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A review of demand response in an efficient smart grid environment

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ABSTRACT

As the electricity system shifts from a conventional operating system into a smart grid system, the paper proposes an efficiency-enhancing mechanism comprised of communication-based demand response (CBDR) and a customer-friendly inclining block tariff (IBT) that takes into consideration customers' income and consumption profiles.

1. Introduction

The management of the electricity market is currently undergoing drastic changes in its structure and operations as it is transformed from a conventional system into a smart and decentralized system with added contributions from renewable sources (Ketter et al., 2016; Yang et al., 2017). The smart grid emphasizes maintaining interactions with users, including power consumption and dynamic pricing; that in turn is achieved through the deployment of various demand-side management programs. By the definition of the U.S. Department of Energy, the smart grid (SG) is an electricity delivery system enhanced with communication facilities and information technologies to enable more efficient and reliable grid operations with improved customer service and a cleaner environment (U.S. Dept. of Energy, 2009). Demand response takes advantage of two-layer communications and information networks in SGs and make the grid multi-layer-intelligent by realizing intelligent demand response.

According to the DOE's definition, demand response is a program established to incentivize end use customers to change their normal consumption patterns in response to changes in electricity prices (U.S. Dept. of Energy, 2006). Through electricity DRs, SGs can achieve energy saving measures, peak load shaving, improve the efficiency of the grid system, and reduce the need for power investments.

Existing literature has thoroughly discussed DR as a measure for curtailing peak demand and increasing grid reliability, networking, marketing policies, and integrated technology in power systems. The work done by Callaway and Hiskens (Callaway and Hiskens, 2010) hypothesized that a DR program should primarily focus on increasing information processing requirements in the smart grid system. They argue that the DR system will incur massive volumes of data that may lead to an inherent internal security problem. There are many contributions in the literature about the architecture and components of a DR system. For instance, Palensky and Dietrich (Palensky and Dietrich, 2011) constructed a web-based energy information system and named its typical components. Tan (Tan et al., 2012) proposed a high-level design of a decision support system for demand-side management. Sui and Sun (Sui et al., 2011) provided a high-level overview on how to utilize smart metering to establish a DR system. Ghazvini (Ghazvini et al., 2017) used an optimization-based HEMS model that was applied under the pricing schemes of RTP and TOU. Many authors in the literature studied incentive-based DR schemes as inputs and scheduled electricity consumption based on DRs and price signals. The DR system of Huang (Huang et al., 2015) used a controller on all electrical appliances, including interruptible, deferrable, and multi-operational controllers. Dan and Kushler (Dan and Kushler, 2005) reviewed the effect of DRs on energy efficiency and found that DR programs generally yielded energy savings. Zareen (Zareen et al., 2015) focused their research on the profit maximization of customers and the revenue maximization of the utility provider.

This paper conducts an extensive literature review of DR programs and proposes a communication and computation-based DR program (CBDR) for future grid systems. The study further enhances the DR program through the deployment of a customer-friendly and cooperative tariff. The objectives are fourfold: to monitor users' consumption behavior by installing home displays and smart meters connected with the grid; to minimize peak demand by employing an inclined-block tariff (IBT) on power volume distribution; to maintain a responsive communication interaction for data sharing between users and the power grid through the (HAN, WAN and NAN) networks. Both, the smart communications and smart tariff will propagate DR intensively among users and utility providers. In this work, CBDR is introduced in order to convey the price and incentive updates to customers through a speedy and secure communication network.

The structure of this paper is organized as follows. Section 2

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provides an extensive overview and categorization of demand response. Section 3 elaborates on the objectives of DR and its significance in the power market. Section 4 describes the different demographic and economic factors that directly influence the true applications of DR. Section 5 demonstrates the future directions for an efficient and customer-responsive DR. Section 6 underlines future limitations and opportunities for DR in the electricity market. Section 7 concludes.

2. Background and classifications

Demand response can be defined as changes in electricity usage by end-use customers from their usual consumption pattern in response to changes in prices. Price-dependent DR refers to the financial incentives or penalties to motivate customers to provide load flexibility (Torriti et al., 2010). Demand response facilitates the reduction of power consumption and saves energy. In addition, it maximizes capacity utilization of the distribution system's infrastructure by reducing or eliminating the need to build new lines and expand the system. The two-way communication capability in the smart grid allows for the widespread deployment of DR technologies and programs, thereby allowing load to adjust to supply variations.

In the US, as of 2015, DR programs alone were estimated to have the potential of 31,754 MW, accounting for 6.6% of total peak demand of all ISO/RTO, and it was estimated that demand response would probably shave 38,000 MW off the country's peak demand in the year 2019 (Wright et al., 2011). The actual peak demand savings was approximately 12,000 MW, equivalent to the total generation capacity of Bulgaria or Denmark in 2012 (CIA: The World Factbook: Denmark, 2001) (Fig. 1).

2.1. Price- based DR (PBDR)

The price based DR program depicts the actual cost for the electricity from production to the distribution in a system. As Fig. 1 shows the different dynamic pricing schemes that provide insight for the customers shifting their consumption pattern from high cost interval to the lower price interval.

2.1.1. Time-of-use (TOU)

The time-of-use scheme is split into two periods of peak and off-peak with high and low rates, respectively. However, the tariff can motivate customers to reduce electricity consumption from peak to off-peak order to balance the interaction between supply and demand. The tariffs are frequently combined with a separate charge for peak usage, which means that customers pay a given price per kilowatt for their maximum demand in the billing period. These demand charges are levied irrespective of whether the system is constrained or not (Borenstein et al., 2002). TOU-pricing-based schemes are effective in reducing peak electrical consumption by incentivizing consumers to use more electricity at cheaper hours and reduce demand in peak hours.

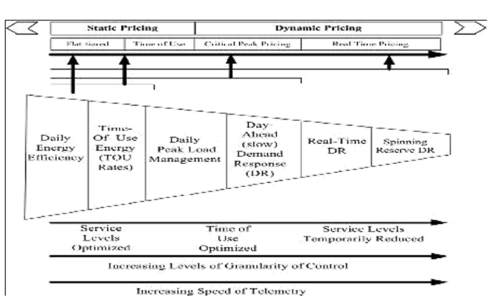

Fig. 1. Conceptual representation of efficiency and the demand response. Adopted from (U.S. Dept. of Energy, 2006).

2.1.2. Critical peak pricing

In critical peak pricing (CPP), a normal tariff, which generally belongs to the TOU family, is valid for most of the days of the year. However, a small number of days are subject to a price change. These occurrences correspond to periods of very high demand (peak loads) during which the generating utilities could not provide a sufficient quantity of electricity if prices were flat (Andrey and Haurie, 2013). It charges higher prices during extreme peak periods or emergency situations, while the rates on other periods remain the same (Fischer, 2008). Both the critical peak periods and the critical peak rates are not fixed. The critical peak periods may be only a few days or a few hours in a year (Mohagheghi et al., 2010).

2.1.3. Peak-time rebate

Critical peak rebate programs are usually offered to residential and small commercial customers without any form of automated control technology, such as via a programmable communicating thermostat (PCT). In a few jurisdictions across the U.S., residential customers are by default enrolled in this program, but otherwise they comprise a relatively limited amount of the national potential peak load reductions (Wright et al., 2011).

2.1.4. Real-time pricing

The RTP scheme reflects the marginal value of continuous electricity according to real-time supply and demand situations. Prices are not predetermined and are subject to hourly changes. There are two common forms of RTP. One provides the 24-hour price schedule a day in advance (DA-RTP) and the other provides the hourly price within 60 min after consumption has already occurred (RT-RTP). In the smart grid infrastructure, the devices that are installed in homes usually show the price signals of utilities during peak hours and the customer instantly reacts by reducing the peak and taking part in the competitive electricity market in an off-time interval so that the RTP prices can become more efficient (Ahn et al., 2011).

2.2. Incentive-based DR (IBDR)

The program includes direct load control (DLC), behavioral demand response (BDR), demand bidding, buyback and ancillary and regulation services. These schemes provide customers with peak shaving incentives. IBDRs are needed and requested when customer demand significantly increases more than supply and system reliability is at risk.

2.2.1. Direct load control (DLC)

Demand response programs have been around for decades and have been proven an effective means for utilities to manage system peaks by controlling customer loads. In DLC programs, the utility directly controls the customers' appliances such as air conditioning systems, hot water heaters, and pumps, by regulating their frequency. The utility benefits from a better ability to manage demand and supply, while the customer benefits from financial incentives for program participation. In the DLC program, customers agree to allow their utilities to directly access some of the selected appliances or equipment during peak time interval in order to shut down or cycle them. In some cases, the utility charges penalties for overrides by users in peak times (Dan and Kushler, 2005).

2.2.2. Behavioral DR

Extensive research has studied the timely feedback to consumers to reduce peak demand of electricity or shifts the demand to off-peak periods (Darby, 2006) (Faruqui et al., 2010). However, some problems have been identified with feedback, including problems with engagement over the long term after the novelty has worn off (Houde et al., 2013) (Sintov and Schultz, 2015). Behavior-based DR programs rely on behavioral changes to produce a change in electricity consumption but are voluntary and do not provide any explicit performance-based