NON-INVASIVE ROTOR BAR FAULTS DIAGNOSIS OF INDUCTION MACHINES USING VIRTUAL INSTRUMENTATION

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Abstract: The condition monitoring of the electrical machines can significantly reduce the costs of maintenance by allowing the early detection of faults, which could be expensive to repair. In this paper some results on non-invasive detection of broken rotor bars in induction motors are presented. The applied method is the so-called motor current signature analysis (MCSA) which utilises the results of spectral analysis of the stator current. The diagnosis procedure was performed by using virtual instruments (VIs).

1. INTRODUCTION

Today, operators of industrial plants strive for high levels of economy and increased life-time for their plants in order to ensure their competitive position. This aim can only be realised if all relevant design solutions are identified and evaluated during the design of a plant, and if all the essential units of the plant are supposed to preventive maintenance and to precise condition monitoring during their operation.

Electrical machines are an integral part of any plant. The squirrel-cage induction motors are the most widely used in most industrial applications because of their simple construction and robustness. Therefore the condition monitoring of this motor type is much more important that of any other.

Usually the electrical machines are designed for 30 years lifetime, but most of them get wrong in a way after 5÷10 years. Therefore the preventive maintenance of the electric machines can be crucial for the plant operators. Hence it is very advantageous to implement time and money saving condition based maintenance rather than periodic or failure based maintenance. This way it is possible to diagnose some faults, even in the first stage of their apparition or when the damages are yet minor [1].

In recent years significant improvements have been achieved in the design and manufacture of stator windings, due to the improved insulating materials and treatment processes. In the same time cage rotor design and manufacturing has undergone little changes [2]. As a result rotor damages now account about 10-15% of total induction motor failures [3]. The diagnosis of the broken rotor bars is also important because after the first bar's breaking the current in the others is increasing, and it is imminent the possibility of a new damage in induction machine's

cage, followed by a rapid destruction of the entire cage. Therefore any results in this field could be of real interest.

In this paper a non-invasive rotor fault diagnosis method of the squirrel cage induction machine performed via virtual instrumentation is presented. The diagnosis technique is based on measuring and processing the stator current signal (*MCSA – Machine Current Signature Analysis*).

2. THE TEST BENCH

The experimental measurements were made on an intelligent test bench. Its block scheme is given in Fig. 1. It consists of two coupled electrical machines, the machine to be tested and a DC machine fed by a controlled rectifier (SIMOREG DC Master of Siemens), used for loading and breaking purposes

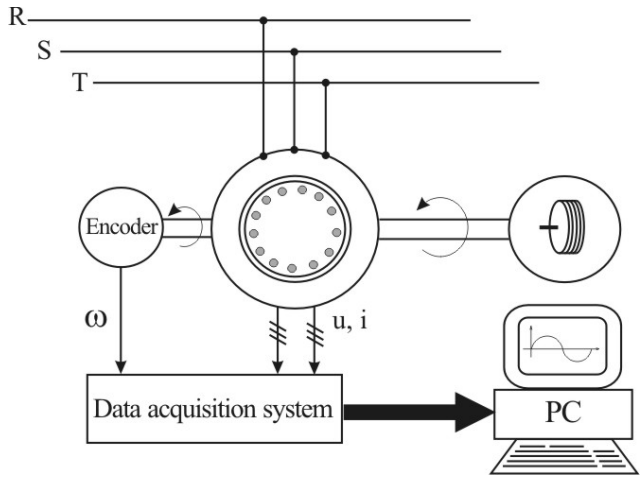


Fig. 1. The block scheme of the test bench

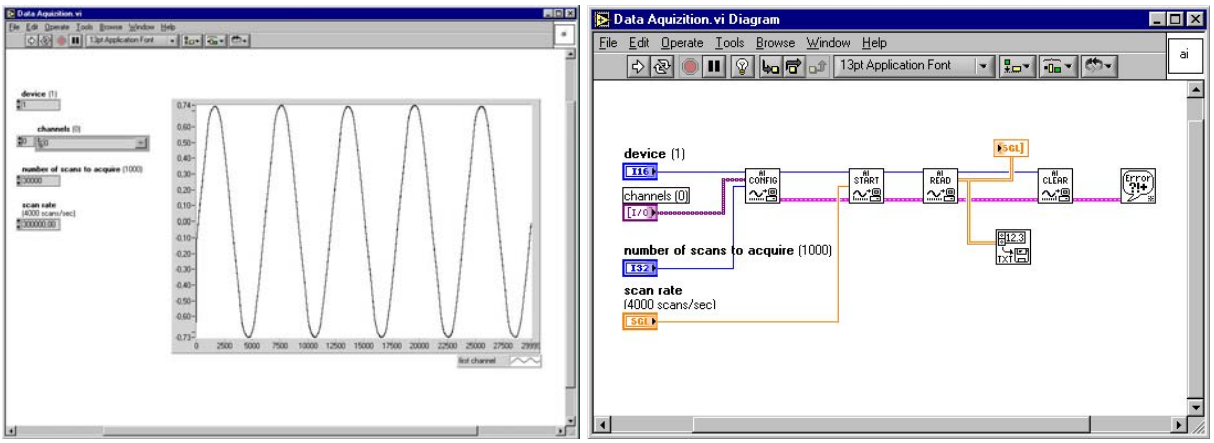
Several sensors can be coupled to the motor: Hall effect transducers for measuring the voltages and the currents. An angular incremental position can measure the position and the speed of the motor. A torque measurement unit can be coupled between the two motors in order to measure both the dynamic and static torque. All the sensors give signals to the data acquisition unit [4].

The measurement part of the test bench consists of a usual, Pentium processor based, PC having a National Instruments PCI-MIO-16E-4 type acquisition board. This delivers high performance and reliable data acquisition capabilities, having 500 kS/s sampling rate, 16 single-ended 12 bit analog inputs. It features both analog and digital triggering capability, as well as two 12-bit analog outputs, two 24-bit, 20 MHz counter/timers and 8 digital I/O lines.

The electrical signals generated by the transducers must be optimised for the input range of the DAQ board. The SCXI signal conditioning accessory amplifies the low-level signals, and then isolates and filters them for more accurate measurements [5].

Several programs were used for the test measurement processes. All of them provide a powerful interface between the operator who co-ordinates the tests and the test bench, because it can be manipulated easy and simply. The programs were written in LabVIEW 6i (a software product of National Instruments Inc.), a powerful graphical programming development for data acquisition and control, data analysis and presentation. LabVIEW gives the flexibility of a powerful programming language without the associated difficulty and complexity because its graphical programming methodology is inherently intuitive to the users. The LabVIEW programs are simply made by assembling via drag-and-drop methods software objects, called virtual instruments (VIs).

The virtual instrument created for the purpose (see Fig. 2) of processing and analyzing the acquired data from the test bench is easy to use and flexible. Its front panel is an interactive control tool for the entire acquisition software. The assembled block diagram ensures its functionality. The acquired data are stored in simple ASCII-type text files in order to be easy imported in any other program.



a) the front panel b) the block diagram

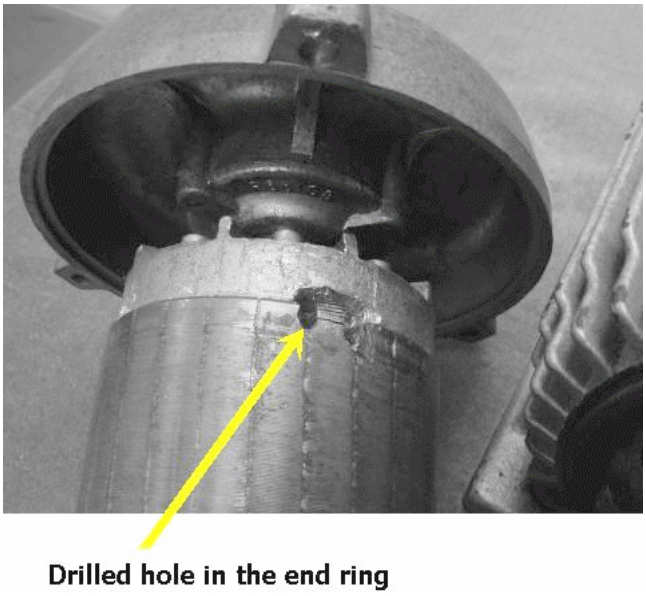
Fig. 2. The virtual instrument for the data acquisition

There are two approaches used for processing the measured signal: time domain and frequency domain. In time domain approach the discrete time signal is directly analyzed by the frequently used DSP techniques (such as filtering, averaging, convolution, correlation, etc.). In frequency domain approach, the signal is first transformed to the frequency domain using Fourier Transform (FT), and then different methods of frequency analysis (such as averaging, convolution, power spectrum, etc.) can be applied [6].

3. RESULTS OF THE TESTS CARRIED OUT

The rated data of the three-phase squirrel cage induction machine (of type B3-90L-1.5×1500) used for testing were: 1.5 kW, 220/380 V (Δ/Y), 6.18/3.56 A (Δ/Y) and 1410 r/min. The rotor cage of the motor has 27 bars.

First of all the machine was tested under healthy condition. Aftertime rotor bar damages were created drilling holes in the squirrel cage (see Fig 3). The order and the position of the damaged rotor bars are shown in Fig. 4.



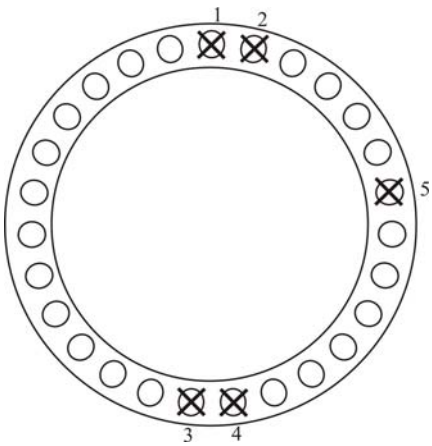


Fig. 3. The destroyed rotor **Fig. 4.** The damaged rotor bars

In all cases the same measurements were performed at no-load and at other 7 loads, including also the rated load of the motor. The line voltages and currents, the motor's speed and torque were measured and saved in text files by the above-presented virtual instrument [7].

For detecting the existence of rotor failures the FFT (Fast Fourier Transform) analysis was performed on the measured terminal currents [8]. Both the harmonic content and the power spectrum of the measured signals were analyzed.

In the particular case of the given motor the harmonic components of the line current up to the 56th order ($2\times n\pm 2p$, where n is the number of the rotor bars and p of the pair poles) had to be analyzed. Upon Nyquist's theorem the corresponding minimum sampling frequency had to be 5.6 kHz. During the data acquisitions a much higher sampling frequency (300 kHz) had been used.

For the harmonic content analysis of the measured line currents a virtual instrument was elaborated in LabView [9]. Its block diagram is given in Fig. 5.

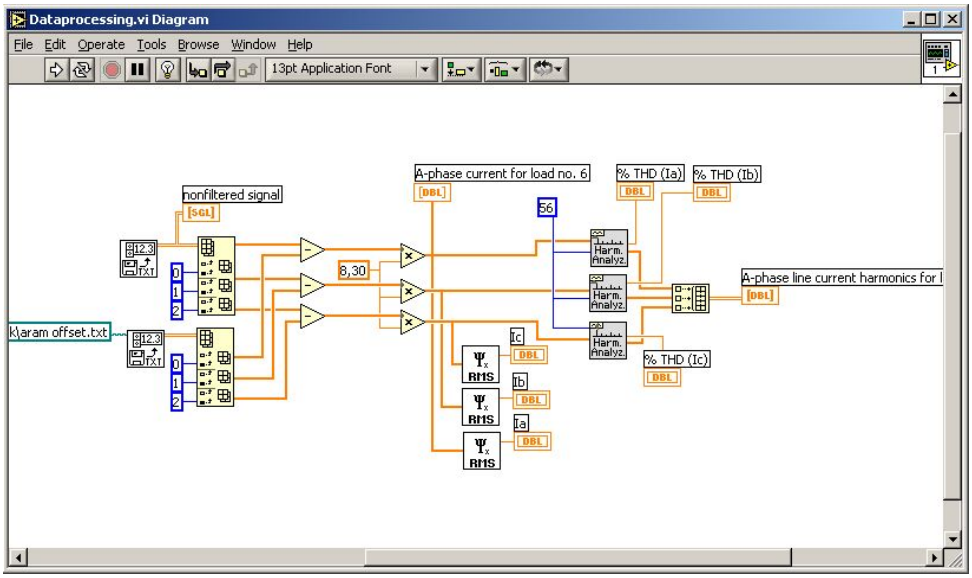


Fig. 5. The block diagram of the harmonic content analysis VI

From the great number of the obtained results only the most significant ones will be discussed here. In Fig. 6 the analyzed line currents obtained by data acquisition when load no. 7 was applied to the induction motor are shown.

Healthy motor **Motor with 3 broken bars**

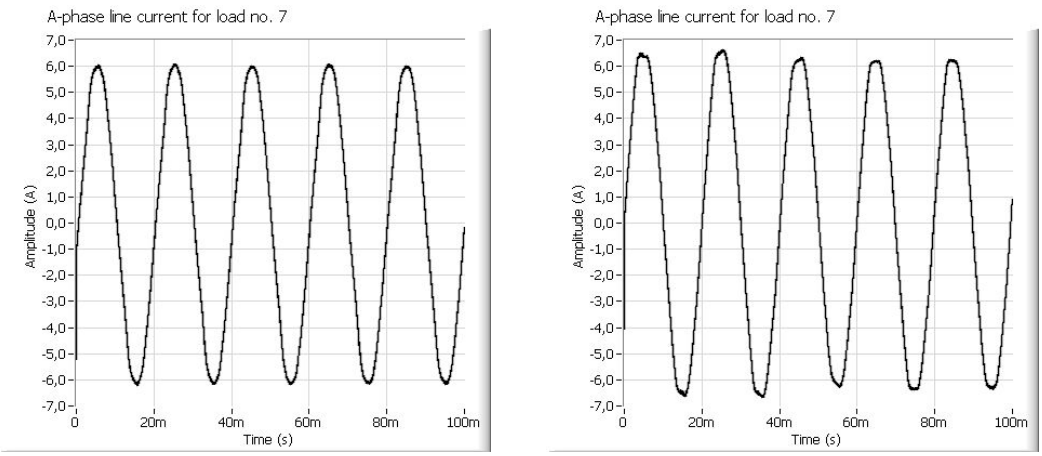
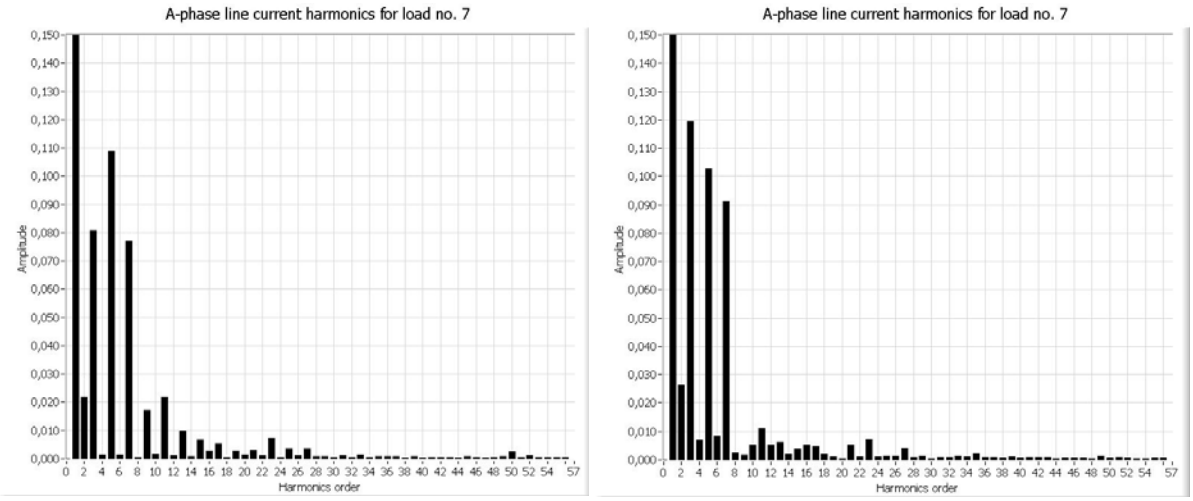


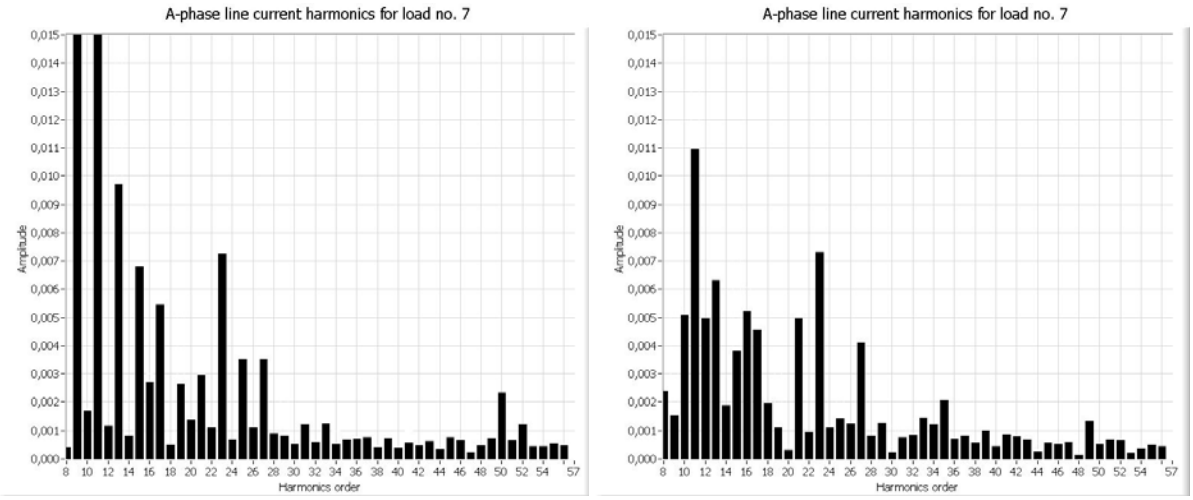
Fig. 6. The measured line currents

The results of the line current's harmonic content analysis are shown in Fig. 7 both for the healthy motor and of that having 3 broken bars. Because there are great differences between the amplitudes of the lower and higher order harmonics, both the entire studied spectra (Fig. 7a) and the harmonics between 8th and 56th order (Fig 7b) are given for the same signal.

Healthy motor **Motor with 3 broken bars**



a) The entire studied spectra of the measured line current



b) The harmonics of order 8÷56

Fig. 7. Results of the line current's harmonic analysis

Firstly it was observed that the harmonics content of measured currents increase for the machine having broken bars. This phenomenon can be explained with the appearance of asymmetries in the motor's structure due the unsymmetrical faults. The best measure of the harmonic content of a signal is its THD (Total Harmonic Distorsion), given by the well-known expression:

$$\mathrm{THD} = 100 \cdot \frac{\sqrt{A(f_1)^2 + A(f_2)^2 + \cdots A(f_n)^2}}{A(f_o)} \quad [\%] \tag{1}$$

The TDH is the smallest in case of the healthy motor, increases after each of the first 3 bars are broken. The THD of the line current of the motor having 4 broken bars is smaller a little bit that of the motor with 3 broken bars. This is due the partial reinstatement of the symmetry in the rotor structure after cutting the 4th bar (see Fig. 4) [7].

The increase of the 2nd harmonic component is a good symptom of the broken bars in the motor. Its amplitude increases function of the number of broken bars and their position. Other higher harmonic components are also increasing when the rotor is damaged.

Next results of another frequency domain analysis, the power spectrum study of the measured line currents will be presented.

The virtual instrument set up for this purpose is given in Fig. 8.

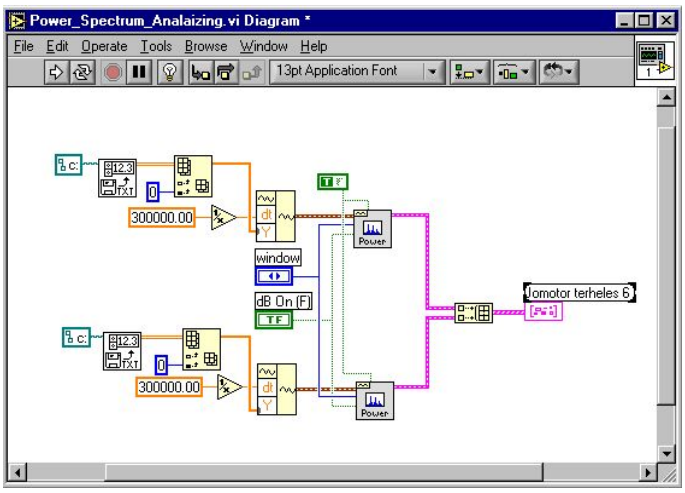


Fig. 8. The block diagram of the spectrum power analysis VI

From the numerous results obtained only two sets of comparative results will be presented here.

In Fig. 9 the power spectrum of the line current for the healthy motor and that having 4 broken bars is given. The measurements were made in both cases at no-load condition.

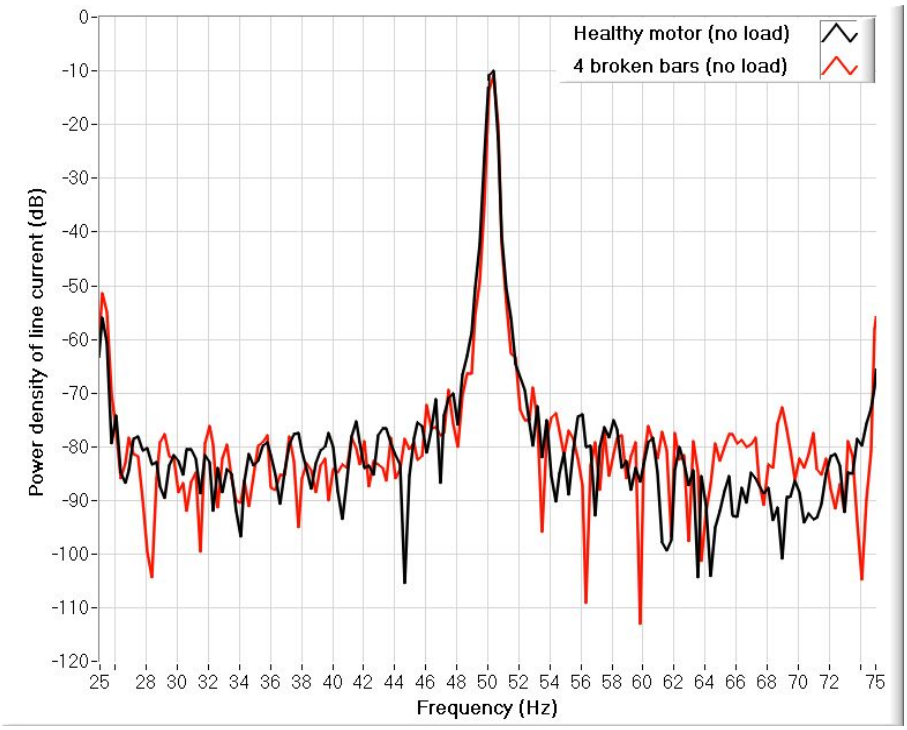


Fig. 9. The power spectrum of the line current for the healthy and the damaged motor

The broken bars in a squirrel cage induction motor give rise to the so-called sideband components around the fundamental supply frequency (f_1) having frequencies given by [10]:

$$f_b = (1 \pm 2s) f_1 \tag{2}$$

In the case of no-load conditions the motor's speed was 1488 r/min, which means a slip (s) equal to 0.008. For these values the two sideband frequencies computed using (2) are 49.2 and 50.8 Hz. Both components of these two frequencies can be easily observed in the power spectrum given in Fig. 9.

From the analysis of the power spectrum also the amount of broken bars can be estimated.

In Fig. 10 the power spectrum of the measured line currents at load no. 4 are given for the cases when the motor had 4, respectively 5 broken bars.

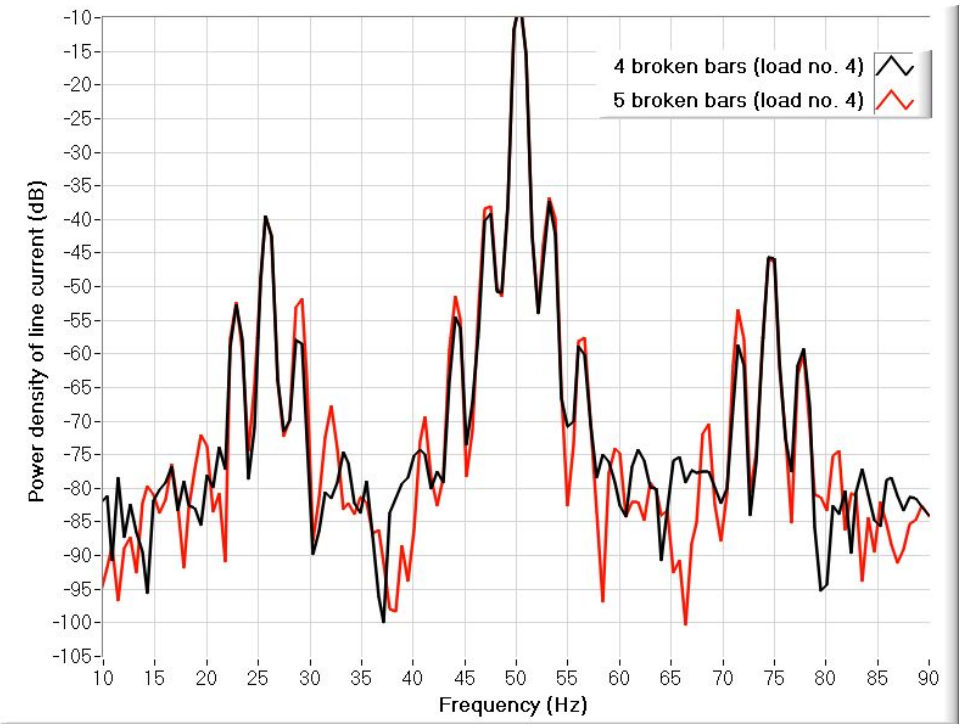


Fig. 10. The power spectrum of the line current for the motor having 4, respectively 5 broken rotor bars

The comparative study of the power spectrums in the two cases clearly shows that both the power spectrum of the measured line current at the sideband frequencies given by (2) and of the higher order sideband frequencies [10] is greater when are more broken bars in the rotor.

All these results show the usefulness of the applied diagnosis methods. They also highlight the remark given in numerous papers regarding the fact that the frequency domain analysis provides the most useful feature set for machine diagnostics [1, 10].

Of course the research must be continued in this field in order to be able to distinguish more accurately a healthy electrical machine from one having broken rotor bars. It should be very useful if also the number of the broken bars could be more precisely estimated from the line current's spectral analysis.

In order to increase the accuracy of the rotor bar faults diagnosis it seems to be necessary to combine the presented examination procedures with others (for example noise and vibration analysis, axial flux based measurements, etc.).

4. ACKNOWLEDGEMENTS

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