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 a result of electrical, mechanical, and thermal stress. Online magnetic field monitoring via permanently installed measuring coils inside the 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 serially 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 \( n = 1, 2, 3, 4, \ldots \) 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 the 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
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 \( n \tau \), where \( \tau \) is a pole pitch, and \( n = 1, 2, 3, 4 \ldots \) 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.

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 \( \tau \).

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

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 \( n = 1, 3, 5, 7 \ldots \) of the pole pitch \( \tau \), 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 will allow mutual subtraction of the voltages that are induced in the measuring coils 1 and 2. If an even multiple of \( n = 2, 4, 6, 8 \ldots \) of the pole pitch \( \tau \) 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.

If an even multiple of \( n = 2, 4, 6, 8 \ldots \) of the pole pitch \( \tau \) is chosen for the distance between the measuring coils 1 and 2, 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 1. Principle of typical installation of measuring sensor on stator tooth; pos.1 measuring coil no. 1, pos. 2 measuring coil no.2.

Figure 2. Measuring coil in PCB technique installed on the stator tooth.
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 $n\tau_p$, 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>
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<tr>
<th>No.</th>
<th>Operating condition</th>
<th>Machine type</th>
<th>Normal load</th>
<th>Deviation load</th>
<th>Voltage with frequency converter</th>
<th>Voltage without frequency converter</th>
<th>No. of calculations</th>
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</table>

**Table 1. Machine operating condition for FEM calculations**

**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

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.
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. 2pT = 40 ms.

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.

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.

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. 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

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.
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.

BIBLIOGRAPHY