A Survey on Development of a Modelling & Simulation Method for Residential Electricity Consumption Analysis in a Community Micro-grid System

Ms. Shikha Rajput[1] Mr. Pradeep Patel[2]
[1]Scholar [2]Assistant Professor
[1]Department of Power System [2]Department of Electrical Engineering
[1,2]Bagula Mukhi College of Technology, Bhopal (M.P.), India

Abstract— There is an increasing number of micro-grid applications for power system networks at different voltage levels. Community micro-grid systems are also being encouraged in order to increase energy efficiency, reduce electricity bills, and alleviate the reliability problem with respect to power delivery for local residential users. Understanding electricity information can help in effective management and control of various energy sources operated in community micro-grid systems. This paper thus aims to develop a simulation-based electricity analysis scheme for a real community micro-grid configuration using a proposed modelling methodology, simulation mechanisms, and a power balancing control strategy under the MATLAB environment. Simulation results considering different weather conditions report the observed performance of electricity analysis. In addition, calculations of electricity bills depending on two electricity rates are discussed, representing the benefits of electricity bill reduction when electricity users accepted the power supply from community micro-grid systems.

Keywords: Micro-Grid; Community Micro-Grid; Electricity Analysis; MATLAB/Simulink

I. Introduction

Security, reliability, and economy are the main basic requirements for the operation of the electric power system. With economic growth driving a gradual increase in electricity demand, electric power systems have recently introduced advanced grid or new energy technologies to satisfy these demands. In many advanced electric grid technologies, the micro-grid (ugrid) system is one of most important applications, acting as a controllable localized electricity supplier for providing reliable energy to area demand facilities, promoting energy savings, minimizing carbon emissions, and reducing electricity bills for electricity users [1,2]. The major components of ugrid systems include distributed/renewable energy resources, different types of energy storage systems (ESSs), grid-connected and islanding operation mechanisms, and various real-time monitoring andmanagement/control methods. According to developed ugrid technologies and market segments, the types of state-of-art ugrid systems can be categorized as follows. The first category refers to the campus ugrid. The University of California, San Diego (UCSD) and Center of Illinois Institute of Technology (IIT) have developed ugrids in this category [3, 4]. Secondly, there is the military ugrid.

Sandia National Laboratories [5] have led a Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) Joint Capability Technology Demonstration (JCD) program that plans a three-phase ugrid demonstration site at military bases in Hickam, Fort Carson, and Camp H.M.

Smith, respectively. Thirdly, there are commercial and industrial (C&I) ugrids. Mesa del Sol in NewMexico has created a commercial-scale ugrid through a Sandia National Laboratories and Japan New Energy and Industrial Technology Development Organization (NEDO) collaboration to offer a clean slate for testing and demonstrating the latest ugrid technologies [6]. Fourthly, remote (off-grid) and island ugrids are shown for example by the University of Chile, which developed Chile’s first ugrid project in a remote area called Huatacondo [6]. This system uses a social supervisory control and data acquisition (Social-SCADA) approach to assist the information exchange among electric system users, and then further improve the operation and maintenance of the system. Another category is comprised of community and utility ugrids, seen in three practical applications in Taiwan:

– Xinglong Public Housing in [7] was constructed by the Taipei City Government using various energy management system designs, electric vehicle (EV) charging station integrations, demand response control, and advanced metering and monitoring technologies to realize a smart house scenario in a community ugrid (C-ugrid).
– The Kaohsiung Xiaolin Village C-ugrid in [8] was supported by a project of the Department of Industrial Technology (DoIT) of the Ministry of Economy Affairs (MOEA), Taiwan. This village suffered from Typhoon Morakot in 2009, and most of electric grid infrastructures were severely damaged. To raise the electrification in this remote village, a C-ugrid system was thus planned and installed. It integrates C-ugrid management control, and uses large amounts of solar power and retired-battery ESSs to provide power supply to the electricity users in village. Even if the utility electric grid fails to supply power, electricity in village continues to be provided and will not be interrupted due the capability of C-ugrid system operating in islanding mode.
– The Kinmen Dongkeng C-ugrid [9], as shown in Figure 1, is an upgrade of Taiwan’s first ESS-based ugrid system at Kinmen Kinshui elementary school, extending from one ugrid user scenario in the original system to a scenario with fifteen community users. The system is also supported by the DoIT project. The operational purpose of this system is to demonstrate C-ugrid integration technology in a low-voltage distribution system.

New Mexico has created a commercial-scale *u*grid through a Sandia National Laboratories and Japan New

Energy and Industrial Technology Development Organization (NEDO) collaboration to offer a clean slate for testing and demonstrating the latest *u*grid technologies [6]. Fourthly, remote (off-grid) and island *u*grids are shown for example by the University of Chile, which developed Chile's first *u*grid project in a remote area called Huatacondo [6]. This *u*grid system uses a social supervisory control and data acquisition (Social-SCADA) approach to assist the information exchange among electric system users, and then further improve the operation and maintenance of the system.

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Fig. 1: Taiwan Kinmen Dongkeng C-ugrid System

The seventh category comprises other ugrids. As seen in [10], a 380 VDC data center as a part of direct current (DC) ugrid at Duke Energy was presented. A "solar-to-EV" project was performed at the San Diego Zoo to present how energy storage, EV charging and solar energy can be successfully integrated in autonomous electric vehicle ugrid [11]. SIEMENS now is trying to develop blockchain technology in the New York Brooklyn ugrid system [12]. Different types of ugrid systems can scale to be economically efficient, environmentally supportive, and produce varied levels of self-sustainable power. Based on these ugrid categories, research related to ugrid technology includes: (1) distributed energy resource (DER) integration technology; (2) ugrid grid-supporting capability; (3) applications of Appl. Sci. 2017, 7, 733 3 of 19 power electronics technology in the ugrid, (4) ugrid economics; (5) operation, control and protection of the ugrid; (6) ugrid communication; and (7) standardization and testing of the ugrid. Authors of [13, 14] present complete surveys on these issues; and in this paper, the residential-type C-ugrid is the major object to be investigated and discussed.

For residential electricity users, the greatest electricity consumption is generally due to use of various electric appliances, like lighting devices, air conditioners, washing machines etc., for each user.

With increasing use of electricity by these users, traditional fuel-type power generations may not able to provide sufficient electricity due to a lacking system upgrade. Furthermore, electricity users are not able to take initiative in participating in demand regulation under the single-direction power flow situation. This may force residential electricity users to face the risk of power outage. To overcome the problem, an application of the C-ugrid is thus introduced, integrated into electric grid to provide sustainable energy sources for electricity supporting services to multiple electricity customers within a community. When the C-ugrid operates into electric grid, the electricity can thus be observed from different locations in system, such as utility grid side, user side, and C-ugrid energy facility (i.e., inverter) output side. Meanwhile, if it can effectively monitor the electricity status on these sides, it will be able to help the electricity users in the C-ugrid carry out correct energy management and system control. Simulations, in addition, are often required for ugrid analysis purposes. Simulations can assist researchers to test different problem scenarios in a simulated domain in an economical way. Overall, this paper thus aims to propose a simulation-based electricity analysis method for a C-ugrid system based on the configuration in Figure 1 by integrating various modelling and simulation methodologies.

The rest of this paper is organized as follows. Section 2 describes the C-ugrid system layout and major characteristics of the study. Section 3 illustrates the proposed modelling methodology, simulation mechanism, and control strategy used in the C-ugrid system. Section 4 presents the simulation results of using different test scenarios in this work, and conclusions are given in Section 5.

II. LAYOUT AND CHARACTERISTICS OF THE STUDIED COMMUNITY MICRO GRID SYSTEM

According to the real configuration in Figure 1, the layout of the studied C-ugrid is illustrated in Figure 2. It consists of following major elements: (1) an utility grid that is in charge of grid-connected support and provides general alternating current (AC) electric power to each home user; (2) when daily solar insolation is sufficient, photovoltaic (PV) systems act as major DERs on site that supply electric power to each home user as well as ESS charging; (3) battery energy storage (BES) units are used to store remaining electricity from PV systems, and release these electricity to home users at nighttime; and (4) electric load units that are formed by an independent or an aggregated home users.

In this study, the C-ugrid is connected to a single-phase 220 V utility grid and normally operates on a grid-connected mode. In this study, the C-ugrid is connected to a single-phase 220 V utility grid and normally operates in grid-connected mode. According to the distinction between the daytime and nighttime, C-ugrid includes following operation states:

- Daytime with sufficient solar insolation—almost all the home users' electricity is supplied by PV systems in the C-ugrid, and the utility grid may only contribute a little or does not provide any electricity; it depends on the level of the load demand. Meanwhile, PV systems may also supply power to BES units for charging.
- Daytime with insufficient solar insolation—all home users' electricity is mainly supplied by the utility grid and a little from PV systems in the C-ugrid. Meanwhile, BES units may charge with limited PV power. Once the PV power is all consumed by home users, the BES unit may stop charging.
- Nighttime with sufficient BES electricity—all home users' electricity is first supplied by BESs until their power exhausted. Then, the utility grid may take the place of BESs to continue to supply power to home users.
- Nighttime without BES electricity—all home users' electricity is only supplied by the utility grid.

Later, a proposed control strategy is developed under these operational principles.

III. Proposed Modelling Methodology, Simulation Mechanism, and Control Strategy

Figure 3 shows the detailed assembly of the C-*u*grid in Figure 2 that is constructed according to the real system configuration in Figure 1. It uses a utility grid, PV systems, and BES units as major power sources to supply home users in the C-*u*grid. All electricity simulation analysis in this C-*u*grid is created in the MATLAB/Simulink environment that integrates the following modelling methodology, real-time simulation mechanism, and power balancing control strategy:

A. Modelling Methodology

MATLAB/Simulink and its SimPowerSystems (SPS) toolbox are used for modelling [15]. In this study, a detailed model is a priority for consideration since it can better present the dynamic behaviour of the circuit assembly. The PV system model in study mainly includes the circuit of the PV array and maximum power point tracking (MPPT) charger that consists of MPPT control and DC converter. For which of Equations (1) to (6) of the solar cell, is used. In Equations (1) to (6), i is the output current of the PV, iPH is the current generated by the incident light, i0 is the reverse saturation or the leakage current of diodes, q is the electron charge, v is the output voltage of.

1) Photovoltaic System Model

As shown in Figure 4, the PV system model in study mainly includes the circuit of the PV array and maximum power point tracking (MPPT) charger that consists of MPPT control and a boost DC/DC converter. For the circuit of the PV array, the single-diode equivalent current source model, which describes the v-i characteristic of Equations (1) to (6) of the solar cell, is used. In Equations Appl. Sci. 2017, 7, 733 5 of 19 (1) to (6), i is the output current of the PV, iPH is the current generated by the incident light, i0 is the reverse saturation or the leakage current of diodes, q is the electron charge, v is the output voltage of the PV, k is Boltzmann constant, T is the temperature in Kelvin, and A is the ideal factor of the PV (generally A = 1–1.5). The series resistance RS and the parallel resistance RP represent the effect on PV conversion efficiency, iSCr is the short-circuit current under the standard testing condition (STC; usually as 1000 W/m2, 25 _C with AM 1.5 G solar spectral), _ is current solar insolation, irs is reverse saturation current, Tr and T are the temperatures under STC and current, respectively, Ns and Np are series and parallel numbers of solar cells, and Ki and Kv are temperature coefficients of short-circuit current and open-circuit voltage, respectively. The required parameters in the model can be obtained from the PV module product datasheets, and the calculation procedures for RS and RP are concluded in [16] and [17]. A boost type DC/DC converter circuit is used to raise the voltage from PV system. In addition, the output performance of the PV system may often be affected by the ambient temperature and sunlight insolation. To ensure the PV output power always stays at a maximum power point, the perturbation and observation (P&O) method is implemented in the PV system [18].

Appl. Sci. 2017, 7, 733 5 of 19 the PV, k is Boltzmann constant, T is the temperature in Kelvin, and A is the ideal factor of the PV (generally A = 1–1.5). The series resistance RS and the parallel resistance RP represent the effect on PV conversion efficiency, iSCr is the short-circuit current under the standard testing condition (STC; usually as 1000 W/m2, 25 °C with AM 1.5 G solar spectral), λ is current solar insolation, irs is reverse saturation current, Tr and T are the temperatures under STC and current, respectively, Ns and Np are series and parallel numbers of solar cells, and Ki and Kv are temperature coefficients of short-circuit current and open-circuit voltage, respectively. The required parameters in the model can be obtained.

IV. Conclusions

Understanding the use of electricity from different energy sources in a C-ugid can be helpful for user demand management and system operation control. In this paper, a modelling and simulation method for a C-ugrid system is developed to study electricity analysis of residential users. To study the performance of electricity analysis, proposed schemes that integrate various modelling methodologies, implementation of real-time simulation, and power balancing control strategies to manage PV and BES facilities are carried out in a real C-ugrid configuration. Meanwhile, collected data including load electricity profile and solar insolation on a real site are used as inputs of the models. Two different weather scenarios, sunny and cloudy, are considered in simulations so as to observe the power supply capabilities among different energy sources to users in the C-ugrid. Results found that, with better solar insolation, users can obtain a power supply for a longer time from DERs in the C-ugrid, and also present a more noticeable benefit in electricity savings than that in poorer weather case. Finally, two different electricity rates are included to provide the calculation information of electricity based on the results from prior simulations. The major contribution of this paper is to present an effective simulation mechanism under the MATLAB/Simulink environment for the electricity analysis in C-ugrid systems, and it can flexibly be modified so as to comply with different simulation requirements when faced with various system topologies.

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Author Contributions

Yu-Jen Liu and Shang-I Chen conceived the system configuration, designed the control strategy, performed MATLAB modelling and simulations; Yu-Jen Liu wrote the paper; Yung-Ruei Chang and Yih-Der Lee modified the paper.

Conflicts of Interest

The authors declare no conflict of interest and the grant or founding mentioned in the Acknowledgments section had no role in the design of the study; in simulation; in the writing and the decision to publish this manuscript.

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