Detection of Inter-Turn Short-Circuit and broken Rotor Bars in Induction Motors Using the Partial Relative Indexes: Application on the MCSA

S. E. Zouzou, M. Sahraoui, A. Ghoggal, and S. Guedidi.

Abstract— **Nowadays, the induction motors became the key element in all industrial plants. Early detection of abnormalities during motor operation would reduce the repair cost and the motor outage time. It was observed that most methods which are presented in literature for diagnosing motor faults are belonged to signal approach. Their philosophy supposes that each fault is characterized by specific spectral signatures on the spectra of acquired signals. However, practical cases show that occurrence of any kind of faults is often accompanied by complicated physical phenomena which extend its influences to other spectral components different from its signatures; this makes too difficult to locate the machine faults and poses then a big question about the concept of: *Fault Signatures*. In this context and in order to ameliorate the fault detection task, the present paper proposes the use of Partial Relative Indexes (PRI) as new fault indicators. Many experimental tests which are carried out on 3kW three-phase induction motors with broken bars and inter turn short-circuit corroborate our theoretical ideas and confirm the effectiveness of the proposed technique to detect such faults under different operation loads.**

Index Terms—**Diagnosis, induction motors, inter-turn short circuit, broken rotor bars, MCSA, partial relative index.**

I. INTRODUCTION

THe induction motors are the key element in all industrial plants. Consequently, any fault that occurs in such machine can lead to an interruption of the manufacturing process causing serious financial losses. Therefore, the main goal is to reduce the maintenance costs and to prevent unscheduled downtime of these machines [1] – [3].

It is well known that faults diagnosis includes two tasks: *detection* and *localization*. The faults detection consists in declaring the presence of abnormal operation, while the localization has the aim of finding the cause of this malfunction. In this context, various diagnosis methods have been studied in literatures [4] – [16], and it was observed that most of these methods belong to the signal approach, which supposes that each fault is characterized by specific spectral signatures. However, practical cases show that most of these spectral signatures are always present on the motor signals spectra, even at healthy state, due to inherent asymmetries.

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Hence, when a fault is occurred, it is often accompanied by complicated physical phenomena (thermal hotspots, vibrations, oscillation in the torque…) which extend its influences to several spectral components related to other kind of faults. This means an overlapping between faults signatures and show that localization of machine faults, via their own spectral signatures, is too difficult.

The philosophy of this paper supposes that main goal of a diagnosis operator is to detect any fault or abnormalities in their first steps; this makes possible to program a shutdown of manufacturing process in order to replace the faulty machine which will be transformed to repair shops, where it will undergo a precise inspection to locate and to repair the defects. Hence, the author's idea is based on separation between the two diagnosis tasks; the major importance will be given to the fault detection task, while the fault localization becomes the responsibility of the repair shops.

Thus, the present work has two aims:

1) Firstly, and in order to show the existence of overlapping between faults signatures, a conventional diagnosis method: MCSA which belongs to signal approach, will be used to detect and locate two kinds of faults: the broken rotor bars and the inter turn short-circuit in a 3kW three-phase squirrel cage induction motor.
2) Secondly, and to ameliorate the reliability of fault detection task, the authors propose a new technique based on the use of the *Partial Relative Indexes* (PRI) as fault indicators. These PRI, computed starting from the spectral component amplitudes, will enable the extraction of all useful information from phase current spectrum.

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II. THE MOTOR CURRENT SIGNATURE ANALYSIS (MCSA)

The MCSA is one of the most powerful methods of motor faults diagnosis [4] – [9], [18]. This method uses the current spectra of one phase, which contains potential information of most motor faults. It doesn't need any estimation of motor parameters and it requires only a simple current sensor.

Theoretically, faults such broken rotor bars or inter-turn short circuit can be diagnosed using MCSA by monitoring, respectively, the spectral components given by (1) and (2) [16] – [19]:

$$f_{br} = (\nu \pm 2ks) f_s \tag{1}$$

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$$f_{sh} = \left| \left(\nu f_s \pm \frac{k(1-s)}{p} \right) f_s \right| \quad (2)$$

where f_s is the electrical supply frequency, f_{br} and f_{sh} are respectively the theoretical signatures of broken rotor bars and inter-turn short-circuit, s is the slip, $\nu = 1, 3, 5, ..$ is the time harmonic order and $k = 1, 2, 3, ..$ an integer.

III. Details Of Test Rig

The test bench used for the experimental investigation is available at the LGEB laboratory in university of Biskra-Algeria (Fig. 1).

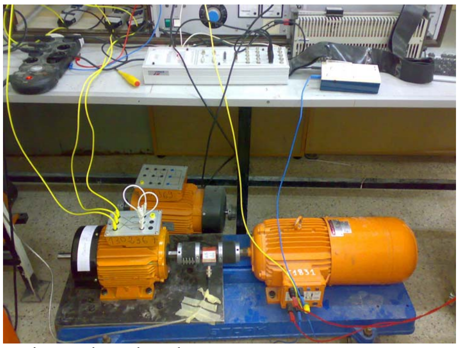

Fig. 1. The experimental test bench.

The tests were carried out on three machines; each one is a three-phase 50-Hz, Y connection, 4-pole, 28 bars, 3kW *Leroy Somer* squirrel-cage induction motor. The first is a healthy motor and it was taken as a reference, the rotor of second motor contains two broken bars (Fig.2) and the stator of the third motor was modified by adding five tappings connected to stator coils of the phase ***W1-W2*** (Fig.3); the other ends of these external wires are connected to a motor terminal box that allows introducing inter-turn short circuits with different number of turns (Fig.4).

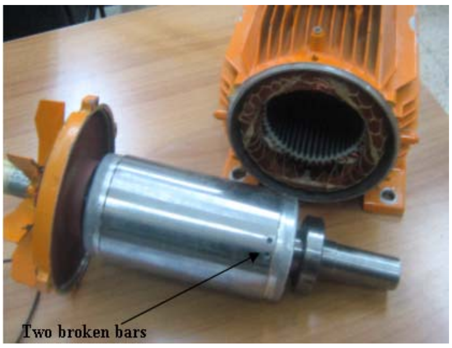

Fig. 2. The rotor with two broken bars.

Many tests were performed at healthy state, with two broken bars and with four then ten turns short-circuited under low, medium and full load. In all cases, 10s of the three-phase currents were sampled at 10 kHz, and five consecutive measurements were averaged to reduce the average noise level.

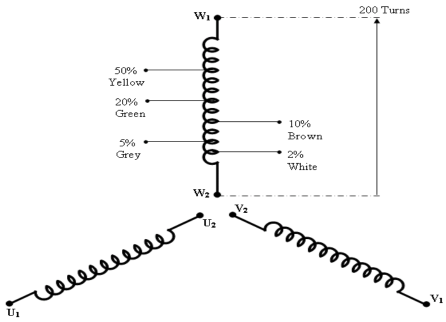

Fig. 3. The five tappings connected to the stator coils of the phase W1-W2.

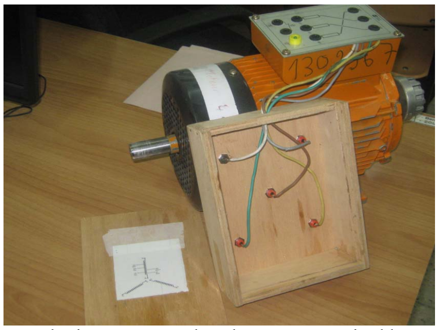

Fig. 4. The external wires connected to the motor terminal box.

IV. Experimental Results

After acquisition, all experimental data were processed to compute the FFT of one phase current. The obtained spectrum is visualized in different frequency ranges (Fig.5). Note that the use of linear scale for vertical axis has improved greatly the legibility of the graphs. Analyzing these figures, one can state the following points:

1) The phase current spectrum is rich in harmonics even at healthy state. It is possible to class these harmonics in four types. Thus, one can state that phase current spectra contains four harmonic types, even at healthy state, due to the supply and some inherent asymmetries, as shown in Table I:

TABLE I
GENERAL EXPRESSION OF DIFFERENT SPECTRAL COMPONENTS APPEARING IN THE SPECTRUM OF STATOR CURRENTS IN HEALTHY STATE

Harmonic Types	**General expression of their frequencies**	**Their causes**
Time Harmonics (TH)	νf_s	Imposed by the supply source or residual asymmetry in stator windings
Rotor Slot Harmonics (RSH)	$\lvert \nu f_s \pm N_r f_r \rvert$	Imposed by the rotor structure (discrete distribution of rotor bars in the rotor slots)
Rotor Bar Fault Harmonics (RBFH)	$\lvert (\nu \pm 2ks) f_s \rvert$	Due to residual rotor cage asymmetries
Eccentricity Fault Harmonics (EFH)	$\lvert \nu f_s \pm k f_r \rvert$	Due to residual level of mixed eccentricity

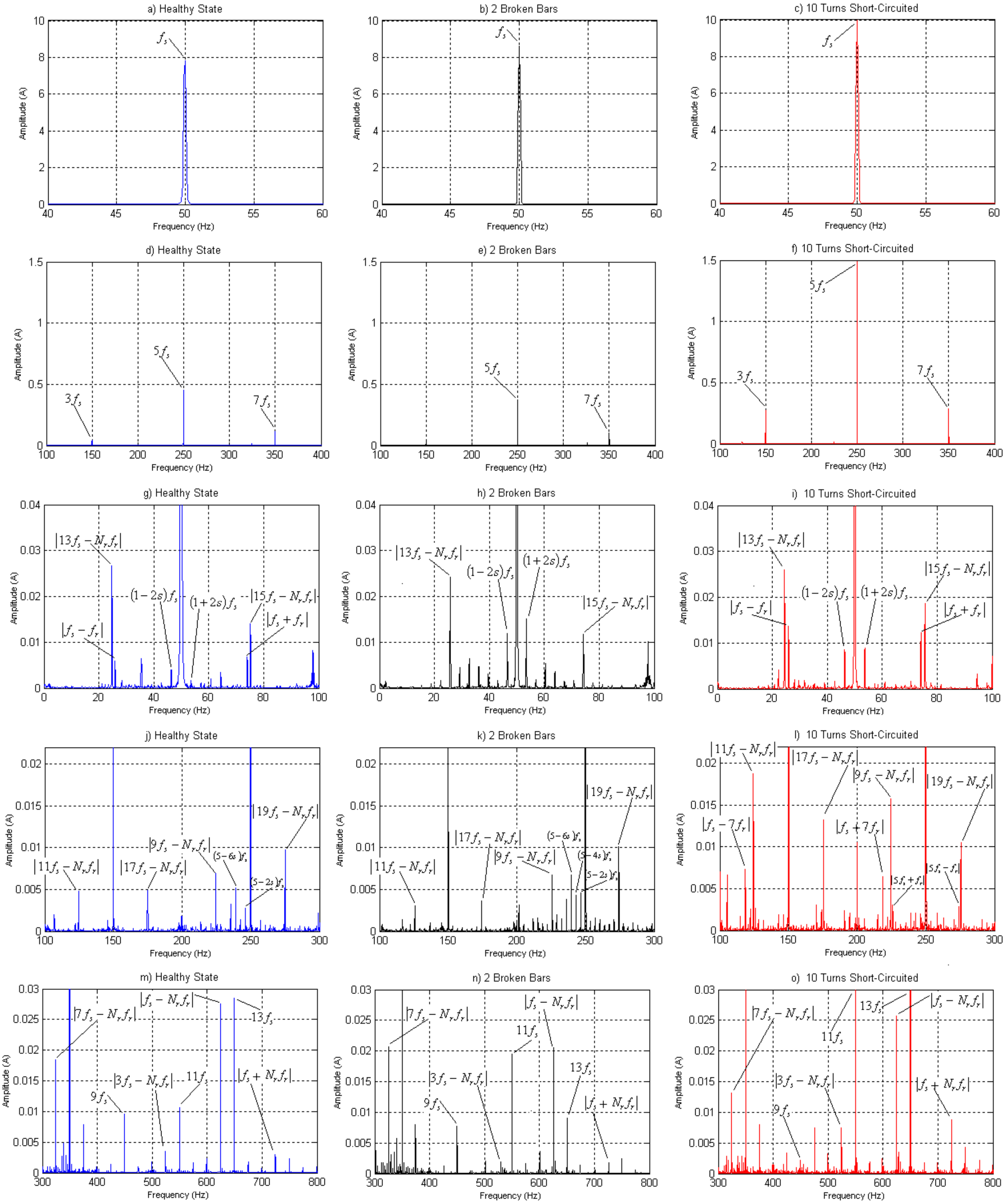

Fig.5. The phase current's spectrum for a motor under medium load: at healthy state (first column), with 2 broken bars (second column) and with 10 short-circuited turns (third column).

2) Fig.5 shows that rotor bar defect has amplified significantly the amplitudes of some RBFH, especially the $(1\pm 2s)f_s$, $(1\pm 4s)f_s$, $(5-2s)f_s$, $(5-4s)f_s$ and $(5-6s)f_s$. Note that no appreciable changes can be observed on the RBFH surrounding 150Hz. In addition, this rotor fault has decreased all the RSH, while the majority of the TH have been declined slightly except for f_s and $11f_s$ which are increased considerably and the $13f_s$ which is diminished significantly.

3) The occurrence of inter-turn short circuit doesn't induce new spectral components in the phase current's spectrum but, it causes considerable increases on the amplitudes of all harmonics even those related to broken rotor bars or mixed eccentricity. These observations demonstrate the existence of overlapping between the defects signatures; that make difficult to find the causes of motor failures. Consequently, one can state that using only the fault signature concept, the fault localization task is too complicated.

4) Since there are a variety of motor defects, their presences induce modifications on the spectral content of phase current; the modifications ratios are highly different from an harmonic to an other and certainly from a motor to an other. This makes difficult to choose the most sensitive components that must be considered as fault indicators. Note that a bad choice of fault indicators leads to an erroneous detection. As a result, the reliability of fault detection task will be reduced significantly. These practical problems demonstrate the need for other techniques enabling amelioration of fault detection task, which is the aim of the following section.

V. Diagnosis Of Faults Using The PRI

The philosophy of this technique considers that all components constituting the spectral contents of phase current represent good sources of information. Since these spectral components were classified in four types, it is possible to define four partial relative indexes; each one is related to a type of harmonic.

The proposed technique is dedicated to improve the reliability of fault detection task and it will be applied initially on the MCSA.

Therefore, the PRI generation process will be based on the following steps:

1) Acquisition of one phase current (i_A for example);
2) Calculation of the FFT related to this phase current;
3) Determination of amplitudes and frequencies corresponding to the four harmonic types;
4) Computation of four Partial Indexes (PI) related to the four harmonic types, as follows:

$$PI_{H.MCSA} = \frac{\sum_{i=1}^{m_H}\left[Amplitude(H)_i\right]}{m_H} \qquad (7)$$

With:
$H = TH, RSH, RBFH\ or\ EFH$ indicates the harmonic's type.
$m_H = m_{TH}, m_{RSH}, m_{RBFH}\ or\ m_{EFH}$ specifies the number of the considered spectral components differenced by type.

TABLE II

THE CONSIDERED HARMONICS WHICH ARE USED TO CALCULATE THE PRI

Harmonic Types	Expressions of the considered harmonics
TH	$m_{TH} = 5$ f_s, $3f_s$, $5f_s$, $7f_s$, $9f_s$
RSH	$m_{RSH} = 15$ $\left\|\{\nu = 1,...15\}f_s - N_r.f_r\right\|$ et $\left\|\{\nu = 1,...13\}f_s + N_r.f_r\right\|$
RBFH	$m_{RBFH} = 32$ $\left\|\left[\{\nu = 1,...7\}\pm 2\{k = 1,...4\}s\right]f_s\right\|$
EFH	$m_{EFH} = 8$ $\left\|\{\nu = 1,...,7\}f_s \pm \{k = 1\}f_r\right\|$

5) Computation of the four Partial Relative Indexes (PRI) corresponding to the four harmonic types, as follows:

$$PRI_{H.MCSA} = \frac{PI_{H.MCSA}}{\left(PI_{H.MCSA}\right)_{HealthyState}} \qquad (8)$$

It is obvious that all the PRI corresponding to healthy state will be equal to 1.

A lot of tests were carried out with different motor states (Healthy state **"HS"**, two broken bars **"2Bb"**, four turns short-circuited **"4Tr.Sh"** and ten turns short-circuited **"10Tr.Sh"**) under three different loads (low, medium and full). After acquisition, the four PRI were calculated and presented in Fig.6.

As can be clearly seen, the proposed technique enables a good exploitation of phase current spectrum. Indeed, the monitoring of the PRI gives pertinent information and describes, in a qualitative and quantitative way, the motor states when a fault is occurred.

Analyzing Fig.6, the following remarks can be drawn:

1) All the PRI are influenced by the occurrence of broken rotor bars or inter-turn short circuit; these influences depend strongly to the fault severity and the operation load.
2) Under full and medium load, the PRI_{RBFH} is the most sensitive index to the presence of broken bars. However,

the PRI_{EFH} becomes the best index allowing the detection of this fault under low load.

3) Under full load, the short-circuit of 4 turns didn't induce great changes on the PRI except for the PRI_{RSH} which has been increased slightly. However, this small fault amplified considerably the PRI_{EFH} under low load.

4) When this fault became more severe (short-circuit of 10 turns in), the majority of the PRI are raised significantly and especially the PRI_{EFH} and the PRI_{TH} .

5) Using PRI_{EFH} , one can state that the detection of inter-turn short-circuit is more easy, under low load. In contrast, and via the PRI_{RBFH} , the detection of broken rotor bars is only easier under full load.

VI. CONCLUSION

This paper has treated the diagnosis activity and its two tasks. The demonstration of fault localization problem and the amelioration of fault detection task were the aims of this work. Indeed, and via the MCSA method which belongs to the signal approach and through a lot of experimental tests that were performed on a 3kW three-phase induction motors under different loads with healthy and faulty states, it was shown that occurrence of broken rotor bars or inter-turn short-circuit has affected other spectral components different from their own signatures. These have proved that fault localization is too difficult.

In addition, a new technique based on the use of the PRI has introduced in order to ameliorate the reliability of fault detection task. The proposed technique has been applied on the MCSA method, and it was shown that the PRI, which were computed, starting from the different spectral components, enabled a good exploitation of phase current spectrum, and it seems that the use of the Partial Relative Indexes will be very helpful for extracting useful information from any other signal. Indeed, the experimental results attested the effectiveness of this technique for detecting faults such e broken rotor bars or inter-turn short-circuits.

Other ameliorations on the computation of the PRI are currently in progress in order to improve the efficiency of proposed technique to detect all anomalies that affect induction motors.

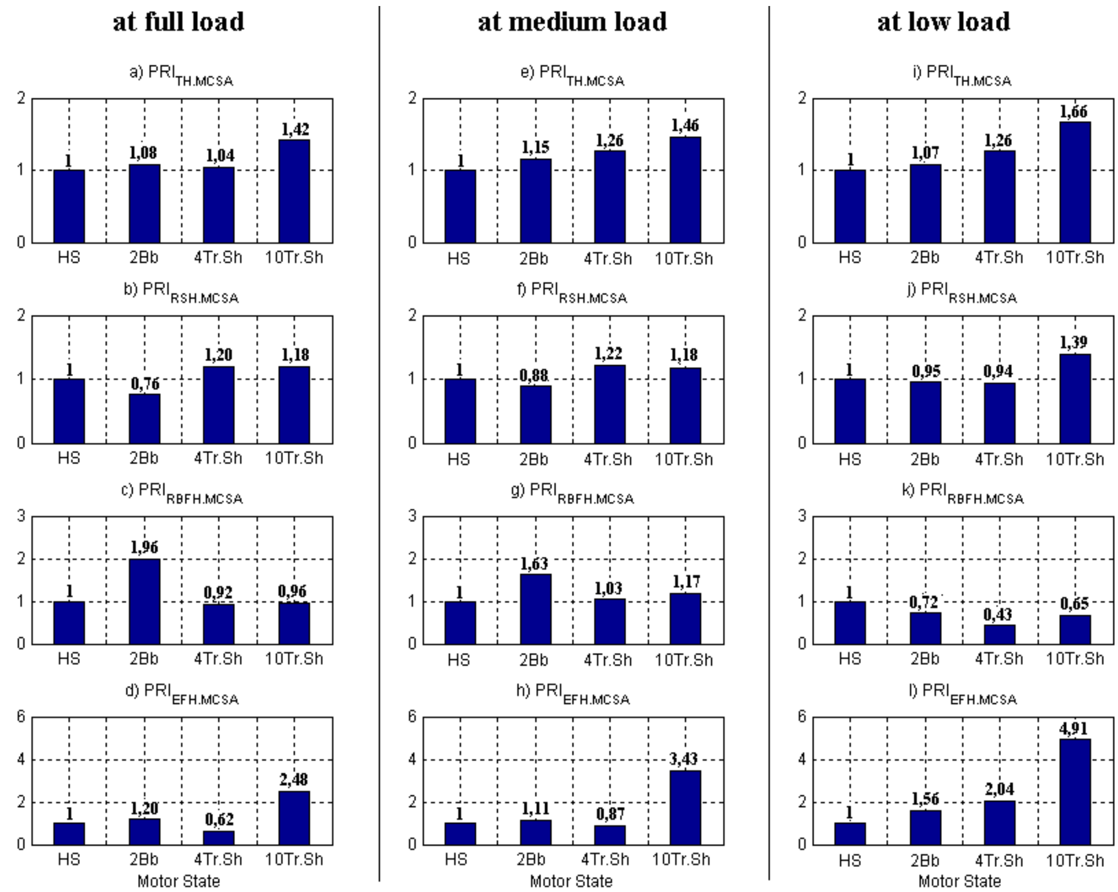

Fig.6. The different PRI corresponding to the MCSA for a motor with different states and under different loads

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VIII. Biographies

Salah Eddine Zouzou was born in Biskra, Algeria on 1963. He received the B.S degree from the "Ecole Nationale Polytechnique d'Alger", Algeria in 1987 and the M.S and Ph.D degrees from the "École Nationale Polytechnique de Grenoble" France, in 1988 and 1991 respectively. His fields of research interests deal with the design and condition monitoring; of electrical machines .He has authored or co-authored more than 40 scientific papers in national and international conferences and journals. Prof. Zouzou is an associate Professor at the University of Biskra, Algeria and he is the director of the "Laboratoire de Génie Electrique de Biskra" since 2004.

Mohamed Sahraoui was born in Biskra, Algeria in 1978. He received the Engineer and the "Magistère" degrees in electrical engineering both from the University of Med Khider of Biskra, Algeria in 2001 and 2003 respectively. He is interested in the modelling, condition monitoring and faults diagnosis of electrical machines and working toward the Ph. D degree on the same axis. He has authored or co-authored many national and international scientific conferences and journal papers. Mr. Sahraoui is an assistant professor with the University of Constantine, Algeria since 2005 and he is a member in the "Laboratoire de Génie Electrique de Biskra".

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