Sustainable Cities and Society 38 (2018) 452–465

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

A multi-agent system for optimal sizing of a cooperative self-sustainable multi-carrier microgrid

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ARTICLE INFO

Keywords:
Multi-agent system
Optimal sizing
Microgrid
Distributed energy resources
Demand-side management

ABSTRACT

In this paper, an interactive multi-agent system (MAS) is applied to the problem of optimal sizing of a cooperative self-sustainable multi-carrier microgrid that includes various privately-owned entities. The proposed microgrid includes photovoltaic (PV) arrays, batteries, an electrolyzer, a hydrogen tank, a fuel cell (FC), a reactor-reformer system, a hydrogen compressor-dispenser system, a converter, residential electrical loads, and a charging/refilling station. The proposed MAS enables information exchange required for the application of demand-side management (DSM) strategy and has five agents, namely generation agent (GA), electrical load agent (LA), charging/refilling station agent (SA), control agent (CA), and design agent (DA). The GA is responsible for managing the distributed energy resources of the microgrid. The LA aggregates the residential electrical loads. The SA is responsible for charging of plug-in hybrid electric vehicles (PHEVs) and refilling of fuel cell electric vehicles (FCEVs). The CA coordinates the interactions between the field level agents. The DA finds the optimal sizes of the system's components by minimizing the total cost of the system through particle swarm optimization (PSO) algorithm. Simulation results demonstrate that the proposed system can reduce the overall cost of the microgrid in comparison with non-interactive methods.

1. Introduction

According to the limitation of fossil fuels, climate change issues, significance of energy diversification, and potential for job creation, governments have been encouraged to increase the share of renewable energies in their energy portfolios (Chmutina, Wiersma, Goodier, & Devine-Wright, 2014). Therefore, using renewable energy technologies would be affordable in remote areas as self-sustainable hybrid energy systems due to the high costs associated with network expansion (Bernal-Agustín & Dufo-López, 2009). From the grid point of view, PV systems and electric vehicles (EVs) will bring a great impact on the grid (Van Roy et al., 2014). Photovoltaic systems are one of the important solar energy utilization technologies that must be integrated into the power grid (Maleki, Khajeh, & Rosen, 2017). Furthermore, it is possible to shift the charging load demand of the EVs to off-peak hours that helps in solving the integration problem of renewable energy sources (Brad & O'Mahony, 2017; Shakouri & Kazemi, 2017).

A microgrid is a discrete and small power grid that provides a platform for the integration of distributed energy resources and loads that can be operated in both grid-connected and islanded modes and is able to open up new opportunities for the utilization of renewable energy sources (Hassanzadehfard, Moghaddas-Tafreshi, & Hakimi, 2015; Lasseter et al., 2002).

Generally, demand curves are desired to be as flat as possible for generation cost and environmental considerations (Eichman, Mueller, Tarroja, Schell, & Samuelsen, 2013). DSM techniques aim at the reduction of the peak demand thereby flattening the load profile. On the other hand, the smart and sustainable microgrids that are based on green energy generation are getting more attention for the charging requirement of EVs and the unscheduled EVs connectivity with power system may lead to unreliable and interrupted power supply (Ahmad, Alam, & Asaad, 2017). Charging scheduling of EVs offers an opportunity for managing fluctuations in electricity generation and consumption (Galus, Fauci, & Andersson, 2010). Therefore, charging coordination of EVs and implementing the DSM strategies in the decarbonized transport sector are very important; hence several coordination scales for the integration of the EVs have been proposed in the literature (Leemput, Van Roy, Geth, Tant, & Driesen, 2011): The vehicle, building, residential distribution, and transmission grid scale. Various studies are conducted for EV fleet management in smart grids (Aghaei, Esmaeel Nezhad, Rabiee, & Rahimi, 2016; Hu, Morais, Sousa, & Lind, 2016; Sabri, Danapalasingam, & Rahmat, 2016). An optimization model for the integration of EVs is presented in (Tanguy, Dubois, Lopez, & Gagné, 2016) to maximize the overall community benefits of using the

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https://doi.org/10.1016/j.scs.2018.01.016
Received 22 September 2017; Received in revised form 11 December 2017; Accepted 10 January 2018
Available online 11 January 2018
2210-6707/

charging coordination for a fleet of EVs on the campus of Université Laval on a daily basis. The optimal locating and sizing of renewable energy sources and EV charging stations while considering the management of vehicle charging process is investigated in (Mozafar, Moradi, & Amini, 2017) and it is proved that using EVs along with renewable energy sources in the power system can reduce the cost of both the system operator and subscribers. A method of simultaneous allocation of EV parking lots and distributed renewable resources is proposed in (Amini, Moghaddam, & Karabasoglu, 2017) and it is shown that the EV parking lots and distributed renewable resources utilization should be obtained in a scheduled way. The real implementation of a fast-charging station for electric vehicles which is incorporated in a microgrid is described in (Sbordone et al., 2015) and the experimental tests have shown that the system can deliver an effective peak shaving in respect of the main grid.

Optimal sizing of the components of a microgrid is necessary as this ensures the reliable power supply while retaining the economic viability of the system. The sizing problem of the microgrid components is a complicated issue since it needs to consider both reliability and cost. In a grid-connected system, the sizing of the microgrid components is less complicated as it only considers the area and time duration to supply energy from the grid. In comparison, the self-sustainable microgrid has a more complex sizing system since it needs to work without disturbances and ensure the quality of power supply within its own boundaries. Therefore, various studies are conducted for optimal sizing of self-sustainable microgrids and different computational optimization techniques are used to realize the sustainable development of them (Bhowmik, Bhowmik, Ray, & Pandey, 2017; Calvillo, Sánchez-Miralles, & Villar, 2016; Fathima & Palanisamy, 2015; Gamarra & Guerrero, 2015; Jung & Villaran, 2017; Saboori, Hemmati, Ghiasi, & Dehghan, 2017). A single-objective optimal sizing approach for an islanded microgrid is proposed in (Bhuiyan, Yazdani, & Primak, 2015). The approach determines the optimal sizes of microgrid components such that the life-cycle cost is minimized while a low loss of power supply probability is ensured. An energy storage sizing method that considers a reliability index and a bi-level control strategy for the isolated grids, where the energy demand is completely supplied by wind power is described in (Luo, Shi, & Tu, 2014). An optimal sizing and management strategy for a stand-alone microgrid including renewable energy sources such as wind turbines and PV generators, diesel generators, and battery storage system is proposed in (Ma, Yang, Wang, Zhao, & Zheng, 2014). The optimization problem is formulated to minimize the annualized system cost through the PSO algorithm. A stochastic optimal planning model based on chance-constrained programming algorithm for islanded microgrids is proposed in (Guo, Liu, Jiao, Hong, & Wang, 2014). Based on multi-objective non-dominated sorting genetic algorithm II, optimal planning for an islanded microgrid is carried out, which has verified the model. A stand-alone wind/PV/FC generation microgrid is designed in (Baghaee, Mirsalim, Gharehpetian, & Talebi, 2016) for a 20-year period of operation using a multi-objective optimization algorithm to minimize the three objective functions, namely annualized cost of the system, loss of energy expected, and loss of load expected. A stand-alone microgrid considering electricity, cooling/heating, and hydrogen consumption is designed in (Li, Roche, Paire, & Miraoui, 2017). The authors have used a genetic algorithm to search for the optimal sizes of the microgrid components and discussed the influence of operation strategy, accuracy of load and renewable generation forecast, and degradation of the fuel cell, electrolyzer, and battery on sizing results.

Few researchers have addressed the problem of optimal sizing of the components of the microgrids considering DSM techniques in their operating strategies. The effects of implementing a demand response program on reducing the optimal size of the renewable energy resources within a microgrid, which in turn reduces its overall cost and improves its reliability are analyzed in (Hakimi & Moghaddas-Tafreshi, 2014). A methodology which incorporates both the sizes of the resources and the strategy by which they will be operated is presented in (Zhao et al., 2014) and it has been implemented on Dongfushan Island, China. The authors have used a genetic algorithm-based method to solve the optimal sizing problem such that it minimizes the life-cycle cost, maximizes the renewable energy source penetration, and minimizes the pollutant emissions. An optimal sizing methodology for finding the optimal size of a battery energy storage system in a microgrid using PSO algorithm is proposed in (Kerdphol, Qudaih, & Mitani, 2016) that incorporates a dynamic demand response program to reduce the capital, operating and maintenance costs of the battery energy storage system. The authors have claimed that their method not only reduces the overall cost but also improves the system's stability and performance during an emergency situation. A bi-objective optimization model that aims at minimization of the total investment and operation costs, as well as minimization of the loss of load expectation for optimal sizing of an energy storage system in a microgrid is proposed in (Nojavan, Majidi, & Esfetanaj, 2017). The authors have employed a demand response program which flattens load curve by shifting some percentage of the load from peak periods to off-peak periods to reduce the total cost of the microgrid. An optimal sizing strategy of power sources and energy storage system in an autonomous microgrid is proposed in (Liu, Chen, Zhuo, & Jia, 2018) that considers DSM and EV scheduling. The authors have concluded that their method results in significant saving in sizing of power sources of the microgrid. A combined microgrid sizing and energy management methodology is proposed in (Li, Roche, & Miraoui, 2017). The authors have formulated their methodology as a leader-follower problem. In the leader problem, they have focused on optimal sizing of the components of the microgrid which is solved using a genetic algorithm. In the follower problem, they have formulated the energy management issue as a unit commitment problem which is solved using a mixed integer linear problem. Based on their results, they have concluded that their proposed bi-level optimization approach for the sizing of the microgrid components reduces the overall cost of the microgrid. A multi-objective optimization method of planning and operation of a microgrid with DSM capability is presented in (Chen et al., 2018) that aims at minimizing the total annual cost as well as maximizing the customer satisfaction. By jointly optimizing the planning design and operation, the authors have demonstrated that DSM is an effective way to achieve the goal of cost reduction while not compromising customer satisfaction.

The above review of the state-of-the-art has shown that an efficient optimal sizing methodology requires an appropriate operating strategy and DSM-based energy management fits this requirement. One question that needs to be asked while optimally sizing the components of a microgrid is whether the microgrid is a single-owner microgrid or a multi-stakeholder microgrid. Current solutions to the optimal sizing of the stand-alone microgrids are inconsistent with the interactive nature of the multi-stakeholder microgrids, in which various privately-owned entities work cooperatively to provide the energy requirements of the customers. Furthermore, it is not yet known how to implement the DSM programs when multiple stakeholders are present in a microgrid while optimally sizing its components. This is an important issue for successfully managing the potential conflicts of interest that might arise between different stakeholders in a microgrid.

Multi-agent systems are inherently distributed and they can be used to model the autonomous entities in solving complicated problems. They have intrinsic advantages such as flexibility, autonomy, and scalability. Therefore using them for the power system operation within the smart grid technology would be beneficial (Dimes & Hatziargyrious, 2004; Logenthiran, Srinivasan, Khambadkone, & Aung, 2012). In this regard, various studies have applied the multi-agent systems to the microgrid control and operation (Coelho, Cohen, Coelho, Liu, & Guimarães, 2017; Howell, Rezgui, Hippolyte, Jayan, & Li, 2017; Kantamneni, Brown, Parker, & Weaver, 2015; Khan & Wang, 2017). A multi-agent supervisory control for optimal economic dispatch in DC microgrids is proposed in (Hamad & El-Saadany, 2016) that can reduce