

# Detecting Rotor Asymmetries with Variable Speed Drive at Standstill

Jordi Burriel-Valencia, Manuel Pineda-Sanchez, Juan Perez-Cruz, Martin V. Riera-Guasp, Ruben Puche-Panadero

**Abstract**—The diagnosis of Induction Motors (IMs) is crucial to avoid unexpected economic losses due to their failures. To reduce the cost associated to its maintenance, a recent trend is the integration of diagnostic procedures in the electronic equipment that control the motor, such as variable speed drives (VSD)s. This paper presents a new methodology to detect rotor asymmetries and unbalanced contact resistances in IMs fed from VSDs, at standstill. The proposed approach is a non-invasive technique, can be executed on-line, and is not expensive because this method does not need extra hardware or additional sensors. Besides, the results of the proposed diagnostic method are presented in a very graphical and easy to understand way, alike to a dashboard, which makes it easily understandable by non-qualified personal maintenance. The proposed methodology is validated experimentally with a commercial induction motor with different rotors, both healthy and faulty.

**Index Terms**—Induction machines, fault diagnosis, condition monitoring, motor current signature analysis, digital signal processor (DSP), field programmable gate array (FPGA), broken rotor bar

## I. INTRODUCTION

The reliability, robustness, low maintenance requirements, and the advances in power electronics have made cage IMs the horsepower in the electromechanical energy conversion in modern industrial installations. Despite its robustness, these machines are not free from suffering failures that may lead to huge economic losses, well beyond the cost of the motor itself. Hence, to avoid unexpected outages, it is crucial to detect the faults at an early stage, before the breakdown of the motor. Among the possible methods and techniques used in the technical literature, the analysis of the current, or motor current signature analysis (MCSA), has become an important method to diagnose the IMs due to its advantages: it is a non-invasive method, and it has low requirements on software and hardware, among others. Besides, each fault generates or amplifies a set of harmonic components on the stator current whose frequencies have been determined theoretically. For example, in case of rotor asymmetries, the harmonic fault components generate frequencies  $f_{bb}$  [1]

$$f_{bb} = f_{mains} \cdot (1 + 2ks) \quad k = \pm 1, \pm 2, \pm 3 \dots, \quad (1)$$

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where  $f_{mains}$  is the frequency of the power supply and  $s$  is the slip. In case, of mixed eccentricity, the frequencies of the fault components  $f_{ecc}$  are

$$f_{ecc} = f_{mains} + 2kf_r \quad k = \pm 1, \pm 2, \pm 3 \dots, \quad (2)$$

where  $f_r$  is the mechanical speed of the rotor.

Although MCSA has proved its validity for detecting faults in IMs, there are still a several drawbacks: the Fourier analysis needed to track the harmonic components generated by each fault, according to (1) or (2), is restricted to IM working in steady state conditions. Besides, an accurate speed (or slip) measurement is required to compute these frequencies. Several techniques have been proposed recently to analyze the stator current in transient regime, such as the start-up transient of IM, but this requires complex signal processing tools and costly devices, which limits its industrial deployment.

On-line fault diagnosis techniques have attracted a rising interest [2], [3]. They monitor continuously the IM checking its condition. Several on-line fault diagnosis methods have been proposed to be implemented in low cost devices such as digital signal processor (DSP) [4], field programmable gate array (FPGA) [5]–[7] or more recently general-purpose graphics processing unit (GPGPU) [8]. However, from the industrial point of view, there are still several drawbacks for the massive use of this devices for fault diagnosis. High sampling frequencies, used to avoid the aliasing distortions, along with long acquisition times, to obtain high spectral resolution, generate a huge amount of data which is difficult to be processed using these devices. Moreover, complex signal processing tools to detect faults in IMs working in transient regime need high power computing requirements. Hence, the diagnostic procedure must be simple, compact and fast, to be executed on-line by embedded devices [9]–[11]. Doubtlessly, the ideal would be the implementation of the fault diagnosis methods in the same equipment that controls the IM, such as variable speed drive (VSD), giving an added value to this equipment.

In this paper, a new diagnostic method is proposed to address these problems, which is simple, fast and with low hardware and software requirements to be implemented in low cost devices, even in the VSDs that feeds the IMs. This method follow the methodology proposed in [12], [13] for detecting the high-resistance connection asymmetries in inverter-fed IMs, and extends it to the detection of rotor asymmetries, such as broken bar faults. For the validation of this methodology different rotors are used, both in healthy and faulty condition. An added feature of the proposed method is that the motor condition is displayed to the operator using an industrial-grade

human-machine interface (HMI), in a very easy to understand graphical display.

The structure of this paper is as follows: the methodology of the proposed method is presented in Section II. In Section III the test bench is described. In Section IV the experimental results are presented, and, finally, in Section V the conclusions of this work are presented.

## II. METHODOLOGY

The methodology followed in this work is very simple and easy to apply from the point of view of a variable speed drive (VSD). The proposed methodology is based on the measurement of the current at standstill, when the IM is fed using only two of its three terminals. Three measurements are made. In a first step the phases A and B of the machine are fed, using half of its rated voltage in order to limit the phase current,  $I_{test1}$ . Next, the machine is fed using phases B and C, obtaining the current  $I_{test2}$ . Finally, the third step consist on feeding the phases C and A, and the resulting current  $I_{test3}$  is obtained. This measurement sequence can be easily programmed in the VSD that supplies the machine.

When the motor is fed using only two terminals, that is, with the same current (but in opposite directions) in two of the motor windings (and no current in the other one), the magnetic field generated by this current is an alternating one, but its spatial position is fixed and does not rotate. So changing the sequence of the two phases that are fed, following the procedure described before, changes the position of the resulting field in the motor air gap (see Fig. 1).

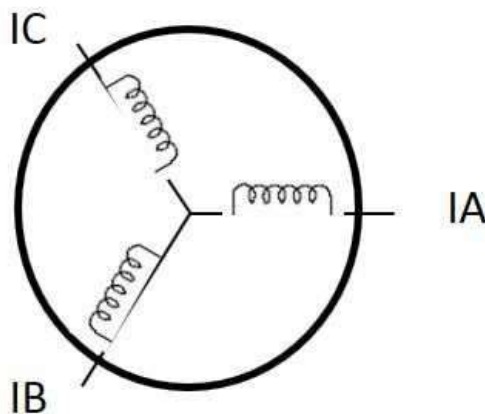


Fig. 1. Scheme of the electrical machine reduced winding.

In a healthy machine, the three currents obtained in the tests ( $I_{test1}$ ,  $I_{test2}$ ,  $I_{test3}$ ) should be quite similar, but in a faulty machine there will be a significant difference between them, depending on the location of the faulty rotor in the stator reference frame. To detect this difference, a current vector is built, with  $x - y$  components given by (3) and (4).

$$I_x = I_{test1} - (I_{test2} + I_{test3}) \cdot \cos(\pi/3) \quad (3)$$

$$I_y = (I_{test2} - I_{test3}) \cdot \sin(\pi/3) \quad (4)$$

The representation of the point with coordinates (3) and (4) coincides with the origin if the machine is in healthy condition, so that the three currents ( $I_{test1}$ ,  $I_{test2}$ ,  $I_{test3}$ ) are balanced. But, if the motor has a rotor asymmetry, or the contact resistance at the motor terminals is unbalanced, this point is displaced, being its distance from the origin a clear indication of the fault.

## III. TEST BED

For validating the proposed methodology, a commercial VSD is used, and the diagnostic algorithm has been run on a personal computer, to verify it. This algorithm is simple enough to be implemented in the VSD microcontroller or DSP.

The scheme of the test bed is shown in Fig. 2 and the real test bed is shown in Fig. 3.

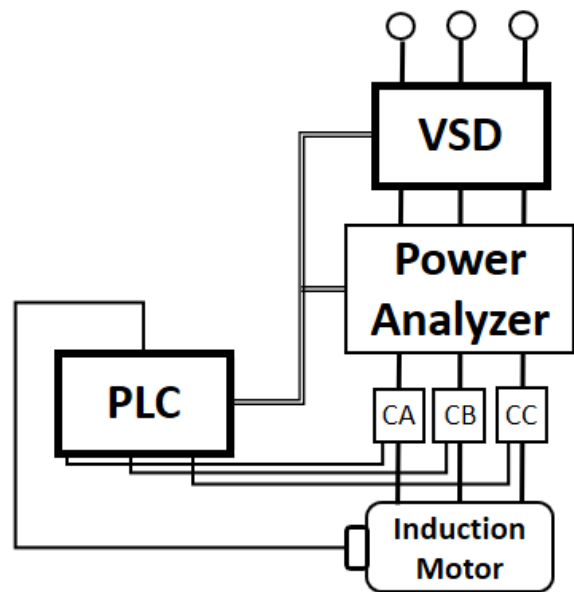


Fig. 2. Schematic diagram of the test bed.

Three motors, whose characteristics are given in Appendix A, have been used for the experimental validation: a healthy IM, and two faulty IMs, one with two broken bars, and the other one with four broken bars (see Fig. 4). To keep the rest of conditions of the different tests unaltered, the same stator has been used with the three tested rotors.

The IM under test is fed from a VSD. In order to do the tests automatically, a programmable logic controller (PLC) is used to manage the sequence of the test. Between the VSD and the IM, the measurement equipment, a power analyzer, has been inserted. Besides, a single-phase contactor in series with each phase of the motor is used to configure the topology of the circuit (two phases connected and the other one disconnected) during each test.



Fig. 3. Picture of the test bed.



Fig. 4. Picture of the three rotors tested; healthy motor (left), motor with four broken bars (center), and motor with two broken bars (right).

The PLC is connected to the VSD and to the power analyzer using a Modbus industrial network. Besides, a touch panel (HMI), which is connected to the Modbus lines, is used to display on-line the results and to plot the points given by (3) and (4) at each test Fig. 5. The touch panel allows to know in "situ" and in real time the machine condition.

For each test, the PLC sends the reference frequency to the converter and the run/stop command, via Modbus, and reads the phase currents from the power analyzer. Moreover, the PLC acts over the digital outputs to connect the single-phase contactors, according to the sequence of each test. The VSD is parametrized with a scalar control with programmable characteristic voltage/frequency (linear but with the voltage limited to half the value of the rated voltage, in order to protect the motor).

For increasing the reliability of this new approach the three tests are repeated at different rotor positions, each 30 mechanical degrees in this work.

Fig. 6 shows a general view of the test bed setup.

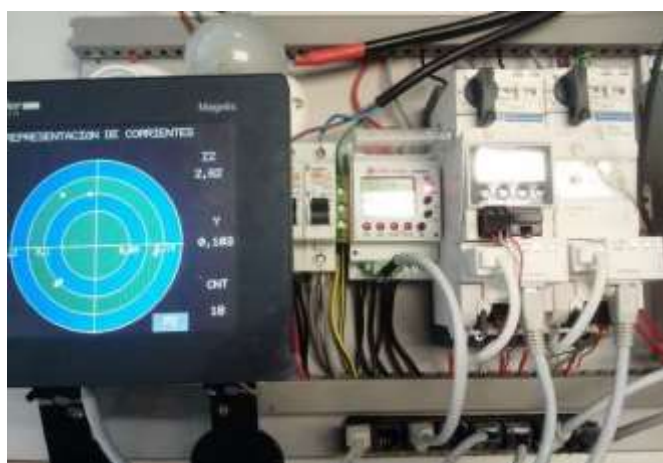


Fig. 5. Representation in the dashboard of the HMI from the two broken bar motor.

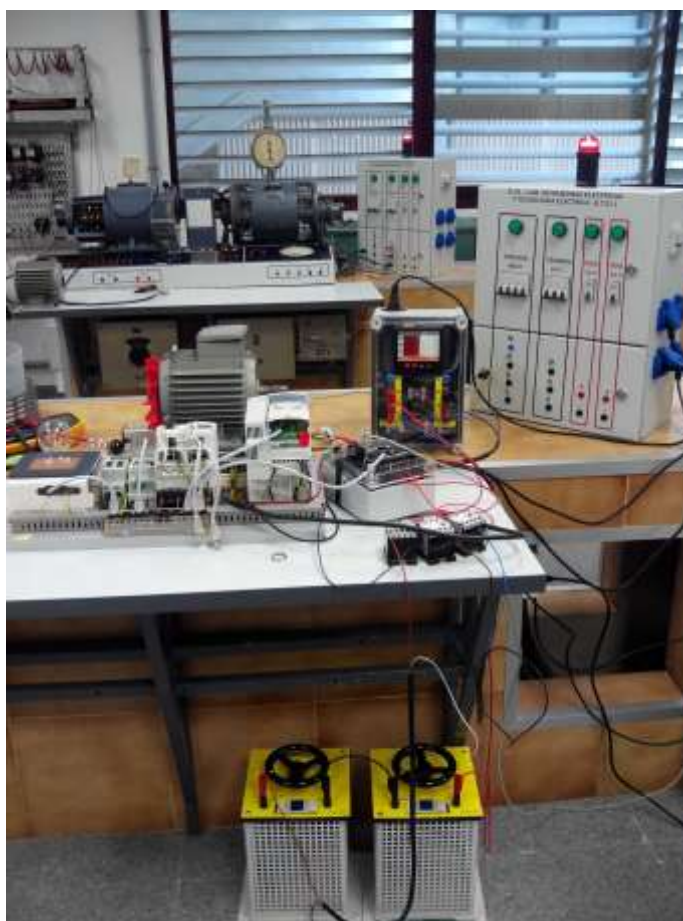


Fig. 6. General view of the test bed used for the experimental validation of the proposed method.

#### IV. RESULTS

Table I presents the results obtained with the healthy motor, using twelve measurements made at every 30 degrees of the rotor angular position. In an industrial environment, where there is no possibility of fixing the position of the rotor, the measurements can be taken at different motor stops, which should give different rotor angular positions after it stops.



TABLE I  
 TEST OF THE MOTOR IN HEALTHY CONDITION

Degrees	Voltage (V)	Current (A)		
		Test1	Test2	Test3
0	115	2.34	2.34	2.35
30	115	2.34	2.34	2.35
60	115	2.32	2.33	2.34
90	115	2.32	2.32	2.34
120	115	2.31	2.31	2.34
150	115	2.30	2.31	2.32
180	115	2.30	2.30	2.32
210	115	2.30	2.30	2.32
240	115	2.31	2.30	2.32
270	115	2.28	2.29	2.30
300	115	2.29	2.29	2.32
330	115	2.29	2.28	2.31

TABLE II  
 TEST OF THE MOTOR WITH TWO BROKEN BARS

Degrees	Voltage (V)	Current (A)		
		Test1	Test2	Test3
0	115	2.60	2.73	2.63
30	115	2.62	2.60	2.73
60	115	2.71	2.62	2.60
90	115	2.59	2.71	2.63
120	115	2.60	2.59	2.72
150	115	2.70	2.60	2.60
180	115	2.57	2.70	2.60
210	115	2.59	2.57	2.70
240	115	2.67	2.60	2.58
270	115	2.55	2.68	2.60
300	115	2.59	2.56	2.68
330	115	2.69	2.61	2.60

The results from Table I are represented alike a dart board in Fig. 7. All of the samples are close to the zero point of the dartboard because the currents are balanced. These results confirm that the machine is in a healthy condition.



Fig. 7. Representation in the dartboard of the results for the healthy motor.

Table II presents the same results as Table I, but obtained with the motor with two broken bars.

The results from Table II are represented as a dart board in the Fig. 8. All of the samples are located far way of the zero point of the dartboard, because the currents are not balanced, which means that the machine is in faulty state.

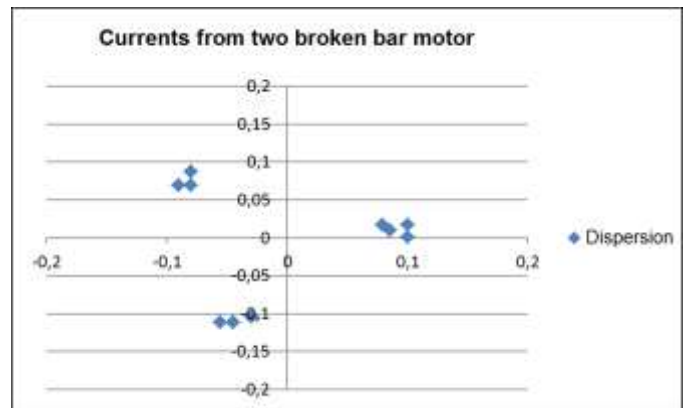


Fig. 8. Representation in the dartboard of the results for the motor with two broken bars

Finally, the results obtained with the tests of the motor with four broken rotor bar are shown in Table III, and depicted in Fig. 9.

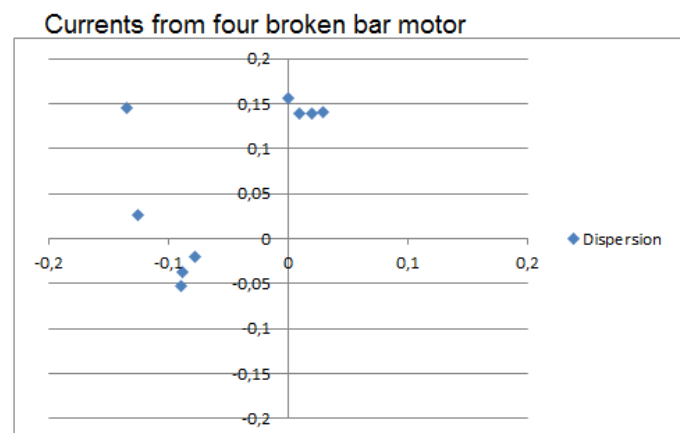


Fig. 9. Representation in the dartboard of the results for the motor with four broken bars.

## V. CONCLUSION

In the present paper a new method has been proposed to detect rotor asymmetries, such as broken bar, when the motor is fed by a VSD at standstill. The main advantages of this new method are the low computing requirements (no spectral analysis is needed) and the easy interpretation of the results, which are presented in a dart board style: if result of the measurements is a point close to the center of the dartboard, the machine is in health condition. In the case of a rotor asymmetry, the resulting measurement point appears far from the display center. Each time that the test is performed, a new point is added to the display. The proposed algorithm is very simple and has a low computational cost, so that it can be implemented along with the control program of the VSD

TABLE III  
 TEST OF THE MOTOR WITH FOUR BROKEN BARS

Degrees	Voltage (V)	Current (A)		
		Test1	Test2	Test3
0	115	2.55	2.57	2.65
30	115	2.58	2.65	2.52
60	115	2.66	2.51	2.54
90	115	2.53	2.55	2.62
120	115	2.55	2.62	2.50
150	115	2.64	2.50	2.53
180	115	2.50	2.52	2.61
210	115	2.55	2.60	2.49
240	115	2.63	2.48	2.51
270	115	2.51	2.52	2.60
300	115	2.51	2.61	2.47
330	115	2.64	2.48	2.49

APPENDIX A  
 CAGE INDUCTION MACHINE MOUNTED IN THE  
 LABORATORY TEST BENCH

Three-phase induction machine, star connection. Rated characteristics:  $P = 1.5 \text{ kW}$ ,  $f = 50 \text{ Hz}$ ,  $U = 400 \text{ V}$ ,  $I = 3.25 \text{ A}$ ,  $n = 2860 \text{ r.p.m.}$ , and  $\cos\phi = 0.85$ .

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