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Measurement system for circulating stator currents: Towards condition monitoring of large MW-scale synchronous motors

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Abstract:
This article discusses a sensor system enabling the acquisition of circulating stator currents in the case of an industry-scale motor. The focus during development of this condition monitoring system was to achieve high measurement fidelity and, at the same time, to provide a robust and flexible sensor system which is suited for final installation in a factory environment. The layout of the sensor system as well as constraints imposed by the motor environment will be discussed. Typical circulating currents recorded with the sensor setup show a complex and rich frequency spectrum caused by the high sensitivity of the method which indicates even small asymmetries in the synchronous motor.

Key words: circulating stator currents, condition monitoring, current sensors, synchronous motor

Introduction

Condition monitoring of large synchronous motors is becoming more and more important because industry-scale motors are expensive and important assets, thus operators try to avoid any downtime. In contrast to conventional condition monitoring approaches, such as vibration monitoring or motor current signature analysis (MCSA) [1, 2], circulating current monitoring promises higher sensitivity to faulty states of the motor [3, 4]. Because circulating currents between parallel stator branches are sensitive to even tiny unbalances in the magnetic flux in the air gap of the motor they allow detecting potential motor faults very early, so that predictive maintenance is enabled.

Measurement of Circulating Currents

Two possible measurement schemes for circulating stator currents are shown in Figure 1: The first scheme is based on the measurement of the individual branch currents I_1 and I_2 (Fig. 1a). To deduce the circulating current $I_C=(I_1-I_2)/2$, two of the absolute current measurements need to be subtracted from each other either electrically, e.g. by an operational amplifier, or numerically after the digitalization of the signals. Because the amplitudes of the branch currents can be very high as compared to the circulating current of interest, this scheme may suffer from noise. Furthermore it requires a high dynamic range and accuracy of the current sensors.

In contrast, the second scheme (Fig. 1b) uses a differential current measurement based on a twisted sensor loop which surrounds the two conductors of interest. This can be implemented with e.g. a flexible Rogowski-sensor.

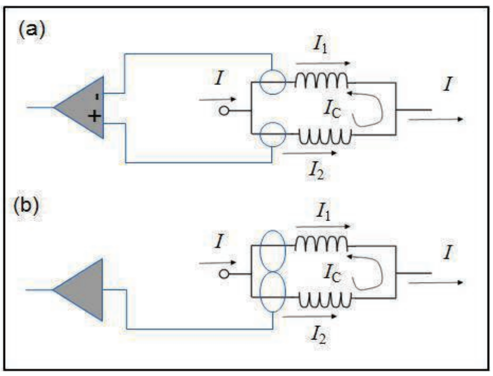

Fig. 1. Two alternative approaches for measuring the circulating current: (a) Two individual branch current signals are subtracted from each other to form the circulating current. (b) The circulating current is directly measured through magnetic subtraction with a single sensor.

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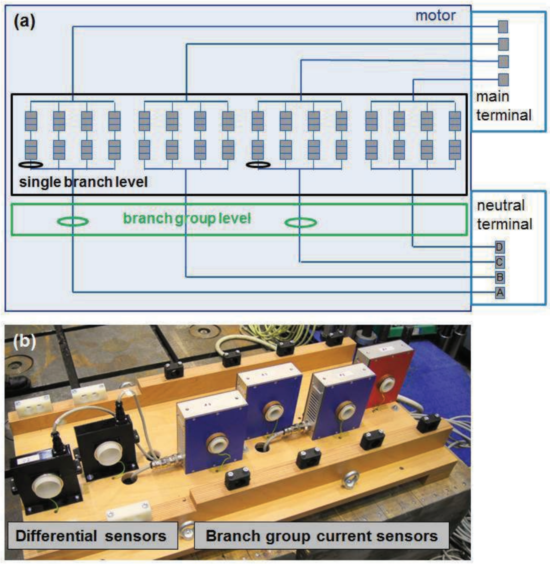

Fig. 2. (a) Schematics of the motor winding of one phase showing the 16 parallel single branches and the branch group level. (b) Measurement system comprising four branch group current sensors and two sensors for direct measurement of the circulating currents. Note the larger central opening of the differential sensors which need to enclose two cables.

As an alternative the conductors of interest can be fed through the central hole of a bulk sensor, e.g. a current transformer or closed-loop type sensor. However, a practical implementation of this measurement scheme may be more challenging as the sensor either needs to enclose two distant stator branches or the branch current conductors need to be rerouted to the sensor location.

Stator Layout and Sensor System

The conditions in the stator winding of an industry-style synchronous motor are very challenging with respect to direct sensor integration: The temperature of the windings may exceed 120°C. Furthermore, high electric and magnetic fields are usually present. Finally, the dielectric stability of the motor requires a minimum clearance between the windings. For these reasons the sensors of our measuring system had to be placed outside the motor, requiring the corresponding cables to be routed to the outside of the stator, as well. As the three phase motor under test contained 16 parallel branches per phase (Fig. 2a), measurement on the single branch level was considered to be too complex due to the high number of cables which would have to be routed. Instead, the branches were arranged in groups of four which were then routed to the outside of the stator.

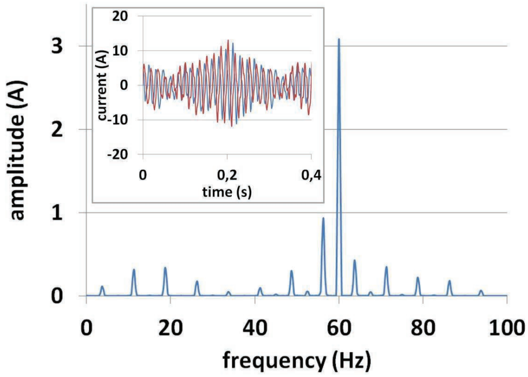

Fig. 3. Frequency spectrum of a circulating current. The component at 60 Hz (line frequency) is modulated by odd harmonics of the rotational frequency of 3.75 Hz, which typically indicates effects from a rotor asymmetry. Inset: Comparison of the respective time domain signals for the two sensor schemes discussed in Fig. 1.

For symmetry reasons all three phases were modified in the same way.

Our measurement system was placed on the neutral terminal of the stator and incorporated six sensors in total (Fig. 2b): Two differential sensors each used for the direct measurement of the circulating current between two branch groups. Additionally, four sensors were used for the measurement of individual branch group currents.

Several parameters have been considered for the selection of the sensors – most prominently the insulation requirements dictated by the operation voltage of the motor and the geometric constraints. For the branch current measurement four LEM ITZ2000-50 were selected which offer very high accuracy. For the differential circulating current measurement two LEM LA200-SD/SP3 were the preferred choice.

Measurement Results

As a typical example of the data recorded with our measurement system, circulating currents measured at 65% of the nominal motor loading show a complicated spectrum in the frequency domain (Fig. 3): Frequency components originating from a static eccentricity (e.g. the line frequency of 60 Hz) are modulated by rotation related contributions (3.75 Hz rotor frequency and harmonics). A detailed quantitative analysis and comparison with simulations is required to infer the exact origin of the components, as the large pole number leads to a rich and complex frequency spectrum.

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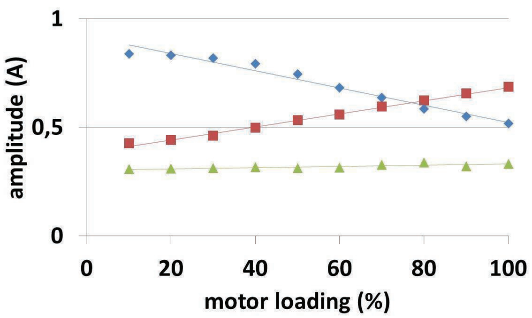

Fig. 4. Dependence of the amplitudes of selected harmonics of the rotational frequency f_R on the motor loading: $1xf_R$ (blue diamonds), $5xf_R$ (red squares), and $7xf_R$ (green triangles). The data has been fitted linearly.

The data measured according to the two different sensing schemes that were discussed above show very similar features as can be seen in the time domain data presented in the inset of Figure 3. Note however, that the signals are phase-shifted as the sensors were placed in different phases of the motor.

For deriving meaningful indicators for specific fault types it is important to know the dependency of the amplitude of certain frequency components on the load condition of the motor. To characterize this effect the load current of the motor was varied between 100 A and the nominal motor current of 1000 A in steps of 100 A. A quite different behavior of selected harmonics of the rotational frequency has been observed (Fig. 4). Frequency components suitable as failure indicators are preferably characterized by a very low dependence on the motor loading.

Conclusion and Outlook

A measurement system for circulating stator currents has been designed and was successfully tested on an industry-style motor. A complicated and rich frequency spectrum has been observed in the circulating stator currents which will require further analysis.

The measurement system was placed outside of the motor allowing for greater flexibility and enabling the acquisition of a large number of circulating currents. For a practical application as a permanent monitoring system a single differential current sensor placed inside the terminal box of the motor could be used. This would only require minimal modification to our measurement setup. However, the necessary modification of the stator windings clearly limits this approach to new machines.

To equip the installed base with a monitoring system, current sensors would need to be placed into the stator winding of the motors. Such a retrofit solution remains challenging as the sensors must withstand quite harsh conditions with respect to temperature as well as electric and magnetic field.

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