

A Dynamic Market Mechanism for Combined Heat and Power Microgrid Energy Management

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Abstract: This paper develops a dynamic market mechanism (DMM) to optimally allocate electric and thermal power in a combined heat and power microgrid. The market is formulated as a receding horizon constrained optimization problem, from which an optimal automated transactive procedure is developed. The market operation is distributed in nature and incorporates the most up-to-date electric and thermal load estimates and renewable generation. These properties make our microgrid DMM, μ DMM, attractive for microgrid energy management systems, as new smart buildings, battery storage systems, and renewable energy resources can be added in a plug-and-play fashion without reformulating the optimization problem and without adding computational complexity to the EMS. The result of the market clearing is the spot prices and set-points for electric and thermal power in addition to non-binding estimates of future prices and set-points. The market mechanism is simulated on a CHP Microgrid model based on the Smart Polygeneration Microgrid (SPM) located on the University of Genoa's Savona campus.

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1. INTRODUCTION

The adoption of microgrids is increasing exponentially around the world with the primary drivers of making the grid more resilient, reliable, while simultaneously incorporating more renewable energy. A popular configuration for microgrids that serve commercial and residential loads is the so-called combined heat and power (CHP) microgrid, which provides both electric power and district heating (and often cooling). Because microgrid installations are relative new and primarily behind-the-meter installations, there is no single ubiquitous control and operation architecture.

Microgrid operation and control is hierarchical (see Guerrero et al. (2011)), although there has been some recent work which suggests alternative non-hierarchical control strategies (see Dorfler et al. (2014)). A hierarchical architecture includes low-level (primary) control which typically ensures stability and high-level control for optimal operation of the microgrid (secondary or tertiary control), sometimes referred to as the energy management system (EMS). The goal of the EMS for a CHP microgrid is to achieve the economic dispatch of real power and thermal power over a specified time horizon.

Historically, microgrid EMS have been implemented by centralized controllers (see Shahidehpour and Khodayar (2013)). Centralized control is a reasonable and often feasible solution because the physical scale and number of devices in a microgrid is typically small enough to make the centralized problem tractable. Additionally, and more importantly, a centralized control is possible when the microgrid and all of its assets are own and operated by a single entity, thus making all of the device parameters and costs available to solve the centralized control problem.

A challenge of the centralized EMS is the plug-and-playability as new microgrid components are installed. A more general way to articulate this limitation is as follows: centralized energy management systems struggle to adapt to changing conditions within the microgrid at every timescale—from installation of new devices to fluctuating renewable generation and sudden unpredictable device failures. Another limitation of centralized controllers is the ability to incentivize third-party investors in microgrid operation, who may not wish to make their detailed device parameters and costs available to the central controller. Furthermore, since microgrids are often used to test models also for wider grids, a centralized EMS is not suitable for the emulation of complex systems such as districts or cities. A decentralized market-based energy management system can overcome these limitations.

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Market-based transactive control strategies have been actively developed in the academic literature over the last few years. Of particular relevance are those that develop fast energy markets (FEMs), which are intended to operate faster than a typical “real-time” energy market, which clears on the order of every 5 minutes. Notably, Kiani and Annaswamy (2014) developed a dynamic market mechanism (DMM) for wholesale energy markets based on the principles of distributed convex optimization and gradient play. It was also shown how the DMM theoretically fit into a broader hierarchical transactive control architecture (see Kiani et al. (2014)). The DMM has been generalized to allow various types of flexible loads and storage devices to act as participants in the real time energy and regulation markets in Knudsen et al. (2016); Garcia et al. (2016). Related market-based optimization methods include Zhang et al. (2015), where the power system model is viewed as a primal-dual gradient system that is then incorporated into the real-time optimal power flow (OPF). The resulting problem solves the optimization problem while ensuring stability of the power system model.

We build on these ideas, and develop a DMM specifically for microgrid operation that takes into account futures forecasts, much like a model predictive control (MPC) architecture. Accounting for futures forecasts is necessary when optimizing state-dependent agents, such as battery storage. Related work by Wang et al. (2015) develops a market mechanism within a model predictive control (MPC) framework for a grid-connected microgrid, allowing for futures bidding. The authors use the alternating direction method of multipliers (ADMM) algorithm from Boyd (2010) to create bids/offers and to clear the market. Additionally, they only consider electric power microgrids. In this paper, we develop a gradient descent based DMM for a CHP microgrid.

The University of Genova, Savona Campus, Smart Poly-generation Microgrid (SPM) Bracco et al. (2016) has been used to test the developed model and approach. The SPM is a research infrastructure funded (2.4 M€) by the Italian Ministry of Research for microgrids and smart grids that is used for the feeding buildings at the Savona Campus. It is a 3-phase low voltage (400 V line-to-line) “intelligent” distribution system and connects: cogeneration microturbines fed by natural gas, a thermal boiler, a photovoltaic field, a concentrating solar powered (CSP) system equipped with Stirling engines, a H₂O/LiBr absorption chiller with a storage tank, an electrical storage based on NaNiCl₂ batteries, and two electric vehicle charging stations. The SPM will be connected to a new low-energy building (SEB) under construction—funded (2.7 M€) by the Italian Ministry of the Environment and Protection of Land and Sea—which acts as an energy prosumer, being characterized by thermal/electrical loads and power plants (geothermal heat pump, wind mill, photovoltaic, thermal solar panels). The SPM, SEB and buildings are used for simulation of a smart district, and for demonstration of smart city solutions inside a living-lab on a campus scale.

The organization of this paper is as follows. Section 2 establishes our notation and formulates the CHP EMS problem. Section 3 develops the μ DMM to solve the CHP EMS problem. Section 4 illustrates the μ DMM operation through simulations of a model based on the SPM campus

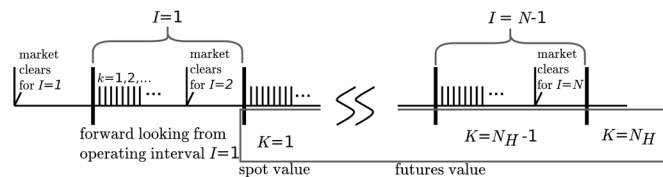


Fig. 1. While at operating interval I , remaining intervals are indexed by $K = 1, \dots, N_H$, where $N_H = N - I$.

microgrid. Section 5 concludes the paper with a review of contributions, a discussion on practical implementation of the μ DMM, and future directions of this work.

2. PROBLEM STATEMENT

The goal of the CHP-EMS is to optimally allocate electric and thermal power set-points at every operating interval over a specified time horizon. This section formulates this multi-period receding horizon optimization problem. First we establish the notation and conventions used throughout the paper.

2.1 Notation

The units (or agents) of our CHP microgrid model can be classified by the following sets

- heating units (e.g., gas boilers), \mathcal{H}
- cogeneration units, \mathcal{C}
- storage units (e.g., batteries), \mathcal{S}
- low voltage side of the network connection (sometimes called *point of common coupling*), \mathcal{N}

We define the set of all CHP agents that participate in the CHP market as

$$\mathcal{A} \triangleq \mathcal{H} \cup \mathcal{C} \cup \mathcal{S} \cup \mathcal{N}. \quad (1)$$

The CHP-EMS is a multi-period optimization problem, and the proposed DMM is an iterative algorithm that solves this problem. The horizon may be a day, a hour, or another specified length of time, which is subdivided into N shorter *operating intervals*. We use three index systems to keep track of the operating interval, the remaining intervals, and the DMM iterations. First, the operating intervals are denoted $I = 1, \dots, N$; these indexes are fixed at the beginning of the horizon, and the length of each interval is T_I . Second, the remaining operating intervals—from the perspective of the current interval I —are denoted $K = 1, \dots, N_H$, where the number of remaining intervals is $N_H = N - I$. The index K will be particularly important when creating bids and offers for future operating intervals. Third, we index DMM iterations, referred to as *negotiations*, by $k = 1, 2, \dots$. Figure 1 visualizes N , N_H , I , K , and k .

For vector-valued variables, we denote the K th component by $[\cdot]_K$. We will distinguish between electrical and thermal energy or power quantities using the superscripts $\{\cdot\}^e$ and $\{\cdot\}^{th}$, respectively.

2.2 CHP Modeling

This section describes the CHP microgrid model including the network assumptions and component models.

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