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Abstract: This paper provides an overview of the role, past, present and future, of demand-side management and demand-side response in electric grids. We address the fundamental principles and objectives behind the use of demand-side-based resources in power systems. We present its inherent challenges and some proposals destined to tackle them in the emerging *smart grid* paradigm.

Résumé : Cet article dresse un portrait du rôle, passé, présent et futur, des moyens de gestion et de pilotage des charges dans les réseaux électriques. Nous y adressons leurs principes de base et leurs objectifs en tant que ressources dans les réseaux. De plus, nous présentons les défis inhérents au développement de ces ressources et certaines stratégies et technologies mises de l'avant pour les surmonter dans un contexte d'émergence des réseaux intelligents (*smart grids*).

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1 Introduction

Traditional electric power utility regulation favours investments in supply-side resources over demand-side flexibility and energy efficiency resources. Accordingly, utilities have preferred capital intensive investments like building power plants, transmission and distribution networks since their profits have been and are still linked to their capital expenditures and energy production and sales. This trend is slowly shifting in modern power systems. The movement being observed is toward ensuring energy security and the reducing industry's carbon footprint by integrating renewable and distributed energy resources, and through the implementation of energy efficiency programs [1, 2].

The proliferation of renewable energy resources, with energy security and environmental betterment objectives, poses significant challenges to the secure operation and planning of power systems. This is particularly due to the need for higher levels of flexibility and controllability to accommodate the intermittency and non-dispatchablility of renewable energy resources [3, 4, 5, 6, 7]. In this environment, the demand-side is expected to play an increasingly active role in maintaining the supply-demand balance by providing the required flexibility to follow non-dispatchable renewable energy resources [8]. This is in distinct contrast with the traditional power systems operation and planning paradigm in which generators are controlled to follow the demand as it varies over hours, days, seasons, and years. Moreover, demand-side management programs in the emerging low carbon grids have had further expectations to leverage their potential over more traditional roles in decreasing the peak demand, reducing the operation of quick-start and peaking units which are the major contributors to green-house gas emissions, and assisting with transmission and distribution investment deferrals.

According to the US Department of Energy (DOE), demand response can be defined as "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [9]. There are other definitions which are more representative of the emerging applications for demand-side flexibility where demand is seen as a dispatchable resource responding to signals from transmission and distribution system operators, flexibility aggregators, and utilities in the wider sense. For instance, the California Energy Commission defines demand response as "a reduction in customers' electricity consumption over a given time interval relative to what would otherwise occur in response to a price signal, other financial incentives, or a reliability signal" [10].

As these definitions suggest demand-side management covers a broad range of activities that are planned to encourage end-users to modify their electricity usage patterns in order to assist power systems operation and planning. The terms, load management, demand response, and energy efficiency, are often time used interchangeably in the context of demand-side management. Nevertheless, there are differences between these terms which should be recognized. Load management programs usually refer to traditional applications for demand-side management which are mainly concerned with reducing power consumptions during peak demand and emergency conditions. Moreover, demand response programs are referred to recent and emerging applications for demand-side management like improving grid reliability by providing ancillary services, or reducing wholesale energy prices and their volatility.

In contrast to load management, and demand response programs that share some similarities, energy efficiency programs are primarily concerned with the permanent reduction in overall energy consumption of specific device or system by employing high-efficiency equipment or system design [11]. Therefore, energy efficiency programs have permanent impact on reducing electricity use while load management/demand response programs entail modifying electricity use temporarily, and at critical times rather than, on permanent basis.

2 Background on demand-side management and demand response

Demand-side management in its most basic form is not a novel concept and has been around for decades under the generic name of load management. Load management and interruptible load tariffs for large industrial and commercial customers and direct load control (DLC) for residential customers became popular in utilities in the 1970s and 1980s in several countries [2, 12].

The load management practices of the 1970s were mostly implemented manually, and due to the unavailability of cheap and reliable communication equipment and slow response times, they were rarely deployed. In the 1980s, however, utilities and policy makers became aware of the load management value as a reliability resource in integrated resource planning [2]. This was partly driven by the penetration of thermostatically controlled loads like air conditioners which contributed in reducing the load factor and generating severe loading conditions particularly after blackouts. The international energy crises of the 1970s and 1980s at the same time increased awareness about the role that demand-side management and especially about how energy efficiency programs can play in improving energy security.

In the 1990s, policy makers and utilities started to redesign many of the vertically-integrated power industries to allow for more competitive wholesale electricity markets, while gradually introducing choice for customers [13]. Policy makers of deregulated electricity markets played a key role in the establishment of the rules to level the playing field in terms of market entry for non-traditional control resources like demand-side management resources. The Energy Policy Act of 2005 [14] in the United States is a prime example where policy makers eliminated unnecessary barriers for demand response entry and participation in the energy, capacity, and ancillary service markets. The problems seen in electricity markets such as in the California market collapse of 2000-2001 [15] was also one of the key drivers for such legislative changes as they highlighted the role that demand-side management and response could play in ensuring the efficient functioning of the wholesale electricity markets and preventing generators from exerting undue market power [16]. Another example of such necessary adaptations to open up demand-side management in the power industry can be found at National Grid in Great Britain, where the *frequency control by demand management* service requires a minimum of 3 MW of capacity which can be obtained through interruptible load aggregation [17]. This contrasts with the technically similar *firm frequency response* service which has a minimum offer size of 10 MW [18] and which is clearly targeted towards traditional generation assets. Article15.8 of the European Commission's Energy Efficiency Directive [19] further outlines specific requirements for member states to enable and encourage demand-side management programs through the participation of demand response providers such as aggregators. Overall, the development of open and organized wholesale markets coupled with policy support by energy regulatory commissions have facilitated the introduction of participation of demand-side resources in the power industry over the past few decades.

In recent years, the advent of smart grid technologies, which include a wide array of sensing, communication, control and decision-support tools all targeted at improving the functioning of girds, has led to many more new opportunities for demand-side management initiatives [20]. The ability of customers to respond to demand-response related price/control signals has increased significantly as smart metres, communication, sensing and embedded control systems are becoming ubiquitous in the power industry, at home, buildings, etc. Smart/communicating metres and telecommunication technologies enable operators, utilities and flexibility aggregators to communicate information's like time of day and time of use prices to end-use customers in semi-real time periods, as well as implementing various types of load control at end-use level. The potential number of applications is enormous, markets are wide open and innovation is driving major players of the information and communication technology sectors into this brand new territory. This potential is also leveraged by the increasing role electricity plays in all economies. Electricity will be the energy carrier *par excellence* in the next 50 plus years. Therefore, potential for control and management of electricity use can only increase in the near future.

3 Benefits offered by demand-side management

Demand-side management can bring a variety of benefits to the power industry, ranging from the economical, to environmental benefits [11].

The economic benefits of demand-side management can be classified into three general categories. The first economic benefit comes from reducing the peak demands. Although peak demands are infrequent in power systems, their economic impacts are significant. This is mainly because the energy prices skyrocket during peak demand and supply shortages. The more frequent occurence of such spikes is what drives traditionally industry capital investment in generation, transmission and distribution.Therefore, reducing peak demands though demand-side measures can be seen as direct substitutes to those investments. Given the scale of the investments involved, choices favouring one avenue over the other can have a huge economic impact [11].

The second economic benefit comes from providing ancillary services, and potentially decreasing the volatility of the demand. Generally, ancillary services are provided by generating units running in a sub-efficient mode operation. Such costly situations could be substituted in part (and even maybe in whole) by employing demand response capacity. The provision of ancillary services by demand response can further reduce the need for running costly power plants such as quick start and peaking units to contribute in driving production costs, prices, and emissions down [11].

The third economic benefit comes from reducing the transmission and distribution losses. This is because the energy usually has to travel a considerable distance from power plants to end-use customers. The transmission losses vary between 5 to 10 percent depending on the loading conditions of transmission and distribution lines. Demand-side management can contribute in relieving heavily loaded lines and reducing losses [11].

Demand-side management provides an excellent reliability resource for the most critical reliability needs [21]. Specifically, it can be used to address capacity inadequacy of power systems which caused by shortage of generation and transmission resources. Moreover, demand response programs can significantly increase the operational security of power systems in the short-run by providing ancillary services. This is mainly because ancillary services provided by responsive demand are technically superior to their counterparts provided by generation assets as they are faster and often highly-distributed—we think here, for example, of the millions of electric waters heaters found in the province Québec, Canada, which can be selectively disconnected to offset morning and evening demand ramps. The only time required to activate most demand-based ancillary services is the time required for the control signal to get from an operator, aggregator or utility to the end-use load. This is much faster than generation response times which are usually on bases of tens of minutes in practice. In specific applications such as frequency control, the demand response times are almost instantaneous as frequency is measured at the load site and communications delays are not present [21].

Demand-side management programs increase power system reliability and lower the likelihood and consequences of generation and transmission forced outages which can impose significant financial costs and discomfort on customers [9].

The use of demand-side management also results in numerous environmental benefits. The environmental benefits of demand-side management programs fall into two groups. The first group originates from the reduction in peak demands. Reducing the peak demands avoids power plant operation and their associated emissions. In addition, they contribute in reducing the need to construct new power plants, transmission lines, substations and distribution assets. This prevents the environmental consequences that may have resulted from such constructions and it enhances the social acceptability of power grids [11].

The second group originates from reducing the need for ancillary services from fast-start units. Fast-start units are mostly fuelled by diesel oil or gas which are the main contributors to green-house gas emissions. The use of demand-side management further leads to the operation of power plants in more efficient operating points. This results in less fuel consumption, and few emissions [11].

4 Types of demand response programs

Demand response programs can broadly be classified into two categories based on customer motivations for participation, i.e., price-based demand response and incentive-based demand response. Each of these categories has a number of variants [9].

4.1 Price-based programs

Price-based demand response programs refer to programs wherein changes in electricity use are made in response to price changes. These are divided into time of use rates, real-time pricing, and critical peak pricing programs [9].

With time-of-use rates, electricity is priced differently depending on the time of day, for instance, peak, partial peak (shoulder) and off-peak hours, as in the province of Ontario, Canada. In this category, the rates are known by customers well in advance. Time-of-use tariffs have traditionally been mandatory for large commercial and industrial loads and varies throughout the year based on the season. This is in contrast with the flat rates paid by most residential customers worldwide. The main problem associated with time-of-use rates is that they do not reflect the real cost of energy delivery as these programs have a static nature [9]. Moreover, in cases where there are more than two rates over the duration of a given day, small customers often see a challenge in trying to optimize their energy use. Some decision-support tools and "mild" automation (e.g., thermostats with timers) on the customer-side are needed to make the most of the time-varying rates.

Real-time pricing programs in contrast with time-of-use rates reflect the wholesale electricity prices on hour-to-hour basis. In real-time pricing programs, customers are typically notified of upcoming real-time prices on a day-ahead or hour-ahead basis. These programs are the most reflective of the true value of electricity at any given time. Nevertheless, they are uncommon as they require the highest level of decision-support sophistication and IT infrastructure at the customer level. The required infrastructure includes automated interval metering, price forecast mechanisms, communications and billing systems as well as need for a "smart" customer-side energy management system. In practice, only the very small fraction of customers with on-site generation has enough demand elasticity to justify investment and participation in real-time pricing programs [9].

Critical peak pricing is a hybrid form of time-of-use rates and real-time pricing. The structure of critical peak pricing programs is similar to time-of-use programs, while the rates are replaced by higher prices which are triggered by reliability-related events or when electricity prices are very high [9]. The key to the success of such programs is to give proper forewarning to customers so that they have enough time to reschedule activities or production accordingly.

4.2 Incentive-based programs

In the case of incentive-based programs, customers allow operators, aggregators or utilities to control their loads in exchange for credits or incentive payments. These credit or incentive payments are separate from a customer's retail electricity rate which may be fixed or time-varying. In most of the incentive-based programs, the sponsors should specify a method for establishing a baseline for energy consumption such that load reductions can be measured and verified. Failure in responding to incentive-based programs may result in penalties or loss of a potential future reward depending on the type of program and contract structure [9].

Incentive based programs can be classified into five subcategories, i.e., direct load control (DLC), interruptible/curtailable service, emergency demand response, capacity market programs and ancillary service market programs [9].

In direct load control programs, customer loads are directly controlled by the utility or aggregator. During demand response calls, these loads are either shut down, cycled on and off, or moved to a lower consumption period on a very short notice. DLC programs are typically directed at small commercial and residential loads.

Incentive payments for DLC programs typically include fixed monthly payments credited to the customer's bill, plus a payment when load reduction events occur. Depending on the type of demand response program, utilities/aggregators give options to customers such as specifying the maximum number and duration of events per year or the ability to override an event if they experience high levels of discomfort. Manual override is usually allowed in peak shaving programs while it is forbidden when spinning reserve or contingency response is supplied. Overall, direct load control programs are relatively simple and inexpensive to implement and reliable in terms of achieving load reduction objectives [9]. Activation signals need not be sophisticated; for example, it could be based on an ambient temperature trigger or even be based on automated telephone calls from the program operator.

Interruptible/curtailable programs are similar to DLC programs. However, they target large commercial and industrial loads. In these programs, large commercial and industrial loads agree to reduce or turn off specific loads for a period of time in exchange for bill credits or discount rates. The participants are usually notified from minutes ahead to days ahead and severe penalties may be applied for failure to perform [9].

Emergency demand response programs are reliability-based programs and provide incentives to customers for measured load reductions during reliability-triggered events. In power systems usually there is a cap on the maximum emergency service that can be provided by demand. The participants in emergency demand response programs only receive payments when they respond to system operator signals. The payments are assessed based on the customer's outage costs or the value of lost load. The participants in such programs receive no up-front payments or capacity credits as their participations are voluntary and no penalty applies when they do not respond [9].

Capacity market programs are designed to attract demand response resources that can offer in market or replace conventional generation or delivery resources. In capacity market programs customers agree to the must-offer requirements in markets and receive capacity credits commensurate with their ability to reduce load and an additional payment for load reductions during specific events. Customers can further receive credits for load reductions during emergency conditions or peak demand. The failure to respond to capacity market or emergency signals entails significant penalties since participants are paid on an ongoing basis for being available to provide capacity [9].

Ancillary service market programs for demand response are an emerging area. The technical capabilities required to participate in ancillary service markets vary depending on the type of ancillary service to be provided. For instance the provision of frequency regulating services requires telemetry and the ability to follow set-point instructions transmitted by operators or aggregators. However, these technical requirements are not as stringent for supplying frequency containment or supplemental reserves [9].

5 Demand response performance, measurement and verification

Considering the increasing role that demand-side management is expected to play in daily operation and planning of power systems, an emerging need is the ability to accurately predict and measure the performance of demand response resources through standardized practices and metrics. Such developments in technology and analytics are necessary to build confidence among policymakers, utilities, system operators, and stakeholders that demand response resources do offer a viable, cost-effective alternative to supply-side resources.

The roll-out of smart metres is the first step toward demand response initiatives. Smart metres allow customers to become more engaged in demand response programs by increasing their awareness about dynamic electricity pricing and incentives. Moreover, real-time metering by smart metres enables accurate measurement and verification of demand response programs. Technology-enabled automatic load control at the customer level is another essential component for successful implementation of demand response programs. Finally, encouraging the establishment of demand response aggregators is another key element for successful implementation of demand response programs. The aggregators can guarantee the participation of customers in demand response programs with zero costs as aggregators are willing to pay for the installation of metering and automation equipment. Moreover, demand response aggregators can guarantee reliable demand response service provision to operators and utilities by diversifying demand response resources over a pool of candidates.

6 The challenges: aligning economics and intelligence

Demand management is often seen as a key resource to the enablement of smart low carbon grids. One major challenge for demand response program implementations is the need to find investment and business models competitive with respect to the traditional utility capital-intensive model. There is an obvious barrier from institutional inertia to overcome. Most utilities often (1) operate as state-mandated monopolies; (2) are the stewards of high levels of supply reliability; (3) may not have the necessary in-house expertise to develop demand management-based solutions; and, (4) have found comfort in a long-tested business model. This is why so many new demand-side management initiatives are emerging at the margins of the traditional industry players, with flexibility aggregation being the prime example. The investments necessary for deploying demand response programs are primarily concerned with the installation of sensing, communication and intelligence. The nature of those investments are more than often closer to the business practices of telecommunication providers. Therefore, there is a definite learning process to happen on the side of the utility industry. Success stories of pilot projects have to serve as the basis for the next generation of deployments.

The challenge does not lie solely on the side of investments. The revenue streams associated with the exploitation of responsive demand are often seen to be victims of their own success, while also it is well-known that, at current electricity prices, potential capacity rents that responsive demand could capture are still limited. Moreover, any rents generated need to be redistributed among all responsive customers. Expected payoffs are quite small, while there is always the fear among customers that their participation in a demand response initiative might result in potential losses (financial, comfort) and in the need to consider risk as part of their electricity use choices.

This is also happening while producers and retailers may end up losing potential sales through substitution by demand-side resources. Thus, it is essential that regulatory bodies arbitrate the conflicting objectives and incentives of all parties at stake. The overall result should be the one where the socially-optimal rules and incentives are adopted.

The implementation of all these require substantial deployment of adequate intelligence at all levels of the grid. A true smart grid is one where it is possible for all stakeholders to find mutually-satisfactory outcomes. It takes smart rules, smart people and smart assets to ensure a systemic coherence and significant benefits.

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