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Efficiency assessment of induction motors operating under different faulty conditions

Maëva Garcia, Panagiotis A. Panagiotou, Jose A. Antonino-Daviu, *IEEE Senior Member,* and Konstantinos N. Gyftakis, *IEEE Member*

Post Conference Paper

***Abstract*—Fault diagnosis in induction motors has been a topic that has drawn an increasing attention among the electrical engineering community, including both industry and academia. Diverse techniques have been developed in order to detect the presence of possible faults in their early stages, so that forced outages of the motor and consequent economic consequences can be avoided. However, little attention has been paid to the implications of the presence of these faults in terms of motor efficiency reduction. The efficiency drops caused by the existence of faults or anomalies in the motor, which can be present during long time intervals, can lead to economic losses that can be even greater than those caused by eventual motor outages. In spite of this fact, many industrial users are not aware of the efficiency repercussions of the operation under non-healthy conditions. As a consequence, it becomes necessary to accurately study and quantify the efficiency decrements caused by the presence of possible failures, so that the users can have this information available to adopt proper maintenance decisions. This paper analyses how different non-catastrophic failures influence the value of motor efficiency; different types of rotor faults as well as bearing failures are considered. In this work it is shown that indeed the presence of these failures strongly affects the motor efficiency and may have serious implications on the motor performance and operational cost.**

***Index Terms*— broken bars; bearings; efficiency; fault detection; induction motors; reliability.**

I. INTRODUCTION

THERE are more than 300 million electric motors in the world. Altogether, they consume near 40% of the world electricity production (in 2012, this meant 7,400 TWh per year) [1]. Induction motors are the most widely spread electric motors in the industry, consuming near 80% of the energy demanded in this sector [2]-[3]. They are part of a huge number of processes and applications of diverse nature and are met in different sectors. In a single factory, there can be hundreds or even thousands of these machines. Therefore, they have a strong influence on the global efficiency and reliability of the plants where they operate.

Over the recent years, there has been an increasing international concern on optimizing the world energy consumption. This has led to the establishment of certain minimum requisites on energy efficiency in many countries (MEPS, Minimum Energy Performance Standards) for several types of equipment, including electric motors [4]. With regards to electrical machines, various regulations such as the IEC 60034-30 try to standardize the definition, measurement and publication format of the efficiency data of the motors and facilitate the selection of these machines depending on the application. In Europe, the efficiency classification currently under use for low voltage motors is the one specified in the IEC 60034-30 [4], which establishes four levels of motor efficiency (IE-1 (standard), IE-2 (high), IE-3 (Premium) and IE-4 (Super-premium)). The application of MEPS in Europe in search for better efficiencies has led to the establishment of certain deadlines for the manufacturers concerning the progressive elimination of models with lower efficiency levels (IE-1, IE-2) in benefit of the adoption of higher efficiency motors (IE-3 or even IE-4) [4]. These higher efficiencies are obtained by modifications in the manufacturing process such as: use of cores with reduced losses, shorter air-gap lengths, special designs in the rotor bars and end ring, optimization and better quality of the stator winding, etc. [1].

However, note that it is not enough to use only motors of higher efficiency classes to enhance the efficiency of a whole plant. One of the factors that strongly influences the actual motor efficiency is its health. The presence of anomalies, defects, damages or problems in the machine components leads to abnormal operations and may increase the losses, reducing the actual efficiency of the machine. For instance, several works proved years ago that that the existence of misalignments between the motor and the driven load may lead to significant efficiency drops due to the higher mechanical losses at the couplings and bearings [5]-[9]. Analogously, the existence of other types of problems such as bearing defects, rotor electrical

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failures, cooling system damages, core defects, etc. can lead to poor motor performance and decrease of its efficiency.

Despite these facts, little research has been devoted to the study of the efficiency repercussions of the presence of different failures in induction motors [10]-[12]. Instead, many works in the literature have been focused on the development of techniques that are aimed to detect the different faults [13]-[15]. The main goal of these techniques is to detect the failures at an incipient stage so that motor outages and catastrophic consequences are avoided. However, it is often neglected that, the mere presence of these faults or anomalies has an impact on the motor performance; even if the motor collapse is not imminent, the existence of the anomaly is affecting the motor efficiency; the aggregate effect of the efficiency reduction for all individual motors means a significant economic impact on the whole plant.

The objective of this paper is to thoroughly investigate the repercussions of different induction motor faults in terms of performance and efficiency reduction. To this end, extensive simulations using the Finite Element Analysis (FEA) have been carried out while an experimental test bench enabling the measurement of the efficiency in a motor operating under different faulty conditions has been developed. Motors with different characteristics are considered in FEA simulations and experiments in order to allow for the generalization of the results. Two specific faults are considered in the work: rotor bar failures and bearing damages. For the first fault type, different fault severities and variants are considered. For each fault condition, the motor is tested under different load levels to analyze the dependence of the efficiency drop with the load. Two different experimental benches are employed to provide generality to the results. The results, that are an expansion of those reached in [23], show interesting conclusions about the impact of the considered failures on the motor efficiency, confirming a clear influence of the health condition of the motor over its actual performance. The main contribution of the paper is the development of experiments to compute the actual efficiency decrements for different fault conditions and load levels. Moreover, for the first time, it is studied the influence of the relative position of broken bars on the efficiency reduction.

The paper is structured as follows: Section II describes the faults that are considered in the paper. In Section III, the FEA simulations results and analysis are presented. Furthermore, the experimental test bench is described in Section IV, while the results of the experimental testing as well as the discussion are shown in Section V. Finally, Section VI summarizes the conclusions of the work.

II. Studied Faults

Two specific faults are considered in this work: rotor bar failures and bearing faults. With regards to rotor bar damages, different numbers of broken rotor bars are considered, as well as different relative positions between the broken bars.

A. Rotor bar failures

Rotor bar failures are related to the damage of the bars or the end rings of the rotor cage. They are much more frequent in fabricated copper motors, in which the bars are brazed to the end rings. Moreover, they are especially likely in large motors that drive high inertias and with frequent heavy startups [3], [16]. Under those conditions, the abrupt thermal gradients in the bars lead to electro-dynamical stresses between the bars and end rings that facilitate the appearance of small cracks in the connection between the bar and end ring [3, 16]. Usually the dimensions of these cracks progressively grow until the point where a breakage occurs [3].

The immediate effect of a bar breakage is a current re-distribution at the other bars, in such a way that an important increase in the current flowing through the neighboring bars occurs. Therefore, these are the bars that are more prone to fail next, since the electrodynamic stresses and thermal gradients are higher now in those bars in comparison with the others. As a consequence, the fault is typically progressive, often starting in one bar and propagating towards the adjacent ones [16]-[17].

Of course, the motor availability is compromised by the presence of the fault. In most cases, the fault severity gets worse (more bars break), until the fault is so severe that few bars are operative and they are unable to provide the demanded rated load torque or even to start the machine. In other cases, the fault may have immediate catastrophic effects due to bar protrusion or detachment of bar fragments that may damage the stator winding insulation, causing a forced motor outage [16]. As a consequence, many works have focused on the development of techniques that are aimed to detect the fault when it is in its early stages of development, in order to prevent its possible negative consequences.

However, there may be another important effect derived from the presence of rotor bar damages. It is reasonable to think that due to the higher motor losses caused by the bar breakages (some rotor bars are overloaded and, at the same time, there is an increase of the inter-bar currents flowing through the rotor core, between the broken bar and the adjacent ones [18]), the motor efficiency will be compromised. However, the literature on this effect is very limited [10].

On the other hand, it is also interesting to analyze other effects, such as the presence of non-adjacent breakages. Although this situation is less probable, some studies have reported the occurrence of breakages in non-consecutive bars of the rotor cage due to several circumstances [19]-[20]. In those situations, the diagnostic of the fault based on the available techniques (such as analysis of motor currents) becomes difficult, since the effects of different breakages can be partially compensated depending on the relative position of the bars that break. With regards to the efficiency, the analysis of the possible influence of the relative position of the broken bars on the efficiency results is of great interest. This objective is pursued in the present paper.

B. Bearing faults

Bearing faults are among the most common faults in induction motors. Some surveys have reported that the occurrence rate of this type of faults can reach around 40% of the total failures in such machines [2], while other studies indicate that this rate can be even higher for low voltage motors

[21].

Bearing damages can be caused by a wide variety of reasons such as: deficient installation, overload (caused by inadequate selection, misalignment, unbalance, etc.), excessive/deficient lubrication (due to excess or lack of grease, inadequate viscosity, lubricant contamination, different operation temperature, etc.), circulation of bearing currents (in inverted-fed motors), brinelling (due to severe impacts, punctual overloads), etc. Bearing wear usually leads to increment in the vibration level as well as high temperatures. A severe damage can even provoke catastrophic failures (rotor-stator rubbing, insulation damage) and cause the forced outage of the motor [16].

The existence of bearings with defects, damages or anomalies implies additional losses in that part of the machine due to their non-proper operation i.e. excessive friction, unbalanced forces, etc. Indeed, some authors have already studied the effect of bearing faults on the motor efficiency and demonstrated the clear worsening of the motor performance when the fault is present in the motor [11]. The present paper also intends to ratify these conclusions and further analyze the dependence of this efficiency decrement on the motor load.

III. FEA SIMULATIONS

In this section, the discussion will focus on the performed work with FEA simulations. Firstly, the motivation behind the use of FEA in this study is that this type of simulations offers realistic results while the non-linear B-H characteristics of the rotor and stator iron core, the skin and proximity effects are taken into account. Most importantly, with FEA simulations the motor is considered symmetrical while the supply balanced and ideal. Those characteristics make FEA a valuable tool for the theoretical analysis of the impact of various broken rotor bars cases on the induction motor efficiency. The only disadvantage of FEA is still the high computational cost.

The FEA induction motor model takes its geometrical and materials characteristics from an industrial 6.6kV, 50Hz, 1.1MW 6-pole induction motor with the cage fabricated from copper. The rotor cage consists of 70 bars in total. The rotor of the real motor is un-skewed so the 2D FEA has been applied. The simulations have been performed with the software Magnet from Infologic Design. All losses but the friction ones are taken into account for this analysis.

A population of eight models has been created: the healthy and seven faulty cases. The first four faulty models have been created to quantitatively evaluate the impact of adjacent broken rotor bars severity. So, one motor has 1 broken bar while the other three have 2, 3 and 4 adjacent broken rotor bars respectively. Then three models have been created to study the impact of non-adjacent broken rotor bars and all of them have 2 broken bars, however the relative spatial location of the bars differs (half pole pitch, one pole pitch, two poles pitch). All motors have been set to operate under rated applied mechanical load 11kNm at steady state. Furthermore, the impact of the iron core saturation has been investigated while the motor has been set to operate under nominal and reduced voltage, always under nominal load though. The reduced voltage has been set equal to $\sqrt{2}$ times less than the nominal one. So, the motor is not only operating under less voltage but also under higher load, which means higher slip. Consequently the saturation level is also kept low due to the higher slip conditions.

The impact of the fault on the spatial distribution of the magnetic field is shown in Fig. 1-2 for various cases while the motors operate under nominal voltage. It is clear that the fault causes some magnetic field asymmetry and local saturation, the level of which depends on the fault's location and severity. However, in all cases of Fig. 2 the maxima of the magnetic flux density is increased compared to the healthy motor. The increase of the magnetic flux density with the simultaneous increase of local saturation explains the increase of the stator current under fixed load conditions, despite the increase of the rotor resistance due to the breakage.

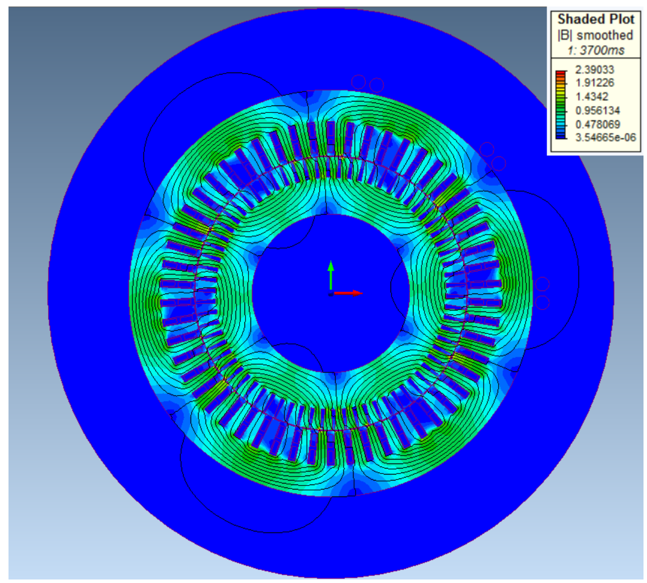
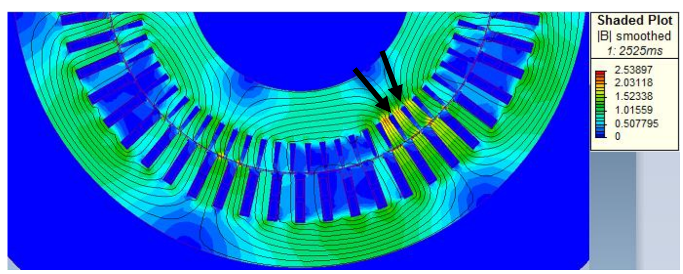
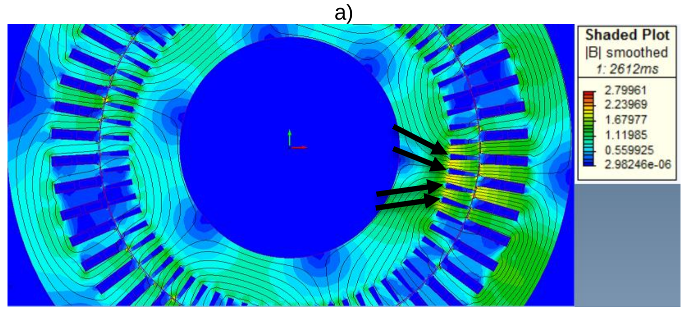


Fig. 1. Spatial distribution of the magnetic flux density at steady state for the healthy induction motor under nominal voltage.



a)



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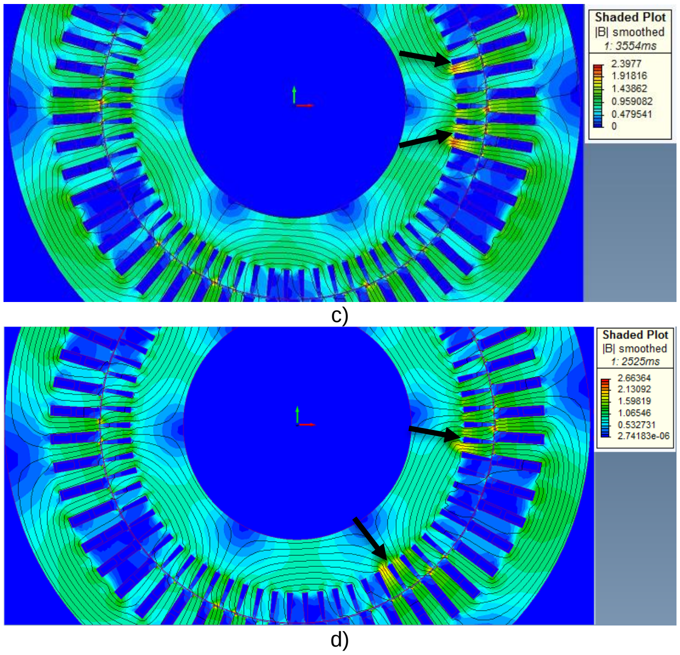

Fig. 2. Spatial asymmetry of the magnetic flux density for the case of: a) 2 adjacent broken bars, b) 4 adjacent broken bars, c) 2 broken bars at half pole pitch distance and d) 2 broken bars at a pole pitch distance under nominal voltage. Broken bars are marked with arrows.

A. Low Saturation Operation

The electromechanical characteristics of all simulated motor cases under low saturation are summarized in Table I. Moreover, Figs. 3-7 illustrate the various electromechanical variables of all studied cases. The stator current appears to increase exponentially with the number of adjacent broken rotor bars. This increase is to be expected while the applied mechanical load is the same and thus the motor requires more stator current to serve it. The stator current has a slight increase in all non-adjacent broken rotor bar fault cases with respect to the healthy one.

Furthermore, the power factor appears to be lower than the healthy motor for all adjacent broken rotor bar fault cases. Despite that, the drop is not monotonic with the fault level severity, which reveals a strong dependency on the local saturation. The outlier power factor of the motor with two adjacent broken rotor bars has to be discussed here. The power factor increases with respect to the motors with less fault severity and this may be the product of several reasons. One is that the iron is of high quality thus the extra current does not cause saturation. This is also enhanced by the drop of the speed.

Moreover, the rotor resistance increases because of the fault due to the reduction of the cross sectional surface of the active rotor conductors. This is clearly expressed through the monotonic drop of the speed when examining the motors with adjacent broken rotor bars. The rotor resistance increase will shift the torque-speed characteristic to the left. So, the motor will cross the load curve at a lower speed. The speed seems less unaffected in the motors with non-adjacent broken rotor bars.

Furthermore, the input active power increases monotonically with the fault level severity in the adjacent broken bar cases, following a similar pattern with the stator current. The motor with half pole pitch distance appears to have similar input active power as the healthy motor while the other two motors present some increases of their input active power.

The efficiency of the motor is similar with the motor with one broken rotor bar. Then it follows a monotonic drop with the increase of the fault level severity (number of adjacent broken rotor bars), as shown in Fig.7. The efficiency of the motor with broken rotor bars by a half pole pitch is similar to that of the healthy induction motor.

The breakdown of the rotor and stator Joule losses and iron losses for the motor under high load and low saturation are shown in Table III. It can be seen that the fault affects the iron losses significantly more than the Joule losses. Moreover, the motor with two non-adjacent broken rotor bars at half pole pitch has a losses breakdown closer to the healthy motor.

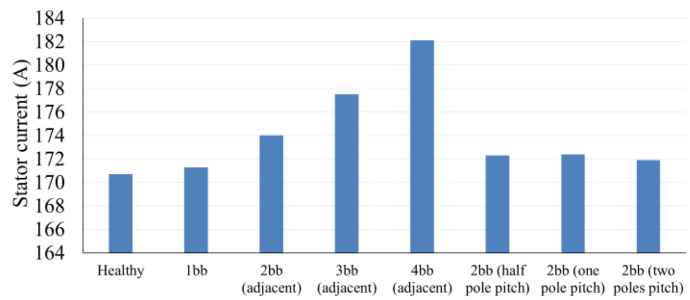

Fig. 3. Stator current versus the fault level severity.

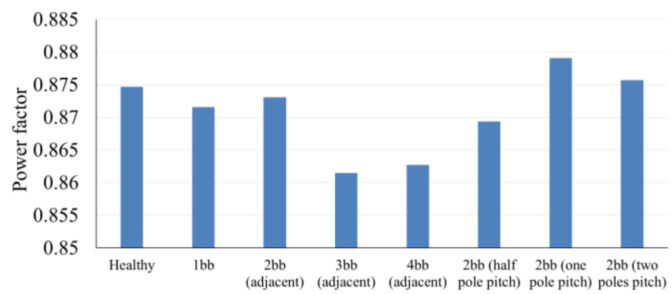

Fig. 4. Power factor versus the fault level severity.

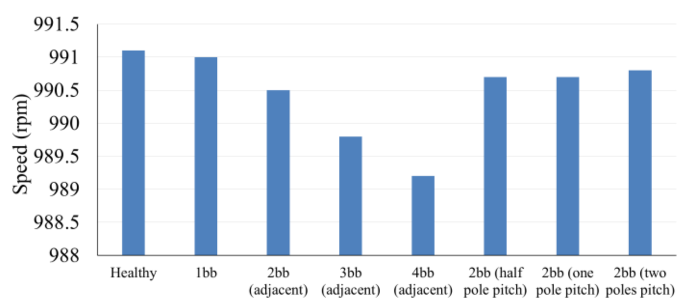

Fig. 5. Rotational speed versus the fault level severity.

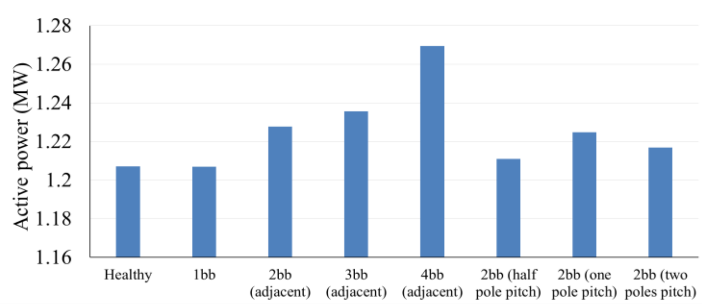

Fig. 6. Input active power versus the fault level severity.

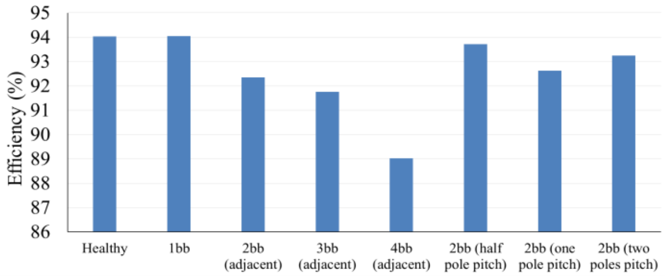

Fig. 7. Efficiency versus the fault level severity.

B. Operation under nominal conditions

All motor cases have been simulated here to operate under nominal voltage and nominal applied mechanical load. The electromechanical characteristics of all simulated motor cases under nominal conditions are summarized in Table II. Interestingly, some of the patterns observed previously under low saturation level are not visible here. For example the stator current of the motor with 4 adjacent broken rotor bars drops instead of increasing, as it happened for low saturation level.

Moreover, no particular speed pattern is observed with respect to the fault severity level. The efficiency of all faulty motors is lower than that of the healthy one. The monotonic drop of the efficiency with the increase of the fault level severity (adjacent broken bars) is similar to the one observed under low saturation conditions (Fig. 7).

In the case of the three motors operating under 2 non adjacent broken rotor bars, the efficiency drops slightly when the two broken bars are half pitch or two poles pitch apart. However, the efficiency drop is still small for the motor with one pole pitch distance between the broken bars.

The losses breakdown for the motor under rated load and voltage supply are shown in Table IV. The higher saturation operating condition is clearly affecting the losses distribution, since the iron losses percentage is significantly higher for every case with respect to the results of Table III under low saturation. Under rated conditions the motors with non-adjacent broken rotor bars by half and two poles pitch present a losses breakdown close to the healthy motor.

The outcome of the FEM investigation is that the local saturation and inherent non-linear behaviour of the induction

TABLE I
ELECTROMECHANICAL CHARACTERISTICS OF THE SIMULATED MOTORS UNDER LOW SATURATION & HIGH LOAD OPERATION

Simulated Case	Phase Voltage (V)	Phase Current (A)	Power Factor	Torque (Nm)	Speed (rpm)	Pmech (kW)	Pel (kW)	Efficiency (%)
Healthy	2694	170.7	0.8747	11000	991.1	1135.0	1207.1	94.03
1bb	2694	171.3	0.8716	11000	991	1135.1	1206.9	94.05
2bb (adjacent)	2694	174	0.8731	11000	990.5	1133.7	1227.7	92.35
3bb (adjacent)	2694	177.5	0.8615	11000	989.8	1133.7	1235.7	91.75
4bb (adjacent)	2694	182.1	0.8627	11000	989.2	1130.2	1269.4	89.03
2bb (half pole pitch)	2694	172.3	0.8694	11000	990.7	1134.7	1210.9	93.71
2bb (one pole pitch)	2694	172.4	0.8791	11000	990.7	1134.4	1224.8	92.62
2bb (two poles pitch)	2694	171.9	0.8757	11000	990.8	1134.7	1216.9	93.24

TABLE II
ELECTROMECHANICAL CHARACTERISTICS OF THE SIMULATED MOTORS UNDER NOMINAL CONDITIONS

Simulated Case	Phase Voltage (V)	Phase Current (A)	Power Factor	Torque (Nm)	Speed (rpm)	Pmech (kW)	Pel (kW)	Efficiency (%)
Healthy	3810	118.1	0.8829	11000	996.1	1142.1	1191.7	95.84
1bb	3810	118.2	0.8866	11000	996	1141.9	1197.6	95.35
2bb (adjacent)	3810	118.4	0.8904	11000	996	1141.7	1205.2	94.73
3bb (adjacent)	3810	121.1	0.8709	11000	995.8	1141.2	1205.2	94.69
4bb (adjacent)	3810	119.9	0.8906	11000	995.9	1141.0	1220.9	93.45
2bb (half pole pitch)	3810	118.7	0.8816	11000	996	1141.7	1196.2	95.45
2bb (one pole pitch)	3810	118.2	0.8894	11000	996	1141.8	1201.8	95.01
2bb (two poles pitch)	3810	119.3	0.8768	11000	995.9	1141.6	1195.6	95.48

TABLE III
LOSSES BREAKDOWN OF THE SIMULATED MOTOR UNDER LOW SATURATION & HIGH LOAD OPERATION

Simulated Case	P_rotor (kW)	P_stator (kW)	P_Fe (kW)
Healthy	11.27	13.12	47.71
1bb	11.49	13.21	47.1
2bb (adjacent)	12.03	13.64	68.34
3bb (adjacent)	12.81	14.12	75.07
4bb (adjacent)	13.64	15.02	110.537
2bb (half pole pitch)	11.77	13.37	51.06
2bb (one pole pitch)	11.75	13.39	65.26
2bb (two poles pitch)	11.69	13.32	57.19

TABLE IV
LOSSES BREAKDOWN OF THE SIMULATED MOTOR UNDER NOMINAL CONDITIONS

Simulated Case	P_rotor (kW)	P_stator (kW)	P_Fe (kW)
Healthy	5.17	6.27	38.16
1bb	5.27	6.28	44.16
2bb (adjacent)	5.26	6.32	51.92
3bb (adjacent)	5.53	6.62	51.85
4bb (adjacent)	5.49	6.48	67.93
2bb (half pole pitch)	5.34	6.34	42.81
2bb (one pole pitch)	5.24	6.29	48.46
2bb (two poles pitch)	5.36	6.41	42.23

motor, enhanced by the rotor electrical faults, may strongly affect the efficiency of an induction motor. An interesting finding is that when the two non-adjacent broken rotor bars exist at half pole pitch, the efficiency of the induction motor is practically the same as a healthy one.

IV. Experimental Testing

In order to assess the induction motor efficiency under the considered fault conditions, two different laboratory test benches were used. The first bench (Test bench 1, see Fig. 8) was based on a 4-pole, 1,1 kW induction motor (see characteristics in Table III) that was driving a D.C. machine that acted as a generator. The voltage generated by this D.C. machine was applied to a resistor bank. The induction motor load level was changed by varying the field current of the D.C. machine.

TABLE III
RATED CHARACTERISTICS OF THE TESTED MOTOR

Model 1LA2080-4AA10	
Rated power (P_n)	1.1 kW
Rated speed (n_n)	1410 rpm
Rated voltage (U_n)	400(Y)/230 (Δ)
Rated current (I_n)	2.7(Y)/4.6 (Δ)
Rated power factor ($cos\ \varphi$)	0.8
Number of rotor bars	28

In the first bench, the two mentioned induction motor fault conditions were tested. On the one hand, the rotor bar failures were forced by drilling the bars in the connection points with the end ring. Different rotor fault severities were considered: 1, 2 and 9 broken bars (see Fig. 9). Moreover, in the case of two broken bars, different relative positions between the broken bars were studied (positions 1-2, 1-3, 1-4, 1-5 and 1-6 in the rotor cage). Also, in the case of nine broken bars, two different cases were tested: nine adjacent broken bars and nine non-adjacent broken bars (random positions).

On the other hand, the motor was supported in rolling element bearings (SKF6205) with N_b=9 balls. Two types of bearing damages were forced: on the one hand, the outer race was damaged in the way shown in Figure 10 (a) by using a saw. On the other hand, the bearing cage was damaged with the aid of a screwdriver and hammer (see Fig. 10(b)). The first case led was classified as a case with medium level of severity while in the second case, a high severity was determined, in concordance with the values of the vibration spectral components that were obtained with a commercial device. This latter was intended to represent a situation in which the collapse of the bearing was imminent.

For each considered fault condition, different tests were carried out, considering different load levels, starting at no load and ending at full load condition. In each test, the demanded electric power (P_e) was measured with the aid of a power analyzer, while the mechanical power (P_m) was obtained by multiplying the shaft torque (which was measured by means of a torque meter) and the angular speed. The motor efficiency (η) was obtained by dividing P_m by P_e.

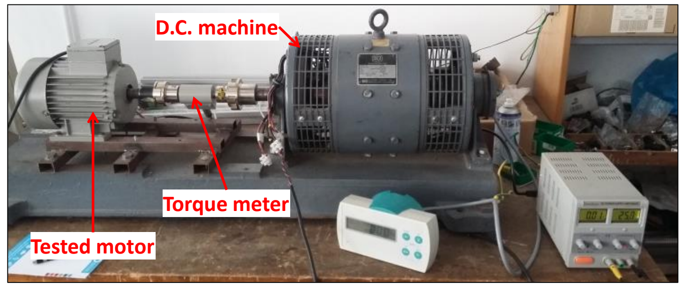

Fig. 8. Experimental test bench 1.

(a) (b) (c)

Fig. 9. Different faulty rotors tested (a) one broken bar, (b) two broken bars (different relative positions) and (c) nine broken bars.

a) b)

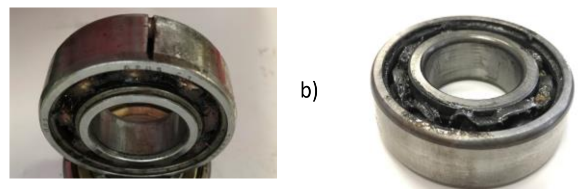

Fig. 10. Faulty bearings.

On the other hand, the second laboratory bench was based on a universal laboratory machine with twelve accessible phases in its secondary winding; this configuration allowed the simple simulation of several rotor fault cases by means of the opening of these phases (see Fig. 11).

The characteristics of the machine (Fig. 12) were: Rated voltage (U_n): 240V, rated power (P_n): 1,25kW, 1 pair of poles, primary rated current (I_{1n}): 5A, rated speed (n_n): 2900 rpm and rated slip (s_n): 0,033. Note that the rated efficiency of this motor was lower than that of the motor of test bench 1. The same rotor fault cases considered before (adjacent and non-adjacent breakages) were tested with the aid of this machine. The objective of using this second test bench was to provide more generality to the results, since the motor characteristics were very different in both benches.

Fig. 11. Experimental test bench 2.

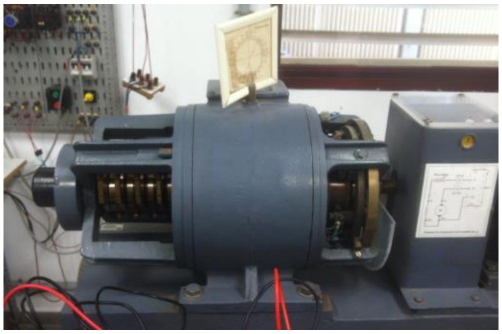

Fig. 12. Tested machine at test bench 2.

V. Experimental Results and Discussion

A. Rotor bar failures

1) Results with laboratory test bench 1

Fig. 13 shows the evolution of the motor efficiency at different load levels (indicated as percentages of the rated load) for the case of a healthy motor and for the motor with one broken bar. Note that the efficiency curve for the faulty motor is always below that of the healthy machine, i.e., for every load condition, the efficiency of the motor with one broken bar is lower than that of the healthy motor. At rated load, the absolute efficiency drop caused by the fault is around 3-4% (from ~76% to ~73%), but it should be remarked that this is a low fault severity (only one bar broken out of 28). Hence, this case clearly shows that the rotor fault has an effect on the motor efficiency, even when its severity is not high.

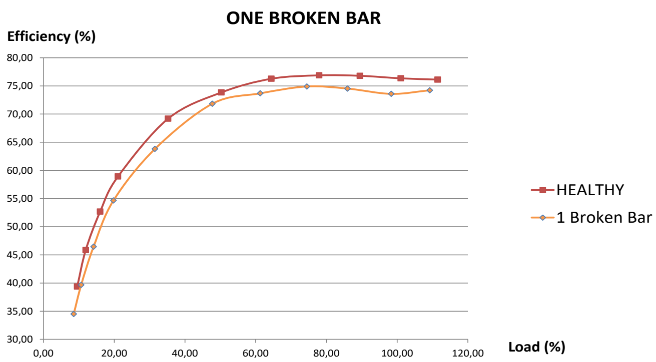

Fig. 13. Comparison between the efficiency values for the healthy motor and for the motor with one broken bar at different load levels (test bench 1).

On the other hand, Fig. 14 shows the comparison between the efficiency curves for the case of the healthy motor and for the case of the motor with two broken rotor bars. Note that there are different curves for this latter case, one for each relative position between the two broken bars. The accurate inspection of the curves reveals that there is a clear difference between the healthy case and the case of two adjacent broken bars (broken bars at positions 1-2). The efficiency curve for this faulty case is clearly below that of the healthy motor. Indeed, at rated load the efficiency drop due to the fault is around 4% (quite similar to the one broken bar case, since the difference between the severities of both cases is not so significant) and this efficiency reduction stands for every other load condition.

However, note that, interestingly, when comparing the curve of the healthy case with the curves of the non-adjacent broken bar cases (1-3, 1-4, 1-5 and 1-6), the differences are not relevant. In other words, the efficiency reductions when the non-adjacent breakages are present are not so evident. These results are coherent with the results of FEA simulations. This is an interesting point and, leaving aside possible unavoidable errors in the measurement and different inherent eccentricity levels due to the assembly process, it seems that the combined effect of both breakages when they are not adjacent is not additive in terms of efficiency reduction. This could be explained by the fact that when the broken bars are not consecutive, the rotor unbalance created by each particular breakage may somehow be partially compensated by the other breakage. Therefore, the stress asymmetry level may be reduced and also the possible losses in some of the motor elements. As a consequence, and taking into consideration that the fault severity levels considered in this case are quite low (less than 10% of the bars broken), the resulting effect of the non-adjacent breakages can be very low and the efficiency could remain almost unaltered in comparison with that of the healthy motor.

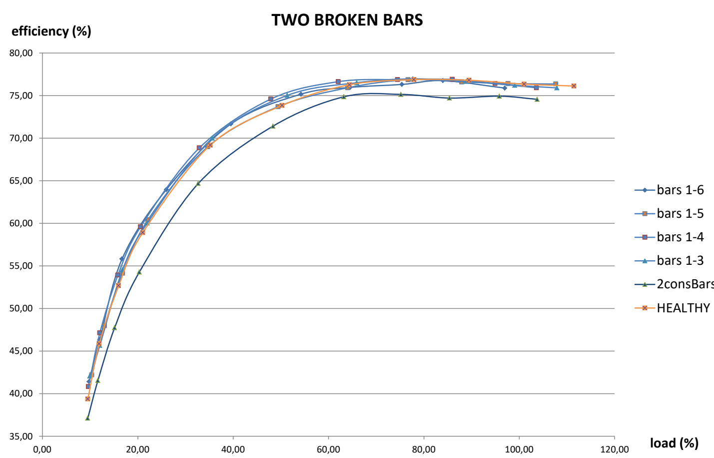

Fig. 14. Comparison between the efficiency values for the healthy motor and for the motor with two broken bar at different load levels and for different relative positions between the broken bars (1-2, 1-3, 1-4, 1-5 and 1-6) (test bench 1).

Finally, Fig. 15 shows the efficiency curves corresponding to the healthy motor and to the two considered cases of motor with nine broken bars: adjacent and non-adjacent broken bars. This is a severe rotor fault condition, since more than a third of the rotor bars are broken. Note, however, that this is not an unrealistic case; similar percentages of broken bars were reported in real H.V. motors that had been operating during long periods which such rotor fault severities [22]. The curves in Fig. 15 are much more illustrative than those of the previous figures: clear differences can be observed between the healthy and the faulty cases. The differences are much more evident is we consider the case of nice adjacent broken bars: indeed, the absolute efficiency reduction at rated load, when the fault is present, is around 13% (from 76% to 63%) which is a very abrupt decrease (near 20% of relative reduction, if we take as a reference the efficiency value in healthy condition). This means a high energy waste that can be present during very long time intervals (note that some motors with broken bars may operate during years). On the other hand, note that the differences are less abrupt when comparing the healthy case with the case of nine broken bars at non-adjacent positions. Similarly to the two broken bar case, this can be explained by the mutual partial compensation of the effects of the breakages at different relative positions. For instance, the rotor unbalance caused by the bars when these are non-adjacent is less pronounced than that caused when the breakages are consecutive. Moreover, the current distribution in the rotor cage and, therefore, the electro-dynamical stresses will be more uniform in the case of non-adjacent breakages than in the case of consecutive breakages.

The presented cases demonstrate that the effect of a rotor fault is not only problematic in terms of risk for the continuity of motor service, but it also has repercussions on the motor efficiency and performance. This is especially important bearing in mind that, unlike other types of motor faults, rotor failures can be present during very long periods, even years. This means prolonged operations during which the motor efficiency is lower than it should and this implies higher energy wastes and subsequent economic costs for the corresponding company.

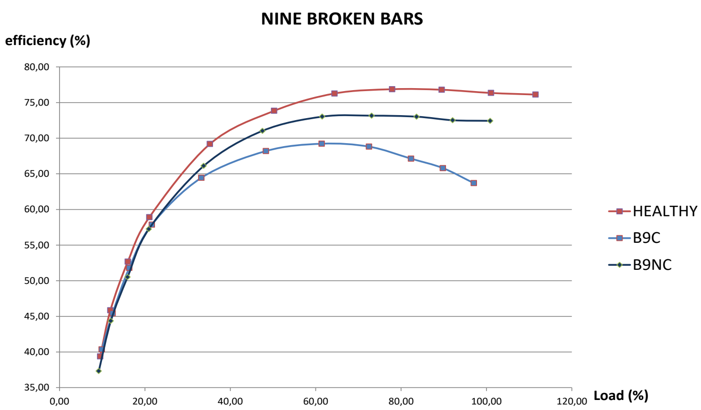

Fig. 15. Comparison between the efficiency values for the healthy motor and for the motor with nine broken bar at different load levels and for two different relative positions between the broken bars (adjacent (B9C) and non-adjacent (B9NC)) (test bench 1).

2) *Results with laboratory test bench 2*

Fig. 16 shows the results corresponding to the efficiency computation for the motor of Test bench 2. The figure compares the efficiency curves of the healthy motor with those of the motor with 2 and 4 adjacent broken bars. The figure shows how the efficiency is clearly reduced, for the different load levels, when the level of fault increases. This is in agreement with the conclusions obtained for the motor of the previous bench as well as for the FE analyses.

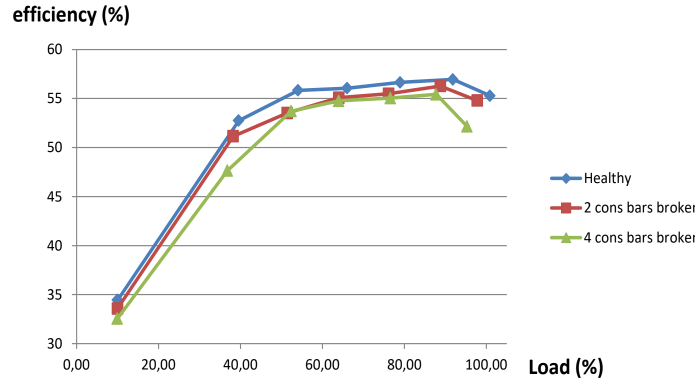

Fig. 16. Comparison between the efficiency values for the healthy motor and for the motor with two and four adjacent broken bars (test bench 2).

On the other hand, Fig. 17 shows the comparison between the efficiency curves of healthy motor and motor with two broken bars, considering different relative positions of the broken bars. Again, the results are in agreement with those observed for the motor of test bench 1 and FE analyses: the highest efficiency decrement occurs for the case of adjacent breakages, whereas for the non-adjacent broken bar cases the obtained efficiency values are intermediate between healthy and adjacent cases. In some non-adjacent cases, the efficiency values are very close to those of a healthy motor.

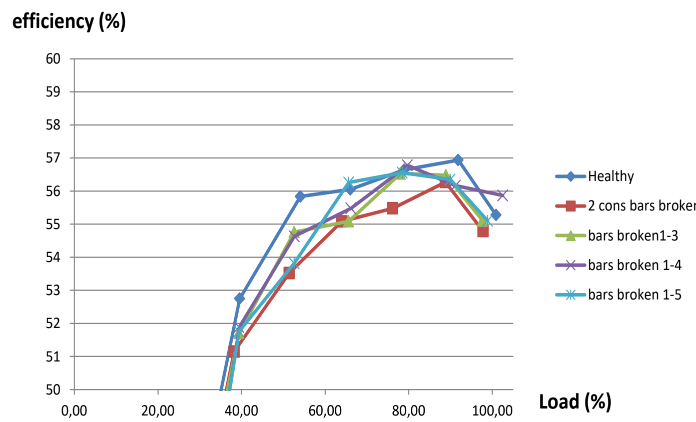

Fig. 17. Comparison between the efficiency values for the healthy motor and for the motor with two broken bar at different load levels and for different relative positions between the broken bars (1-2, 1-3, 1-4, 1-5) (test bench 2).

B. *Bearing faults*

The efficiency curves were also computed and compared for the case of the motor with faulty bearings. Fig. 18 shows the efficiency values for the healthy motor and for the two considered cases of motor with faulty bearings (see Fig.10), at different load levels. The efficiency differences between the compared cases are evident. The presence of the bearing damages decreases the motor efficiency for every load condition. Even bearing in mind that the level of damage was not severe for both cases, the efficiency drop at rated load was from 76% to around 73%.

These results show that even for slight levels of bearing damage, the efficiency of the motor is affected. If we consider that these types of damages are rather frequent in these motor components and that they can co-exist with other types of anomalies that also reduce the motor efficiency, it is evident the joint repercussions on the whole efficiency of the machine.

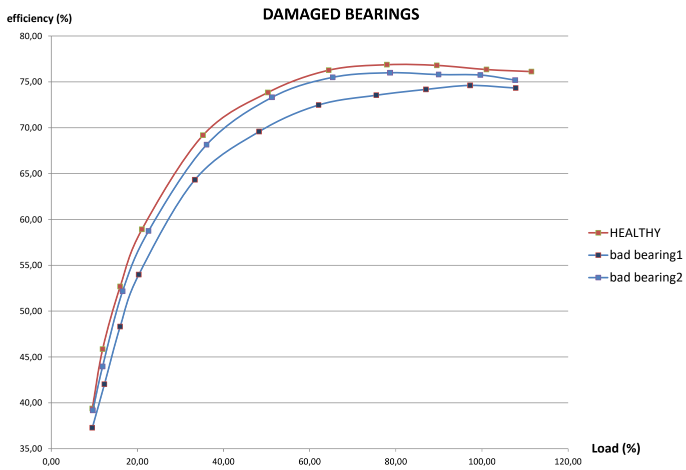

Fig. 18. Comparison between the efficiency values for the healthy motor and for the two considered cases of motor with faulty bearings at different load levels.

VI. Conclusion

This paper has studied the effect of different types of failures on the efficiency of an induction motor. Two specific faults have been considered: rotor bar failures and bearing damages. The FEA simulations and experimental tests carried out in the work show that the presence of any of these faults has a direct impact on the motor performance, causing significant efficiency drops due to additional losses in machine.

On the one hand, it has been proven how the presence of rotor cage damages decreases the machine efficiency, especially when the severity of the fault is greater. For lower severities of rotor bar failure, the impact is not high but still noticeable. It is interesting to note the important influence of the relative locations of the rotor damages: according to the results, if the bar breakages are contiguous the efficiency drops are greater than when they are not. This may be explained by the mutual compensation of their respective effects when the faults are placed at certain relative positions. On the other hand, it is also shown how bearing faults decrease the efficiency of the motor, even when the severity of the fault is low.

The conclusions of the work are of interest for the field since, although many industrial users are aware of the danger that the existence of a certain damage implies in terms of motor availability, it has been often ignored its important effects on the motor performance and efficiency, which can imply notorious losses when considering the motors of a whole factory.

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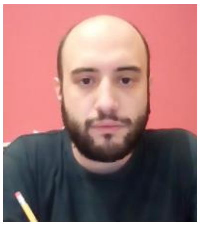

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