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Balancing collective and individual interests in transactive energy management of interconnected micro-grid clusters

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The emerging technology, transactive energy network, can allow multiple interconnected micro-grids (a.k.a. micro-grid clusters) to exchange energy for greater energy efficiency. Existing research has demonstrated that the micro-grid clusters can achieve some collective interests (e.g., minimizing total energy cost). However, some micro-grids may have to make sacrifices of their individual interests (e.g., increasing cost) for collective interests of the clusters. To bridge these research gaps, we propose four different transactive energy management models for micro-grid clusters where each micro-grid is allowed to have energy transactions with others. The first model focuses on maximizing collective interests, both the collective and individual interests are considered in the second model, and the last two models aim to maximize both the collective and individual interests. The performances of the proposed models are evaluated using a cluster of sixteen micro-grids with different energy profiles. It is demonstrated that 1) all of the four models can maximize the collective interests, 2) the third model can maximize the relative individual interests where each micro-grid can achieve the same percentage of cost savings as the clusters, and 3) the fourth model can maximize the absolute individual interests where each micro-grid can achieve the same amount of cost savings.

1. Introduction

Among all the energy consumption sectors, the building sector is responsible for more than 40% of domestic primary energy consumption since 2010, which is 44% more than transportation sector and 36% more than industrial sector in the U.S. [1]. Although several efforts have been made to improve energy efficiency which include stricter energy codes, appliance standards, the overall energy efficiency of the U.S. only ranks 13th out of 16 countries with an eighth place for building sector in the International Energy Efficiency Scorecard assessed by American Council for an Energy-Efficient Economy [2]. Facing with increasing energy demands, aging and overburdened power grid infrastructure, the micro-grid technology has been developed rapidly in recent years [3,4] which can provide a good opportunity and a more desirable infrastructure to enable energy efficiency [5]. A typical micro-grid consists of distributed energy sources (such as power generators, storage system, etc.) and loads, and is able to operate in parallel with, or independently from, the main power grid [6]. Specifically, a micro-grid for buildings can utilize both distributed energy generator, such as fuel cell, CCHP (combined cooling, heating and power) system, solar PV (photovoltaic), and distributed energy storage, such as electric and thermal storage, to satisfy electric, cooling and heating demand. In the past few decades, extensive research has been conducted to develop energy efficient operation strategies for micro-grid which can be classified to two categories: 1) individual micro-grid operation and 2) multiple interconnected micro-girds (a.k.a. micro-grid clusters) operation.

The research on individual micro-grid operation focuses on developing optimal operation strategies for the energy systems (e.g., distributed generator, distributed energy storage) in the micro-grid. In general, two different models, such as deterministic and stochastic models, are developed to study the micro-grid operation where the random issues in the micro-grid are ignored in the deterministic models. A simulation optimization approach is proposed in Ref. [7] to operate heating, ventilating and air conditioning system which can achieve 7% energy saving comparing with existing rule-based operational strategies. A near-optimal control strategy is developed for cooling storage system with real-time utility rate [8] which can make the annual cost within 2% of the

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gap with optimal control. A simulation optimization program is developed in Ref. [9] to optimally operate and control a hybrid micro-grid including a battery, wind generator and PV module. An economic power dispatch decision model for micro-grid with the objective of minimizing fuel cost during grid-connected operation while ensuring stable operation after islanding [10] shows that a micro-grid can be economically operated during grid-connected mode and operated in a near-optimal way during islanded mode with cost increasing up to 0.7%. An integrated micro-grid with CCHP and energy storage is demonstrated to be very effective to reduce energy cost [11]. A multi-objective mixed integer nonlinear programming model is proposed in Ref. [12] to find optimal operation decisions for a building level micro-grid and enable further analysis of micro-grid under various load conditions. A novel double-layer coordinated control approach for both grid-connected and stand-alone micro-grid energy management is proposed in Ref. [13] where the simulation results for a typical micro-grid show good convergence in either mode. It is demonstrated that the energy supply and demand in a residential micro-grid can be balanced using a three-step methodology in advance planning and real-time control of domestic appliances [14].

The stochastic operation decision models are developed to mitigate the impacts of uncertainties to micro-grid operations. The energy scheduling of micro-grid is formulated as MIP (mixed integer programming) problem in Ref. [5] under the practical background of a low energy building where uncertainties in demand and renewable energy sources are considered. A multi-objective optimization model with probability constraints is developed to optimize CCHP operation strategy for different climate conditions [15]. Stochastic energy scheduling model is formulated and solved using decomposition scheme to address operational challenges associated with intermittent renewable energy resources in micro-grid [16]. A dynamic decision model which aims to integrate hybrid renewable energy sources for green buildings [17] has shown that all the energy demands can be satisfied with the presence of a storage system. A two-stage stochastic programming formulation is proposed in Ref. [18] to study a micro-grid where responsive loads (residential, commercial and industrial ones) and distributed generation units are applied to provide reserve for compensating forecast errors of renewable energy, and reserve capacity allocation and optimal battery scheduling are considered. In terms of secure power supply with integration of massive number of small-scale wind turbines and EVs (electric vehicles) [19], three coordinated wind-EV energy dispatching algorithms are explored for stochastic energy dispatching in micro-grid. Results demonstrate that interruptible dispatching method and variable-rate dispatching method can achieve better matching between power generation and demands as well as EV user satisfaction. An online optimal energy/power control method based on a MIP model using rolling horizon window is presented [20] for the operation of energy storage in grid-connected micro-grids, and a robust counterpart model is proposed to handle uncertainty in system states prediction with a very modest increase in computational time.

Other than the main stream of research that focuses on seeking optimal operation strategies within single micro-grid, another noteworthy emerging effort is to form transaction energy network to allow multiple micro-grids sharing and exchanging energy for better energy performance. It is demonstrated that the building level micro-grid clusters are more energy efficient than a single building level micro-grid [21], and the first attempt to make operation decisions for micro-grid clusters is a memetic algorithm based framework [21]. The proposed framework is capable of deriving Pareto solutions for micro-grid clusters in a decentralized manner. The high computational cost of memetic algorithm based decision framework prohibits its use for short time scale (e.g., hourly) operation decisions of micro-grid clusters. To this end, a particle swarm optimization based decision framework is proposed in Ref. [22] to enable short time scale operation decisions which can significantly improve energy efficiency and achieve more energy cost savings. Other than cost savings, the micro-grid clusters can also improve environmental sustainability, reduce primary energy consumption and enhance micro-grid's resilience capability to power disruptions and extreme events [23]. The micro-grid clusters can be self-organized to guarantee energy reliability of critical loads and overall energy efficiency after extreme event which isolates the micro-grid clusters from the main power grid [24]. For example, each micro-grid can decide whether to connect to the clusters depending on available generation resources, and negotiate with other micro-grids in the clusters for optimal energy exchange. A hierarchical bi-level decision framework based on the system of systems concept is proposed [25] to enable coordination between micro-grid clusters and distribution grid, and optimally operate micro-grid clusters. A self-organizing map based clustering algorithm is proposed in Ref. [26] to group different micro-grids into different clusters based on their energy profiles, and a distributed decision model is proposed to study homogeneous and heterogeneous micro-grid clusters.

Although the micro-grid clusters can significantly reduce energy cost, improve environmental sustainability and resilience capability to extreme events, most of the existing operation decision models for micro-grid clusters focus on maximizing the collective interests, such as minimizing energy cost for the micro-grid clusters. The individual interests of some micro-grids cannot be guaranteed. For example, some micro-grids may be more cost expensive if they join the clusters to exchange and trade energy with other micro-grids. The transformation of micro-grid clusters concept will be prohibited without a model to balance the collective and individual interests.

To bridge these research gaps, we propose four operation decision models to study the transactive energy management for the micro-grid clusters and balance the collective and individual interests. In this research, the collective interest for the micro-grid clusters is to minimize the total energy cost for the clusters, and the individual interest is defined to maximize the relative percentage of cost savings or the absolute amount of cost savings for each micro-grid. In our proposed models, each micro-grid has its own CCHP, PV, electric and thermal storage to satisfy its electric and thermal loads, and can freely share electric and thermal energy with other micro-grids. The first model is developed to maximize the collective interests (e.g., minimize total energy cost) only, and the second model is to maximize the collective interests and keep the individual interests (e.g., the percentage of cost savings for each micro-grid) at satisfactory levels. The third and fourth models aim to maximize both the collective and individual interests. The individual interest in the third model is defined to maximize the relative percentage of cost savings for each micro-grid. We model the price for the local transactive energy in the fourth model, and define the individual interest as maximizing the absolute amount of cost savings for each micro-grid. According to the study on a cluster of sixteen micro-grids, we can conclude that: 1) all of the four models can maximize the collective interests, 2) all the micro-grids can have the same percentage of cost savings as the micro-grid clusters using the third model, and 3) the absolute amount of cost savings can be evenly shared by each micro-grid and the local energy transaction price can be determined using the fourth model. It can also be concluded from this research that: 1) the first model is appropriate when all the micro-grids are operated by one manager, 2) the second model is suitable when the micro-grids have heterogeneous individual interests, 3) the third and fourth