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Smart charging and appliance scheduling approaches to demand side management

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ABSTRACT

Various forms of demand side management (DSM) programs are being deployed by utility companies for load flattening amongst the residential power users. These programs are tailored to offer monetary incentives to electricity customers so that they voluntarily consume electricity in an efficient way. Thus, DSM presents households with numerous opportunities to lower their electricity bills. However, systems that combine the various DSM strategies with a view to maximizing energy management benefits have not received sufficient attention. This study therefore proposes an intelligent energy management framework that can be used to implement both energy storage and appliance scheduling schemes. By adopting appliance scheduling, customers can realize cost savings by appropriately scheduling their power consumption during the low peak hours. More savings could further be achieved through smart electricity storage. Power storage allows electricity consumers to purchase power during off-peak hours when electricity prices are low and satisfy their demands when prices are high by discharging the batteries. For optimal cost savings, the customers must constantly monitor the price fluctuations in order to determine when to switch between the utility grid and the electricity storage devices. However, with a high penetration of consumer owned storage devices, the charging of the batteries must be properly coordinated and appropriately scheduled to avoid creating new peaks. This paper therefore proposes an autonomous smart charging framework that ensures both the stability of the power grid and customer savings.

1. Introduction

House energy management [1–3] will play an important role in the enhancement of the security of the next-generation electric grid [4]. By deploying demand side management (DSM) strategies [5–9], significant electricity savings can be achieved by more efficient power utilization of each household [10]. DSM is increasingly being adopted by many utility companies to encourage efficient power usage by their customers. In the residential sector, dynamic pricing [11,12] of electricity could be a viable incentive to electricity consumers to encourage power conservation. By adopting time of use pricing and real time electricity billing systems, utility companies can motivate households to significantly cut down on their electricity costs by taking advantage of price fluctuations.

Customers could respond to electricity signals by scheduling their loads during off peak hours or by storing power purchased when electricity prices are low and use it during peak hours. Appliance scheduling requires that customers modify their consumption profiles continuously with changing prices. In [13] residential loads are scheduled based on 1–2 days electricity prices prediction. Electrical appliances time of use is planned so that consumer deadlines and their need to save money are realized. Another study [14] considers price based simultaneous scheduling of users. In this case multiple electricity consumers with common power source are considered. Game-theory based electricity scheduling approaches have also been applied. In [15], price prediction and electricity demand scheduling based demand responses have been realized by game theory. The schedules are formulated as an electricity consumption game where users make use of power prices and the grid loading condition to modify their demands. A thermostatically controlled household load based on price and consumption forecasts is also presented in [16]. Similar studies have been carried out in [17–22].

However, appliance scheduling approach on its own has not realized much success [23–27]. Electricity storage is another viable DSM strategy that has been proposed as a key component of the future smart grid [28–32]. However, due to high costs as well as short battery life, power storage was not previously considered as an economically viable approach to energy management. Nonetheless, renewed interest in electricity storage has been sparked by a number of factors, some of which include: the advancements in renewable energy technologies [33,34], the integration of

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renewable energy sources into the main grid [35] and the development of more efficient batteries. In [36], a hydrogen storage system is considered for a wind farm selling electricity in the Ontario electricity market. A given amount of wind power is stored as hydrogen during low peak periods and sold to the utility grid in periods of high electricity prices. A battery storage plant (BSP) approach to achieve grid reliability and stability has been presented in [37]. BSP has been proposed as a long term strategy to reduce the vulnerability of the grid in large urban centers. The authors in [38] present an automated real time control system for scheduling of thermal storage. The results show that a 10% cost savings is realized as compared to the existing time-of-use (TOU)-based control system with no storage. The influence of demand side management and electricity storage on profitability for service providers has been studied in [39]. Their findings reveal that electricity storage profitability is significantly influenced by even very small load shifting from peaks to off-peaks.

In order to realize maximum cost benefits by the customer, this study proposes a DSM framework that incorporates both appliance scheduling and power storage. In order to address the challenge of manual demand response, our proposed scheme incorporates intelligent smart meters and an aggregator to autonomously schedule appliances and storage devices. In the proposed scheme, each smart meter uses historical data to learn and predict appliances' power consumption behavior. It is therefore able to automatically generate the expected appliance schedules. These schedules are then relayed to the aggregator which is a central controller tasked with processing energy management information to achieve load flattening. Thus, the aggregator does not track the power consumption of a single device but it monitors the electricity use of a set of devices. We have therefore applied the concept of load clustering where loads that consume electricity within the same time period are grouped together in the cluster. The goal of the aggregator is to ensure that within each cluster, power is efficiently utilized and the peak to average ratio is kept within the desired limits. To guarantee grid stability, the aggregator uses the customers' load demand, power supply profile and day-ahead electricity prices to generate the most cost effective electricity consumption profiles for all the households.

2. Major contribution of the work

As has already been explained, electricity pricing alone has not had significant influence on load consumption patterns by customers. On the other hand, even though numerous authors have proposed electricity storage as a strategy to realizing load flattening, most of these studies are concerned with macroscopic implementation of storage facilities. Moreover, the storage devices considered have largely been PHEV batteries. However, PHEV may not be suitable for peak shaving applications. This is due to the fact that most PHEV owners would find it convenient to fully charge their PHEVs before they leave their homes. The charged PHEV would then deplete all or a portion of their charge during driving and therefore might not necessarily be available for peak shaving. In order to enhance households' electricity consumption efficiency and further maximize on customers' electric bills savings, this paper therefore combines these two demand response strategies. Thus, we present a smart storage-real time electricity pricing framework for residential load management. Further, we have proposed a customer owned dedicated storage device that can be appropriately scheduled anytime by the households to achieve the desired load flattening.

To properly coordinate the charging/discharging of the batteries, this paper has proposed an aggregator-coordinated smart charging scheme. The aggregator acts as the link between the electricity supplier and the households by relaying critical electricity information between them. The aggregator is responsible for generation of expected total load profiles from the customers in each hour of the planning horizon. By aggregation of power requests from each smart meter, it develops the total hourly electrical load forecasts. Further, based load forecasts, historical electricity tariff data and interpolation technique, it autonomously computes the anticipated real time electricity prices aimed at influencing the power consumption behavior among the customers. Thus, this study addresses the challenge of manual demand response by proposing a framework to autonomously generate customers' load profile, compute electricity tariffs and schedule customer electrical loads. Further, this paper provides useful insights on harnessing historical electricity consumption data for intelligent energy management. The results demonstrate the importance of load and price forecasting accuracy in realizing an effective energy management scheme by presenting the effect of uncertainties on load flattening and customer financial savings.

Since the peak load problem is as a consequence of several electrical appliances using power at the same time during certain periods, it is important to monitor the power usage of these set of appliances to effectively monitor the peak load. Therefore, we have introduced the concept of load clustering for peak load management. Clustering has been used in this study to group electrical devices with similar electrical consumption profiles. By appropriately grouping several slots within the planning horizon together to form a cluster, the aggregator is able to monitor the aggregate loads within that cluster.

3. The scheduling problem

In the scheduling problem, the grid operator accepts appliance requests to consume a certain amount of power within a pre-defined time period for a specified duration. In this study, customers' appliance schedules are generated and relayed to an aggregator by a smart meter installed in each household. Based on the submitted load demands and electricity prices, the aggregator then determines the most optimal electricity consumption and battery array charging patterns for all the households.

3.1. Price based appliance scheduling

In the price based scheduling strategy, the scheduler capitalizes on the customers' need to save on their electricity bills to implement appliances' electricity consumption. The prices are carefully designed with a view of discouraging requests during peak hours. That is, prices are generally high during peak hours. Requests from devices with flexible deadlines are manipulated by shifting their operation to times when electricity prices are low. However, if the price difference between two consecutive periods is insignificant, we have assumed the customer would prefer the appliance to run as scheduled.

3.2. Customer load profile

In this study, we have grouped the household electrical appliances loads into deferrable and non-deferrable. The deferrable loads are those appliances whose power consumption schedules can be altered or interrupted without significantly inconveniencing the customer. On the contrary, non-deferrable loads consist of critical customer devices whose schedules must be executed as requested by the household. Therefore, once these devices are activated, they must not be interrupted. Individual household's electricity utilization pattern is generated by considering that each home owns the same set of N electrical devices.