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A game-theoretic approach to decentralized control of heterogeneous load population

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ABSTRACT

This paper investigates the aggregated control problem of a large number of residential responsive loads for various demand response applications. A unified hybrid system model is proposed, capturing the dynamics of both TCLs (Thermostatically Controlled Loads) such as HVACs (Heating, Ventilating and Air Conditioning) and water heaters, and deferrable loads such as washers, dryers, and PHEVs (Plug-in Hybrid Electric Vehicle). Based on the unified hybrid system model, we formulate the aggregated control problem as an optimal control problem, which seeks for an optimal energy usage plan for a population of heterogeneous loads. We then propose a game-theoretic approach to develop a decentralized aggregated control algorithm. Convergence of the proposed algorithm is shown by employing potential game theory. The hybrid system modeling framework and the proposed decentralized aggregated control algorithm are validated through several realistic demand response simulations using GridLAB-D. The simulation results demonstrate that the aggregated power response can accurately track a reference trajectory, effectively reduce the peak power consumption, and efficiently save electricity cost.

1. Introduction

Demand response has attracted considerable research attention in recent years due to the potential to shift and sculpt energy use, and to help maintain the supply-demand balance of the grid. In [1,2], various control and scheduling algorithms are developed based on different real time pricing schemes. In [3], a distributed bisection algorithm based on consensus-like iteration is proposed to control a network of TCLs. In [4], a decentralized water-filling-based algorithm is proposed to solve the PHEV charging control problem. In addition to the aforementioned individual load control strategies, the aggregated modeling and control for a large load population has also been studied extensively recently [5], mainly focusing on first-order Thermostatically Controlled Loads.

This article is an extension of our conference paper [6], focusing on the aggregated control of a heterogeneous load population, including TCLs, deferrable loads and community batteries. The main goal is to develop a practical control strategy to coordinate the loads to achieve a desired aggregated power response. The main challenge lies in that in practice the load model parameters and user's end-use preferences are heterogeneous, time-varying, and unknown to the system operator (aggregator or Curtailment Service Provider). Existing works cannot address all these realistic issues in the same framework.

In this article, we employ a unified hybrid system model, describing a variety of responsive loads, e.g., TCLs, PHEVs, community batteries etc. Then a decentralized control framework is presented, for which a sub-optimal control problem is solved by each responsive through the coordination with the central aggregator. Different from [7], we assume that the communication channels only exist between the aggregator and responsive loads. To accomplish the decentralized control, a coordination signal generated and broadcasted by the aggregator is introduced. The system-level information is transmitted to each responsive load through this signal. Hence, the responsive loads can improve the system performance cooperatively by deciding their own optimal operations. Convergence of the decentralized control algorithm is proved by employing the potential game theory. The existence of Nash Equilibrium (NE) is guaranteed as long as each responsive load has a finite number of operation modes. Hence, it is not necessary to design any specific price function [8]. Although only sub-optimum of the overall aggregated control problem is given by the NE, impressive performance is achieved as demonstrated in our simulations. This tradeoff is acceptable since the centralized method is costly or even impossible. Different from many other game-theoretic based results [7,8], the payoff or cost in this work does not represent the explicit welfare received from the market. Instead, it is a local indicator reflecting the fulfillment of the system-level

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objective. Moreover, different from other game-based works such as potential games proposed in [9], the Mean Field Games [10] and optimization-based works such as [11], the discrete strategy set is considered in our work. Theoretical convergence can be guaranteed by continuous and convex strategy set as well as convex objective functions. However, a large number of responsive loads have non convex operational constrains. For example, HVAC units have the so-called "lockout" effect, namely, to avoid short-cycling issues the compressor cannot be immediately turned back on after being turned off. Furthermore, if more complicated market scheme is employed in future smart grid, it is no longer appropriate to consider convex or even more restricted objective function, e.g., [10] deals with continuously differentiable and strictly increasing objective function. Our work handles the above realistic issues by considering the discrete strategy set which is suitable for employing the potential game theory to provide theoretical convergence. Compare with heuristic algorithms, e.g., in [12], our method has the flexibility in dealing with time varying user preferences and system parameters. Moreover, we do not require extra effort on dimension reduction or penalty design.

More specifically, the contributions of this work are as follows. Our approach can handle load heterogeneity in terms of both load types and load parameters due to its decentralized nature. Moreover, it is not necessary for the aggregator to know any information about the participating loads. Each responsive load is capable of making control decision according to its own preference, e.g., favorite temperature range, charging time etc. Hence, the users' privacy is protected. In many cases, load dynamics are time varying due to the environmental changes. For example, the ETP model parameters are highly dependent on the outdoor temperature [13]. The proposed framework can deal with this time varying effect as well. In addition, the proposed decentralized control framework allows for simple incorporation of operational constraints of individual loads such as the "lockout" effect of HVAC units. Finally, the proposed framework is general enough such that a broad class of decentralized demand response problem can be formulated by imposing different optimization objectives, e.g., reference tracking, peak reduction, valley filling, cost minimization.

Several realistic simulations are provided to demonstrate the effectiveness of the proposed decentralized aggregated control strategy. Both HVACs and PHEVs with heterogeneous load parameters are involved in the simulations. More specifically, the "lockout" effect and the dependence on outdoor temperature of HVACs are taken into account in the simulations. Under such realistic and challenging setup, our approach is capable of solving several aggregated control problems, e.g., reference tracking, peak reduction, and cost minimization applications.

2. Problem formulation

2.1. General hybrid system model for responsive loads

Consider a large number of heterogeneous responsive loads in the grid. Denote $\mathcal{M}$ as the responsive load set with $M = |\mathcal{M}|$ being the number of the loads. Many responsive loads have multiple discrete operation modes. Transitions among these modes are governed by certain switching logic rules that depend on the evolution of some continuous state variables or exogenous controls. Such dynamic can be described by a hybrid system model, i.e., $\forall i \in \mathcal{M}$

$$\begin{cases} x^i(k+1) = f^i_{v^i(k)}(x^i(k); \theta^i(k)) \\ y^i(k) = h^i(v^i(k)), \quad k = 0, \ldots, N-1 \end{cases} \tag{1}$$

where $[0, \ldots, N-1]$ is the time horizon, $x^i(k) \in \mathcal{X}^i$ is the continuous state at discrete time instant k with a known initial state $x^i(0)$, $v^i(k) \in \mathcal{V}^i = \{1, \ldots, m\}$ represents the discrete operation mode of the system. For each discrete mode $v \in \mathcal{V}^i$, the function $f^i_v(\cdot\,; \theta) : \mathcal{X}^i \to \mathbb{R}^n$ is the state update equation that governs the state evolution in mode v, and $h^i(v)$ denotes the output that is assumed to be independent of the continuous state. Here, $\theta^i(k) \in \mathbb{R}^{n_{\theta i}}$ is the model parameter which is possibly time varying due to environmental changes. Denote by $\mathbf{v}^i = [v^i(0)\ldots v^i(N-1)]^T \in \mathcal{Q}^i$ an admissible mode sequence. Define $\mathcal{Q}^i$ as the set of all feasible mode sequences for load i starting from initial state $x^i(0)$, i.e., $\mathcal{Q}^i(x^i(0)) \triangleq \{\mathbf{v}^i \in (\mathcal{V}^i)^N | x^i(k) \in \mathcal{X}^i\}$. Furthermore, define $\mathcal{Q}_p \triangleq \prod_{i=1}^{M} \mathcal{Q}^i$ and let $\mathbf{v}_p = (\mathbf{v}^1, \ldots, \mathbf{v}^M) \in \mathcal{Q}_p$ be an admissible mode sequence profile. We may write $\mathbf{v}_p^{-i} = (\mathbf{v}^1, \ldots, \mathbf{v}^{i-1}, \mathbf{v}^{i+1}, \ldots, \mathbf{v}^M)$, where $\mathbf{v}_p^{-i}$ is an admissible mode sequence profile without load i. Denote $\mathcal{Q}^{-i} = \prod_{j \neq i} \mathcal{Q}^j$. Denote $\mathbf{y}^i = [y^i(0)\ldots y^i(N-1)]^T$, we can thus write

$$\mathbf{y}^i = \mathbf{h}^i(\mathbf{v}^i) \tag{2}$$

which is consistent with (1).

In this work, we have powers of responsive loads as their outputs, i.e.,

$$h^i(v^i) = p^i_{v^i}.$$

Before stating the aggregated control problem, we will first use HAVCs and PHEVs as examples to illustrate the application of the hybrid system load model described above.

2.2. Example for HVAC

HVACs are the most important type of TCLs for demand response. In the literature, the HVAC system is typically modeled as a first-order Ordinary Differential Equation (ODE) that governs the time-course evolution of air temperature inside the house. It has been recently pointed out that the mass temperature contributes significantly to the thermodynamics of a HVAC system, especially under demand response control such as setpoint change. Therefore, throughout this article, we will adopt a second-order Equivalent Thermal Parameter (ETP) model that describes the coupled dynamics of the air and mass temperatures as follows:

$$\begin{cases} \dot{x}_a(t) = \dfrac{1}{C_a}[x_m(t)H_m - (U_a + H_m)x_a(t) + Q_a + T_o U_a] \\ \dot{x}_m(t) = \dfrac{1}{C_m}[H_m(x_a(t) - x_m(t)) + Q_m] \end{cases} \tag{3}$$

Here, x_a is the indoor air temperature, x_m is the inner mass (due to the building materials and furnishings) temperature, U_a is the conductance of the building envelope, T_o is the outdoor air temperature, H_m is the conductance between the inner air and inner solid mass, C_a is the thermal mass of the air, C_m is the thermal mass of the building materials and furnishings, Q_a is the heat flux into the interior air mass and Q_m is the heat flux to the interior solid mass. The total heat flux Q_a consists of three main contributing factors Q_i, Q_s and Q_h, where Q_i is the heat gain from the internal load, Q_s is the solar heat gain and Q_h is the heat gain from the heating/cooling system. Depending on the power state of the unit, the heat flux Q_a could take the following two values:

$$Q_a^{\text{on}} = Q_i + Q_s + Q_h \quad \text{and} \quad Q_a^{\text{off}} = Q_i + Q_s$$

The ETP model parameters such as U_a, C_m, C_a, H_m, and Q_h, Q_i, Q_s are determined by the various physical parameters of the building such as floor area, glazing layers and material, infiltration volumetric air exchange rate, area per floor, to name a few. The readers are referred to [13] for a detailed description of these physical parameters and their relations to the ETP model parameters.

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