Advanced and Smart Maintenance of Induction Motors Based on an Algorithm for Motor Faults Recognition

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***Abstract* - The paper describes the algorithm and the methodology to recognize rotor faults of the squirrel-cage motor based on the induced voltages in the measuring coils spatially spaced for the pole pitch. Based on the FEM calculations and measurements, the functional algorithm for early fault detection and reliable recognition of rotor faults was designed. In the paper is presented and described flowchart of the proposed algorithm. Furthermore, the two special algorithms were designed, based on the obtained research results. The input parameters for the proposed algorithm are induced voltages in four measuring coils spatially spaced for pole pitch. The first algorithm is intended for early and reliable detection of the broken rotor bars and the broken ring of the squirrel-cage induction motor. The second algorithm is proposed for early and reliable detection of the rotor static eccentricity. The proposed algorithm uses induced voltage in four measuring coils. In the case of the broken rotor bars and ring, the algorithm uses voltage difference between two induced voltages in measuring coils spatially spaced for 2τ$_p$. In the case of static eccentricity, the difference between the RMS value of each measuring coil installed in the air gap of the induction motor is analyzed. The proposed algorithms are aimed to improve and contribute to the advanced and smart maintenance of induction motors.**

Keywords – FEM; broken rotor bar; broken rotor ring; squirrel-cage rotor; static eccentricity; magnetic field; air gap; measuring coils; faults detection

I. INTRODUCTION

Induction motors are one of the most common types of electrical machines, and they play a key role in various industrial plants and processes (power plants, oil refineries, chemical plants, metal foundries, pumping stations, coal mills, paper industry, etc.). Because of their importance in the process, these machines must achieve reliable and safe operation. To ensure this, all key machines contain some types of protection, supervision, and monitoring. The main goal is early machine fault detection and the possibility to recognize the type and nature of a fault. The cause of induction machines faults lies in electrical and mechanical conditions together with operational environment. According to the literature [1 – 4], the most common faults of induction machines are bearing faults, following stator and rotor faults and other faults such as different types of eccentricity (static, dynamic or both). In order to detect and recognize induction machine faults early, various types of fault detection methods have been developed [5, 6, 7, 8]. These methods are a result of long-term testing, measurement, and monitoring of the induction machine operation. All these methods with more or less success enable fault detection of induction motor.

Online magnetic field monitoring via permanently installed measuring coils inside air gap is a well-established methodology which enables winding fault detection [1, 9, 10, 11, 12]. In industry and according to the literature [3, 4, 13, 14], rotor winding faults are very common problem. Most commonly used method for detection of broken rotor bars is method based on current signature analysis (MCSA) [8, 15, 16, 17, 18, 19, 20, 21].

The next very common motor problem is the occurrence of rotor static eccentricity that exceeds the allowable limit [22]. There are generally two kinds of rotor eccentricities: static or dynamic (showed on the figure 1). In the case of static eccentricity, the rotor turns around its center of gravity, but this centre is displaced of the stator centre line. From the stator point of view, the place of minimal air gap occurs at unchanged circular position. In the dynamic eccentricity case, the central axis of the rotor is not fixed but during rotation changes its position relative to the stator centre line. In this case the position of minimal airgap does not stay at the same stator circular position, but rather changes in time. Within this paper only the phenomenon of static eccentricity was analyzed. The occurrence of rotor static eccentricity in induction machine can cause some of the following undesirable effects: vibrations, unbalanced magnetic pull (UMP), additional losses in the rotor winding and in parallel circuits of the stator windings, occurrence of the shaft voltages and currents, additional losses in the stator or rotor core, and finally in the worst-case scenario physical contact of the rotor with the stator [23]. These undesirable effects either reduce the machine performance and efficiency or make secure operation of the machine impossible and therefore lead to the complete machine shutdown.

In this paper, a method based on the magnetic field measurement in the air gap using the measuring coils embedded in the machine is presented. This methodology is used for reliable and unambiguous detection of squirrel-cage rotor faults such as: broken rotor bar, broken rotor ring, and static eccentricity. Within this paper, the issues regarding the rotor faults detection are discussed. Also, the corresponding algorithm for rotor faults recognition has been designed. The aim of the paper is to contribute to the early and reliable fault detection of electrical rotating machines based on the magnetic field analysis in the air gap, with application in advanced and smart maintenance of induction motors.

II. THEORETICAL APPROACH

A. *Theory*

The novelty of this methodology is measurement of the magnetic field in a rotating machine with four measuring coils, installed on the places in the machine which have, by absolute value, equal magnetic vector potential. The distance between the measuring coils is $n \cdot \tau_p$, where τ_p is a pole pitch, and n=1, 2, 3, 4, … is a multiple of the pole pitch. The Fig.1. shows a presentation of the magnetic field line distribution in a four-pole induction machine along with locations for installation of measuring coils.

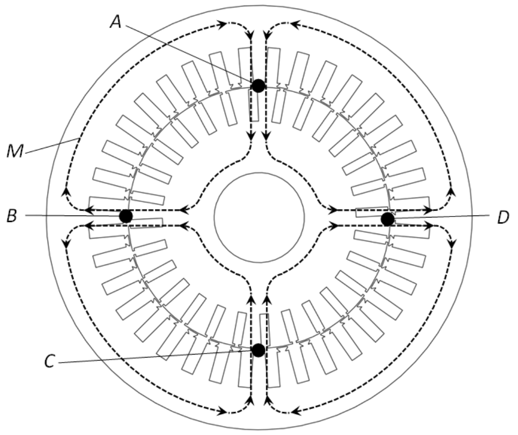

Figure 1. Presentation of the magnetic field line distribution along with locations for installation of measuring coils for magnetic filed measurement [24].

Positions for installation of measuring coils in a four-pole machine, at a mutual distance of multiple pole pitch $n \cdot \tau_p$, where n=1, 2, 3, 4, 5, 6, 7…, marked by positions A, B, C and D as presented in Fig. 1, have by absolute value equal magnetic potential for one selected time point. However, the direction of the magnetic field lines (pos. M Fig. 1) on the observed positions is not the same, but it differs on the positions A and C in relation to positions B and D. At positions A and C the magnetic field lines are in the direction from the periphery of the machine toward the center, whereas at positions B and D they are in the direction from the center toward the periphery. This spatial arrangement enables the detection of squirrel-cage induction motor rotor failures depending on the type and location of the failure. This new methodology is based on the magnetic field analysis obtained by measuring coils installed in the airgap of induction machine. The main advantage of this methodology is that it avoids complex signal processing and the need for harmonic analysis of the measured signal. The presence of rotor faults, such as static eccentricity is determined by detection of changes in induced voltage waveform and RMS, and detection of broken rotor bar or broken rotor ring is detected based on the differential measurement of the induced voltages in the two measuring coils. These statements are proven by numerous FEM calculations and by experimental measurements in the laboratory [24, 25].

B. *FEM Analysis*

The FEM analysis was performed in the commercial software *Simcenter Infolytica Magnet*. A two-dimensional FEM model of the squirrel-cage induction motor is shown on Fig.2. The Fig.3. shows distribution of the magnetic field together with the position of the measuring coils. These measuring coils are in the airgap, installed on the stator teeth and circularly spaced for a pole pitch, τ_p. To achieve reliable static eccentricity or broken rotor bar detection, it is necessary to ensure exactly this kind of measuring coils layout. Based on the waveform and RMS value of the induced voltage in the measuring coils, or based on their voltage difference it is possible to detect rotor eccentricity or rotor winding damages (such as broken rotor bars and ring) of the of the induction machine.

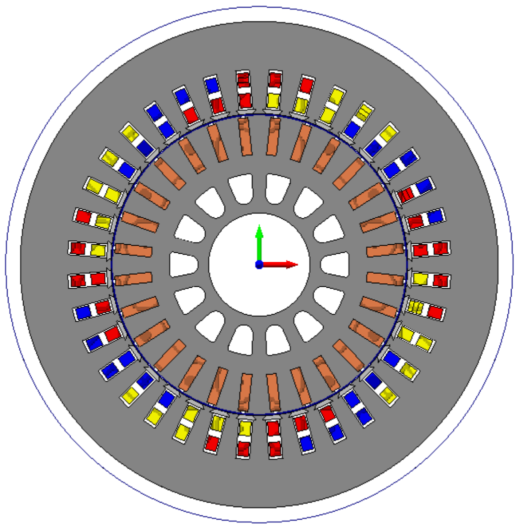

Figure 2. 2D FEM model of induction motor.

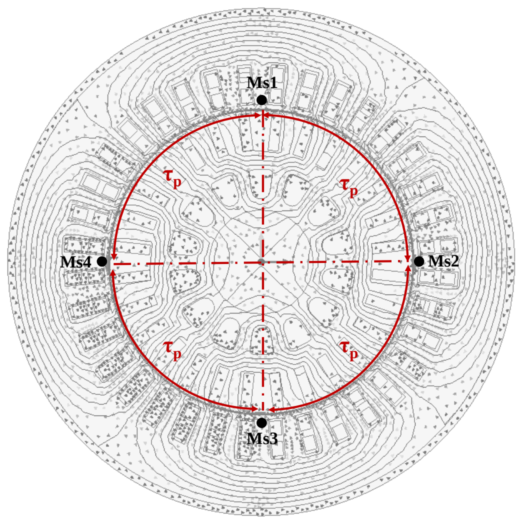

Figure 3. Distribution of the magnetic field with position of the measuring coils.

To determine changes of these voltage values, numerical simulations on the FEM model have been performed. Table 1 lists regular and simulated faulty conditions of the analyzed induction motor. In the case of static eccentricity simulation, percentage of eccentricity is given in relation to the minimal air gap width. First, FEM calculation for a regular machine operation was performed. Then, using the same model with corresponding modifications the simulations of static eccentricity and rotor winding damages (broken rotor bars and broken rotor ring) were performed. In the FEM model, the machine rotor was shifted in the direction of ±y axes for achieving changes of static eccentricity.

TABLE I. CALCULATED NORMAL AND FAULTY CONDITIONS OF THE INDUCTION MACHINE

Operating state	*Normal condition*	*Faulty condition*	*Model variant*
Rated load of the induction motor	•	static eccentricity	15 %
		static eccentricity	20 %
		static eccentricity	25 %
		broken rotor bar	1 bar
		broken rotor bar	2 bars
		broken rotor ring	1 ring

The influence on the induced voltage in measuring coils circularly spaced for a pole pitch was observed and analyzed with the aim to detect the static eccentricity presence and presence of broken rotor bars and ring. Based on the RMS value change of the induced voltage in the coils, the presence of rotor displacement and static eccentricity is determined. The rotor winding damages are detected based on the voltage difference between two measuring coils circularly spaced for a pole pitch, τ_p. Fig. 4 shows the voltage waveform induced in the measuring coils mutually spaced for the pole pitch, τ_p obtained for normal operation condition. For correct voltage waveform interpretation, it is necessary to have certain information regarding machine active part elements and understand their impact on the measuring coil voltage waveform. Fig. 5 presents the impact of the squirrel-cage rotor bars on the induced voltage waveform in the measuring coils. Numbers on this figure mark the impact of every rotor bar on the waveform. In one rotor turn, the waveform contains the number of rises and drops of the voltage that is exactly equal to the number of rotor bars. In the analyzed case the induction machine has 28 rotor bars. Following the regular machine operation, FEM simulations of static eccentricity listed in the table I were performed. Fig. 6 shows induced voltage waveform in the measuring coils when rotor is displaced for 25 % of the air gap width in the + y axis direction. Fig. 6 shows comparison of the induced voltage in the measuring coils Ms1 and Ms3, and Fig. 7. comparison of the voltage in the measuring coils Ms2 and Ms4. Through observation of these figures, it can be noticed that the absolute value of voltage induced in the coil Ms1 is greater than the voltage induced in the coil Ms3. This result is expected, as the chosen rotor displacement direction places squirrel-cage rotor nearest to the coil Ms1, and farthest apart from the coil Ms3.

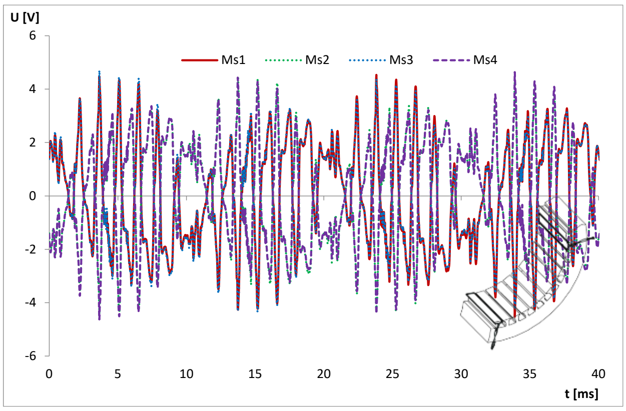

Figure 4. Induced voltage waveform in the measuring coils Ms1, Ms2, Ms3 and Ms4 – normal condition.

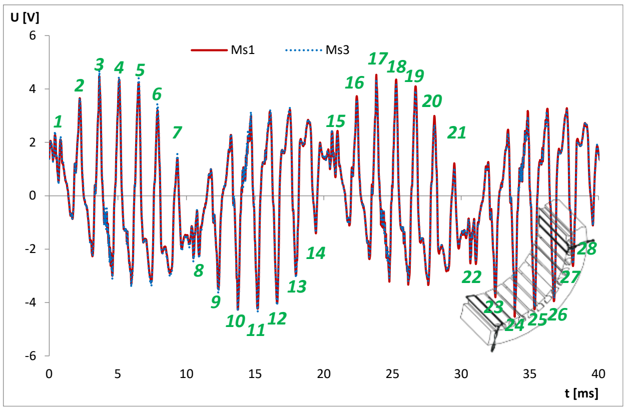

Figure 5. Impact of the squirrel-cage rotor bars on the induced voltage waveform in measuring coils.

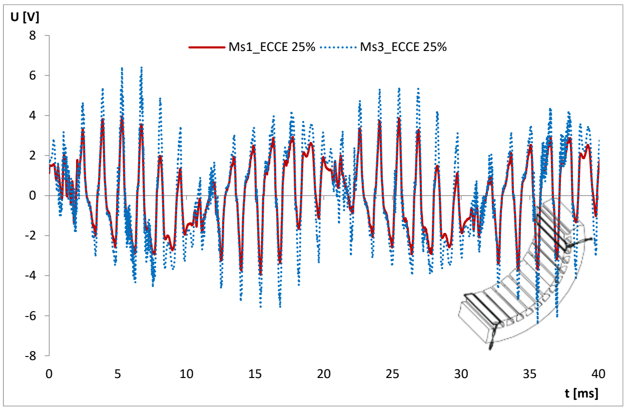

Figure 6. Comparison of the induced voltage waveform in the measuring coils for the static eccentricity amount 25% of the air gap (a shift in the + y axis): Ms1 and Ms3 diametrically spaced.

The comparison of the induced voltage in the measuring coils Ms2 and Ms4 is shown on Fig. 7. From this figure it can be concluded that the induced voltage in the mentioned measuring coils is equal. This result is expected as, in the case of the chosen rotor displacement direction, the relative position of the rotor to these two coils stays the same.

On Fig. 8 the voltage difference between two measuring coils, Ms1 and Ms3 spatially spaced for 2 τ_p is shown. The voltage difference is shown for the normal (blue waveform) and for the faulty (red waveform) condition. The observed fault is a broken rotor bar of the squirrel-cage induction motor.

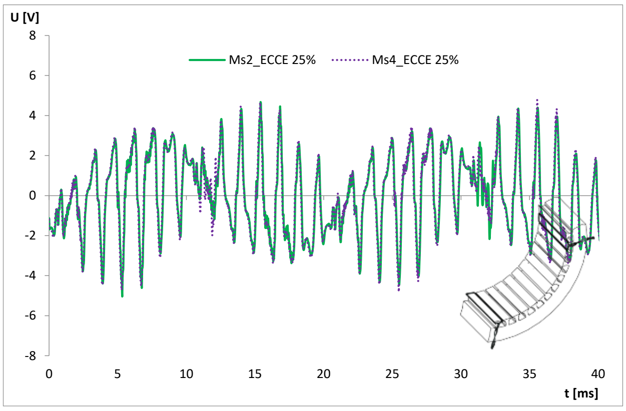

Figure 7. Comparison of the induced voltage waveform in the measuring coils for the static eccentricity amount 25% of the air gap (a shift in the + y axis): Ms2 and Ms4 diametrically spaced.

By observing the waveform of voltage difference for two measuring coils, presented in Fig. 8, the rotor winding damage is easy to detect. The measuring voltage is sensitive only to machine faults. In Fig. 8, winding damage is marked with voltage peek, which is repeated two times during a full turn in the case of one broken rotor bar. When the broken rotor bar comes across the measuring coil, one voltage peak appears. Therefore, in the measured waveform during one machine turn two extremely high voltage peaks will appear. The waveform is presented for the two machine turns, which in this case is 80 ms, because the analyzed induction motor is four-pole.

Accordingly, the number of such measured peaks of the measured voltage during one full machine turn, divided by two, gives the number of broken rotor bars.

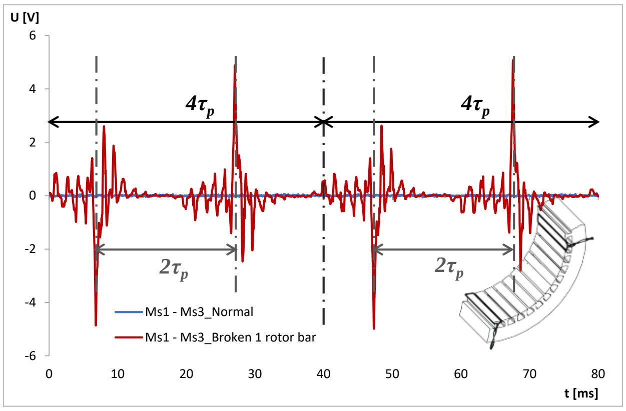

Figure 8. Voltage difference between measuring coils Ms1 and Ms3 for normal (blue waveform) and for one broken rotor bar (red waveform).

Fig. 9 presents waveform of the voltage difference for two measuring coils Ms1 and Ms3, installed around stator tooth without fault (blue waveform) and with two broken rotor bars (red waveform). By observing the voltage waveform obtained from two measuring coils and presented in Fig. 9, four extremely high voltage peaks can be seen for one machine turn. Therefore, the machine with this voltage waveform has two broken rotor bars.

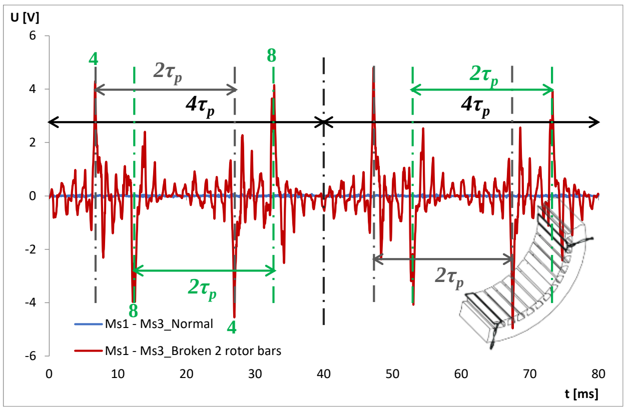

Figure 9. Voltage difference between measuring coils Ms1 and Ms3 for normal (blue curve) and for two broken rotor bar (red curve).

Furthermore, Fig. 10 presents waveform of the voltage difference for two measuring coils Ms1 and Ms3, installed around stator tooth without fault (blue waveform) and with broken rotor ring (red waveform). By observing the voltage waveform obtained from two measuring coils and presented in Fig. 10, extremely high voltage peaks can be seen for one machine turn. If you look in more detail, it can be seen that obtained waveform for the observed failure is different than in the case of broken rotor bars. The waveform is very similar to the waveform obtained for two broken bars. But, if you look closer it can be seen that the peaks are closer to each other and more pronounced (the higher voltage value). Therefore, it is possible to recognize the type and nature of the rotor fault. Based on these waveforms, obtained for different types of induction motor rotor failures, it was possible to design an algorithm for reliable and early detection and mutual recognition of induction motor faults.

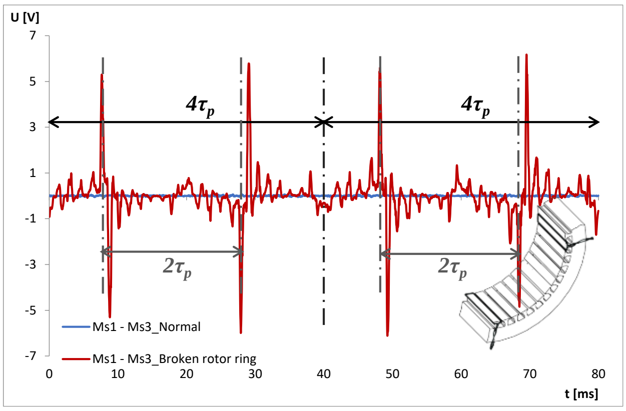

Figure 10. Voltage difference between measuring coils Ms1 and Ms3 for normal (blue curve) and for broken rotor ring (red curve).

This methodology is verified experimentally via series of laboratory tests performed on the real machines specially designed for fault study of broken rotor bars, broken ring and inter-coil short circuit in a rotor winding. Because of the complexity and extensiveness of the observed failures, measurement results are not shown within this paper.

III. ALGORITHM FOR MOTOR FAULTS RECOGNITION

Based on the FEM calculations and measurements, the functional algorithm for early fault detection and reliable recognition of rotor faults was designed. Fig. 11 presents and describes the flowchart of the proposed algorithm. Based on the obtained research results. Two special algorithms were designed. The input parameters for the proposed algorithm are induced voltages in four measuring coils spatially spaced for pole pitch. The first algorithm is intended for early and reliable detection of the broken rotor bars and the broken ring of the squirrel-cage induction motor. Based on the voltage difference obtained from induced voltages in measuring coils spatially spaced for $2\tau_p$, it is possible to detect and reliably recognize the fault of the squirrel-cage rotor. The algorithm mutually recognizes the broken bar and the broken ring of the rotor with a high degree of reliability. The second algorithm is proposed for early and reliable detection of rotor static eccentricity. The proposed algorithm uses induced voltage in four measuring coils. In the case of broken rotor bars and ring, the algorithm uses voltage difference between two induced voltages in measuring coils spatially spaced for $2\tau_p$. In the case of static eccentricity, the difference between the RMS value of each measuring coil installed in the air gap of the induction motor is analyzed. If there is a deviation between RMS values greater than the permissible value, the algorithm alarms the end user to the occurrence of a static eccentricity. Both algorithms for output results give graphical signalization with the corresponding message of the occurrence of each fault.

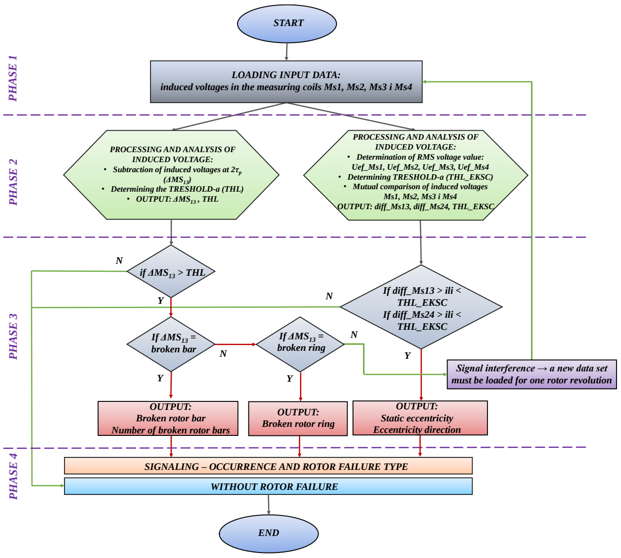

Figure 11. Flowchart of the smart and advanced algorithm for reliable faults detection and their mutual recognition.

Based on the input data (induced voltage in the measuring coils), using the function for determining characteristic peaks in the voltage waveform and voltage threshold, the algorithm detects and recognizes rotor faults of the induction motor. Respectively, Figures 12, 13, 14 and 15 shows algorithm output message for various conditions of the squirrel-cage rotor. In the case of static eccentricity, algorithms output message is type of fault and occurrence of static eccentricity in the direction of one of measuring coils. The output message in the case of static eccentricity occurrence is shown on Fig. 16 and 17, respectively.

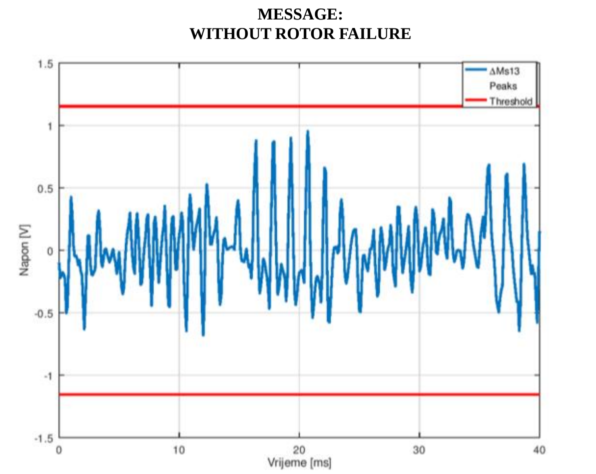

Figure 12. Algorithm output message – without rotor failure

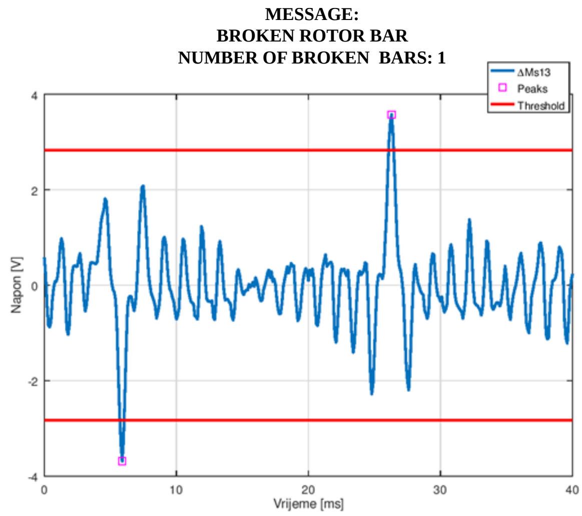

Figure 13. Algorithm output message – broken one rotor bar

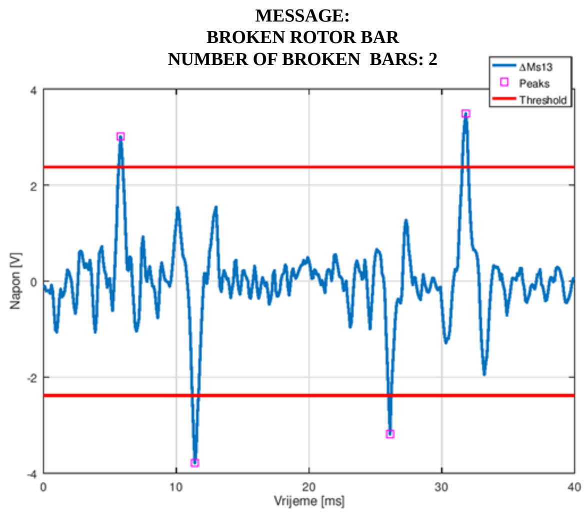

Figure 14. Algorithm output message – broken two rotor bars

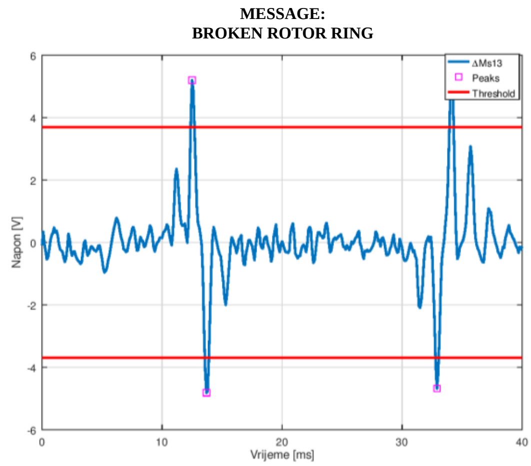

Figure 15. Algorithm output message – broken rotor ring

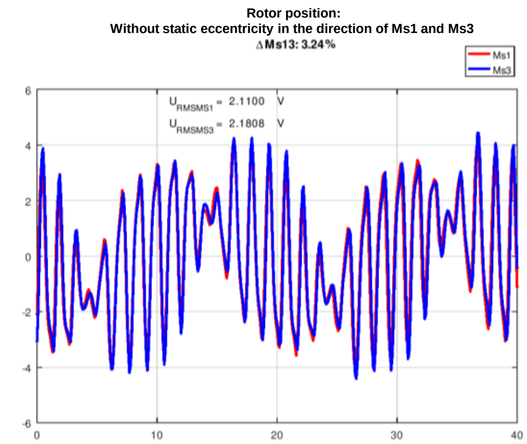

Figure 16. Algorithm output message – without the presence of static eccentricity

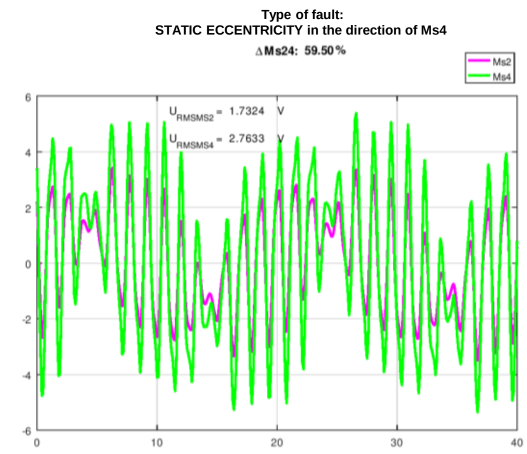

Figure 17. Algorithm output message – occurrence of static eccentriciy in the direction of the measuring coil Ms4

IV. Conclusion

The aim of this paper is to contribute to the early and reliable rotor eccentricity and rotor winding damages detection of induction machines based on the magnetic field analysis in the air gap. The two new and innovative approaches for rotor static eccentricity and rotor winding damages are presented. The novelty of this new methodology is magnetic field analysis obtained by measuring coils installed in the airgap of induction machine, and spatially spaced for pole pitch, τ_p. By FEM calculations, it is proven that by using the measuring coils on the stator teeth it is possible to detect static eccentricity occurrence or broken rotor bars, in an early stage. One of the main advantages of this methodology is that it avoids complex signal processing and the need for harmonic analysis of the measured signals. Determination of rotor static eccentricity is based on the changes in induced voltage waveform and RMS value of the measuring coil voltage. Determination of broken rotor bar and rotor ring is based on the voltage difference between two measuring coils spatially spaced for pole pitch, τ_p. The result of these simulations is an algorithm that is used for reliable and early rotor fault detection and recognition of the squirrel-cage induction motor and can be used for smart and advanced maintenance of induction motors.

References

[1] S. Nandi, H.A. Toliyat, X. Li: "Condition Monitoring and Fault Diagnosis of Electrical Motors", IEEE transactions on energy conversion, Vol. 20, No. 4, December 2005.

[2] P. Tavner, L. Ran, J. Penman, H. Sedding: "Condition Monitoring of Rotating Electrical Machines", The Institution of Engineering and Technology, London, United Kingdom, 2008.

[3] O.V. Thorsen,M. Dalva: "A Survey of Faults on Induction Motors in Offshore Oil Industry, Petrochemical Industry, Gas Terminals, and Oil Refineries", IEEE transactions on industry applications, Vol. 31, No.5, September/October 1995.

[4] O.V. Thorsen, M. Dalva: "Failure Identification and Analysis for High Voltage Induction Motors in Petrochemical Industry", IEEE, 1998.

[5] M.L. Sin, W.L. Soong, N. Ertugrul: "Induction machine on-line monitoring and fault diagnosis – a survey", AUPEC 2003, Australasian Universities Power Engineering Conference, Christchurch, New Zealand, October 2003.T. Seppa "Fried Wire?" (Public Utilities Fortnightly, December 2003, pages 39-41)

[6] A. Siddique, G.S. Yadava, B. Singh: "A Review of Stator Fault Monitoring Techniques of Induction Motors", IEEE transactions on energy conversion, Vol. 20, No. 1, March 2005.Prospectiva del Sector Eléctrico 2002-2011. (Secretaría de Energía. Mexico, 2002).

[7] M.J. Picazo-Rodenas, R. Royo, J. Antonino-Daviu, J. Roger-Folch: "Use of Infrared thermography for computation of heating curves and preliminary failure detection in induction motors", ICEM 2012, XXth International Conference on Electrical Machines, Marseille, France, September 2012.

[8] M.E.H. Benbouzid: "A Review of Induction Motors Signature Analysis as a Medium for Faults Detection", IEEE transactions on industrial electronics, Vol. 47, No.5, October 2000.

[9] D.R. Albright, "Inter turn Short-circuit Detector for Turbine-Generator Rotor Windings", IEEE trans. on power apparatus and systems, Vol. PAS-90 Number 2, March/April 1971.

[10] M. Sasic, B.A. Lloyd, S.R. Campbell, "Flux Monitoring Improvement", IEEE industry applications magazine, Sept/Oct 2011.

[11] M. Šašić, L. Blake, A. Elez, "Finite Element Analysis of Turbine Generator Rotor Winding Shorted Turns", IEEE trans. on energy conversion. 27 (2012), 4; 930-937.

[12] A. Elez, S. Car, Z. Maljković, "A new method for inter-coil short circuit detection in synchronous machine armature winding", The international review of electrical engineering (IREE). Vol. 7, N. 6 (2012).

[13] H. C. Karmaker; - "Broken Damper Bar Detection Studies Using Flux Probe Measurements and Time-Stepping Finite Element Analysis For Salient – Pole Synchronous Machines", SDEMPED

2003, Symposium for Electric Machines, Atlanta USA August 2003.

[14] P. O'Donell: "Report of Large Motor Reliability Survey of Industrial and Commercial Installations Parts I, II and III", IEEE Transactions on Industry Applications, Motor Reliability Working Group, IEEE Industry Applications Society, July/August 1985, January/February 1987.

[15] B.M. Ebrahimi, J. Faiz, S. Lotfi-fard, P. Pillay: "Novel indices for broken rotor bars fault diagnosis in induction motors using wavelet transform", Elsevier ScienceDirect, Journal of Mechanical Systems and Signal Processing 30, 131-145, February 2012.

[16] C.C. Yeh, G. Sizov, A. Sayed-Ahmed, N.A.O. Demerdash, R.J. Povinelli, E.E. Yaz, D.M. Ionel: "A Reconfigurable Motor for Experimental Emulation of Stator Winding Interturn and Broken Bar Faults in Polyphase Induction Machines", IEEE transactions on energy conversion, Vol. 23, No. 4, December 2008.

[17] N.M. Elkasabgy, A.R. Eastham, G.E. Dawson: "Detection of Broken Bars in the Cage Rotor on an Induction Machine", IEEE transactions on industry applications, Vol. 28, No.1, January/February 1992.

[18] G. Didier, E. Ternisien, O. Caspary, H. Razika: "A new approach to detect broken rotor bars in induction machines by current spectrum analysis", Elsevier, Mechanical Systems and Signal Processing, Vol.21, 2007.

[19] Z. Ye, B. Wu,A. Sadeghian: "Current Signature Analysis of Induction Motor Mechanical Faults by Wavelet Packet Decomposition", IEEE transactions on industrial electronics, Vol. 50, No.6, December 2003.

[20] H. Douglas, P. Pillay, A. Ziarani: "Detection of broken rotor bars in induction motors using wavelet analysis", IEEE International Electric Machines and Drives Conference, IEMDC'03, June 2003.

[21] V.V.Thomas, K. Vasudevan, V.J. Kumar: "Online Cage Rotor Fault Detection Using Air-Gap Torque Spectra", IEEE transactions on energy conversion, Vol.18, No. 2, June 2003.

[22] W.T. Thomson, R.J. Gilmore: "Motor current signature analysis to detect faults in induction drives – fundamentals, data interpretation and industrial case histories", Proceedings of the thirty-second turbomachinery symposium, 2003.

[23] M.Y. Kaikaa, M. Hadjami: "Effects of the Simultaneous Presence of Static Eccentricity and Broken Rotor Bars on the Stator Current of Induction Machine", IEEE Transactions on Industrial Electronics, Vol.61, No.5, May 2014.

[24] S. Tvorić: "Rotor Faults Detection in Squirrel-Cage Induction Motor based on Magnetic Field Analysis in Air-Gap", doctoral thesis, Faculty of Electrical Engineering and Computing, Zagreb 2019.

[25] A. Elez, S. Car, S. Tvorić, B. Vaseghi: "Rotor cage and winding fault detection based on machine differential magnetic field measurement (DMFM)", IEEE Transactions on Industry Applications, 53(3):3156–3163, 2016.