Applied Energy 206 (2017) 991–1008

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Distributed demand-side energy management scheme in residential smart grids: An ordinal state-based potential game approach

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HIGHLIGHTS

- A fully distributed energy management scheme for residential smart grids is proposed.
- It minimizes total energy purchase satisfying supply capacities and demand targets.
- It can work for arbitrary topologies of communication graphs as shown in case study.
- It is robust to imperfect communication as shown in case study.

ARTICLE INFO

Keywords:
Optimal energy management
Ordinal state-based potential game
Distributed optimization
Smart grid

ABSTRACT

This paper proposes a distributed demand-side energy management scheme in residential smart grids based on ordinal state-based potential game (SPG) with various kinds of household electrical appliances. Involving the total electricity costs, the supply capacity limits incurred by the distribution infrastructures and the required energy demands for individual appliances, the optimal energy management (OEM) of demand-side users, i.e., homes, turns out to be a complicated optimization problem associated with a coupled objective function subject to spatially and temporally coupled constraints. Such a problem is difficult to solve in a distributed fashion. In this paper, we formulate it as an ordinal SPG, devising a distributed algorithm to achieve the optimum of the original centralized OEM with no need of any central coordinator during the process of execution. Our scheme does not require any private information of individual users to be shared, while both the optimality and convergence are obtained. We also show the scheme is robust to unreliable communications. And the proposed scheme is illustrated and verified by simulations.

1. Introduction

With the arrival of smart grid era, as shiftable household appliances, such as plug-in hybrid electric vehicles (PHEVs), become more and more popular, individual residential demand-side users will be able to shape their electricity consumption in response to economic or other incentives. Hence, the optimal energy management (OEM) problem of demand-side users will play a crucially important role in facilitating the efficiency, economy, reliability as well as energy conservation of distribution systems [1–5], as shown in the existing studies [6,7] that it can provide the system operation with great flexibility and optimization potential. Moreover, enabled by the advanced communication and metering infrastructures, we have been facing a profound transition for the modern demand-side energy management system from the conventional centralized control architecture towards an autonomous-cooperative one [8,9].

In such a paradigm, due to the computation, communication as well as privacy concerns, how to implement the OEM problem of a residential district in a distributed way is drawing increasing attention [10–17]. Its essence is to design a distributed scheme providing each demand-side user, i.e., each home, with appropriate (economic) incentives, so that the minimum total costs for purchasing electricity can be automatically approached while self-regarding users are individually making their own electricity consumption decisions to minimize their own electricity bills. It should be noted that, in such a circumstance, only local information and limited communication are available.

In this paper, we are interested in designing the distributed scheme for the OEM problem of a residential district, with the goal of minimizing the total expenses of purchasing electricity over all time slots of interest. As the OEM problem involves the aggregate load demand of all

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http://dx.doi.org/10.1016/j.apenergy.2017.08.123
Received 4 May 2017; Received in revised form 26 June 2017; Accepted 12 August 2017

Table 1
Summary of representative works.

	Coupled Objective Function	Temporally Coupled Constraints	Spatially Coupled Constraints	Coordinator in Process
Ref. [10]	√	×	√	√
Refs. [11–13,15]	√	√	×	√
Ref. [14]	√	√	×	×
Refs.	×	√	√	√

home users, the objective function is coupled across all homes. Besides, we also consider some realistic operational constraints, including the distribution infrastructure limits, e.g., the thermal limits of the feeders or step-down transformers, which restrict the amount of the aggregate demand all the time and constitute a set of spatially coupled constraints across all users. On the other hand, the shiftable appliances require cumulative power consumption to reach a certain target over their operation period to complete the daily task, thus temporally coupled constraints are also inevitable [9,16]. As a result, the OEM problem we address here has not only coupled objective function, but also spatially and temporally coupled constraints, making it difficult to solve in a distributed manner.

1.1. Literature review

In recent years, there have been a series of literatures about distributed energy management schemes for residential smart grids. The representative works and their main features are summarized in Table 1. Among them, [10–12] introduce distributed and iterative algorithms for the OEM problem, relying on the coordination of a central coordinator at each iteration during implementation, thus making it vulnerable to single point of failure. Ref. [13] proposes a dynamic real-time pricing scheme to coordinate the power scheduling of electric appliances in a residential energy management system with the same communication strucuture. In [14], a distributed algorithm is suggested for the OEM problem based on non-cooperative game, where the users independently schedule their daily energy consumption to minimize their daily electricity bills, without providing private scheduling details. Yet, the algorithm requires each end user to observe the complete joint action profile at each iteration, resulting in a huge communication burden. To fix this problem, Ref. [15] further proposes a distributed energy management scheme by introducing the energy provider as a central coordinator. All the aforementioned works, however, ignore spatially coupled operational constraints. Refs. [16,17] derive distributed demand response schemes based on the dual decomposition theory, considering the supply capacity restrictions and required demand constraints simultaneously, as well as obtaining fast convergence rates. However, a central coordinator is still needed, and both of the schemes do not cope with the coupled objective function, thus they may not reduce the total expense effectively.

To the best of our knowledge, there is still no distributed energy management schemes proposed for the OEM problem of the residential smart grid that can both handle the above factors in a comprehensive way and work with no coordinator during implementation. Moreover, it still remains an open question whether all these aforementioned schemes are robust to unreliable communication environment.

Most recently, potential game [18,19] has emerged as an effective design paradigm for distributed optimization in multi-agent systems, where each agent is self-optimizing and interactively converges to a Nash equilibrium. Furthermore, an adjunct state space can be introduced to provide an additional degree of freedom to deal with complicatedly coupled centralized objective functions and constraints across the agents [20–23], extending to the state-based potential game (SPG). Moreover, a rich body of distributed learning algorithms could be utilized to obtain the convergence, even if the process of execution is corrupted with delays or losses in communication information [19,20,24]. And it can also be extended to time-varying communication networks with proper modifications [22].

Based on [19,22], we leverage the ordinal SPG to design a distributed energy management scheme for a residential district, considering the aforementioned aspects comprehensively.

It should be noted that there are other works related to the problem of finding an equilibrium point of a distributed game, where game players selfishly desire to optimize their own performance even though the global objective may not be minimized. This is another important topic which has plenty of applications in the field of power system and also in the problem of demand-side energy management. Interested readers can refer to [25–28]. It is different from the work we focus on since we seek to align the individual-level optimality with the system-level optimality through energy management scheme design.

1.2. Main features of the proposed approach

Inspired by [19–22,24], this paper intends to propose an ordinal SPG based approach for distributed optimization algorithm design, tackling a class of *optimization problem with a coupled objective function subject to coupled constraints* (*OP-COCC*) across all local decision makers. And we address a more practical OEM problem of a residential district compared with the existing works [10–17], which aims to minimize the total expenses of purchasing electricity, subject to both the thermal limits of the feeders or step-down transformers and operational requests of the shiftable appliances, thus casting into a *OP-COCC problem.* Then we apply the proposed approach to derive a novel distributed scheme for the OEM problem. The salient features of our methodology can be summarized as follows:

(1) Based on the proposed approach of ordinal SPG, we design the distributed energy management scheme by introducing a set of additional coordinating terms to decouple the cost function as well as the coupled constraints to localize the decision making of individual home users. Even though we derive a distributed scheme with respect to the specific OEM problem, the methodology is generic and results in a systematic approach to solve the OP-COCC in a distributed manner.
(2) Compared with [10–13,15–17], our distributed scheme requires only local communications among neighboring users, without any central coordinator during the process of execution. Moreover, the information being exchanged includes just public information and auxiliary variables of the proposed scheme, which are introduced to help the computation, and to ensure the accuracy of the scheme. None of them reveals detailed information on the preferences, economic factors or loads of the home users. Thus the privacy of individual home users can also be well preserved.
(3) Our distributed scheme can obtain the optimum of the original centralized OEM problem. Moreover, compared with the existing distributed OEM schemes [10,17], our scheme is robust to imperfect communication, such as information losses, and can be further extended to time-varying communication networks when ignoring the spatially coupled constraints, as we will show in the simulation results.

The reminder of the paper is organized as follows: Section 2 introduces the basic definitions and properties of the ordinal SPG. Section 3 presents the system model and the general problem formulation of the OEM problem of a residential district. A distributed energy management scheme is proposed in Section 4. The properties and implementations of the scheme are discussed in Section 5 and 6, respectively. Simulation study is given in Section 7, and conclusions are drawn in Section 8.