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Operational analysis of hybrid solar/wind microgrids using measured data

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ABSTRACT

Microgrids offer a pathway for electricity access to communities located far from the existing grid. Although the simulated operation of microgrids is well-reported in the literature, there is a dearth of analyses based on post-installation high-resolution measured data. This article examines the operation of hybrid solar/wind microgrids using measured data from a 5 kW system in Muhuru Bay, Kenya. The system was outfitted with data acquisition and broadcast equipment that samples battery voltage, current from the solar panels and wind turbines and other quantities on a minutely basis. Considering 14 months of data, this article provides statistical and time-series analyses and interpretation of hybrid solar/wind microgrid operation. The microgrid's energy supply and efficiency are analyzed and data-driven system diagnostic methods are presented. It is shown how microgrid controller set-points influence the prioritization of energy sources, favoring wind over solar energy, and that the long-term efficiency of the microgrid is 67%. Perspectives on how operational data can be used to improve utilization and prevent pre-mature failure are provided.

Introduction

The expansion of centralized grids to serve the 1.1 billion people without electricity is fraught with challenges (International Energy Agency, 2012; Nerini et al., 2014; Alliance for Rural Electrification; Mahapatra and Dasappa, 2012). Low load density and an often impoverished customer base make it difficult to economically justify the extension of distributions lines, which may cost as much as US$20,000 (Alliance for Rural Electrification) per kilometer to install. Constructing and maintaining the lines across rugged terrain coupled with a lack of supporting infrastructure such as roadways add further barriers. In many countries, communities more than 20 km from the grid are not actively considered for electrification by grid extension (Mahapatra and Dasappa, 2012; Japan International Cooperation Agency, 2006; Barfour, 2014). These communities must look to off-grid electrical systems to meet their needs.

The prospects for off-grid systems are promising due to rapidly decreasing component prices and innovative business models. Solar panel prices have plummeted from US$3.17/Wp in 2003 to US$1.15/Wp in 2012 (U.S. Energy Information Administration, 2013). LED bulbs, which are approximately five times more efficient than incandescent lights (U.S. Energy Information Administration, 2014), have also dramatically reduced in price, decreasing from US$66/bulb in 2010 to US$10/bulb in 2014 (U.S. Energy Information Administration, 2014), making the transition from kerosene lamps to electric lighting within reach.

Stand-alone electrical systems serving customers via a local distribution network – hereafter referred to as simply "microgrids" – can supply higher-tiered electricity access when compared with solar home systems or portable battery kits (Sustainable Energy for All, 2015). Research has shown that microgrids, if designed properly, are economically superior to grid extension in many scenarios (Nerini et al., 2014; Alliance for Rural Electrification; Mahapatra and Dasappa, 2012).

Microgrids exist in a variety of architectures, often integrating generation, load, energy storage and protection and control systems. Hybrid microgrids combine two or more energy sources such as photovoltaic (PV) panels, combustion generators, wind turbines and hydro turbines (Nema et al., 2009; Domenech et al., 2014). The most notable advantage of hybrid systems over single-source microgrids is increased security of supply due to the diversification of the energy sources (Nerini et al., 2014; Nema et al., 2009; Domenech et al., 2014). Hybrid solar/wind systems are increasingly being used (Domenech et al., 2014; Nema et al., 2009). They offer the additional benefits of having zero fuel costs and being emission free. However, the operation of hybrid solar/wind microgrids is a complex, as the stochastic load must be matched with the also stochastic weather-driven energy sources (Domenech et al., 2014).

Existing research on the operation and design of hybrid microgrids in general has relied on computer-aided simulation (Alliance for Rural Electrification; Leger, 2015; Ding and Buckeridge, 2000; Bae and Kwasinski, 2012; Valenciaga and Puleston, 2005; Fung et al., 2002). Several innovative control schemes have also been proposed. Use of a multiple input DC–DC converter to manage the sources and loads is used in Bae and Kwasinski (2012). A supervisory control methodology is

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developed in Valenciaga and Puleston (2005). Fuzzy control methods are proposed in Chedid et al. and Yang et al. (2014) and neural network-based control is used in Lin et al. (2011).

Although these methods are innovative, they are not yet commercialized and therefore their use to the practitioner community is limited. Microgrid implementers must use commercially available off-the-shelf products for their immediate needs, yet there is a dearth of literature that analyzes the operation of these in-the-ground systems using measured – not simulated – data. This is unfortunate because operational data can be a powerful tool in validating system performance, maximizing energy production and guarding against premature failure, which haunts many microgrid installations (Tamir et al., 2015; Louie et al., 2014).

Some, but few, analyses that use measured data are available. Data from several off-grid PV installations are considered in Díaz et al. (2011), but these data have only monthly resolution and do not include operational quantities such as voltages and currents. In Tamir et al. (2015), data are provided from post-installation assessment reports but, again, do not include operational data. Higher resolution (10-minutely) operational data are reported in Weber et al. (2014) for a hydroelectric microgrid system. However, Weber et al. (2014)focus exclusively on the load profile of a microgrid. Several researchers have called out the need and value of additional operational data in the research community (Díaz et al., 2011; Cross and Gaunt, 2003; Howells et al., 2002).

This article begins to fill the gap in the literature. Recent advances in cellular network connectivity, cloud-based solutions and measurement hardware have made it possible to obtain near-real time operational data from microgrids (SteamaCo, 2015; PowerHive, 2015; Morningstar Corporation, 2014). Rather than relying on simulation, this paper examines 14 months of data from a 5 kW hybrid solar/wind microgrid in Muhuru Bay, Kenya. The microgrid is outfitted with a data acquisition system that samples battery voltage and branch currents every minute and broadcasts them to a remote server in near-real time. Based on the measured data, this article provides statistical and time-series analyses and interpretation of hybrid solar/wind microgrid operation. The microgrid's energy supply and efficiency are analyzed and data-driven system diagnostic methods are presented.

It is shown how the analyses in this paper were used to maximize the benefit of the microgrid in Muhuru Bay and to prevent premature failure. Although the analyses focus on a specific installation, several of the results are generalizable to hybrid solar/wind microgrids and will be noted as such. For concision, hereafter “hybrid microgrid” specifically refers to solar/wind microgrids.

The remainder of this paper is arranged as follows. The Data and methodology section provides technical information about the microgrid and describes the methodology used to collect and process the data considered in this article. Microgrid control aspects are discussed in the Hybrid microgrid control section. Statistical analyses and time-series interpretation are performed in the Statistical analysis and Time-series analyses sections, respectively. The Microgrid diagnostics section describes a simple diagnostic method for assessing microgrid performance. The efficiency of the microgrid is analyzed in the Efficiency analysis section. Conclusions and future outlook are provided in the Conclusion and future outloook section.

Data and methodology

Microgrid architecture

The data examined in this article are from a hybrid microgrid in Muhuru Bay, Kenya. Muhuru Bay is situated on Lake Victoria, near the border with Tanzania. The system was installed in August 2014 and supplies electricity to the home of a school headmaster and a kiosk where community members can recharge mobile phones, rent portable battery kits and purchase refrigerated beverages and ice. Additional background information about the microgrid, including its community development goals, is found in Van Acker et al. (2014) and Louie et al. (2015).

A high-level schematic of the microgrid architecture is provided in Fig. 1. The architecture and components are typical of solar/wind hybrid microgrids. Wind turbines and PV panels supply power to the system. Two permanent magnet synchronous generator wind turbines harness the strong onshore winds from Lake Victoria. The wind turbines are each rated at 1000 W. The wind turbines output three-phase AC, which is rectified to DC before connecting to the DC bus.

There are twelve 235 W poly-crystalline photovoltaic (PV) panels for a total solar capacity of 2.82 kW. Due to spatial limitations, the PV panels are divided into two sets of six. The natural output of PV panels is DC, so no rectifier is required. Controllers manage the charging of the battery by the PV panels. The controllers play an important and often overlooked role in the operation of the system, which is discussed in detail in the Microgrid diagnostics section. Integrated into each controller is a maximum power point tracker (MPPT). MPPTs increase the power production of PV panels by decoupling their operating voltage from the voltage of the DC bus (Enslin, 1990).

The DC bus voltage is established by the series connection of eight 6 V flooded lead-acid batteries for a nominal voltage of 48 V. Each battery is rated at 400 Ah for a total capacity of 19.2 kWh. Although there are multiple batteries, hereafter they will be referred to as a single unit without loss of specificity.

Also connected to the DC bus is a diversion load controller, which is used to protect the battery from over-voltage conditions. When an over-voltage condition is sensed, a diversion load is connected to the DC bus, thereby reducing the current into the battery and thus lowering the battery's terminal voltage. The diversion load itself is a high-power resistor. It is important to note that the two PV controllers and the diversion load controller are operated autonomously—there are no communication channels between them. Rather, their coordination is achieved solely on the set-points programmed during their installation. This is the reality for many hybrid microgrid systems.

Finally, a single-phase 3000 VA inverter is used to convert DC to AC, which is output to the loads in the house and kiosk. The output voltage is nominally 230 VAC at 50 Hz.

Measurement framework

A data acquisition and broadcast system was integrated into the microgrid. The system measures: total PV current I_{PV}, total wind turbine current I_{WT}, diversion load current I_{DL}, battery terminal voltage V_B, inverter RMS current I_{AC}, inverter RMS voltage V_{AC}, and inverter power factor ψ. Inverter output frequency is also measured but it is not relevant in this article.

The battery current I_B is not directly measured, but it can be computed through the application of Kirchhoff's current law, once all the currents in the branches connected to the DC bus are known. The current into the inverter from the DC bus I_{DC} is also not measured, but it can be reasonably estimated from the measured inverter output quantities as follows. First, the AC power output of the inverter P_{AC} is computed:

$$P_{AC} = V_{AC} I_{AC} \psi. \tag{1}$$

The input power of the inverter P_{DC} is then estimated from:

$$P_{DC} = \frac{P_{AC}}{\eta(P_{AC})} \tag{2}$$

where $\eta(\cdot)$ is the efficiency of the inverter, which is dependent on the AC power output. The assumed efficiency curve of the inverter is provided