Applied Energy 188 (2017) 444–455

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Decentralized control of a scalable photovoltaic (PV)-battery hybrid power system

Myungchin Kim [a], Sungwoo Bae [b,*]

[a] Agency for Defense Development, Daejeon 34186, South Korea
[b] Department of Electrical Engineering, Yeungnam University, Gyeongsan-si 38541, South Korea

HIGHLIGHTS

- This paper introduces the design and control of a PV-battery hybrid power system.
- Reliable and scalable operation of hybrid power systems is achieved.
- System and power control are performed without a centralized controller.
- Reliability and scalability characteristics are studied in a quantitative manner.
- The system control performance is verified using realistic solar irradiation data.

ARTICLE INFO

Article history:
Received 9 September 2016
Received in revised form 5 December 2016
Accepted 8 December 2016

Keywords:
Hybrid power system
Power management
Standalone energy system
Solar-battery system

ABSTRACT

This paper presents the design and control of a sustainable standalone photovoltaic (PV)-battery hybrid power system (HPS). The research aims to develop an approach that contributes to increased level of reliability and scalability for an HPS. To achieve such objectives, a PV-battery HPS with a passively connected battery was studied. A quantitative hardware reliability analysis was performed to assess the effect of energy storage configuration to the overall system reliability. Instead of requiring the feedback control information of load power through a centralized supervisory controller, the power flow in the proposed HPS is managed by a decentralized control approach that takes advantage of the system architecture. Reliable system operation of an HPS is achieved through the proposed control approach by not requiring a separate supervisory controller. Furthermore, performance degradation of energy storage can be prevented by selecting the controller gains such that the charge rate does not exceed operational requirements. The performance of the proposed system architecture with the control strategy was verified by simulation results using realistic irradiance data and a battery model in which its temperature effect was considered. With an objective to support scalable operation, details on how the proposed design could be applied were also studied so that the HPS could satisfy potential system growth requirements. Such scalability was verified by simulating various cases that involve connection and disconnection of sources and loads. The quantitative reliability analysis and verification results show that the proposed architecture with power control strategy provides a straightforward approach for designing a reliable and scalable PV-Battery HPS. Although PVs and batteries have been used in this paper, the design and control approach can be applied to other hybrid power systems (HPSs) that involve the connection of various power sources.

1. Introduction

There is a dire demand to ensure reliable power supply for sustainable growth. In order to address this demand, hybrid power systems (HPSs) have been adopted for various applications. Representative examples of power sources in an HPS include photovoltaic (PV) modules [1–3], wind turbines [4–6], fuel cells [7,8], batteries [9,10], and supercapacitors [11,12]. The installation of different types of power sources can decrease the probability that a power system could be affected by unmanageable operational constraints (e.g., environmental conditions, fuel supply options). However, the sizing of power sources and design of power control algorithms should still be conducted in a comprehensive manner to ensure stable operation for various operating scenarios. Examples of objectives to be accomplished by system

* Corresponding author.
E-mail address: sbae@yu.ac.kr (S. Bae).

http://dx.doi.org/10.1016/j.apenergy.2016.12.037
0306-2619/

control approaches include maintaining the power balance and ensuring that energy storage devices are not exposed to operation conditions that lead to performance degradation. Since an HPS is operated with various power sources connected to the system, the design of system architecture with control for a HPS is not a trivial task. For example, intermittent characteristics of renewable sources and slow response speed of fuel cells [10] can cause either short-term or long-term power imbalance. Although the installation of energy storage can be the most intuitive approach to solve power imbalance issues, additional challenges caused by operational or safety requirements of different energy storage technologies can increase the level of complexity in the energy management [12,13]. Compliance with such requirements (e.g., charge rate, depth-of-discharge) has a nontrivial effect on the performance and life periods of the energy storage [13].

Architectures and control approaches for a standalone HPS have been researched on both stationary [1,4,5] and onboard power systems [8,9]. Centralized control approaches have been studied for a power system that consists of renewable sources and an energy storage device [4,14]. In such approaches, the system transits its operation mode depending on the relationship between the available power and the load power. The renewable sources (i.e., PV modules and wind turbines) change the operation mode depending on the power balance of the power system, while the energy storage is used to ensure power balance. A system control approach for an HPS with PV plants, batteries, and supercapacitors has been explored for grid-connected applications [15]. The proposed rule-based controller performs power sharing by changing the command value for each power source depending on the operation mode. Predictive control approaches have also been applied for power management in PV-Battery HPS [16] and PV-wind-diesel-battery HPS applications [17]. By utilizing the predicted information of the power system (e.g. load demand and output power), the HPS power flow is controlled to achieve satisfactory operation. The combination of a battery and a fuel cell has also been adopted to power an electric drive system [8,10]. This hybrid system is controlled such that the battery handles the power imbalance during the transient period to mitigate the slow response of the fuel cell. An approach that controls the operating pressure of the fuel cell in a fuel cell-battery power system was also proposed [7]. The control strategy enables active power sharing between the fuel cell and the battery. The study of [9] proposed using the state-of-charge (SOC) level to generate reference commands for fuel cells in a fuel cell-battery HPS. Results of proportional-integral (PI) and fuzzy logic control that use the feedback of the battery SOC information demonstrated the applicability of such a power system in hybrid vehicles. Studies on an HPS for public buses [11,18,19] and unmanned aerial vehicles [20,21] also showed that an HPS can demonstrate satisfactory performance for most practical mission profiles. Furthermore, benefits such as cost effective operation and optimal use of energy storage can be achieved through the optimized design of system architecture with control for a PV-integrated HPS [1,2,22].

This paper introduces the design and control of a PV-battery HPS that effectively addresses the challenges caused by the intermittent output of PV sources. Especially, emphasis has been placed on achieving a high level of reliability and scalability. As HPSs require connection of various power sources, the operation characteristics of the overall power system would be affected by how the system hardware is configured and how the different power sources are controlled. Accordingly, this paper proposes an approach for a system architecture with control for a PV-battery HPS operating in a standalone configuration. The battery is directly connected to the system main bus (i.e., passive configuration) in order to realize a reliable and cost effective design [7]. The possible advantages of such a design approach from a hardware reliability perspective are studied by performing a quantitative reliability analysis using failure rates of previous studies. Compared with studies on controller design [4,14], system architecture [23] and efficiency analysis [24], research on the quantitative reliability performance for an HPS with a passively connected battery seems to be rather limited. This paper proposes a system control approach for an HPS with a passive configuration that does not require a centralized supervisory control unit or algorithm. That is, the proposed system can be controlled without explicit feedback of loads and does not require a separate supervisory controller. Because the exchange of information or commands among sources, loads, and the controller is not required, the burden for implementing stable communication paths can be relieved. In addition, with an objective to achieve the maximum life cycle, the proposed control approach considers the operational requirements of the energy storage. In particular, this study focuses on the requirement that the charge rate of the battery should be limited, which is a requirement that was not thoroughly explored in the past research works on the control of an HPS with a passive configuration [21]. Such design features allow the proposed approach to be a more reliable and robust design alternative for an HPS with passive configurations. Furthermore, the proposed approach for system architecture with control enables scalable design of an HPS. The system size can be easily increased or decreased in a straightforward manner such that it does not require significant efforts for hardware and software modifications. Such scalable operation behavior is possible, as the system does not rely on a centralized supervisory controller and extensive communication between various units (i.e., sources and loads) of the HPS. As the system is easily scalable, changes in the system size can be performed with minimal effort. Necessary activities to be performed as a result of the system size changes are limited to local activities such as connection/disconnection of the hardware unit and control logic updates for the corresponding unit without modifications to the rest of the HPS. Not only the system is scalable, but also the proposed power management approach ensures that the PV modules share the load demand with respect to power ratings. While research works on the considered power architecture (i.e., HPS with a passive connection of energy storage) have been reported in various studies, most research works have only focused on how to control the power flow during different operation conditions [4,14] or have not provided sufficient discussions on the effect of future source connection to system performance [9,20,21,25].

The rest of this paper is organized as follows. Section 2 illustrates the system architecture. The characteristics of the power system architecture are also discussed. Section 3 initiates the operation of the HPS with the proposed control approach. The system design and performance of the HPS with multiple PV sources are discussed in Section 4. The simulation results of the power system and control strategy are shown in Section 5, while Section 6 provides a concluding remark on the study.

2. HPS architecture

This study investigates the improvement of the existing works on the architecture of HPSs. As shown in Fig. 1, the HPS of this paper consists of PV sources, energy storage, and loads. Although the proposed HPS control scheme can also be applied to a grid-connected configuration, the scope of this paper is limited to a standalone configuration such as a remote telecommunication power system for the simplicity of the analysis. The proposed system can also be used as a back-up power system for critical facilities such as data centers and hospitals when a power outage occurs in the utility grid. While such secure facilities could operate with the power supplied from the utility grid during normal situations,