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Detection and modelling of incipient failures in internal combustion engine driven generators using Electrical Signature Analysis

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ABSTRACT

Condition-based maintenance of electric generators have been gaining increasing importance due to the electricity demand and the criticality that this equipment represents to electrical power systems. In this context, this paper proposes a methodology and a system for detection and modeling of incipient failures in the components of internal combustion engine-driven generators based on Electrical Signature Analysis (ESA). The proposed methodology enables the detection of incipient faults both in the prime mover and in the coupled synchronous generator, only relying on measurements of the generator stator voltages and currents. The proposed ESA failure patterns are based on defined frequencies and the structural features of the machine, so they can be reproduced in a wide range of engine-generators sets. The main advantages of the proposed system are its low intrusiveness, feasible installation and cost efficiency. A scale model laboratory has been designed to simulate faults in a small diesel generator and apply the ESA methodology to detect these faults and obtain the failure patterns. Experimental results are presented to prove the effectiveness of the proposed methodology. The main results include the findings that exciter generator unbalance induces electrical unbalance components, exciter diode short circuit induces even harmonics, intake valve failure and piston ring failure induce multiples of rotation frequency components, and mechanical misalignment of the engine generator set induces multiples of half order speed frequency components on ESA. Moreover, the proposed prototype is installed at two large in-service internal combustion engine-driven generators and examples of signal analysis are provided.

1. Introduction

Internal combustion engine-driven generators are common in fossil-fuel power stations for power generation and in industries and commercial buildings as supplementary electricity supply. The presence of an abnormal event in such a machine can influence its operation, efficiency and can cause even power interruption [1]. It is known that the current global scenario is related to an ever-increasing electric power demand, because of industrialization, general facilities, society habits, including, for instance, the increasing modern agriculture and irrigation systems, which also leads to more energy consumption [2–5]. Thus, an unforeseen power interruption can be disastrous, causing losses to electric power companies, industries and to society as a whole.

Careful evaluation of the operation condition of electric generators can lead to a substantial increase of their reliability and to an effective program of asset management. Prognostics and health monitoring of these equipment are no longer a supplementary accessory to the system, but a necessary element to ensure reliability and productivity in an optimized, effective and cost-efficient way [6].

In this context, it is known that condition monitoring and novel maintenance techniques applied to electric generators can increase the reliability of the power generation process as a whole. Thus, several works in this field have been proposed in the literature, including early fault diagnosis [7–10].

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Condition monitoring of electrical machines can be defined as the continuous process for assessing the health of the equipment under supervision during its life cycle. This process brings significant benefits to power generation companies and their customers, including avoidance of potentially unsafe conditions, minimization of damage to components, timely performance of maintenance actions, more efficiency in the electricity generation, reduction of penalties and losses by non-scheduled stops, and the creation of historical data of failures [11,12].

Combined with condition monitoring systems, the condition-based maintenance aims to develop a process for the diagnosis of equipment under supervision indicating incipient failures based on the variables acquired by the mentioned associated systems. Thus, the indication for a maintenance intervention occurs only when the operational state of the equipment presents an important deterioration condition. This indication can inform even the deterioration level of the equipment and provide a forecast of how much time it can still work before a general breakdown occurs [13,14].

Among the condition-based maintenance techniques for electrical machines, Electrical Signature Analysis (ESA) has been gaining attention in the last years. This technique uses the electrical machine as a transducer and consists in the analysis of the machine voltages and currents in the frequency domain. ESA became widespread in the predictive maintenance of induction motors. In this case, the focus is on Motor Current Signature Analysis (MCSA), which has been proposed in several related works and successfully applied in practice [13–17]. The application of ESA has been extended to predictive maintenance of synchronous generators. In this case, the Current Signature Analysis (CSA) is useful to detect mechanical problems in the generator and the rotating assembly. To detect electrical problems, it is also important to apply the Voltage Signature Analysis (VSA) and Extended Park's Vector Approach (EPVA) techniques [14,18–20].

One of the advantages of ESA-based techniques is that it is a low-intrusion method, as it only requires access to the machine electrical quantities. Thus, focus is given to methods relying only on the stator electrical quantities because they are usually easily accessible in the generation unit panels at power stations. Some works are based on field currents or search coils, however, it can be difficult to access the field winding on in-service generators at power stations to take measurements. Besides, the use of search coils is somehow intrusive. Based on the aforementioned topics, several works have been proposed to detect faults in electrical machines by applying ESA-based techniques [7,11,19–24].

In the case of fossil-fuel power stations, in particular that driven by internal combustion engines, the presence of a condition-based maintenance technique that correlates the electrical quantities of the generators and the thermomechanical data of the engines is not usual. The most common systems available in the market are based on Vibration Analysis and are not specific to remote acquisition and automatic analysis of data in a flexible way. Thus, this correlation can be obtained by using ESA. This approach has potential to detect automatically electrical and thermomechanical faults and allows the creation of a database to establish possible prognostics for the machine.

Considering the described scenario, this paper proposes an innovative system for condition-based maintenance of internal combustion engine-driven generators based on ESA. The novelty consists of analyzing only the stator voltages and currents of the coupled synchronous generator to detect possible faults in the coupled generator and the internal combustion engine. The advantages of the proposed methodology are easy access to the electric signals of the generator (low intrusiveness); potential to perform the diagnostics of the internal combustion engine and the generator by using a single technique; evaluation of the impact of the motor condition to the generator output; and correlation of the ESA diagnostics with other techniques such as Vibration Analysis.

The proposed software performs data acquisition, sampling, windowing, and spectral estimation by using Fast Fourier Transform (FFT). The software implements parameters estimation (supply frequency, rotational frequency) and a process of search and identification of frequency components related to faults. Then, with the help of lists of severity and history of failures, the software assesses the severity and the system provides the diagnosis for the user by presenting notifications with traffic lights and alerts. The process of signal acquisition and evaluation occurs periodically, so the trend curves of the failure patterns are continuously analyzed.

Thus, the main contributions of this paper are (1) proposition of a practicable methodology for ESA-based maintenance of internal combustion engine driven generators capable to detect faults in both the machines, only relying on stator electrical quantities, and being low intrusive and cost-effective; (2) a summary of obtained ESA failure patterns based only on defined frequencies and machine structural features, which can be reproduced for a wide range of engine-generator sets with synchronous generators; (3) description of a custom-made scale model laboratory designed for simulating faults in a small engine-generator set to validate the proposed methodology without the need for an intervention in a real power station. The main innovation of this work is the application of ESA to the generator output signals to detect faults in the coupled internal combustion engine, as this has not been found in previous works. The proposed ESA based methodology only requires the use of voltage and current transducers and it is low intrusive, whereas the common methods for condition monitoring in power plants as Vibration Analysis requires several transducers placed in special places and are somewhat intrusive. Finally, the proposed system is installed in a real Brazilian power station to perform the condition-based maintenance of two in-service 28-MVA generation units.

This paper is divided as described as follows. In Section 2, it is described the Electrical Signature Analysis technique applied for synchronous generators. In Section 3, the proposed methodology is presented, including the system and the ESA failure patterns. The development of the scale model laboratory is presented in Section 4. In Section 5, it is presented the planning of the tests, including the statistical analysis and the methodology of experiments. In Section 6, the experimental results are presented, highlighting the verification of the ESA failure patterns. Section 7 presents the application of the proposed methodology applied on a real power station.

2. Analysis for synchronous generators

The principle of ESA-based techniques is to perform the analysis of the voltage and current signals of the equipment under supervision in the frequency domain. The ESA presupposition is that the electrical signature of a "healthy" machine is different from the electrical signature of a faulty machine and each type of failure excites some particular frequency components. Thus, it is possible to detect the presence of an incipient failure and, if positive, the exact part of the machine where the failure is developing. These assumptions enable the determination of a set of ESA failure patterns based only on definite frequencies and machine structural features (e.g., number of poles, number of stator slots), which can list each type of failure with determinate frequency components in a generalized way [14].

The main advantages of ESA-based techniques for predictive maintenance of electrical machines are that they are low intrusive, as they only rely on electrical quantities; they can provide a diagnosis of incipient failures, so the user can program the maintenance intervention; and they can be implemented in an economically feasible way, as they mainly depend on voltage and current trans-