Solar Energy 150 (2017) 177–191

Contents lists available at ScienceDirect

Solar Energy

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

Multi-agent based operational cost and inconvenience optimization of PV-based microgrid ☆

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ARTICLE INFO

Article history:
Received 24 October 2016
Received in revised form 7 March 2017
Accepted 10 April 2017

2010 MSC:
00-01
99-00

Keywords:
Solar energy
PV-based microgrid
Mutil-agent system
Energy management

ABSTRACT

The integration of solar power generation into microgrid systems has become very popular due to its positive environmental aspects and cost effectiveness. Nevertheless the existence of natural intermittency and fluctuations in PV generation incurs extra cost or service interruption in PV-based microgrids. The power generation of PV systems follows a natural schedule based on a sunny day. Similarly, the usage profiles in a microgrid are known from experience. When there is a mismatch in load or generation schedule, the system has to react to maintain a balance. In this work, both a centralized and a decentralized demand-responsive multi-agent control and management system are devised which include backup diesel generation and load curtailment. The latter affects user satisfaction. Wpose new realistic models to measure user satisfaction depending on the type of appliance curtailed. Our simulation shows that the inclusion of demand-side management lowers the cost of a mismatch even when user satisfaction is considered. Expectedly, the centralized implementation achieves a lower cost in more difficult conditions - when the peak consumption happens earlier than anticipated - but the decentralised approach provides acceptable cost levels when a centralized model cannot be implemented.

1. Introduction

Microgrids are considered as small size low-voltage power networks consisting of small loads and distributed energy resources (DER) which can autonomously coordinate local generations and demands in a dynamic manner while having the capability of operating either stand-alone or in grid-connected mode (Chowdhury and Crossley, 2009; Barnes et al., 2007).

Theoretically, microgrids have been shown to be more cost effective and even robust than the conventional centralized grids. Nevertheless, several regulatory and technical issues exist. One of the prime technical challenges in the control and management of microgrids arises from the intermittence and fluctuations caused by renewable energy resources such as photovoltaic systems, the use of which has sustainability-related benefits (Scolari et al., 2016; Mathiesen et al., 2013; Seyedmahmoudian et al., 2015; Seyedmahmoudian et al., 2016).

Improving the energy efficiency using demand-side management (DSM) has been studied recently. Thanks to the technique of load shifting, demand response (DR) can manipulate the load profiles in a fashion that reduces the total costs of generation, even with the same total energy consumption. It helps flattens the demand curve in the microgrid to shave peak demand. All existing demand response programs are extensively explained in Deng et al. (2015).

Recently, performing generation and load demand scheduling as a result of DR, has become popular (Law et al., 2012; Li et al., 2011; Jones et al., 2016). Demand response-based load scheduling technically provides a planned optimal schedule for the power allocation of the microgrid system which takes the consumers' preferences as well as the total operational costs and the power generation profiles into account.

Sustainable energy generation based on wind and PV is subject to uncertainty as is user behavior.

The features of PV-based microgrid are different from other renewable energy based self-sufficient microgrids. This is due to unpredictable fluctuations in the generation pattern of PV. For example, wind power prediction can be quite accurate for aggregated wind power, as the variations are levelled out, and the larger the area, the better the overall prediction. Unlike solar energy generation systems, other renewable energy systems such as wind,

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http://dx.doi.org/10.1016/j.solener.2017.04.019
0038-092X/

tidal, and hydro-kinetic are relatively less sensitive transient to environmental phenomena such as clouding and shading.

These fluctuations and intermittency in generation degrades the performance of microgrids, especially in island configurations. Therefore, there is a need for an intelligent control and management system which can dynamically handle unpredicted events in the generation or deviations in the load demand.

So far, all operational control and management systems proposed have focused on the generation costs and applied some optimization strategies to minimize them. The inconvenience caused by load shedding or curtailment has not been considered in earlier approaches. The satisfaction of the electricity consumers is an important socio-economic factor in a society where the consumer's cooperation in the scheduling process can be beneficial, especially in small communities.

The main goal of this research is to incorporate the inconvenience and generation costs in a single mathematical model of the mismatch and minimizing the handling cost of the mismatch by proposing a sophisticated multi-agent based algorithm. This paper proposes an intelligent demand response based multi-agent control and management system which can be applied in both centralized and decentralized microgrid architectures. The proposed technique minimizes the cost and inconvenience of mismatches occurring during 24 h of a pre-scheduled stand-alone microgrid where PV generation is the main source of power. The approach includes mathematical models of the diesel generation cost as well as the drop in user satisfaction due to possible load curtailment of flexible and controllable appliances are being proposed.

2. Related work

The existing work that addresses demand side management can be divided into two main groups. Control and management systems focus on the technical stability and generation cost minimization while aiming to balance the generation and demand by applying load curtailment, if necessary (Olivares et al., 2014) but disregard user satisfaction.

A number of studies concern themselves with the technical aspects of power quality in microgrid or generally in relation to renewable energy utilization (Du et al., 2013; Han et al., 2016; Xiang et al., 2016; Li et al., 2016). Kim et al. (2010) proposed a strategy for cooperative control and management of micro-power sources and energy storage in an islanded microgrid. The paper focuses on the quality control of the waveforms (frequency and voltage control) during the changes in renewable power generation (solar and wind). Another good example of this focus is the work presented by Singh et al. (2015) in which they considered the problem of using renewable energy (RE) and battery energy storage system (BESS) forming a microgrid.

Fewer studies within this group address the problem of demand side management.

Raziei and Mohsenian-Rad (2013) focused on the utilization of full demand response capacity of automatic lighting control systems. They investigated the aggregate utility of all occupied spots across the layout of a smart building versus the load curtailment target, by considering a realistic logarithmic-based utility function for lighting comfort.

Mohsenian-Rad and Leon-Garcia (2010) presented a real time electricity pricing model by developing an intelligent system which can respond to tariffs and optimize the residential load control in real-time based on the generation cost. The authors identified the lack of user competence regarding time-varying prices and absence of adequate building automation systems as the two major barriers of utilizing real-time pricing tariffs.

Dimeas and Hatziargyriou (2005) proposed an agent-based supervisory control strategy where consumption and production agents negotiate the price of electricity in the microgrid market enabled by links to the grid.

Lagorse et al. (2010) tackled fault tolerance and adaptability issues with agents in a centralized energy management system. Their system comprises PV panels, battery storage, supercapacitor, grid connection and active load which are all connected through a DC bus. Agents control the voltage of converters.

Another study was presented by Dou et al. (2015), who proposed a multi-agent system (MAS) based hierarchical control scheme for energy management of distributed generation system. The system comprises distributed agent-regulated energy resources (DERs) (wind turbine (WT), PV panels, Storage, microturbine (MT) and fuel cell (FC)), utility grid, and load units.

A MAS-based energy management system for a stand-alone microgrid consisting of hybrid RE and storage was proposed by Zhao et al. (2015). The energy price was established by applying a virtual bidding system (VBS) from which the operation, schedule and capacity reserve were determined. Agents control PV generation, diesel generation, battery storage, schedule, frequency and storage as well as the general operation of the system.

The second group applies DR for minimizing the total cost, peak shaving, and generating ahead optimal schedule for the whole system (Deng et al., 2015; Yingdan and Xin, 2013).

Li et al. (2011) proposed an optimal demand side management with the objective of maximizing social welfare. The authors defined social welfare as a subtraction of cost from utility. The proposed system considers one utility company communicating with the load agents in order to fix the electricity price for the next day. Each load agent schedules its appliances based on the social welfare objective and sends it to the utility agent which communicates with all the load agents. The utility agent calculates the electricity price based on the total load consumption collected and releases it to the load agents. The each agent uses gradient descent as its optimization technique during the exchanges (iterations). The load agents know that they can affect the price by avoiding the use of electricity during peak demand hours; however, there is no obligation to follow the schedules and therefore the system works based on trust.

In some scheduling techniques either consider no model for user utility in their techniques (Yue et al., 2014; Remani et al., 2015) or model the user's utility as a direct function of the amount of electricity consumption (Mohsenian-Rad et al., 2010).

None of the proposed optimization strategies for microgrid control and management can be considered as a dynamic solution for unforecast mismatches in the generation and load demand by taking the generation, storage and consumer satisfaction costs into account. In this work, we propose a demand response based algorithm for control and management of a microgrid which incorporates user satisfaction drop as a cost caused by sudden load curtailment. The proposed technique minimizes the cost and inconvenience caused by unforeseen deviations from generation forecast or demand schedule during 24 h of a pre-scheduled stand-alone microgrid with PV generation as the main source of power. The optimization model contains mathematical models for diesel generation cost in addition to user satisfaction drop due to possible load curtailment of flexible and controllable appliances.

3. Problem description

In most control and management techniques, obtaining an optimal schedule for electricity generation, storage and demand is known as the solution to an optimization problem where a cost