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Prioritized rule based load management technique for residential building powered by PV/battery system

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ABSTRACT

In recent years, Solar Photovoltaic (PV) system has presented itself as one of the main solutions to the electricity poverty plaguing the majority of buildings in rural communities with solar energy potential. However, the stochasticity associated with solar PV power output owing to vagaries in weather conditions is a major challenge in the deployment of the systems. This study investigates approach for maximizing the benefits of a Stand-Alone Photovoltaic-Battery (SAPVB) system via techniques that provide for optimum energy gleaning and management. A rule-based load management scheme is developed and tested for a residential building. The approach allows load prioritizing and shifting based on certain rules. To achieve this, the residential loads are classified into Critical Loads (CLs) and Uncritical Loads (ULs). The CLs are given higher priority and therefore are allowed to operate at their scheduled time while the ULs are of less priority, hence can be shifted to a time where there is enough electric power generation from the PV arrays rather than the loads being operated at the time period set by the user. Four scenarios were created to give insight into the applicability of the proposed rule based load management scheme. The result revealed that when the load management technique is not utilized as in the case of scenario 1 (Base case), the percentage satisfaction of the critical and uncritical loads by the PV system are 49.8% and 23.7%. However with the implementation of the load management scheme in scenarios 2, 3 and 4, the percentage satisfaction of the loads (CLs, ULs) are (93.8%, 74.2%), (90.9%, 70.1%) and (87.2%, 65.4%) for scenarios 2, 3 and 4, respectively.

1. Introduction

In the wake of rising electricity demand owing to global population increase, Renewable Energy Sources (RES) present a more favorable means of electricity generation compared to their fossil fuel counterpart – whose reserves are depleting and are strong contributors to global warming. Also, the cost and technical difficulties associated with grid expansion to remote and rural areas have favored the development of localized and modular power systems based on RES [1,2]

Amongst the various RES, wind and Photovoltaic (PV) sources are gaining predominance in rural and remote area electrification across the globe [3,4]. However, electricity generation due to solar PV has been more favored for residential and domestic applications owing to several advantages viz the ubiquity of solar resource, modularity, noiseless operation, low maintenance cost and appreciable level of reliability [5,6]. These advantages of PV systems have led to a growth in their deployment all over the world. Germany ranks highest in this regard (having a total deployed PV capacity of about 38.2GW), closely followed by China and Japan having 28.2 and 23.3GW respectively [7].

Despite the aforementioned advantages that solar PV offers in terms of meeting the electricity demand of remote residential buildings, there are still some challenges associated with the usage of the PV systems. A major one is the vagaries in weather conditions: solar irradiance and temperature, which affect the power output of PV modules. Of these weather elements, solar irradiance has the most pronounced effect [8]. Therefore, continued deployment of PV systems in the region (especially in remote and off-grid areas) will require integration of techniques and schemes that provide for the maximization of these systems in the region [9]. A good number of research endeavors have been undertaken towards overcoming the challenges created by the vagaries in solar irradiance (and other weather conditions that affect the performance of PV systems) in order to provide for the maximization of the techno-economic benefits of these systems. Module performance

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prediction using deterministic models [10–12] and probabilistic approaches [13,14] have been investigated. Also, development of optimal system sizing methodologies for PV systems based on statistical methods [15–17] and artificial intelligence [18] have been studied. Other authors have investigated hybrid systems combining solar PV with other renewable energy sources as well as battery storage [19–21].

Energy management strategies for PV systems have also been reported in the literature. Some of the works on energy management for PV systems proposed Demand Side Management (DSM) strategy for obtaining reduced electricity cost (for grid-connected systems), maximization of energy production from RES, and optimum consumer comfort. Kallel et al. [3] have developed a demand side management strategy that aims at battery life extension (gained by reduced battery charge/discharge cycles), reduction in CO_2 emission as well as system component size for isolated PV-diesel-battery hybrid system. The proposed DSM acts so as to modify the load profile using time shifting of load approach and amplitude modulation technique for the load profile modification. Also, in the work of Wu et al. [22], a DSM strategy based on time-of-use (TOU) with contracted selling was evaluated for a grid-connected PV-battery system. Optimal scheduling of consumer's appliances via a dual loop control to earn cost savings and customer comfort under varying prices in the TOU program as well as consumption management allowing for selling surplus power to the grid were the main subjects of this work. Similarly, Tascikaraoglu et al. [23] investigated a DSM technique for an experimental smart home in Turkey with renewable energy sources (solar PV and wind), storage systems and connection to the utility. A multi-agent system for securing critical loads and maintaining system health and stability in a PV-based micro-grid was investigated by Pipathanasomporn et al. [24]. Similarly, Lu and Francois [25] developed a strategic framework for energy management in a micro-grid in which a PV-based active generator was developed. Groumpos and Papegeorgiou [26] have investigated an optimum load management strategy for a standalone PV-battery system. Sequel to carrying out a load classification for the system, they employed traditional optimization methods viz. the 'slack variable method' and 'penalty function method' to manipulate the controllable loads in order to obtain an optimum load curve for controllable loads, as well as reduce battery size and cycles. Also, Lalouni and Rekouia [27] have proposed an energy management strategy for a standalone PV system designed to cater for the energy needs of a small residential housing. They defined five operating modes for the system and implemented a supervisory control that determines the appropriate mode the system will take at any time in the day in order to control energy flow between the PV array, battery and the load. Wu and Xia [28] have developed an optimal switching model for grid connected PV system with storage. In their work, Time of Use (TOU) was adopted as the demand response to achieve the optimal switching model with the objective of reducing electricity cost. The control of the switch was based on system state-space equations. The performance of the developed optimal control system was thereafter compared to that of intuitive control method. It was concluded that the proposed switching model performed better compared to the intuitive control techniques.

Fuzzy logic approaches have also been proposed for energy management of loads within residential buildings installed with Solar PV based system: Fuzzy logic controller based power management for a standalone solar/wind/fuel cell fed hybrid system was proposed by Saravanan and Thangavel [29]. The authors concluded that the proposed fuzzy controller was able to perform well for all the different possible combinations of input powers from the various sources to meet the load demand. A fuzzy control strategy for battery charging or discharging used in a renewable power generation system consisting of Solar PV and Wind System was analyzed by Saranya et al. [30]. The proposed fuzzy controller was intended for improving the life cycle of the battery by managing the desired state of charge (SOC) of the battery. Simulation results revealed that the control unit has satisfied performance in a laboratory environment. A fuzzy logic controller was designed by Dey et al. [31] to extract maximum power from both solar and wind energies and then supplies the load. The surplus power is fed to the electrolyzer which generates hydrogen for the fuel cells and the batteries. The simulation results proved the efficacy of the fuzzy logic controller and establish the fact that these renewable resources can be a viable solution to distributed production of electricity for standalone applications at inaccessible remote location. While fuzzy logic controllers have been effective in in load management, they have the main disadvantage of slow response time due to the number of rules [32]. Another disadvantage of fuzzy logic is that they give the same importance to all factors that are to be combined [32]

From the aforementioned studies, it is apparent that majority of the research works on energy management strategy development for solar PV systems only propose approaches for grid-connected PV systems or PV hybrid systems employing other energy sources (renewable and non-renewable). This work investigates approaches that provides for optimum energy gleaning and management in a Stand-Alone Photovoltaic-Battery (SAPVB) system. The demand response is based on priority of loads as determined by the user. The loads are classified in order of priority as it affects the quality of life of the user (i.e. the more critical loads are given preference in the time of low PV power supply over the less critical loads). Therefore the aim of this work is to modify load profile in accordance to order of priority as determined by the user in time of low solar irradiation. In this way the power line of the less critical loads are de-energized and will only be energized only at the time when there is sufficient solar irradiation The SAPVB system being considered is that for a mid-class off-grid residential building situated on the outskirts of the cosmopolitan city of Ibadan (7.3964° N and 3.9167° E), Nigeria. Owing to variation in solar irradiance characteristics from the site, module performance may also vary likewise. Thus, for optimum energy gleaning, an optimum module selection procedure using capacity factor estimation based on probabilistic approach in [6] was employed to determine the optimum solar module. The manufacturer data sheet values as well as the current-voltage characteristics of the optimum module are depicted in Table I and Fig. 8 in the Appendix. Subsequently, the selected module was used in the proposed rule based load management scheme. The load management approaches investigated was tested via simulation in MatLab environment.

2. SAPVB system description

In this section, loads within the residential building to be met by the SAPVB installation were classified based on their priority to the quality of life of the user. The components of the standalone SAPVB system are also described.

2.1. Load classification

A listing of possible basic appliances for a typical 3-bedroom residence located in the city of Ibadan was used for this study. A load classification approach that groups the system loads into two major categories viz. critical and uncritical loads was employed. Loads demanding continuous and instantaneous power and having low degree of flexibility in the manipulation of their periods of operation were grouped into the Critical Load (CL) category. These loads have more pronounced effect on the comfort