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# Changing of Magnetic Flux Density Distribution in a Squirrel-Cage Induction Motor with Broken Rotor Bars

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***Abstract*—This paper presents the finite element modelling of three-phase squirrel-cage induction motor with broken rotor bar faults. Finite element model based on a real machine is constructed, propagation of broken rotor bar fault and its influence on the magnetic flux density distribution of the machine cage is observed. As the propagation of the fault will result in total breakdown of the induction machine rotor, if the fault is not detected and solved, necessity of condition monitoring is pointed out. Analysis of the fault and its affect to the magnetic field in the rotor cage as well as changes in the phase voltage spectrum are presented.**

***Index Terms*—Electric machines, induction motors, fault diagnosis, electromagnetic fields, rotors, finite element analysis.**

## I. INTRODUCTION

Broken rotor bars of squirrel-cage induction machines have been the subject of interest in numerous scientific studies. A comprehensive yet ever growing list of the researches dealing with diagnostic problems of electrical machines is presented in [1]. As the given fault is one of the more usual types of failures, condition monitoring to predict the possible fault and detection of broken bars can be considered an important issue in the field of induction machine diagnostics.

Squirrel-cage induction machines are one of the most used machine types in the industry nowadays. They are preferred due to their rugged build, reliability and cost efficiency. This also means that induction machines are used in such applications, where sudden failures result with high economic loss and also possible threat to the surrounding environment as well as people manipulating them.

Induction machines are also often used as generators in small hydro and wind power plants. Failures of the machines used in such applications means a sudden drop of supply reliability and power quality to the customers using electricity produced in those units. With the world moving towards distributed generation, number of such small generation units is expected to rise [2]. Due to that, rise in the use of induction machines can also be expected.

Induction machine rotor faults usually start from a fracture or a high resistivity spot in the rotor bar [3]. The fractured or cracked rotor bar starts to overheat around the crack until the bar breaks [4], [5]. This means that at the same time the resistance of such bars is rising and becomes significantly higher than the resistance of healthy bars in the rotor cage. As there is a lack of induced current in those bars, the magnetic field will become gradually more asymmetrical, which will lead to local saturation in stator and rotor teeth near the broken bar and disproportional distribution of magnetic field in the air-gap [6].

Breaking of the consecutive rotor bars is the most probable case in practice [7]. This happens, because currents that are unable to flow in the broken bars are flowing through the adjacent bars, which means that those bars situated next to the broken ones are under higher thermal stress due to higher current density. This means that if the fault is not treated, it will propagate in time resulting in the destruction of the whole rotor cage [8].

The aim of this paper is to show through a series of finite element modelling how the magnetic field in the machine is changing due to the presence of broken bars. Changes in the field are expected to be growing as the severity of the fault is rising and the fault propagates.

## II. MODELLING OF THE INDUCTION MACHINE

Experiments of the induction machine's behavior were performed on a three-phase squirrel-cage induction motor with a healthy rotor and a rotor with up to three consecutive broken bars. These tests, where the same machine is fed through frequency converter supply are described in [9].

For the modelling of magnetic flux density distribution in case of broken rotor bar fault of an induction machine, the same motor as in previously mentioned experiments was used. Data of the machine is presented in Table I.

Using the listed data and the machine layout, two dimensional finite element model of the induction machine

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was constructed. The model of the machine showing the magnetic flux density distribution in case of healthy rotor cage is presented in Fig. 1.

TABLE I. DATA OF THE INDUCTION MACHINE.

| Parameter | Symbol | Value |
|---|---|---|
| Rated voltage | $U_n$ | 400V@60 Hz; 333V@50 Hz |
| Rated current | $I_n$ | 41 A |
| Rated speed | $n_n$ | 1680 rpm@60 Hz; 1400 rpm@50 Hz |
| Rated power | $P_n$ | 22 kW@60 Hz; 18 kW@50 Hz |
| Frequency | $f$ | 50-60 Hz |
| Power factor | cosφ | 0.86 |
| Number of poles | $p$ | 4 |
| Number of rotor bars | $Q_r$ | 40 |
| Number of stator slots | $Q_s$ | 48 |

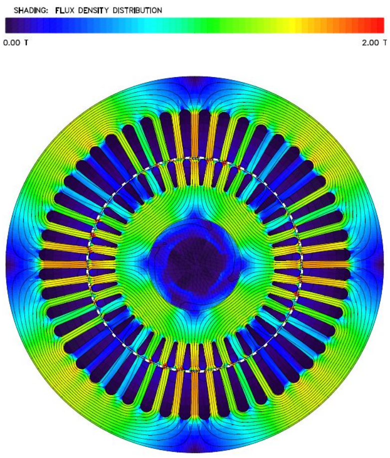



Fig. 1. Magnetic flux density distribution of a healthy induction motor.

## III. EFFECT OF BROKEN BARS TO THE MAGNETIC FIELD

The necessity to detect the fault in an early stage, to prevent further damage of the equipment due to fault propagation, is one of the most important features of any condition monitoring or diagnostic techniques. At the same time, minor faults and early stages of the propagating fault are less obvious to detect and are significantly harder to grasp [10].

Based on this, the fault propagation in the given paper is modelled from healthy rotor cage up to three consecutive broken bars (which is 7.5 % of all the rotor bars of the machine). The broken bars were modelled as areas with significantly higher resistance and low conductivity, so they would not contribute to the cage circuit [11], [12]. Figure 2 presents the flux density distribution of the induction motor in case of one broken rotor bar.

As previously said, minor faults are very difficult to detect. Comparing Fig. 1 and Fig. 2, the difference between the flux density distributions is visible to some extent but not clearly detectable for the naked eye. The difference becomes easier to observe when one field distribution is subtracted from another and only the difference in the two presented flux density distributions remain. This difference of the flux density distributions of the healthy cage and the machine with one broken rotor bar is shown on Fig. 3.

It can be seen from Fig. 3 that already in case of one broken rotor bar in the cage, the magnetic field distribution is becoming distorted. Higher amount of magnetic saturation can be seen around the broken bar in the rotor as a lack of frequency-induced current in these rotor bars. Magnetic flux density in the studied machine is increasing by 0.15 T around the broken bar.

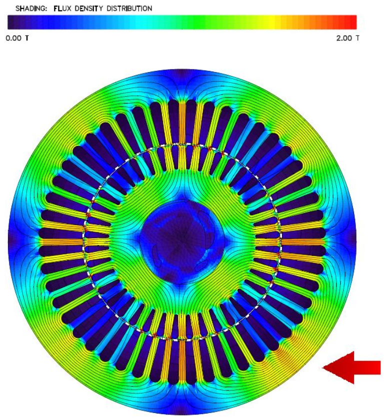



Fig. 2. Magnetic flux density distribution of an induction motor with one broken rotor bar.

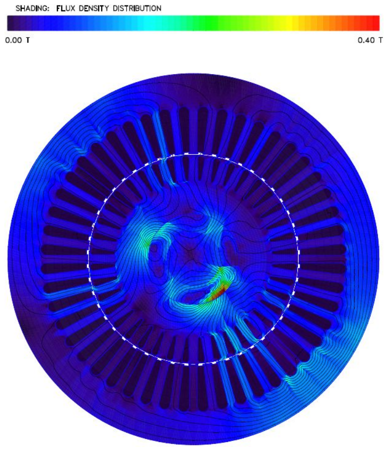



Fig. 3. Magnetic flux density distribution difference between the healthy induction motor cage and the cage with one broken rotor bar.

Additionally, as the rotor magnetic field distribution is distorted, this effect also influences the stator. In the stator higher saturation can be seen in the teeth facing the broken rotor bar and in stator yoke, where the magnetic flux density is also increasing by approximately 0.15 T.

Further study was made with two broken rotor bars. The simulation results of flux density distribution of this fault are given in the Fig 4. Figure 5 presents a comparison of magnetic field distribution difference between healthy cage machine and an induction machine with two broken rotor bars.

It can be seen that in case of two broken rotor bars the magnetic field flux density is increasing around the broken rotor bars and also in the stator facing the broken rotor bar 0.2 T. The phenomenon can be described similarly to the one broken bar case, although the value of the magnetic flux density is rising even more. Also it can be seen that the magnetic flux density is increasing both in the stator and rotor yoke opposite to the broken rotor bars. It should be noted, that difference in the magnetic flux density distribution between the healthy machine and the one with broken bars corresponds to an asymmetric field inducing eddy-currents in the shaft of the machine. Such current if free to circulate, will cause bearing currents that usually result in damaging the bearings.

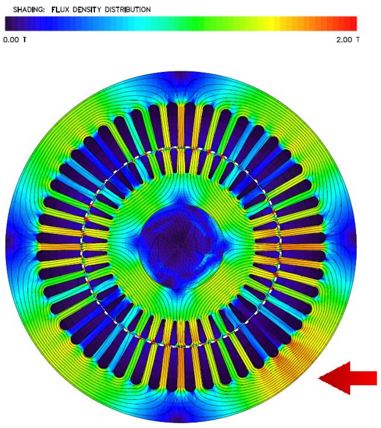



Fig. 4. Magnetic flux density distribution of an induction motor with two broken bars.

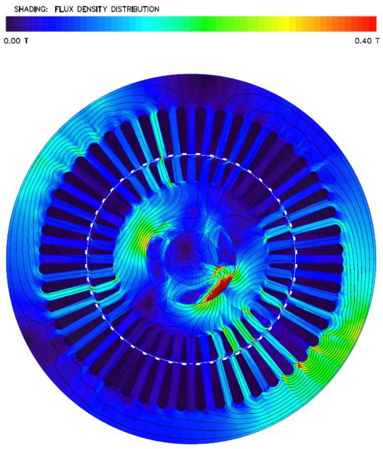



Fig. 5. Magnetic flux density distribution difference between the healthy induction motor cage and the cage with two broken bars.

Magnetic field distribution simulation results in case of three broken rotor bars are given in Fig. 6 and the comparison with healthy induction machine cage is presented in Fig. 7. It can be seen from Fig. 7 that three broken rotor bars lead to relatively high saturation of the iron around the broken rotor bars and opposite to the broken bars. Flux density is increasing up to 0.4 T compared to healthy machine and even more in the tooth between the broken bars as well as the shaft of the machine.

It can be said that due to the increased magnetic flux density, degradation in the mechanical performance of the induction machine can be expected. In the regions where the flux density is rising (around the broken bars and opposite to the broken bars), the core loss density is higher compared to other regions of the machine. These adjacent bars become more susceptible to thermal stress due to overheating and will lead to further breaking of rotor bar [13].

Although no currents pass through the broken bars and no heat losses are generated, it becomes obvious from the presented figures, that the currents passing through the bars adjacent to the broken ones are dramatically increased and the heat losses in the bars are increased in a large scale [14].

The air-gap field becomes asymmetrical due to the presence of broken bars in the rotor cage and the harmonic components of air-gap magnetic flux density vary significantly. As the flux density is fluctuating, it was assumed that it can also be traceable in the machine phase voltage due to the presence of counter-electromotive force. To visualize that effect, simulations were carried out and machine phase voltages were found. A comparison was made using the differences between healthy and faulty machine phase voltages. These results are presented in Fig. 8.

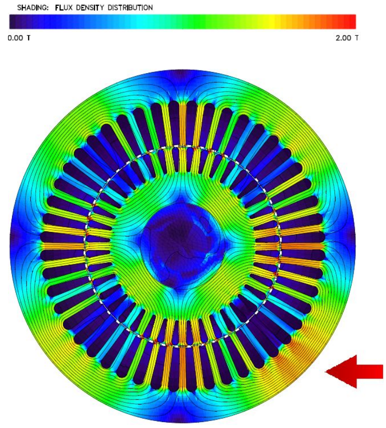



Fig. 6. Magnetic flux density distribution of an induction motor with three broken bars.

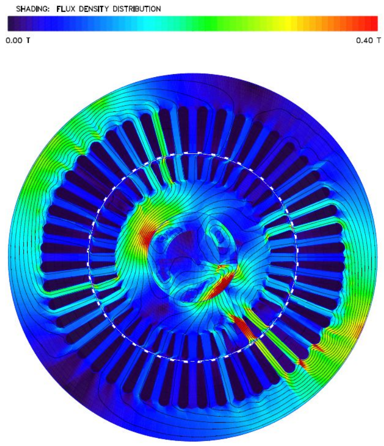
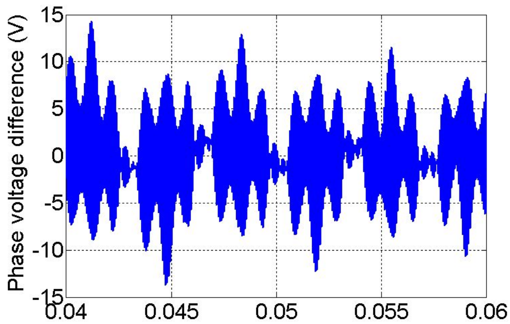
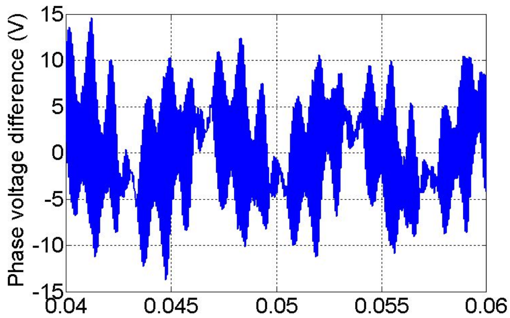


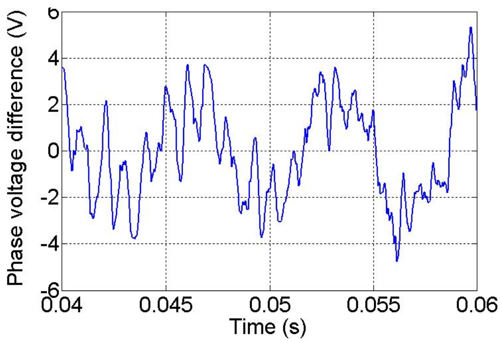

Fig. 7. Magnetic flux density distribution difference between the healthy induction motor cage and the cage with three broken bars.




(a)




(b)




(c)

Fig. 8. Phase voltage difference: upper – phase voltage difference between healthy cage and one broken rotor bar case; middle – phase voltage difference between healthy cage and three broken rotor bars case; bottom – phase voltage difference between one broken bar case and three broken rotor bars case.

From Fig. 8 it can be seen that compared to healthy machine, the faulty machine phase voltage is fluctuating. The fluctuation is increasing with the amount of broken bars. In the studied machine, one broken bar in the cage leads to voltage difference up to ±10 V and three broken bars raise that difference up to ±15 V. It can also be seen that the third harmonic component is dominating the voltage spectrum but also higher harmonic presence up to 21st and higher can be noted in the spectrum of the machine. The higher harmonic presence can also be detected on the bottom graph of Fig. 8, which shows phase voltage difference between one broken bar case and three broken rotor bars case.

## IV. CONCLUSIONS

Magnetic field modelling regarding the magnetic flux distribution of the induction machine in case of healthy machine and propagating severity of the broken rotor bars fault was made and analyzed. It was found that presence of broken rotor bars results in uneven distribution of magnetic field in the rotor cage and the whole machine.

Magnetic field strength is increasing around the broken bar in rotor and also in stator facing the broken bar. In addition to that, the magnetic field strength is also increasing on the opposite side of the broken rotor bar as well as the shaft of the machine. The latter can be explained by the asymmetric field that induces eddy-currents in the shaft and will most likely cause bearing currents, which in time will result in bearings damage.

When the fault propagates and the number of broken bars in the rotor cage increases, the magnetic field asymmetry is rising, resulting in higher local saturation in both rotor and stator teeth. Uneven magnetic field distribution starts affecting the machine phase voltage, resulting in the presence of higher harmonic components in the voltage spectrum. With increase of the number of consecutive broken bars, higher harmonic amplitude in phase voltage is also increasing, which means that various disturbances and undesired phenomena (i.e. increase of noise, increase of mechanical vibrations etc.) can be expected.

Based on the acquired magnetic field distribution figures, it can be estimated that broken rotor bars fault can lead to severe consequences if the fault is not dealt with in an early stage. The propagation of the fault will not only result in the destruction of the rotor cage but can also lead to various stator failures (i.e. stator winding turn to turn short circuits, lamination short circuits etc.) due to the broken rotor bar influenced local saturation in and around stator teeth. Additionally, such fault propagation can lead to bearings problems as mentioned previously.

To prevent the possible economic losses, danger to surrounding environment and people operating the machines, condition monitoring of the machines should be considered. This would grant the possibility of detecting the faults during the stage where repairing of the machine would still be reasonable and possible. Usage of sufficient diagnostic measures would also mean lower down-time for the industries where such machines are used.

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