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Framework for minimum user participation rate determination to achieve specific demand response management objectives in residential smart grids ☆

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ABSTRACT

In this paper, we develop a framework for grid operators to determine the minimum required user participation rate to achieve specific Demand Response Management (DRM) objectives in residential smart grids. Under this framework, we propose power limit and inconvenience limit methodologies. In the power limit methodology, the grid communicates a power limit to participating users to achieve a desired amount of peak load reduction. In the inconvenience limit methodology, the grid communicates an inconvenience limit to participating users and demand is reduced accordingly to achieve the desired peak load reduction. We define indexes to measure user inconvenience and recommend physical and thermal load models for flexible appliances to measure temperature deviations and scheduling delays. We then analyze the performance of our developed framework in a residential community comprising of 780 homes. We generate power consumption data for individual devices of different users to match an aggregated load curve shape from the RELOAD database on a typical summer day. We determine the required user participation, experienced inconvenience temperature variations and scheduling delays for various DRM objectives. By determining the minimum required user participation, this framework can help the grid operators in designing proper incentives for specific DRM goals.

Introduction

The traditional electrical grid has been in service for several decades. A lack of communication and information flow between operators and consumers remains a major obstacle in load balancing and demand shaping. All of this is changing as the interest in smart grids is growing and it is enabling the operators and users to optimize their electricity consumption according to their desired objectives [1–9].

In a smart grid, communication between the users and the grid operator is bi-directional. The grid operator can employ Demand Response Management (DRM) strategies to achieve specific objectives such as peak load reduction. However, peak reduction cannot be achieved unless users change their temporal power consumption patterns and are willing to tolerate the resulting inconvenience. It is therefore equally important for the grid operator to compensate users (by offering proper incentives) for their inconvenience and make its DRM program successful. The most important question for the grid therefore is the determination of a minimum user participation rate such that the inconvenience it creates for users does not overwhelm the advantage that could otherwise be gained through peak reduction.

State of the art

Different electric utilities and grid operators around the world have implemented various strategies to encourage user participation for peak load reduction. The ColorPower architecture proposed in [10] automatically matches the demand shaping requests of a utility with qualitative flexibility preferences marked by customers as “colors”. In [11], the authors use queuing based energy

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consumption management techniques and use neural network techniques to develop distributed algorithms. The authors in [12,13] develop demand response algorithms in micro-grids in the presence of renewable and distributed energy resources in the system. In [14], the authors developed an algorithm to predict day-ahead prices in order to reduce peak load while targeting maximization of the electricity provider's profits. In [15], the authors proposed an algorithm which in the presence of special ECS (Energy Consumption Scheduling) devices deployed in the smart meters of each home, determine the optimal energy consumption schedule. In [16], an algorithm is developed that reduces peak load based on the amount of information share between the users. In [17], the authors study the impact of scheduling flexibility on demand profile flatness and user inconvenience. The objective is to achieve as flat demand profile as possible by shifting flexible loads and also measuring the resulting impact on user inconvenience. Recently in [18], we develop customer engagement plans for peak load reduction in residential smart grids. These plans clearly describe the inconvenience and then the effectiveness of these plans for the grid operator in terms of peak load reduction is determined. All these papers, assume that users are always willing to participate in DRM programs offered by the grid.

Surveys [19] have shown that many potential consumers in residential smart grids remain wary of participating in DRM programs due to various reasons such as security concerns [20], fear of facing inconvenience, or reluctance in accepting new technologies. However, it is also interesting to note that the same survey [19], also suggests that up to 60% of the users if given proper incentives might be encouraged to participate in DRM programs. Therefore, it is extremely crucial that the grid should know the required user participation rate in order to achieve specific DRM objectives.[1]

System model

We develop our framework for a residential smart grid comprising of several homes (interchangeably called users or consumers) as shown in Fig. 1. Power flow is uni-directional i.e. from grid to users. In our framework some users can participate in the DRM scheme proposed by the grid through a Home Control Center (HCC) (grid cannot directly control user loads). There is a bi-directional information exchange between the grid and the HCC of users participating in the DRM program as well as among the HCC and the various devices (we use devices and loads interchangeably throughout the paper) in each home. Power consumption of each device is constantly monitored and reported at regular intervals to the HCC. Users not participating in the DRM program are treated in a similar way as in a traditional grid. Such users are not given any incentives and their electricity load demands are treated as essential load.

Contributions

We develop a framework to determine minimum required user participation to achieve specific DRM objectives. We propose two different methodologies. In the first methodology, a power limit is computed by the grid in each time slot (depending on the specified peak load reduction) and is communicated to the HCC of all participating users. If flexible load demand of a participating user is greater than the power limit, HCC breaks and shifts the load of its devices to restrict its power consumption below this limit. In the second methodology, an inconvenience limit is computed by the grid in each time slot (depending on the specified average inconvenience threshold) and is communicated to the HCC of all participating users. Unlike the power limit method, each HCC is now required to reduce its power consumption and experience some inconvenience in response to the inconvenience limit regardless of the power demands. Generally more user participation is required if the inconvenience limit method is adopted as compared to the power limit method. However, in the inconvenience limit method each participating user experiences a relatively similar amount of inconvenience, i.e. temperature deviations from the desired thermostat set points and scheduling delays compared to the power limit method.

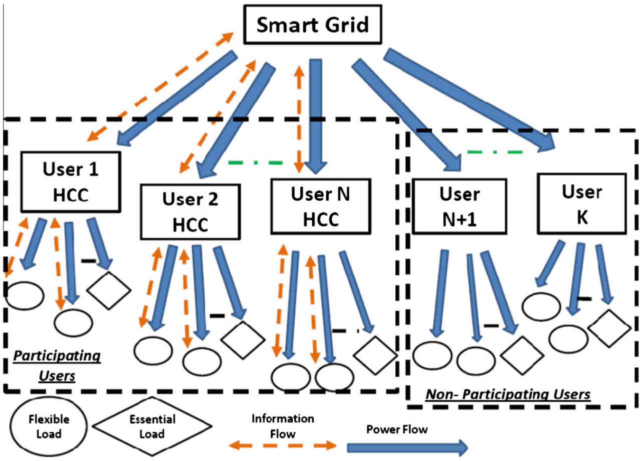

Fig. 1. System model.

Another contribution in this paper is the definition of indices to measure inconvenience for various flexible loads such as Air Conditioner (AC), Water Heater (WH), Clothes Dryer (CD) and Optional Lighting Load (OLL). The developed indexes for different flexible loads are such that they can be combined into a single value to reflect net inconvenience experienced by a participating user. In the framework, we also consider physical and thermal load models for flexible loads, which allow us to measure the actual temperature variations and scheduling delays in response to a DRM objectives.

We demonstrate the application of our framework through a case study. We consider an aggregated load curve shape from the RELOAD database [21,22] on a typical summer day. The RELOAD database is an industry accepted database of load curve shapes and is used by the electricity module of the National Energy Modelling System (NEMS) and several authors for their studies [23]. A load curve shape only consists of a sequence of hourly aggregated electricity load demands. Individual household data specifying power consumption and usage pattern of various flexible devices is generally not made available by the grid operators due to privacy concerns [24–26]. For our simulations, we therefore develop data-set assuming realistic constraints on power consumption and usage pattern of various appliances in each household. This data-set matches the given aggregated load curve shape and we make it available online for future studies, research and development [27].

Paper organization

The rest of the paper is organized as follows. In Section “Load model and measure of user inconvenience” we describe the load model, user preferences and inconvenience indexes. The problem formulation and proposed framework are detailed in Section “Framework to determine minimum user participation rate”. Various DRM algorithms are developed in Section “DRM methodologies”.

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[1] How exactly grid offers incentives to encourage user participation is out of scope of this paper. In fact, this framework will determine the required minimum user participation rate which could be used in future to design incentives.