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Occupancy-based demand response and thermal comfort optimization in microgrids with renewable energy sources and energy storage

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HIGHLIGHTS

- Demand response management is considered under thermal comfort requirements.
- Exploiting occupancy and thermal information for HVAC regulation.
- A two-level supervisory control strategy for scalabity to large microgrids is implemented.
- Creation of a robust solution in front of changing occupancy patterns and weather conditions.

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ABSTRACT

Integration of renewable energy sources in microgrids can be achieved via demand response programs, which change the electric usage in response to changes in the availability and price of electricity over time. This paper presents a novel control algorithm for joint demand response management and thermal comfort optimization in microgrids equipped with renewable energy sources and energy storage units. The proposed work aims at covering two main gaps in current state-of-the-art demand response programs. The first gap is integrating the objective of matching energy generation and consumption with the occupant behavior and with the objective of guaranteeing thermal comfort of the occupants. The second gap is developing a scalable and robust demand response program. Large-scale nature of the optimization problem and robustness are achieved via a two-level supervisory closed-loop feedback strategy: at the lower level, each building of the microgrid employs a local closed-loop feedback controller that processes only local measurements; at the upper level, a centralized unit supervises and updates the local controllers with the aim of minimizing the aggregate energy cost and thermal discomfort of the microgrid. The effectiveness of the proposed method is validated in a microgrid composed of three buildings, a photovoltaic array, a wind turbine, and an energy storage unit. Comparisons with alternative demand response strategies reveal that the proposed strategy efficiently integrates the renewable sources; energy costs are reduced and at the same time thermal comfort of the occupants is guaranteed. Furthermore, robustness is proved via consistent improvements achieved under heterogeneous conditions (different occupancy schedules and different weather conditions).

1. Introduction

Increasing energy demand and stricter environmental regulations are promoting the transition from traditional electric grids with centralized power plants to smart electrical microgrids where the existing power grid is enhanced by distributed, small-scale, renewable-energy generation systems such as photovoltaic panels, wind turbines, and energy storage units [1]. Microgrids can be seen as miniature versions of the larger utility grid except that, when necessary, they can disconnect from the main grid and can continue to operate in 'islanded mode' [2]. Despite their potential advantages, a main challenge needs to be overcome: the widespread availability of renewable sources inserts uncertainty into the grid, due to their stochastic output profile which strongly depends on local weather conditions. Lack of monitoring and control of these energy sources might contribute to the instability of the electric grid: this is

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especially true in grids where fluctuating power may be delivered due to the high participation of renewable energy sources [3]. Energy storage systems play a central role in the integration of renewable energy sources in microgrids, as they provide the necessary flexibility to compensate unbalances between the power supply and the demand. The interesting experimental work in [4] assesses how the timing of an electric outage affects the islanding lifetime of a microgrid, with and without energy storage. For these reasons, one of the pivotal questions in the widespread diffusion of microgrids is to deploy a control system which will take the appropriate decisions for the energy distribution and consumption, in order to minimize the energy consumption and cost: this task goes under the name of 'demand response' [5].

Demand response requires the development of control mechanisms that can autonomously facilitate changes in electric usage by end-use customers in response to changes in the price of electricity over time, or in response to the availability of renewable energy [6]. The implementation of these mechanisms require the presence of loads whose operation can be regulated, i.e. controllable loads. Many studies show that HVAC operations account for nearly 50% of the energy consumed by a building [7]: furthermore, good HVAC control is one of the most cost-effective option to implement demand response and improve the energy efficiency of microgrids. For example, it has been shown that raising summer set point temperature might have good and universal energy saving potential as it can be applied to both new and existing buildings [8]. However, HVAC operation cannot aim exclusively at energy savings without taking into account the effect of changing the control strategy on indoor comfort: the ASHRAE55 and EN15251 standards [9,10] pose strict constraints on the end-user (building occupant) thermal comfort, with bounds and constraints that should not be violated except for small intervals during the building operation. The literature on demand response with thermal comfort optimization is vast: without aiming at being comprehensive, in the following we give a brief overview on the topic.

1.1. State-of-the-art in demand response with thermal comfort

As a large portion of building energy consumption is used for thermal comfort, optimization of energy and comfort calls for delicate trade-offs, which have been studied by many researchers: the simulation tool of [11] can predict the effect of changing the control strategy on indoor comfort and energy consumption. The authors of [12] develop control strategies for intelligent glazed facades and investigate the influence of different control strategies on energy and comfort performance in office buildings. Particle swarm optimization has been applied in [13] to optimize the set points based on the comfort zone. In [14] the operation of variable air volume air conditioning is optimized with respect to comfort and indoor air quality. The influence on energy consumption of thermostat operation and thermal comfort requirements is the object of the study in [15]. All this approaches show, sometimes also via real-life experiments, that relevant energy savings can be achieved without compromising thermal comfort.

The use of occupancy information plays a major role in decreasing energy costs and improving thermal comfort: the potential of using occupancy information in model predictive-based building climate control is investigated in [16]. The approach of [17] aligns the distribution of residents' thermostat preferences with the indoor temperature to maximize thermal comfort while reducing energy savings. Using the expected room occupancy schedule, the evolutionary algorithm of [18] produces optimized ventilation strategies with reduced CO_2 concentration and energy costs. The goal of [19] is to use occupancy information to reduce energy use while maintaining thermal comfort and indoor air quality.

Multi-objective optimization of energy consumption and thermal comfort is well established at the building level: at the microgrid level, however, most state-of-the-art microgrid energy management systems aiming at improving resilience and enabling islanded mode, consider only matching energy generation and consumption [20–22]: other multi-objective optimization examples include optimize the power dispatch of the microgrid according to economy and reliability interests of the power grid [23], decreasing the expenses for power purchase or increasing revenues from power selling [24]. Operational results of real-life microgrids have also been provided [25–27]. However, in the aforementioned works and experimental evaluations, thermal comfort of the occupants is often neglected, or, when considered, it is oversimplified. A typical oversimplification involves considering bounds on the dry-bulb temperature [28]: this is a poor comfort-maintaining criterion, since neglecting humidity and radiant temperatures can lead to insufficient estimation of actual thermal comfort. The Fanger index [9] or adaptive thermal comfort models [29] can yield a realistic estimate of thermal comfort. Summarizing, to the best of the authors' knowledge the following gaps can be identified in the state of the art of demand response in microgrids:

- (G1) *Thermal and occupancy information in microgrids:* a part from some recent contributions by the authors [30], there is no demand response program at the microgrid level that can exploit occupancy information with the objective of guaranteeing thermal comfort of the occupants. Note that the work in [30] do not consider the presence of multiple renewable energy sources (possibly with different prices) and of energy storage.
- (G2) *Scalability to large microgrids:* there is no demand response program that can be scalable to large-scale microgrids: also the recent work in [19] considers a centralized architecture stemming information from the entire microgrid: this might be impractical in microgrids of large dimension.
- (G3) *Robustness of solution:* there is no real study on robustness of demand response programs in front of changing conditions, including changing occupancy patterns and changing weather conditions: due to the computational complexity of predictive control strategies, most of the cited state-of-the-art demand response are tested over relatively short horizons, and it is not clear whether they can achieve consistent improvements over longer ones. Furthermore, their predictive control nature requires the optimization task to be continuously active: it is not clear whether it is possible to develop a demand response program that, after optimization over a short horizon, can be used over longer horizons with consistent improvements.

With this work we try to cover the identified gaps in demand response and thermal comfort optimization in microgrids, as explained hereafter.

1.2. Main contributions of the work

This paper presents a novel control algorithm for joint demand response management and thermal comfort optimization in microgrids equipped with renewable energy sources and energy storage. With respect to the three identified gaps, the work provides the following contributions:

- (C1) *Thermal and occupancy information in microgrids:* demand response is achieved by controlling the HVAC system of each building: the final objective is not only the reduction of the energy absorbed from the traditional electrical grid, but also guaranteeing acceptable thermal comfort conditions. The Fanger index is used as a realistic measure for thermal