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A multi-agent based energy management solution for integrated buildings and microgrid system

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HIGHLIGHTS

- A practical framework for coordinated DR and DG management is proposed.
- An ontology-driven multi-agent based energy management system is presented.
- Efficient strategies for real-time management of batteries are proposed.
- Cost-effective and comfort-aware energy management solutions are presented.

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ABSTRACT

In this paper, an ontology-driven multi-agent based energy management system (EMS) is proposed for monitoring and optimal control of an integrated homes/buildings and microgrid system with various renewable energy resources (RESs) and controllable loads. Different agents ranging from simple-reflex to complex learning agents are designed and implemented to cooperate with each other to reach an optimal operating strategy for the mentioned integrated energy system (IES) while meeting the system's objectives and related constraints. The optimization process for the EMS is defined as a coordinated distributed generation (DG) and demand response (DR) management problem within the studied environment and is solved by the proposed agent-based approach utilizing cooperation and communication among decision agents. To verify the effectiveness and applicability of the proposed multi-agent based EMS, several case studies are carried out and corresponding results are presented.

1. Introduction

The steady increase in the price of conventional energy sources and concerns about pollutants emissions along with the needs for improved operational efficiency, introduces smart renewable microgrids as promising solutions. These systems which are capable of working in standalone or grid-tied modes [1], accept different kinds of energy sources as input and meet the end-user's demand with minimal human intervention. However, to provide energy of the required quality in a reliable, clean and economical way, different distributed energy resources (DERs) within the microgrid must be operated in a coordinated manner [2,3]. On the other hand, given the persistent trend in modernization and urbanization, growth in residential energy demand is expected to stay high, which in turn necessitates demand response (DR) and demand side management (DSM) policies for optimal operation of the system [4–6].

In order to draw the best performance of such integrated energy systems (IESs), smart system optimizers (SSOs) have to be designed and implemented. The SSOs must take both real-time information and forecast data into account and optimally schedule operating set-points based on the system's objectives and constraints. So far, several contributions on optimal dispatch of IESs and related control strategies have been made. The authors in [7,8] provided details about the control tasks and strategies involved in the IES management with a review on the main types of controls proposed in the literature. The most straightforward solution to fulfill the mentioned control objective is deemed to be a centralized SSO implementation. For example, Olivares et al. [9] proposed a centralized energy management system (EMS) to economically dispatch an isolated microgrid in presence of both schedulable and non-schedulable distributed generators (DGs). Although, the proposed EMS strategy decomposed the main

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problem into unit commitment (UC) and optimal power flow (OPF) sub-problems to avoid nonlinearity in formulation, it introduced high level of required coordination among DERs, which made this strategy inefficient for real-time implementation. Yuan et al. [10] developed a penny-wise energy scheduling approach for residential microgrids with high penetration of renewable energy sources (RESs) and applied a two-stage optimization process to determine optimal utilization of DERs. However, that paper neglected the interaction among controllable energy sources at demand and supply sides for a multiple-period model. Research works in [11–14] mainly focused on DER management from a canalized perspective (i.e., system operator's viewpoint) and introduced minimum cost of operation for the examined IES as an objective. Other research works (e.g., [15–17]) made efforts on developing integrated DSM strategies for optimal energy management within residential microgrids considering user's preferences as objectives. However, references [12–17] did not develop optimum operating strategies under sudden changes of working conditions due to the presence of uncertain parameters in the environment. Moreover, the proposed DR and DG management strategies in [14–17] were not optimized together, although these aspects are interdependent and the execution of one can greatly affect the other. In the above-mentioned works, there are also some technical issues which need to be addressed suitably. For example in the proposed centralized schemes (e.g., [9–12,14,16]), a central entity derives all the elements within the network, observes the environment, performs the calculations and sends back the control signals to the actuators, thus the whole system suffers from a single point of failure. Moreover, it can be easily observed that the computational complexity increases exponentially as the system size increases and considerable communication expenditure is accordingly needed to fulfill the requirements. From the information security viewpoint, the proposed centralized database might be also exposed to unauthorized access, disclosure, disruption or modification.

An alternative approach for SSO implementation within a typical IES is a decentralized scheme that utilizes distributed controllers for energy management and optimization [18,19]. Most of the research works in this area have focused on hierarchical control architecture using multi-agent systems (MASs) [20–33]. In [21] a MAS-based optimal energy management solution was proposed for smart grids where interactive operation of generation units and DR was formulated as an optimization problem. In that work, although each system participant was assigned with an energy management agent, the proposed problem was solved by the system operator in a centralized market-oriented scheme. Similarly, authors in [22,23] elaborated on multi-level management and control schemes for microgrid systems taking into account the interaction among agents at different levels, however they failed to satisfy system-level objectives such as social-welfares or economic operation of DG units. In [24], a multi-agent framework was developed to automate building energy optimization and to support distributed decision making with limited engineering effort. However, some issues related to a robust MAS design and hardware implementations were not considered. Also, the proposed multi-agent control algorithm had some limitations on dealing with some types of equipment such as heating, ventilation and air conditioning (HVAC) systems that have multiple operating modes and their optimal control becomes a mixed-integer programming problem that cannot be solved with the proposed algorithm. The work in [25] presented an efficient consumption scheduling framework for schedule consumption plan in small residential areas. By using a decentralized game theoretic method and decomposing the centralized optimization, authors demonstrated that the computational complexity can be distributed among the individual home demand management units. However, they failed to show the effectiveness and applicability of the proposed model on larger test systems where the scheduling optimization might not converge to an equilibrium. Similarly, authors in [26] introduced a decentralized agent-based approach for optimal residential demand planning. Although they tackled the problem of scalability and complexity of computation for larger scale systems (which was a remaining issue in previous works) through a tree topology for the proposed MAS, they failed to construct a fault tolerant topology with self-organization mechanisms. Other distributed agent-based solutions to energy management were also presented for grid-tied microgrids in [27,28], islanded microgrids in [29,30], and multiple microgrids in [31]. Motivated by the idea of decentralized control, authors of [32,33] also presented MAS-based management and control strategies for integrated energy systems. Although the reviewed decentralized schemes demonstrated more robust operation (e.g., [20,21,26,30–33]), less complexity (e.g., [20,24,25,27]) and fewer communication requirements ([22–24,29]) compared to the centralized ones, they can still suffer from degradation of performance on large networks due to the increased communication frequency and network induced delays (e.g., [25,28–30]), increased use of database space (e.g., [21,23,25,32]) and complex use and administration (e.g., [24,26–29,33]).

This paper proposes a practical framework for coordinated DR and DG management in an integrated building and microgrid system (here named as a residential microgrid) using MAS concept within a local area network. In this framework, the SSO is not conceived as a single system to operate and control but as a cluster of self-contained entities that nevertheless collaborate effectively. This scheme also offers a distributed monitoring and control architecture for the emerging smart microgrids, where communication among different nodes with different tasks is necessary for optimal management of energy generation and consumption in real-time. Moreover, within the proposed framework, similar types of energy-related production and consumption units are grouped and controlled by local SSOs, while global coordination among different groups is achieved through a centralized coordinator. It is noteworthy that the term "energy management" in this work refers to the process of energy conservation and optimal use of energy sources within a residential microgrid which is the key to meet the system's objectives. The main contributions of this paper can be summarized as follows:

- A practical framework is proposed for optimal demand response and dispersed generation management in a typical IES where multiple objectives and different hard/soft constraints need to be satisfied simultaneously,
- A fault-tolerant ontology-driven agent-based energy management solution is proposed for real-time monitoring and optimal control using standard configurations and communication languages for agents,
- An efficient strategy for real-time management of energy storage devices is proposed to optimally compensate any power mismatch in the IES and to mitigate the effects of uncertain parameters on system operation.

The remainder of this paper is structured as follows: Section 2 presents the system configuration and specifications as well as the proposed MAS architecture. Section 3 introduces the EMS design and mathematical modeling. Evaluation of the functionality and applicability of the proposed MAS framework for efficient energy management in a residential microgrid is performed in Section 4. Finally, Section 5 concludes this paper.