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Energy management and load shaping for commercial microgrids coupled with flexible building environment control

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ABSTRACT

This paper explores the load shaping ability of microgrid power systems coupled with flexible operation of HVAC systems for commercial customers. In the proposed framework, this integrated system is treated as a dispatchable power source/sink in order to mitigate the uncertainty and variability imposed on the external utility company. The load shaping required is enabled by the natural flexibility in space heating and cooling, along with dispatchable microgrid resources such as batteries. A hierarchical control approach is formulated for the scheduling and supervisory control of the flexible loads and dispatchable energy units within the microgrid. Stochastic optimization is used for scheduling at the slow time scale to ensure forecasting errors in renewable availability and energy demands can be rejected. Deterministic optimization is used at the fast time scale to update dispatch decisions in response to realized conditions. A case study demonstrates that this proposed control approach is able to substantially reduce the uncertainty and variability in energy exchange with the external utility across a variety of commercial load types and in different seasons.

1. Introduction

Policymakers at various levels of government around the world have established ambitious goals for renewable power integration. Large renewable power installations like wind farms can be regulated similar to traditional power plants, e.g. through direct participation in the wholesale power market. However, the penetration of distributed, customer-sited renewables (e.g. rooftop photovoltaics) is expected to become more significant over the coming decades. This paradigm shift brings a host of new technical challenges which must be addressed. In particular, the uncertainty and variability introduced by unregulated distributed renewables must be mitigated by other controllable resources [1,2].

At the utility-scale, large power plants can be operated to complement the renewable availability as in [3,4]. However, this approach would increase the actuation effort (i.e. ramping up and down of power plants), decrease average capacity factor of existing plants, and necessitate a transition to a more flexible but less efficient generation fleet [2,1,5]. Consequently, the cost of traditional, utility-scale generation would increase, and the fossil fuel efficiency would decrease. These problems are particularly exacerbated for customer-sited renewables since their output is aggregated with customer loads and not directly measurable for utilities or network operators. This challenge of integrating a deep penetration of customer-sited renewable production without imposing an undue burden on the existing infrastructure/utility companies is the topic of this paper.

As an alternative, collocated dispatchable generation and/or storage units can be used to mitigate the inherent intermittency and variability of distributed renewable assets. These customer-sited, integrated energy systems are called microgrids. For systems incorporating just renewable power generation and battery storage, simple rule-based energy management schemes can be designed to balance generation and consumption or to flatten the residual load profile[1] as in [6,7]. However, rule-based management schemes are difficult to effectively design for complex systems which have multiple sources of generation and storage. In contrast, model-based optimal control, e.g. Model Predictive Control (MPC), is well-suited to coordinating the various dispatchable generation and storage units in these complex microgrids. In addition, these model-based methods allow for proactive control given forecasts for future weather or energy prices. Previous authors have considered optimization-based control for microgrids in response

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[1] Residual refers to the net difference between local power consumption and local power generation (including any charging/discharging of storage. This residual load must be satisfied by importing/exporting power to the external macrogrid.

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to dynamic electricity pricing, e.g. Real-Time Pricing schemes, which provide some implicit incentive to flatten the residual load profile or complement macrogrid generation [8–10]. Such frameworks are also readily extended to incorporating uncertainty, as demonstrated by previous authors employing stochastic and robust optimization formulations for microgrid control [11–15]. However, the emphasis is still placed on minimizing microgrid operating cost and not on responsible interaction with the macrogrid.

Similar approaches have been applied to integrating renewables with flexible demands. For example, [16] considers control of a renewable power system coupled with a flexible reverse osmosis water desalination system. They show that the MPC controller is able to effectively manage water production and respond to time-varying electricity prices. Similarly, industrial-scale flexible loads, such as data centers, can be coordinated to help absorb stranded wind power and enable system-wide flexibility using two-stage stochastic programming [17]. Heating, ventilation, and air conditioning (HVAC) loads are a particularly attractive class of demands as they are inherently flexible and ubiquitously present. Other authors have used the inherent flexibility of HVAC loads to improve energy efficiency or take advantage of dynamic electricity pricing, e.g. [18–27]. In [18], a detailed first-principles building model is developed which accounts for both temperature and humidity/moisture effects. The authors show that utilizing such models in an MPC framework can reduce energy consumption for building cooling by up to 42% with negligible impact on the comfort of occupants. Hierarchical control approaches are also often used for this energy management problem to address the natural stiffness that arises (i.e. due to the difference in time scales between process equipment and air-temperature dynamics versus the temperature dynamics of the solid building elements). In [28,24], a slow time scale problem is solved considering the evolution of the building temperature and storage dynamics to maximize user comfort, and a fast time scale problem is solved to supply the heat/cooling requested by the slow time scale while minimizing cost. A similar hierarchical approach is employed in [20,21], with the difference that an economic objective is considered at both time scales and the comfort considerations are incorporated as constraints. In addition, [20,21] employ a continuous reformulation of the problem to improve computational tractability of the problem. In particular, they assume that discrete changes in operating mode will occur in a known pattern, and focus on deciding the timing of these events (i.e. a continuous variable). [26] shows that the rolling horizon implementation of MPC ensures that the HVAC system is able to achieve satisfactory closed-loop control despite forecasting error, and that planning horizons of 1-2 days are typically sufficient to ensure good economic performance. The optimal sizing of thermal storage capacity for such systems is also an important consideration. An optimal sizing method for thermal storage is presented in [29] to take advantage of peak load reduction (i.e. in response to more expensive midday electricity prices) and to participate in demand response programs which require an on-call reduction in electricity usage. They show that a well-designed system can achieve payback periods in the range of 3-9 years depending on how much occupants are willing to give up on the maximum indoor temperature. Finally, [25] presents a generic and flexible formation for this building energy management problem that is easily extended for application to cogeneration or multi-generation use cases.

Previous authors have explored the coupling of microgrid systems with flexible HVAC loads. In [30], a system is considered which consists of flexible HVAC loads, battery storage, and other deferrable loads. The authors show that the incorporation of these multiple sources of flexibility results in improved economic performance for the microgrid without a significant impact on end-user satisfaction. However, in these past works, end-users are still free to update their planned residual load at any time (e.g. in response to realized forecasting errors) without regard to the impact on the overall grid. In such cases, the actual response of customers to different price signals can be difficult to predict [31].

In our work, we incorporate flexible HVAC loads into the control problem to complement traditional electrical storage devices (i.e. batteries) to mitigate the impact of stochasticity in non-HVAC demands and renewable generation. Specifically, we have proposed a novel market structure for microgrids that seeks to explicitly limit their disruptive impact (i.e. by explicitly limiting uncertainty and variability in energy exchange), rather than relying solely on the implicit incentive from dynamic pricing to encourage good behavior [32]. In this case, the available reserve capacity in local generation, battery storage, and flexible demands are critical to ensuring forecasting errors can be effectively rejected. In our past work, we formulated a scheduling and supervisory control layer for the optimal operation of a microgrid in the context of this proposed market structure, and showed that this load shaping regulation can be achieved at little opportunity cost by leveraging flexible cooling loads in addition to battery storage [33]. However, the case study was limited to an office building located in Minneapolis, MN over a 1 week period in the summer. In this paper, we extend our formulation and analysis to demonstrate that not only can this approach be applied to a variety of other commercial customers, but also that similar low-cost, load shaping can be achieved in other seasons, i.e. Spring/Fall (when cooling loads are much milder) and winter (when one can leverage flexible heating loads instead). Importantly, this shows that the microgrid paradigm can be used to locally absorb much of the stochasticity and variability of embedded renewable generation. Thus, with our proposed market/regulatory structure, microgrids could be used to achieve a very deep penetration of renewable power with little to no negative impact on existing utilities/infrastructure.

The primary contributions of this work are an extension of our previous formulation to consider process units and thermal dynamics associated with space heating, consideration of a more generic building model that can represent a wide variety of end-users, and analysis of an extended case study across a diverse group of commercial load shapes and seasons. In Section 2 the optimization model used in scheduling and supervisory control is formulated. In addition, a brief description of the underlying real-time, dynamic system is provided. In particular, the microgrid units, which primarily generate and store electrical power, are described in Sections 2.2-2.4. Then, the building thermal model and HVAC system, which consume power to manage the indoor air temperature, are described in Sections 2.5 and 2.6. Finally the overall energy balances and economic costs of the integrated system are described in Sections 2.7 and 2.8. In Section 3, a case study over multiple commercial load shapes and seasons is described. Finally, specific results and overall conclusions from this case study are showcased in Sections 4 and 5, respectively.

2. Model formulation

A microgrid scheduling and supervisory control problem is formulated for the system shown in Fig. 1. This supervisory controller seeks to regulate the indoor air temperature and the net power flow between the microgrid system and the external utility. In this problem, a fast time scale (on the order of minutes) is associated with stochastic fluctuations in weather and loads, and with the dynamics of building air temperatures (which can be changed relatively rapidly by the HVAC system). A slower time scale (on the order of hours) is associated with the battery storage level, slow temperature dynamics (i.e. those of walls and floors),