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# Application of Differential Magnetic Field Measurement (DMFM method) in winding fault detection of AC rotating machines as part of expert monitoring systems

## SUMMARY

Stator and rotor winding damages in rotating machines are result of electrical, mechanical, and thermal stress. Online magnetic field monitoring via permanently installed measuring coils inside air gap is a well-established methodology which enables winding fault detection. The paper deals with a new method for detection of stator and rotor winding inter-turn short circuits of synchronous machines and slip rings induction machines, as well as rupture of rotor bars and cage ring of induction machines. The method novelty is based on differential measurement of magnetic field by using two serial connected measuring coils. They are installed on the places (stator or rotor teeth) in the machine which have, by absolute value, equal magnetic vector potential. The distance between the measuring coils is $n \cdot \tau_p$, where $\tau_p$ is a pole pitch, and $n = 1, 2, 3, 4,...$ is a multiple of the pole pitch. Measuring the coil-induced voltage enables us to detect stator and rotor winding faults, which means that measured voltage is approximately zero without fault and increases in the presence of fault. Analysis of the measuring signal allows us to detect and locate fault. With this new method it is possible with high sensitivity to determine winding fault, which enables more reliable fault detection. For example, in comparison with the motor current signature analysis method (the most widely used method for motor faults detection), this new method gives 200 times higher sensitivity to fault occurrence. Also, by using the DMFM method, faults can be detected in the time domain and there is no need for spectral or other complex signal analysis. This is very important because the measuring equipment used for machine fault detection can be simple and more economically acceptable. The DMFM method enables fault detection for even small machines with small expense in a very effective way. The only downside of the DMFM method is the fact that machine should be disassembled in order to install measuring coils. This problem is solved during the machine overhaul or during the manufacturing of the machine, when sensors can be easily implemented in the machine. For machines with large air gap, measuring coils can be installed without a machine disassembly. For the purpose of the method testing, numerous finite-element (FE) simulations on the 2- and 3-D machine models have been carried out to verify the method. Powerful numerical tools generate realistic results with properly selected starting and boundary conditions. By FEM models, actual machines with embedded measuring coils where created and simulated. The voltage induced inside the measuring coils is calculated for different machine states, load point and with and without a fault (broken rotor bar or inter-turn short circuit). Also, this method was experimentally validated via series of laboratory tests performed on the real electric machines specially designed for fault study (broken rotor bars, broken ring and inter-turn short circuits in a stator and rotor winding). Additionally, this method is applied on more than 20 real machines in industry. Due to the large amount of measured data, in this paper, it will be presented only one measurement performed on an induction motor on which we have detected one broken rotor bar. The thickness of the measuring coil designed in the printed circuit board technique is 0.3 mm. The number of turns is from 3 to 10. This new method and performed FEM calculations together with the experimental measurements improve fault detection portfolio knowledge that can be used in monitoring and diagnostics of rotating machines. Furthermore, this patent-pending method is already implemented in three innovative products placed on market (expert monitoring systems), so this method is fully confirmed in practice.

## KEYWORDS

finite element, induction machine, inter-turn shorted circuits, rotor bars, rotor cage faults, synchronous generator, magnetic field, measuring coil, induced voltage, air gap

# INTRODUCTION

Stator and rotor winding damages in rotating machines are result of electrical, mechanical, and thermal stress. Online magnetic field monitoring via permanently installed measuring coils inside air gap is a well-established methodology which enables winding fault detection [1, 2, 3, 4, 5]. In the industry and according to the literature [6, 7, 8, 9], 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) [10, 11, 12, 13, 14, 15, 16, 17].

The novelty of DMFM method is differential measurement of the magnetic field in a rotating machine with two serial connected 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 $\tau_p$ is a pole pitch, and *n=1, 2, 3, 4 …* is a multiple of the pole pitch. A typical installation of measuring coils is presented in Figure 1. Measuring coils 1 and 2 are installed around stator tooth so that they encompass the whole stator tooth or just part of the tooth.

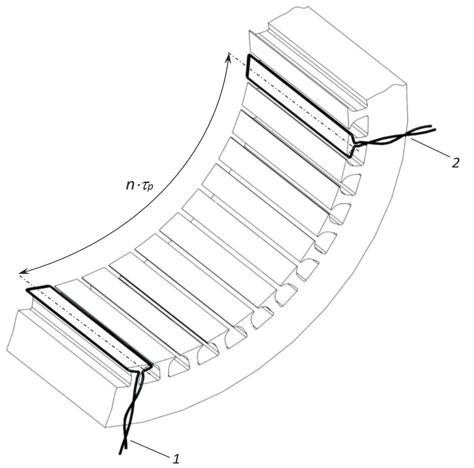



Figure 1. Principle of typical installation of measuring sensor on stator tooth: pos.1 measuring coil no. 1, pos. 2 measuring coil no.2.

The measuring coils 1 and 2 are installed on the stator tooth, and this way the area through which magnetic field is measured is strictly defined. With this type of installation, the area on which a magnetic field is measured is equal for both measuring coils, which is crucial for this differential measurement method.

In some cases, measuring coils can encompass only a section of the stator tooth for machines with radial ventilation gaps, or two identical measuring coils can be installed in the same position on the tooth. The measuring coils 1 and 2 are made in PCB technique, as shown in Figure 2 (installation on the stator tooth of the induction motor in the real condition).

Figure 2. Measuring coil in PCB technique installed on the stator tooth

The measuring coils 1 and 2 must be installed to such locations in the machine that have the same magnetic vector potential by absolute value. To meet this requirement and realize the measurement method, it is necessary to connect the measuring coils 1 and 2 with each other in series depending on the parity of the multiple of the pole pitch $\tau_p$.

If an odd multiple of *n=1, 3, 5, 7…* of the pole pitch $\tau_p$ is chosen for the distance between the measuring coils, then the measuring coils 1 and 2 should be connected as shown in Figure 3.

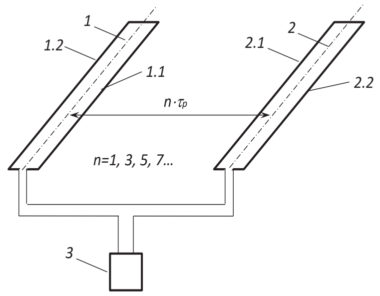



Figure 3. Typical measuring sensor installation if an odd multiple of the pole pitch is chosen for the distance between the measuring coils 1 and 2.

The inner side (pos.1.1 Figure 3) of the coil 1 connects with the inner side 2.1 of the coil 2. The outer side (pos.1.2 Figure 3) of the coil 1, through measuring system (pos.3 Figure 3), connects with the outer side (pos.2.2 Figure 3) of the coil 2. The measuring coils 1 and 2 connected in series according to Figure 3, whose mutual distance is an odd multiple *n=1, 3, 5, 7…* of the pole pitch $\tau_p$, will have the same absolute value of a magnetic field, but the direction of the magnetic field lines will be different. The measuring coils connected and installed in this way allow mutual subtraction of the voltages that are induced in the measuring coils 1 and 2. If an even multiple of *n=2, 4, 6, 8…* of the pole pitch $\tau_p$ is chosen for the mutual distance of the measuring coils, then the measuring coils 1 and 2 should be connected as shown in Figure 4.

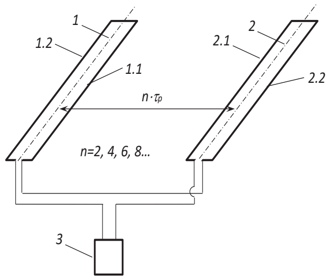



Figure 4. Typical measuring sensor installation if an even multiple of the pole pitch is chosen for the distance between the measuring coils 1 and 2

The inner side (pos.1.1 Figure 4) of the coil 1 connects with the outer side (pos.2.2 Figure 4) of the coil 2. The outer side (pos.1.2 Figure 4) of the coil 1, through measuring system (pos.3 Figure 4), connects with the inner side (pos.2.1 Figure 4) of the coil 2. The measuring coils 1 and 2 connected in series according to Figure 4, whose mutual distance is an even multiple *n=2, 4, 6, 8…* of the pole pitch $\tau_p$, will have the same absolute value of a magnetic field and the same direction of the magnetic field lines. The measuring coils connected and installed in this way allow mutual subtraction of the voltages that are induced in the measuring coils 1 and 2. The measuring system (pos. 3 Figure 3 and 4) measures the total voltage *U* that is induced in two measuring coils 1 and 2, connected in series. In simple application, this method can be used in a following way: if the measured voltage *U* exceeds a predefined value, the measuring system can activate an output relay which signals the user that a winding fault is present in the machine. Figure 5 shows a simplified presentation of the magnetic field line distribution in a four-pole induction machine along with possible locations for installation of measuring coils.

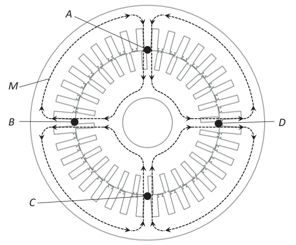



Figure 5. Simplified presentation of the magnetic field line distribution along with possible locations for magnetic field installation

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 Figure 5, have by absolute value equal magnetic potential for one selected time point. However, the direction of the magnetic field lines (pos. M Figure 5) on the observed positions is not the same, but it differs on the positions A and C in relation to positions B and D. If the pole pitch $\tau_p$ or odd multiple of pole pitch $\tau_p$ is chosen as a mutual distance of the measuring coils during their installation in the machine, then the measuring coils 1 and 2 should be installed at the positions A and B or A and D or C and B or C and D; and connected according to Figure 3. If an even multiple pole pitch $\tau_p$ is chosen as a mutual distance of the measuring coils during their installation in the machine, then the measuring coils 1 and 2 should be installed at the positions A and C or B and D and connected according to the Figure 4. In the case of a normal machine operation, in the measuring coils 1 and 2 installed in the corresponding places in the machine and connected according to the Figure 3 or Figure 4, the same voltage will be induced due to the changing magnetic field of the machine. Therefore, in the case of a normal machine operation (no fault), the total voltage of two measuring coils, connected in series, is approximately equal to zero for each selected time during one turn of the machine. In case of rotor winding damage, and at the moment of the arrival of the damaged rotor winding on one of the measuring coils 1 and 2, the voltages that are induced in the measuring coils 1 and 2 will no longer be equal. Thus, the total voltage of two measuring coils connected in series will not be equal to zero for any chosen moment during one turn of the machine. By measuring the total voltage of two measuring coils connected in series during one turn of the machine, one can unambiguously detect a rotor winding failure in induction and synchronous machines. In addition to winding failure detection, the number of rotor winding failures can be determined as well. By serial connection of the measuring coils 1 and 2, the magnetic field present in a machine operating without damage is eliminated from the measured value and the measured value depends only on the magnetic field caused by rotor winding damage. The method for rotor winding damage detection was tested by numerical calculations using Finite Element Method (FEM). Furthermore, the laboratory tests confirmed the effectiveness of this method through experiments on a synchronous and an induction machine.

# FEM ANALYSIS

For the purpose of the method testing numerous two and three-dimensional machine models were created. Powerful numerical tools generate realistic results with properly selected starting and boundary conditions. By FEM models, actual machines with embedded measuring coils where created and simulated. The voltage induced inside the measuring coils is calculated for different machine states, load point and with and without a fault (rotor bare rupture or inter-coil short circuit). Table 1 presents machine operating conditions for which calculations are performed.

Table.1. Machine operating condition for FEM calculations

| *No* | *Operating condition* | *Machine type* | *Nominal load* | *Decreased load* | *With frequency converter* | *Without frequency converter* | *No. of simulations* |
|---|---|---|---|---|---|---|---|
| *1* | *No fault* | *Induction* | • | • | • | • | *4* |
| 2 | *With one broken rotor* | | • | • | • | • | *10* |
| *3* | *With two broken rotor* | | • | • | • | • | *20* |
| 4 | *With five rotor broken* | | • | • | • | • | *20* |
| 5 | *With one broken rotor bar and eccentricity* | | • | • | • | • | *20* |
| 6 | *With two broken rotor bar and eccentricity* | | • | • | • | • | *20* |
| 7 | *No fault* | *Synchronous* | • | • | | | *4* |
| 8 | *With 1% or shorted* | | • | • | | | *5* |
| 9 | *With 2 % of shorted* | | • | • | | | *5* |
| 10 | *With 5% of shorted* | | • | • | | | *3* |
| 11 | *With 1% of shorted turns and eccentricity* | | • | • | | | *10* |
| 12 | *With 2% of shorted turns and eccentricity* | | • | • | | | *10* |

Figure 6 and Figure 7 present the magnetic field line distribution in the cross section of the induction machine with and without broken rotor bars acquired by FEM simulations. On Figure 7 machine cross section zone where rotor broken bars effect can be noticed is marked by white dashed line. Figure 8 presents calculated voltage waveform induced in two measuring coils connected in series and installed around stator tooth without fault and with one broken rotor bar.

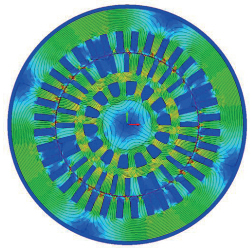


Figure 6. Presentation of the magnetic field line distribution in the cross section of four pole induction machine without broken rotor bars.

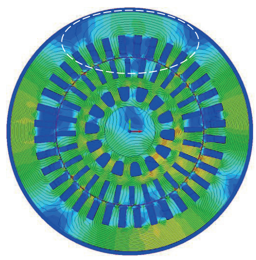


Figure 7. Presentation of the magnetic field line distribution in the cross section of four pole induction machine with broken rotor bars.

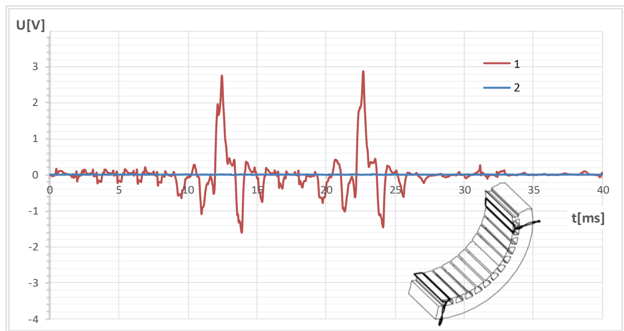


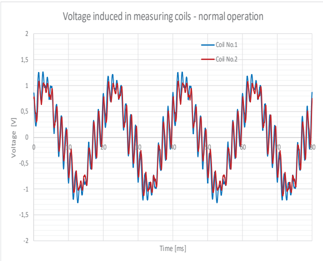

Figure 8. Calculated voltage induced in two measuring coils connected in series: 1 – with one broken rotor bar, 2 – without fault.

By observing the waveform of voltage induced in two measuring coils connected in series, presented in the Figure 8, the rotor winding damage is easy to detect. The measuring voltage is sensitive only to machine faults. In the Figure 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. 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. Similar results were calculated for a synchronous machine with inter-coil short circuit in excitation winding.

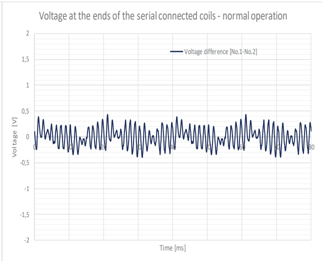
# MEASUREMENT RESULTS AND APPLICATION

This method 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. Additionally, this method is applied on more than 20 real machines in industry. Due to the large amount of measured data, in this paper we will present only one measurement performed on an induction motor on which we have detected one broken rotor bar. The rating of the machines where method as applied are:  15, 65, 725, 800, 1200, 1250 kW. The thickness of the measuring coil designed in the PCB technique is 0,3 mm. The number of turns is from 3 to 10. From our experience the 1 turn is enough to obtain good signals, but our practice is to use 10 turns.

Figure 9 presents the measured induced voltage at the end of each measuring coil and also on the terminal of series connected coils for normal operation without fault. The voltage waveform is periodic and repeated for each turn of the machine, which corresponds to the time of 40 ms, i.e. 4 pole pitches, i.e. $4\tau_p$. It can be seen that the difference voltage for series connected coils are less than 0.5 V for healthy machine and the induced voltage waveform has the same shape for the measuring coil 1 and for the measuring coil 2.



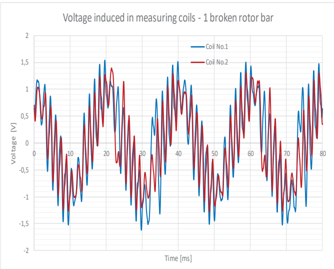

a)



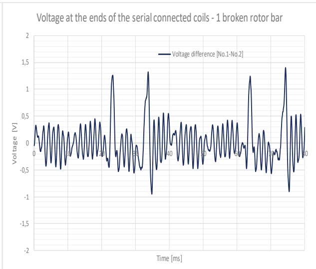

b)

Figure 9. Voltage induced in coils without fault: a) voltage induced in each measuring coil without fault, b) voltage induced in series connected coils terminal

Figure 10 presents the measured induced voltage at the end of each measuring coil and also on the terminal of series connected coils for machine with one broken rotor bar. It can be seen that the difference voltage for series connected coils are now greater than 1.25 V for machine with one broken bar and could be detected.




a)




b)

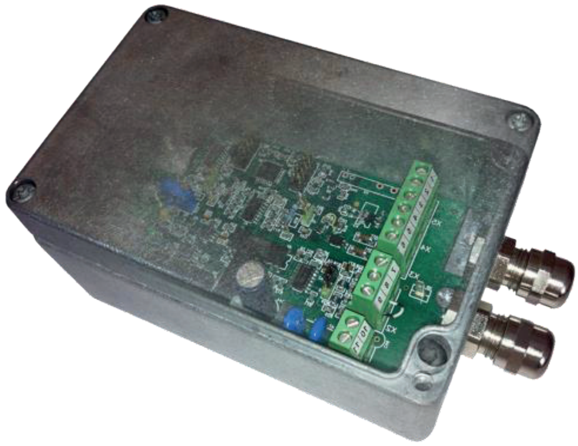
Figure 10. Voltage induced in coils with one broken bar: a) voltage induced in each measuring coil with fault, b) voltage induced in series connected coils terminal

Broken rotor bar detection based on the voltage waveform induced in one measuring coil, as presented in Figure 10.a), requires a complex signal processing. However, by observing the voltage waveform induced in two measuring coils connected in series, as presented in Figure 10.b), one can conclude that a rotor winding damage is easy to detect. The serial connection of two measuring coils cancels out a magnetic field present inside the machine without fault from the measuring signal. In that way two measuring coils connected in series measure the magnetic field caused only by rotor broken bar.

From Figure 10 it can be seen that the voltage peaks amplitude, caused by rotor broken bar, is between 1 V and 1.25 V. This level of signal is a sufficient for reliable damage detection and there is no need for amplification of the measured signal. This method, besides for broken rotor bar detection, can be used for determination of the number of the broken bars, but also for determination of their mutual positions. From Figure 10 it can be seen that the voltage of two measuring coils connected in series, for the rotor part without any winding damage, is not equal to zero. This occurs due to allowed tolerances in the machine manufacturing and assembly and imperfections of measuring coils installation. However, one can clearly see the change in the value of the measured voltage in the case of rotor broken bar, which is almost 150% for the presented machine. The method has been tested for the entire operating range of the machine and it successfully detects rotor winding damage in the entire operating range. The method has been tested and verified in the case when machine is powered from the frequency converter. Voltage oscillation around zero enables in combination with a key phasor sensor determination of the fault position. Each voltage oscillation represents one rotor bar.

The measuring system connected to measuring coils can be of different complexity level. The simplest type, presented in Figure 11, is basically a comparator which triggers an output relay when voltage excides the preset value.

a)



b)

*Figure 11. a) measuring coil, b) FDSS (Fault Detecting Smart Sensor) enables detection of rotor broken bars and inter-coil short circuits in rotor winding*

More complex product in which this patent-pending method is implemented is presented in Figure 12. This product enables fault detection, determination of number of faults and also fault positions. It can be applied for induction machine but also for synchronous hydro and turbo machines. Measurement can be permanent through an on-line measurement or users can periodically measure in order to locate rotor winding faults.


Figure 12. HG-WFD System (Hydro Generator Winding Fault Detection)

The concept of the EMCM system (Expert Machine Condition Monitoring) is presented in Figure 13. This system is specially designed for condition monitoring of the induction machines. The Figure 14 shows the web interface of the EMCM system. Through this interface the end user can monitor all relevant parameters of the induction motor, such as current, voltage, bearing vibrations, speed, temperatures, and especially the condition of the squirrel-cage winding. The condition of rotor winding (with or without fault) is monitored by application of the DMFM method. On the Figure 15 it is showed the measured induced voltage obtained by measuring coil embedded in the air gap of the motor and recorded by EMCM system. From the presented expert solutions, it can be seen that the DMFM method is fully confirmed in practice and has a significant industrial application in condition monitoring of rotating machines in various drives.

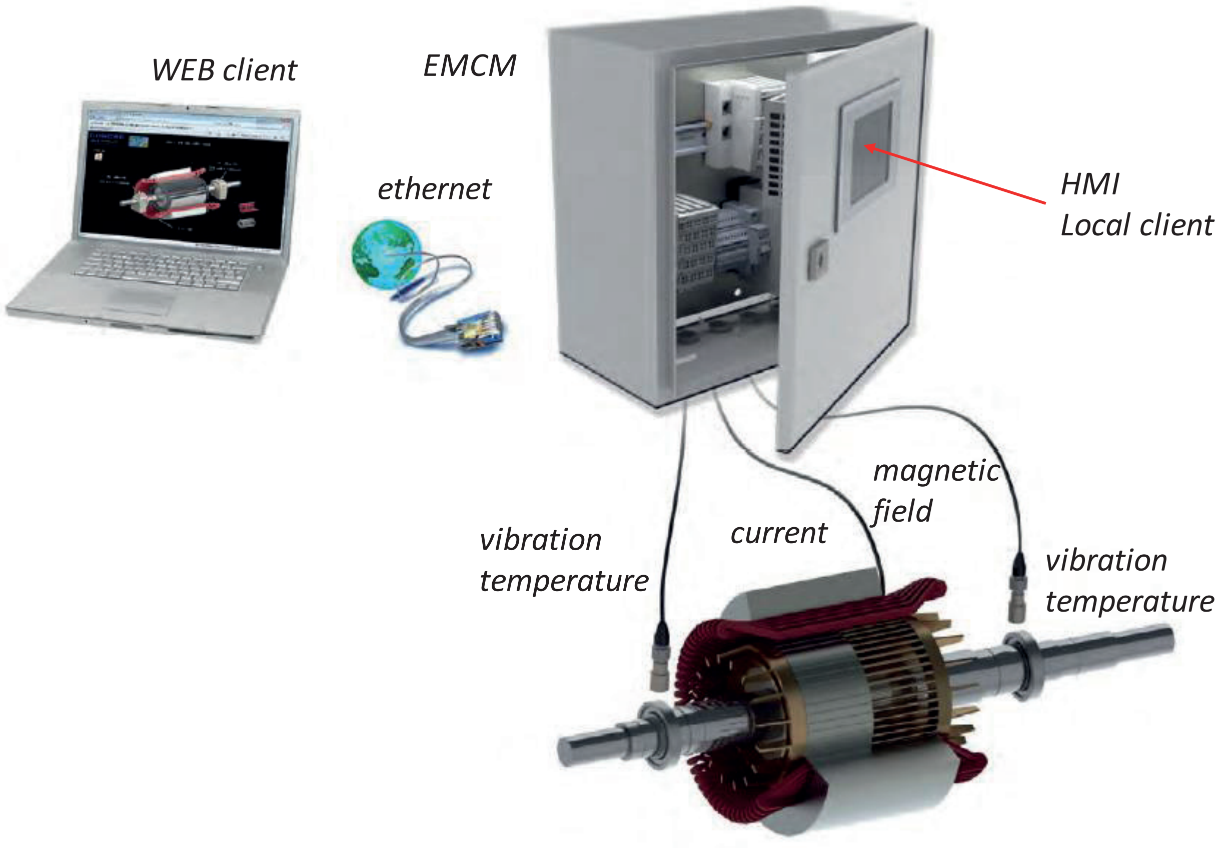



Figure 13. Concept of EMCM system

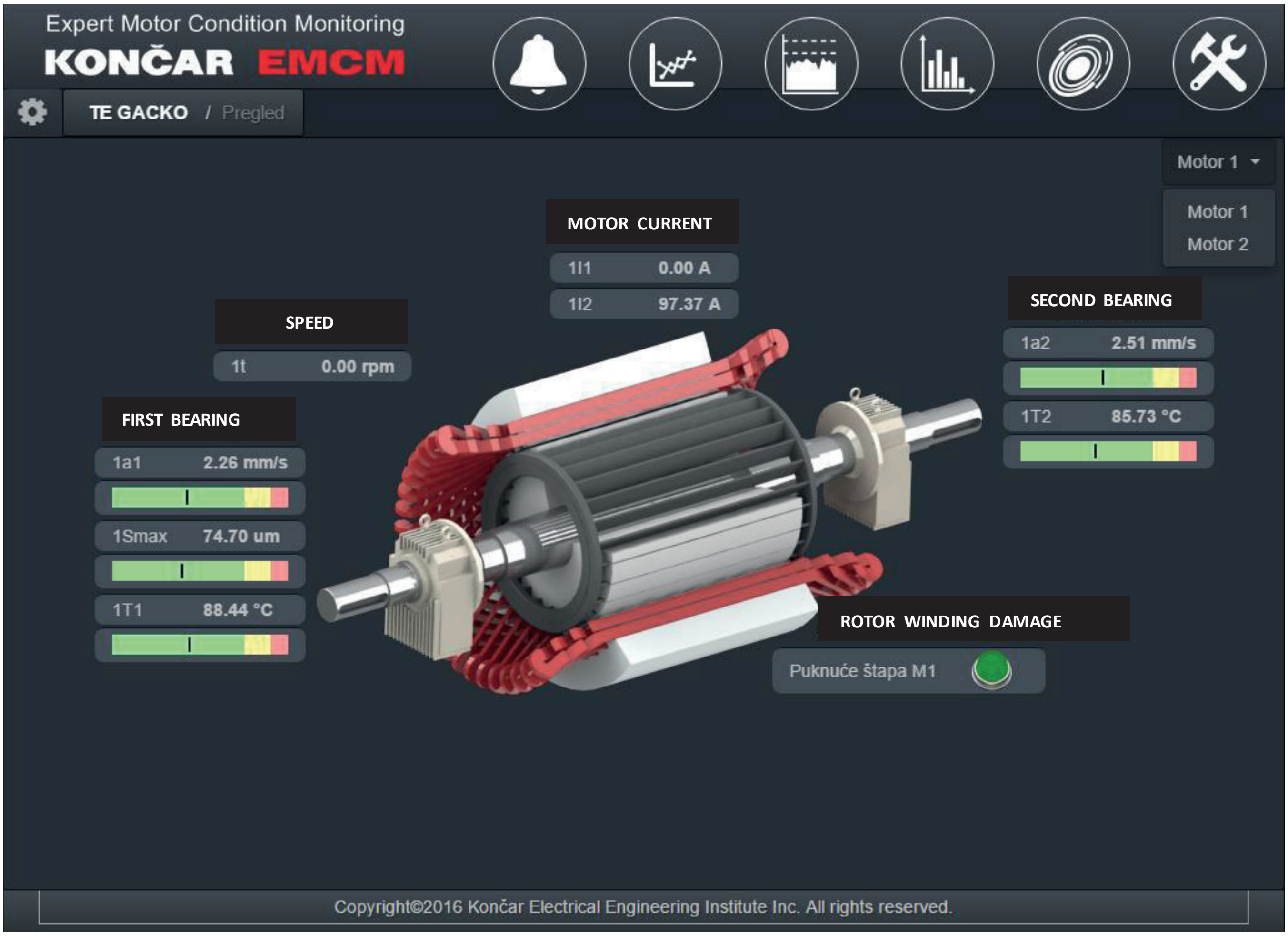



Figure 14. WEB interface of the EMCM system

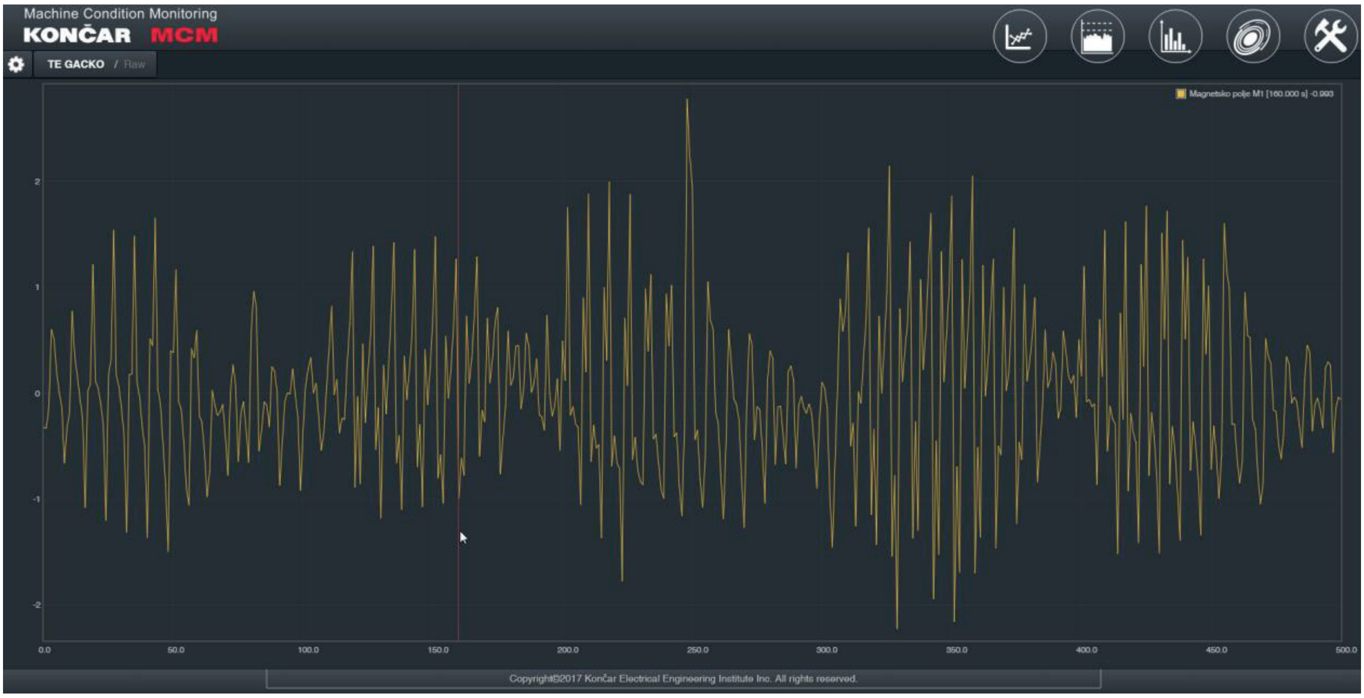



Figure 15. The induced voltage signal from measuring coil recorded by EMCM system

# CONCLUSION

This paper describes a new patent-pending method applicable for rotor winding inter-coil short circuit detection of synchronous machines and induction machines with slip rings, as well as rupture of one or more rotor bars and cage ring of induction machines. The DMFM method presented in this paper enables reliable detection of these faults. The technical novelty of this new method is a differential measurement of the magnetic field inside the machine. Measurement is performed by two serial connected measuring coils, installed on the stator tooth inside a machine air gap. Measuring coils must be installed on two stator teeth which, by absolute value, have equal magnetic vector potential.

A numerous FEM models have been developed to confirm this method. The method is tested for wide range of fault combinations but also for different machine operating conditions. Method is confirmed by the extensive laboratory tests on real models for various machine loads and for machines operating with and without a frequency converter. Method has already implemented on more than 20 machines in the industry and is tested and proven. From measuring results, one can conclude that this new DMFM method enables much simpler fault detection with significantly higher sensitivities.

Furthermore, this new method and performed FEM calculations improves fault detection portfolio knowledge that can be used in monitoring and diagnostics of rotating machines.

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