first standard deviation, noted σ_j will be calculated on the frequency range (*RANGE1*), this range identifies where is the phase jump whose frequency *(3-4s)f_s*. The second standard deviation, which is noted by σ_n will be calculated on the frequency range (*RANGE2*), this standard deviation is a picture of measurement noise present between jumps being located at frequencies *(3-4s)f_s* and the next jump *(3-6s)f_s*.

$$\begin{aligned} RANGE\,1 &= \left[(3-4s)f_s - \frac{\delta}{2} \quad , \quad (3-4s)f_s + \frac{\delta}{2}\right] \\ RANGE\,1 &= \left[(3-6s)f_s + \frac{\delta}{2} \quad , \quad (3-4s)f_s - \frac{\delta}{2}\right] \end{aligned} \tag{7}$$

where δ=1Hz.

The mathematical relationship that can calculate the standard deviation is:

$$\sigma_x = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_n - \frac{1}{N}\sum_{i=1}^{N}x_n\right)^2} \tag{8}$$

For an adequate understanding of the principle of calculation of these standard deviations, Fig. 1 shows a representation where the standard deviation σ_j is calculated on the red frequency range while the standard deviation σ_n is calculated on the black frequency range.

In order to make our indicator more robust and to limit false alarms detection, a threshold has been introduced in the criterion that will symbolize with: C_{th}. This threshold compares the variance σ_j with the variance σ_n of $\varphi_F(f)$. Therefore, the authors have defined the following criterion (Table 1):

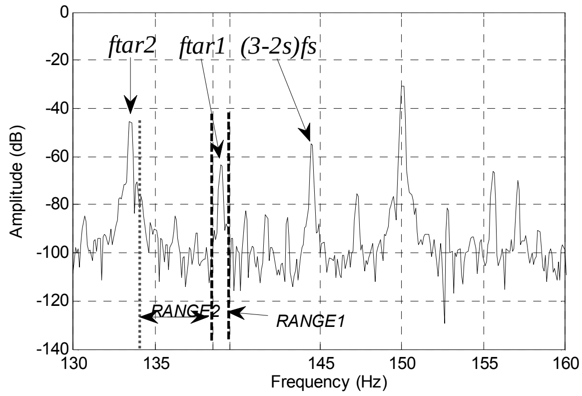

Fig. 1. Explication of the proposed method

Table 1. Rotor asymmetry decision module

Criterion	Rotor State
$C_{RF} \leq C_{th}$	Healthy rotor
$C_{RF} \geq C_{th}$	Defective rotor

Where $C_{RF} = \sigma_j/\sigma_n$, and C_{th} is the sensitivity degree of our fault detection indicator and it is determined in function of the studied IM. Both, the rotor fault index C_{RF} and the corresponding threshold parameter C_{th} are determined from experimental results based on the signal detection theory.

The proposed method can be summarized as follows:

- After acquisition, the zero-sequence voltage is sampled, and the slip is measured for each case (to be used just for comparison with the estimated slip),
- The slip estimation module is built using (5) and (6).
- The estimated slip is used to search the frequency component (*3-2s*)f_s near the 3rd harmonic.
- Once this frequency is estimated, the f_{tar1} and f_{tar2} are estimated too, and the standard deviation in the two ranges is calculated to build the criterion and these values can be compared with predefined thresholds to evaluate the machine's condition.

Validation of the Proposed Methodology

To perform a further experimental validation, the proposed method is applied under laboratory conditions to a commercial motor, whose characteristics are explained in the next subsection.

In this section, the proposed method will be illustrated using the case of an IM with rotor asymmetry. Nevertheless, the same procedure can be followed to the treatment of any other type of machine fault or working conditions.

The test bench used is designed to monitor the voltage, current, vibration and speed of IM by using sensor in each measurement. Fig. 2 shows the structure of the laboratory setup. The motor under test is a *3*kW, 50Hz, 220V=380V, 4-poles. This motor is directly coupled to a DC machine acting as a load. The sampling frequency was *26* kHz. Voltage and current signals are measured by using LEM Hall sensors to monitor the Line neutral voltage and the line current of the motor. These sensors are connected to the data acquisition board, which is connected to a personal computer.

For motor conditions, three types of test motors were used: a healthy motor, a motor with one broken bar and a motor with two broken rotor bars. The motor consists also on inverter which is connected to the load motor to connect the load condition of the tested motor.

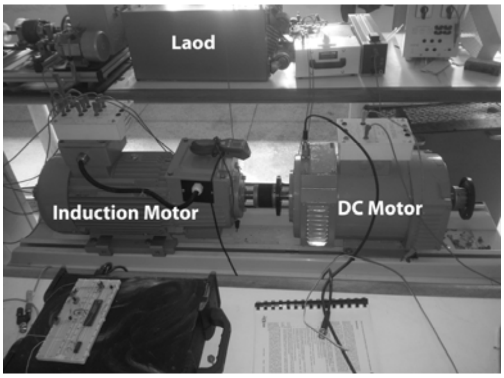

Fig. 2. Experimental laboratory setup

The measured signals were analyzed by using Fast Fourier Transform (FFT). For the tested motor, the experiments were performed in the steady state condition to obtain accurate information about the broken rotor bars. For FFT analysis, the Hanning window is used to minimize the frequency leakage.

First, the algorithm is implemented by using a Matlab function. The results of this algorithm are presented in Table. 2, the first column in this table corresponds to the machine supply (supply fed or inverter Fed), the rotor state is presented in the second column, the third and fourth gives the value of the frequencies f_{tar1} and f_{tar2} respectively, fifth and sixth column gives the calculated and estimated slip. The values of σ_j and σ_n calculated on the frequency ranges *RANGE1* and *RANGE2* are presented in the seventh and eighth column respectively. And then the module decision is presented in the two last columns.

Fig.3 shows an example of the application of the frequency tracking module in the S-1bb50 case (Induction motor with one broken rotor bar at 50% of load). In the first plot of this figure, Fig. 3(a), the fault can be observed in the spectrum of the line neutral voltage the target frequencies f_{tar}, f_{tar1} and f_{tar2}.

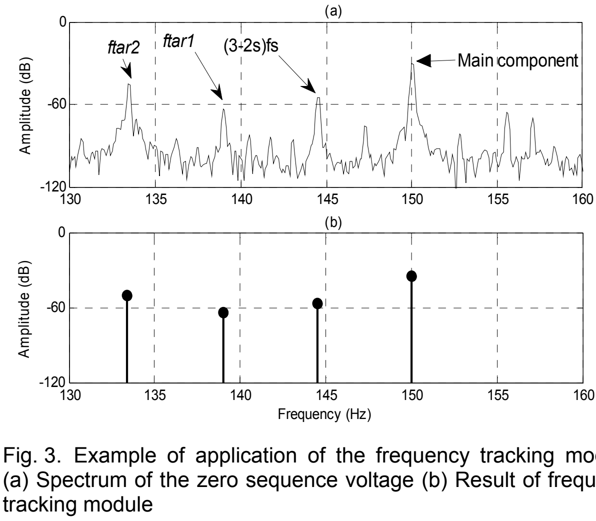

Fig. 3. Example of application of the frequency tracking module. (a) Spectrum of the zero sequence voltage (b) Result of frequency tracking module

In Fig. 3(b), frequency tracking module is shown. It has been built by keeping only the amplitudes of the components of the searched harmonics. For the rest, the same process in done for all tests in table 2.

The method described above (Section III) is applied on the zero-sequence voltage when the machine is directly star-connected to the three-phase network. According to the column giving σ_j/σ_n report we note that it is low for a machine operating with a healthy rotor (S-H100 and S-H50), then we perceive that for some healthy functioning we do not detect jump phase $(3-2s)f_s$ in this case we consider the rotor in good condition (S-H0).

The appearance of a partial rotor fault does not induce a significant increase of σ_j relative to σ_n, which does not allow to conclude on such a failure. For an important rotor fault (S-2bb50) we note that this report is greater 10 times that in tests where the machine is healthy. From these results, it can be concluded that the proposed approach is validated, even if σ_j/σ_n report in tests S-2bb25 and S-1bb25 is less pronounced as seen in Table 2, but the results are satisfactory.

It is noted that the $\sigma j/\sigma n$ report does not vary too much despite the variation in the load level. In the defective case a notable variation between fault conditions is seen. From the table 2, the $\sigma j/\sigma n$ report does not exceed 5 for a healthy machine and it is greater than 5 for a defective machine.

This conclusion led us to make an induction machine diagnosis method without reference (this reference usually obtained from a healthy functioning). In other words, if the report $\sigma j/\sigma n$ is less than 5 then the machine is healthy, and defective if greater than 5 (as indicated in the last column of table 2).

The practical limitation of this approach is the high level of noise in the frequency range studied. The second problem is the wrong detection of the phase jump at frequencies located at frequency characterizing the rotor fault for the NVSA. In fact, the presence of random phase jumps in the frequency range does not allow proper detection of the phase jump required to calculate the slip.

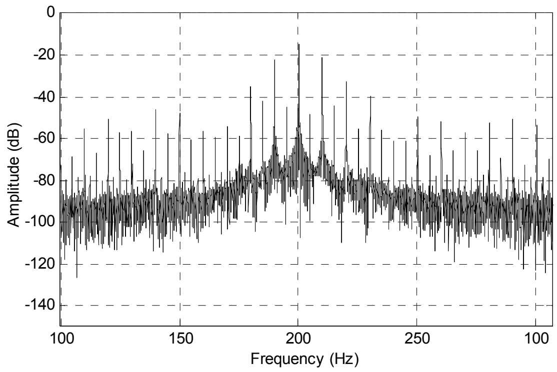

Fig. 4. Zero sequence voltage result in case of motor supplied with inverter and 2 broken rotor bars under 3/4 of load

Case study: Induction machine supplied by inverter Fed

The theoretical development of the proposed method, and its comparison with previous approaches, is illustrated with a case study, a 3kW star-connected induction motor supplied with an inverter, which drives a variable load.

After tests, the results are shown in the second part of Table. 2. if the motor operates at a very low slip (I-H0), the diagnosis of this type of fault is especially challenging because the fault harmonics are very close to the mains component and because the harmonic generated by the inverter as shown in Fig. 4. Compared to other works from the literature [12], the proposed method gives better result even the machine is supplied with an inverter.

Table 2. Results of the proposed method.

	Rotor condition	f_{tar}	f_{tar1}	Measured Slip (%)	Estimated Slip (%)	σ_j	σ_n	Decision Module	
								C_{RF}	Decision
Supply Fed	S-H0	No Max detection							
	S-H50	145.23	139.19	4.79	4.77	0.384	0.108	3.55	Healthy
	S-H100	144.9	139.23	5.14	5.09	0.105	0.073	1.45	Healthy
	S-1bb0	No Max detection							
	S-1bb25	145.41	140.82	4.63	4.59	0.610	0.067	9.11	Defective
	S-1bb50	144.40	138.81	5.71	5.60	0.015	0.007	4.89	Defective
	S-1bb100	142.33	134.66	3.78	7.67	0.29	0.003	79.30	Defective
	S-2bb0	148.56	147.06	1.47	1.44	0.0316	0.005	6.32	Defective
	S-2bb25	144.37	138.74	5.71	5.63	0.088	0.0082	10.74	Defective
	S-2bb50	143.8	138	6.25	6.2	0.302	0.006	48.01	Defective
	S-2bb100	142.95	137.31	7.11	7.05	0.36	0.006	56.3	Defective
Inverter Fed	I-H0	No max detection							
	I-H100	144.9	139.23	5.14	5.09	0.105	0.073	1.45	Healthy
	I-1bb0	147.40	144.80	2.54	2.61	0.015	0.007	4.89	Defective
	I-1bb75	145.34	140.68	4.72	4.66	2.218	0.093	23.86	Defective

Conclusion

In this paper, a novel approach to detect rotor fault in IM has been proposed, it is based on the analysis of a new fault indicator that uses both the harmonic tracking and the zero-sequence voltage. The presented indicator allows to have a knowledge about the rotor state, the fault severity, and the corresponding slip for the data acquisition. With the proposed method, the decision making is done, regardless of the motor load or the type of supply. It was shown that the harmonics tracked in this paper are derived to evaluate their immunity to false alarms. The description of the proposed method, its theoretical justification, and the experimental validation under a wide variety of supply types and working conditions have been presented in this paper. As extension of the proposed method, the detection of multiple faults in IMs is currently under development, and will be presented in a future paper.

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