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Fault prediction of power electronics modules and systems under complex working conditions

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ABSTRACT

Power electronics modules such as inverters and rectifiers are crucial in industry and they are indispensable in various power conversion systems. There have been many studies on the fault diagnosis of power converters or power modules in the system but recently more attention has been paid on predicting failures. Most conventional techniques often rely on accurate physical models or high frequently sampled electric signals in simulation or experiment environments. In practice, however, the life and the degradation of power electrics devices are highly influenced by loads and operation regimes. The analysis needs considering various identical or similar devices in a networked power grid as well. Thus, it is not trivial to achieve the predictive analysis in such complex working conditions. This paper presents a systematic approach investigating the fault prediction of power converters in power conversion systems. Two data-driven methods with novel techniques, which take into account working condition variances and the data imbalance, have been developed and applied to an industry use case where only high level system heartbeat signals are available. These methods are validated to effectively predict the power converter failures.

1. Introduction

Power electronics technology has played an indispensable role in the power industry and its applications have been widely used on manipulating the electric energy for power conversion purposes. The power electronics converters, such as rectifiers and inverters, have gained acceptance as core components in battery charging systems [1], uninterruptable power supplies, wind generators [2], etc. Recently, besides the topology design and the control development of these power conversion systems, the health conditions of the power electronics converters have obtained increasing attractions, since the degradation or the malfunction of these critical components might result in catastrophic failures. On the other hand, conventional proactive maintenance and operation strategy would influence the efficiency and the availability of the equipment. Therefore, it is crucial to continuously monitor the performance of these converters, assess the health states, diagnose the failures or even detect the precursors before failures happen. Therefore, condition monitoring and advanced data analytics can help enhance the operation efficiency and prevent the unexpected downtime. Also, the power conversion system's usage and maintenance can be well organized.

Extensive studies have been dedicated towards the fault diagnosis of power electronics converters in decades. Among all types of converters the inverter failures have attracted the most attention. An et al. [3] proposed an open-switch fault detection method for the voltage-source inverter based on the switching function model. The voltage related fault signature was investigated by comparing the voltage-time sequence under healthy and faulty conditions. Choi et al. [4] presented another open-switch fault detection method for the inverter based on the phase current. The three-phase currents were transformed to two-dimensional signals and then the patterns of these signals on a two-dimensional plane including the radius and the angle were calculated to detect the fault [5]. Besides the inverter, researchers are also interested in other converters. For rectifier fault diagnosis, most studies have focused on both short-circuit and open-circuit failures. Compared with the short-circuit fault which will bring immediate system shutdown, open-circuit fault induced system might not lead to downtime but degrade its performance and generate disturbances in AC-DC conversion. Ku et al. [6] presented an open-switch fault detection method and a tolerant control approach for a multi-level

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rectifier. A vector trajectory which combined the phase angle of the grid and the DC-link voltage oscillation was obtained. Research on fault detection of the DC-DC converter has been done as well. Wu, Wang and Sun [7] tracked and predicted the degradation of the DC-DC converter under different working regimes.

Giving insight into converters, plenty of research has been concentrated on Insulated Gate Bipolar Transistors (IGBTs). Conventional techniques mainly focused on detecting any type of malfunctioning of an IGBT. IGBTs' degradation phenomenon has been proved and modeled by Ginart et al. [8] in the application of power drive. Failure modes such as transistor aging, hot-carrier injection, time-dependent breakdown, and thermocycling were investigated by measuring voltage, capacitance, current and time through the system. Tian et al. [9] looked at other IGBT faults such as the solder failure and the bond wire wear-out by performing accelerated aging tests and measuring junction temperature variations. Sutrisno [10] provided a study on building a fault detection model for IGBT using k-nearest neighbor classification algorithm. The targeted failure mode was thermos-mechanical fatigue and the signals collected included voltage, current, and temperature. Lu and Sharma [11] provided a relatively comprehensive study for the fault detection approaches for IGBT modules. Failure modes of an IGBT could be roughly categorized into two classes: open-circuit fault and short-circuit fault. For open-circuit faults, there are more than twenty methods available, and the favorable signals to be collected include inverter pole voltages, motor three-phase voltages, power supply three-phase voltages, and motor stator three-phase voltages. For short-circuit faults, methods mainly detect the differences in gate currents. The approaches surveyed are mainly signal processing-based approaches.

The aforementioned approaches, which could successfully detect and isolate different failures in power electronics converters, however, failed to address the analysis in practice. Signals utilized in most research require high sampling rates, which are difficult to be achieved practically due to the data storage and the transmission. Also, instead of the fault diagnosis for a specific converter component, the prognosis for the whole power conversion equipment is raising more attentions due to the purpose of predictive maintenance and optimal decision making [12]. Successfully predicting the pending failure can leave a sufficient time window for the maintenance and logistics. Further, limited literature considered the context of the power converters in detecting and diagnosing the fault. From a practical point of view, there are multiple challenges that need to be addressed in order to develop a satisfied fault prediction system for power convertors: 1) power conversion systems work in different operation modes e.g. bypass or double conversion [13] and these operation modes switch between each other dynamically according to the grid control; and 2) Unit-by-unit variations, which are affected by unit's age, model, configuration, ambient environment, load and maintenance history, cause highly variable patterns in the data. Therefore, it is not trivial to achieve the fault prediction for power conversion systems in such complex working conditions.

This paper proposes a systematic data-driven methodology for monitoring a fleet of power electronics equipment with considerations of complex operating regimes and various power generation and storage capacities. Input and output electric signals from the equipment were utilized and statistical features were extracted. An anomaly detection method and an ensemble classification technique were proposed to deal with the fault prediction. The approaches were evaluated through an industry use case. The rest of the paper is arranged as following: Section 2 describes the analysis procedure of the proposed techniques. Section 3 goes through an implementation of the approaches on an industry use case and discusses the evaluation results. A summary can be found in the final section.

2. Proposed approaches

2.1. Methodology overview

Since each equipment experiences various working and environment stresses, it is difficult to build an accurate physical model illustrating their characteristics. Therefore, a data-driven method, which employs the measured data and derives the health model without considering the system-specific knowledge, is developed. The proposed approach is outlined in Fig. 1. The input and output electric signals from the power conversion system in the database are partitioned into training data and testing data. Training data are used to understand the hidden patterns and build the health model, while the model would be evaluated and verified by the testing data. Concerning the training data, firstly, the preprocessing activities including data segmentation are applied. Useful features, which are related to the health condition of the equipment, are then extracted and a more relevant feature subset is selected for the purpose of lower dimension and less redundancy. Features under healthy conditions or that with both healthy data and converter faults are trained to construct health models. Thereafter, in the testing phase, the same types of features from the testing data are extracted for fault prediction. Each sample would be classified into either a healthy or a warning class, which indicates pending converter failures in the power conversion equipment, by the model.

2.2. Preprocessing and feature extraction

In preprocessing, besides the data cleaning, the continuous measured data from the equipment need to be segmented. After preprocessing, instead of directly utilizing the raw signals, a set of features, which abstract the behaviors of the raw data, are extracted. In this study, the features include several statistical representations, namely, mean, mode, standard deviation, range, root mean square (RMS), and crest factor. The mathematical expression of these features are:

$$Mean = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

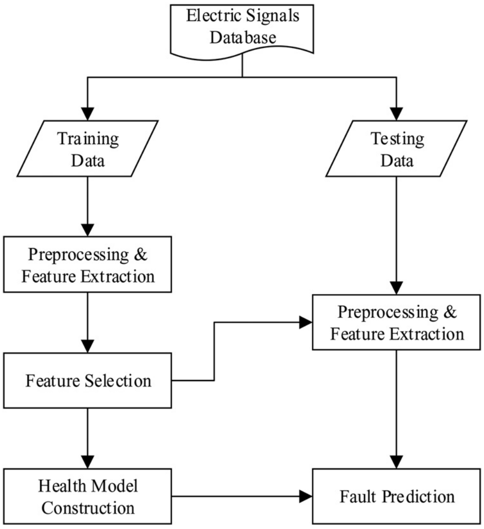

Fig. 1. Overview of the prognostics methodology.