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Fault diagnostics in smart micro-grids: A survey

James Hare, Xiaofang Shi [1], Shalabh Gupta *, Ali Bazzi

Department of Electrical and Computer Engineering, University of Connecticut, Storrs, CT 06269, USA

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ABSTRACT

Due to rising awareness on environmental protection and for maintenance of clean habitable communities, current and next generation micro-grids are desired to have significant penetration of renewable and clean energy sources. However, a critical issue is the growth of faults in various components of micro-grids, which comprise the underlying energy generation and distribution infrastructure. Moreover, faults can manifest through different failure modes in the same component. If timely diagnostics and maintenance actions are not undertaken, then these faults can cause instabilities, inefficient power generation, and other losses. Therefore, it is important not only to understand the various failure modes, and their root causes and effects, but also to develop real-time automated diagnostics tools that can capture the early signatures of fault evolution for mitigating actions.

In this respect, this paper presents a review of different failure modes occurring in various micro-grid components including both clean and conventional energy generation systems. Subsequently, the paper also provides a review on the state-of-the-art of various fault diagnosis approaches available in technical literature. Since multiple approaches can be implemented utilizing the model-based or data-driven methods given the system monitoring and communication infrastructures, the paper has presented the material in a systematic manner for easy understanding. The information presented in this paper will benefit not only the diagnostic engineers but also the control engineers who aim to develop control methodologies for fault-tolerance, mitigation, and equipment life extension based on the tools of early diagnostics.

Contents

* Corresponding author.
E-mail addresses: shixiaofang1991@hotmail.com (X. Shi), shalabh.gupta@engr.uconn.edu (S. Gupta).
[1] Current address: China Telecommunications Corporation, China.

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1. Introduction

With rapid growth of sensing, control and communication technologies in the last few decades, the power systems community has witnessed the emergence of *smart micro-grids* [1,2] as a viable solution to respond to the emergency situations of the main grid. A smart micro-grid [3,4] is a self-contained distributed power system that allows for high system-level energy sustainability, reliability, availability, and load support. Typically, the energy infrastructure of a micro-grid can have clean energy penetration even up to the consumer level to maintain sustainable performance. Under critical circumstances or emergency situations when the main grid is unable to meet the demand due to catastrophic failures or instabilities, a micro-grid can utilize clean as well as conventional systems for continual and reliable power generation. During the regular operation period, the micro-grids enable load sharing with the main grid for efficient performance.

In general, the energy infrastructure of a micro-grid can vary depending on the geographical conditions, availability of the type of generation systems, and socio-economics such as acceptability, availability, and accessibility. For example, micro-grids can be developed with no renewable energy resources in regions where renewable energy cannot be harvested, while the micro-grids in regions with abundance of sun light can be primarily built upon the Solar Photovoltaic renewable energy. However, due to rising awareness on environmental protection and for maintenance of clean habitable communities, current and next generation micro-grids are desired to have significant penetration of renewable and clean energy sources.

Faults and failures can occur in the main grid or the micro-grid without early warnings due to a variety of possible causes including but not limited to equipment failures, falling of trees on electrical lines, lightning strikes, animal/tree contacts, and malicious attacks [5]. When a fault occurs in a certain region of a traditional power system, some other regions of the grid may become overloaded or isolated through tipped switchgear due to load redistribution [6,7]. This continuous load redistribution often turns into a cascading phenomenon that is propagated throughout the power system that in turn can cause a catastrophic failure leading to large power disruptions and huge social and economic impacts on society [8,9]. For example, this phenomenon occurred in August 2003 when significant portions of Northeastern US and Ontario, Canada, experienced a cascading failure leading to large power blackout, thus lending ~50 million people without power and causing an estimated loss of ~$4 to $10 billion [10].

To circumvent this phenomenon, smart micro-grids are typically designed to disconnect energy supply from the main grid and shift into a self-contained island mode to mitigate the effects of cascading failures, while maintaining power using clean and/or conventional technologies and by storing it using energy storage devices. But even in the island mode, a micro-grid is itself subject to faults. Since micro-grids are being implemented and installed world-wide [1], a thorough study is necessary to understand the failure modes of the various components of the clean and conventional energy generation infrastructure of the micro-grids and the causes and effects of these failures. It is also useful to review the technical literature for the state-of-the-art methods used for diagnosis of these faults.

Technical literature reports several fault diagnosis methods that consist of primarily model-based and data-driven methods. Model-based methods rely on experimentally verified models of the physical system, which can accurately represent the nominal operating condition and also the effects of failure modes. In the case when real data is not available, these models could be utilized to generate time-series data for the healthy system and under faulty scenarios, wherein fault diagnosis algorithms and probabilistic tests could be developed to diagnose the system's health. On the other hand, purely data-driven methods rely on the real data measured from the physical system, which can be used to train fault diagnosis algorithms as needed.

This paper provides a review of the current methods of fault diagnosis in micro-grids with significant clean energy penetration. This review extends the authors' prior work [11] from a basic overview of faults in the micro-grid components to include: methods used to recognize any significant changes in the main grid performance, a discussion of the micro-grids' electrical infrastructure, detailed description of component failure modes with a focus on clean and conventional systems, construction of a Failure modes, Causes and Effects Table, and systematic representation of various diagnostic methods to identify faults based on the monitoring techniques and information available to the user. Several papers in literature have discussed the futuristic aspects, challenges, control aspects, and distributed generation systems in smart micro-grids [4], [12–18], however they lack a detailed discussion of the clean/conventional energy sources' failure modes and the state-of-the-art diagnostic methods. This paper could also provide useful information to control engineers who aim to develop intelligent reconfiguration control schemes for fault mitigation and equipment life extension via utilizing the tools of early diagnostics to enhance the reliability, resiliency and availability of next generation micro-grids.

The main contributions of this paper are as follows:

- Description of the micro-grid infrastructure including various monitoring devices and system configurations,
- Construction of a Failure modes, Causes, and Effects Table that provides the readers an easy access in understanding the various categories of faults in micro-grid components,
- A systematic representation of the diagnostics approaches based on the information available to the reader, and
- A review of state-of-the-art methods of fault diagnosis for various components of a micro-grid.

This paper is organized in the following structure. Section 2 describes a smart micro-grid, its electrical energy infrastructure, current monitoring methods, and configuration modes of operation. Section 3 discusses the faults within the various components of a micro-grid while Section 4 presents a study of the state-of-the-art diagnosis methods. Section 5 summarizes the paper via discussing the possibilities of future work needed to improve the existing diagnostic methods of micro-grids.

2. Micro-grid energy infrastructure

2.1. System description

Fig. 1 shows an essential feature of smart micro-grids, which is the integration of sensing, control and communication technologies with the distributed power generation system to form an efficient and reliable micro power system capable of delivering power even