Decentralized Coordination of Controlled Loads and Transformers in a hierarchical structure

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Abstract: The paper considers the coordination of controlled loads in a setting where the loads are connected to the distribution network through transformers. Our objective is to design a decentralized control method that can motivate selfish loads to achieve global benefits. This problem has a hierarchical structure. At the lower level, each transformer broadcasts a price signal to the loads connect to it, under which loads establish their best usage strategies. At the upper level, transformers communicate with the distribution network and obtain a price reflecting the system generation cost. The price broadcast by each transformer includes this system price together with another component that reflects individual loading characteristics. By proposing a dynamic update algorithm, it is shown that the system converges to the unique and efficient solution with fast convergence rate.

1. INTRODUCTION

The paper considers a system where loads are served with energy through transformers possessing limited capacities. Various centralized methods for scheduling the loads, such as traditional direct load control, have been widely developed, see Li et al. [2014], Han et al. [2010], Hao et al. [2015], Zhang et al. [2013] and references therein. Due to the desire of loads for privacy and autonomy, as well as the fast communication requirements and high computational burden of centralized schemes, decentralized methods are potentially more practical. We would therefore like to design a decentralized method that enables the system to converge to the efficient (globally optimal) strategy while taking into account loading constraints on transformers.

We explore a decentralized approach motivated by a real-time price model, Ma et al. [2016], where participating loads simultaneously determine their optimal strategies with respect to a given price. While strategies that rely on time or a fixed-price schedule tend to result in suboptimal solutions, a real-time price model has been widely applied for demand response management Mohebian-Rad and Leon-Garcia [2010], Samadi et al. [2010] and EV charging/discharging coordination Ma et al. [2015, 2016, 2013], Gan et al. [2013], Wu et al. [2012]. First, each individual load calculates its best strategy with respect to a price profile broadcast by the transformer to which it is connected, and then each transformer communicates with the distribution network and obtains a price reflecting the system generation cost. By adding the part of the price reflecting their own characteristics, each transformer determines a revised price profile which is reapplied to loads for computing optimal strategies, and the process repeats. It is shown that under mild conditions, system convergence is ensured by applying the proposed iterative process. The converged price is coincident with the optimal system price. As a consequence, the resulting collection of load strategies is efficient. Moreover, we quantify the convergence rate of our algorithm.

The remainder of the paper is organized as follows. In Section 2, we formalize a cost-based economic model for transformers and loads. Centralized load coordination is considered in Section 3. A decentralized coordination method is constructed in Section 4 to implement the efficient strategy and the convergence of the proposed algorithm is analyzed. In Section 5, simulation results are presented to demonstrate the results developed in this paper. Section 6 concludes the paper and discusses ongoing research.

2. MODEL FORMULATION

Consider a load coordination problem where loads are connected to the distribution network through transformers. Fig. 1 provides an illustration. The objective is to coordinate the loads to minimize the global system cost.
Suppose that each controllable load is equipped with a smart controller that can specify its own energy consumption and communicate with the transformer it connects to. Denote by \( \mathcal{N} = \{1, \cdots, N\} \) the population set of all the controllable loads in the system, and \( \mathcal{N}_m \) the set of loads connected to transformer \( m \). Hence we have \( \bigcup_{m \in \mathcal{M}} \mathcal{N}_m = \mathcal{N} \).

For each load \( n \in \mathcal{N}_m \), the power consumption at time \( t \) is denoted by \( u_{mn,t} \) (with units of kW, and the energy delivered over this period is \( u_{mn,t} \Delta T \)). A load consumption strategy \( u_{mn} \equiv \{u_{mn,t}; t \in \mathcal{T}\} \) is admissible if,

\[
\begin{align*}
    u_{mn,t} \in \begin{cases} 
    [0, \bar{u}_{mn,t}], & t \in \mathcal{T}_m \\
    0, & \text{otherwise}
\end{cases},
\end{align*}
\]

and

\[
||u_{mn}||_1 \Delta T \equiv \sum_{t \in \mathcal{T}} u_{mn,t} \Delta T \leq \Xi_{mn},
\]

where \( \bar{u}_{mn,t} \) represents the maximum power consumed by load \( n \), \( \mathcal{T}_m \subset \mathcal{T} \) is the time horizon that load \( n \) is “on” and \( \Xi_{mn} = \Gamma_{mn} \Delta T \) is the maximum total demand of load \( n \).

The objective of each load is to implement a demand schedule that maximizes its individual payoff, i.e., loads’ benefit by consuming energy minus individual costs. Typically, the coordination problem across a group of loads has generally sought to minimize total generation cost over the time horizon, e.g. Denholm and Short [2006], Ma et al. [2013], Gan et al. [2013]. In practice, loads suffer from some local cost fee arising from high distribution-level demand and device degradation etc. To consider this point, we define a valuation function for each load that captures the load benefit and costs on its energy consumption.

Let the value assigned by load \( n \in \mathcal{N}_m \) be denoted by \( v_{mn}(u_{mn}) \), such that:

\[
v_{mn}(u_{mn}) = h_{mn}(||u_{mn}||_1) - \sum_{t \in \mathcal{T}} g_{mn,t}(u_{mn,t}),
\]

where \( h_{mn}(||u_{mn}||_1) \) describes the benefit derived from the total consumption over the time horizon, and \( g_{mn,t}(\cdot) \) is the local cost at time \( t \) reflecting demand charge and degradation cost etc. Consistent with Kirsch [2003], we consider that:

(A2) \( g_{mn,t}(u_{mn,t}) \) is monotonically increasing, differentiable, and convex, for all \( m \in \mathcal{M}, n \in \mathcal{N}_m, t \in \mathcal{T} \).

In Han et al. [2010], the benefit function \( h_{mn}(\cdot) \) has the quadratic form,

\[
h_{mn}(||u_{mn}||_1) = -\delta_{mn}(||u_{mn}||_1 - \Gamma_{mn})^2,
\]

with the factor \( \delta_{mn} \) reflecting the relative importance to consume maximum energy over the horizon. Moreover, the marginal valuation of load \( n \) is specified as:

\[
\nu_{mn,t}(u_{mn}) = \frac{\partial}{\partial u_{mn,t}} v_{mn}(u_{mn}) = \frac{h'_{mn}(||u_{mn}||_1) - g'_{mn,t}(u_{mn,t})}{||u_{mn}||_1}.
\]
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