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The reflection of evolving bearing faults in the stator current's extended park vector approach for induction machines

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ABSTRACT

Stator current analysis has the potential of becoming the most cost-effective condition monitoring technology regarding electric rotating machinery. Since both electrical and mechanical faults are detected by inexpensive and robust current-sensors, measuring current is advantageous on other techniques such as vibration, acoustic or temperature analysis. However, this technology is struggling to breach into the market of condition monitoring as the electrical interpretation of mechanical machine-problems is highly complicated. Recently, the authors built a test-rig which facilitates the emulation of several representative mechanical faults on an 11 kW induction machine with high accuracy and reproducibility. Operating this test-rig, the stator current of the induction machine under test can be analyzed while mechanical faults are emulated. Furthermore, while emulating, the fault-severity can be manipulated adaptively under controllable environmental conditions. This creates the opportunity of examining the relation between the magnitude of the well-known current fault components and the corresponding fault-severity. This paper presents the emulation of evolving bearing faults and their reflection in the Extended Park Vector Approach for the 11 kW induction machine under test. The results confirm the strong relation between the bearing faults and the stator current fault components in both identification and fault-severity. Conclusively, stator current analysis increases reliability in the application as a complete, robust, on-line condition monitoring technology.

1. Introduction

Condition Monitoring (CM), a key-tool in performing prognostic and/or predictive maintenance for rotating equipment. By applying these kind of maintenance strategies, the machines' problems are meant to be detected before an unexpected failure occurs, resulting in significant economic savings [1–5]. Considering head-to-tail production processes, applying CM on several rotating equipments can really make the difference in the company's costs of maintenance. Regarding electric machines, several CM-technologies can be applied depending on the application, criticality and economic profitability. The most straight-forward and cheapest way of performing condition monitoring is measuring the overall temperature.

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Based on the criticality of the monitored machine, this low-cost, non-specific and rough condition-estimation can be the best economic solution (e.g. an induction machine driving a ventilation-unit). The most applied, thorough and nowadays reliable CM-technology is undoubtedly vibration analysis. By measuring the vibrations on the operating machine, the healthy condition can be analyzed on component-level with high accuracy and reliability. Nevertheless, some core-properties of measuring vibrations are quite obstructive in the applicability e.g. price, sensitivity to interference, fault propagation, acceleration interpretation…[6] When considering monitoring the electrical machine only (motor or generator modus), a worthy alternative is stator current analysis. Moreover, due to the cheaper, robuster, and easier measurement-methodology, stator current analysis gains interest for electric machinery implemented in various applications [7–9]. Additionally, both electrical and mechanical problems that can evolve into unexpected failures can be detected e.g. stator winding shortcuts, mechanical bearing pitting, electro-pitting, broken rotor bars and misalignment. Unfortunately, one disadvantage is obstructing the real success of stator current analysis as a full CM-technology. Once a mechanical fault is detected in the stator current, it is proven to be far too complex to estimate the exact fault-severity out of the current's faulty magnitudes, [4,6,10]. Reasonably, the propagation-path of the mechanical fault to the stator current is susceptible to all kinds of influences e.g. torque, rotational speed, power quality, physical properties, temperature…Nevertheless, when this transition of the mechanical fault to its corresponding reflection in the current is elucidated sufficiently in terms of severity, stator current analysis can be assumed to be a competitive CM-technology for monitoring electric rotating machinery.

Many authors invested a lot of time and energy in finding relevant methods on artificially implementing mechanical faults in electric rotating machinery [11–15]. This not only within the scope of stator current analysis, but as well on validating other CM-technologies. Although most methods are successful in many perspectives, they generally lack the flexibility of controlling the fault-severity and obtaining a fully reproducible emulation method. To cope with this, previous work of the authors presents the construction and dimensioning of a novel mechanical fault emulator. This test-rig contains an 11 kW Induction Machine (IM) of which the mechanical drive-end-side bearing is replaced by an Active Magnetic Bearing (AMB). By accurately controlling the AMB, the rotor can be dynamically moved with respect to the stator (within the physical boundaries of the air-gap). Because most mechanical problems e.g. misalignment, mechanical unbalance or bearing faults can be defined as a specific and unique rotor/stator-movement, they can be induced into the IM by controlling the set-points for the AMB. Two main challenges are related with this approach. The first challenge is building an AMB which can take over the key-functionalities of the original bearing and additionally induce some high-dynamic rotor-movements. These requirements demand the AMB to be balanced in terms of strength and flexibility. For the test-rig to be effective, the control-system of the AMB has to be fed with the fault-related rotor-movements. Consequently, the second challenge is stated: finding the relation between evolving mechanical faults and their corresponding rotor-movement under different environmental influences such as torque, speed, physical dimensions and power-quality-related aspects. These two challenges are discussed thoroughly in previously published material, [16–18]. Nevertheless, a brief overview is handled in Sections 2 and 3 respectively. In this paper, experiments are conducted to obtain the relation between changing/evolving bearing faults and their reflection in the stator current. The method of analyzing the three-phased stator currents is presented in Section 4. By applying a demodulation technique in the shape of the Extended Park Vector Approach (EPVA), the spectral analysis of the current is shown to be similar to the vibration analysis in terms of fault-signatures. The emulation of inner-race, outer-race and bearing cage faults with their corresponding signatures in the stator current will be described, performed and discussed in Section 5. The conclusion of this paper can be found in Section 6.

2. Fault-induced rotor-movements

When most common mechanical faults in IMs are evaluated, it can be concluded that almost every fault induces a specific movement of the rotor with respect to the stator. Consequently, the fault has an impact on the magnetic behavior of the IM. The change in air-gap implies a change of reluctance and flux-linkage, detectable in the stator current [4,6]. Considering misalignment and mechanical unbalance, a respectively static and dynamic rotor-eccentricity is observed. The emulation and evaluation of these defects on the previously described mechanical fault-emulator is thoroughly presented in [16–18]. However, 40–95% of unexpected failures of electric rotating machines are related to bearings (depending on the operating voltage and power-size, [19,4]). Consequently, for a CM-technology to be effective, the detection and interpretation of bearing faults is obligatory. Considering bearing-problems, more specific single point bearing race pitting, the relation between the fault and the rotor-movement is far more advanced. Although emulating the exact dynamic behavior of a bearing fault is complicated, the corresponding rotor movement and signature in the current can be approximated. The movements are analytically obtained by defining the crossing of the bearing pit and one of the bearing-balls as a periodic impact of force between the rotor and the stator. That pulse-train of forces can mathematically be imposed on a simplified Two-Degree-Of-Freedom (2DOF) bearing-model, resulting in an approximate movement between the rotor and the stator when single point bearing-pitting occurs. The axial rotor-movement is neglected in this paper, as it does not affect the change in reluctance-path significantly. The 2DOF system (or stator/rotor-relation at the bearing's position) is completely described by a mass m_r, radial stiffness k_r and radial damping c_r, combined in the set of force-equations, [16,20]:

$$\begin{cases} h_y(t) = m_r \cdot \ddot{y}(t) + c_r \cdot \dot{y}(t) + k_r \cdot y(t) \\ h_x(t) = m_r \cdot \ddot{x}(t) + c_r \cdot \dot{x}(t) + k_r \cdot x(t) \end{cases} \tag{1}$$