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Demand Side Management in Future Smart Grid: A Review of current state-of-the-art

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ABSTRACT

Demand side management (DSM) and demand response (DR) is an area of the smart grid paradigm that helps utilities shape the demand according to a pre-determined load profile. In this paper, the state-of-the-art of DR in literature is overviewed. This paper discusses the various DR programmes, DR benefits and challenges, new smart grid technologies for DR and recent DR mathematical models in literature.

Keywords: Demand Side Management, Demand Response, Smart Grid, Peak to Average Demand Ratio

1. INTRODUCTION

The concept of smart grid has been a topic that is the focus of researchers and energy policy makers in the past two decades. According to [1], a smart grid is an electricity network allowing devices to communicate between suppliers to consumers, allowing them to manage demand, protect the distribution network, save energy and reduce costs. The current electricity grid infrastructure in most developed countries is based on designs that are more than half a century old. This old electricity grid infrastructure generates power centrally and delivers the power to consumers through transmission and distribution networks. There is an urgent need for this old electricity grid to evolve in order to be able to incorporate new generation technologies particularly distributed energy resources (DERs) (e.g. renewable energy), energy storage technologies (e.g. plug-in Electric Vehicles) and micro-grids. New Smart Grid technologies such as the communications infrastructure for conveying information among various agents will also need to be incorporated into the existing grid infrastructure.

The classical approach of power delivery is to match power demand with supply whatever the demand maybe at a fixed price. This however means that the load profile with peaks at certain periods of the day must be matched with generation capacity. More importantly, the critical peaks in the load profile over a year usually occur in less than 5% of the time leading to a high peak-to-average demand ratio (PAR). This means that huge capacity investment have to be made to meet these peaks which seriously reduce capacity utilization and system efficiency. For instance capacity utilization in UK is less than 50%. This is where the idea of demand side management (DSM) comes in. Smart Grid technologies such as information and communication technology (ICT) and Advanced Metering Infrastructure serve as enablers for DSM. With the traditional grid infrastructure, it is not possible to change the load profile but as new smart grid technologies emerge DSM become a possibility. DSM is particularly attractive for reducing the peak-to-average demand ratio.

2. DEMAND SIDE MANAGEMENT IN SMART GRID

DSM is the aggregation of all utility mechanisms designed to influence or directly change consumer electricity consumption in order to achieve a desirable load profile. The shaping of the load profile according to a pre-determined pattern is at the heart of every DSM technique. According to [2] this desirable pattern or load profile can belong to one of the following six categories namely peak clipping, flexible load shape, load shifting,

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strategic load growth, valley filling and strategic conservation. These six load profiles are shown in Fig. 1.

DR is a program designed to influence consumers to change their immediate electricity consumption in response to changes in price (indicative of scarcity) or some form of incentive payment. DR as defined by the US department of Energy [3] is an incentive payment programme to reduce electricity usage when grid safety and reliability is imperiled. The distinction between DSM and DR is that DSM seeks to change consumer electricity consumption behaviour overtime to increase capacity utilization and grid efficiency while DR deals with changing power demand at the moment. DR programmes can be grouped into two: tariff based programmes and incentive based programmes.

3. DEMAND RESPONSE CLASSIFICATION

3.1 Tariff based demand response programmes

According to [4] there are three major types of tariff-based DR programmes. The first one is critical peak pricing (CPP). In this programme, consumers are influenced to shed load during critical peak periods by charging a very high price. These periods occur less than 5% of the time in a year. The second DR programme is time of use (TOU) pricing where consumers are charged two different tariffs depending on the time of day. They are charged higher tariff during peak period and a lower tariff during off-peak period. This DR programme encourages consumers to shift their loads from peak period to off-peak period. The third DR programme is real-time pricing (RTP). Consumers are charged a price that changes in real time reflecting the availability or scarcity of power. In general, tariff based DR programmes (excluding RTP) have the advantage that they have no privacy issues as no collection of usage data is required.

CPP is a tariff programme that address critical load spikes such as widespread use of air-conditioning systems during the summer months of the year. Its implementation has a few challenges including lack of regulatory frameworks that back its use [5]. Whilst [6] investigated the potential impact of CPP on consumer behaviour and benefits to the utility system operator (USO), there have been relatively few works that investigate the potential benefits of CPP in different demographics with the best framework for their implementation in those demographics. TOU tariff is the more commonly implemented programme in most national grids but it is believed that in order for the current grid to fully become a full smart grid, the

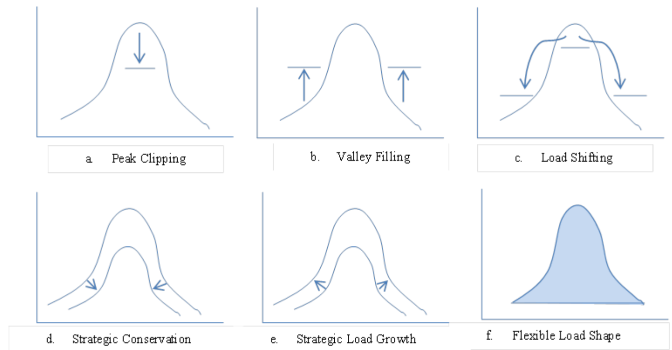

Fig. 1 Load shaping types in DSM

transition has to be made to RTP as this tariff programme has been reported to be best for sustainable energy systems such as in Net Zero Energy Building NZEB [7]. The challenge is the development of state-of-the-art (SoA) RTP algorithm [8] for calculating the tariff that is most representative of the availability of energy resources. The high penetration of renewable energy in recent years makes it more difficult to predict the real-time available energy resources. SoA state estimation algorithms will also be needed to estimate the real-time price a day-ahead and in real-time for update. The day-ahead prediction is needed in order for participating DERs to optimally schedule their generation commitment [9] or for demand bidding contracts in wholesale electricity markets. Finally, to the best of our knowledge the combination of the CPP and TOU has not been tested in most electricity markets and using CPP and TOU together can help to significantly increase grid capacity utilization and defer grid infrastructure (generation and transmission) expansion. This should be implemented while the TOU framework evolves to the RTP in the future smart grid.

3.2 Incentive-Based DR Programmes

In the incentive based programmes consumers are paid a certain amount by reducing their power consumption based on a pre-signed contract The incentive-based DR programmes include interruptible service, capacity market, direct load control and demand bidding.

In *interruptible service* customers that are enrolled in this service are offered an incentive payment (discount) in order to reduce their electricity consumption. If they refuse to reduce their electricity consumption they will be penalized.

In *capacity market* enrolled customers commit to providing pre-determined load reductions when system contingencies arise. If they do not curtail load as agreed they will be penalized. Customers enrolled in this service receive guaranteed incentive payment irrespective of whether the load curtailment event is called by the utility. Capacity market programmes are usually offered by wholesale market providers such as USOs.

Direct load control (DLC) programmes includes appliances that can be directly controlled by utilities for shaping the load profile during critical periods when the grid reliability is jeopardized. The major challenge in participation of DLC by consumers is the privacy concerns. Regulatory frameworks need to be put in place to regulate how utilities use data from these appliances.

Demand Bidding (DB) is a DR programme that encourages large energy consumers to reduce their electricity consumption at times when a DB event is called. Consumers can voluntarily agree to reduce their electricity consumption at a predetermined price and there is no penalty for refusing to accept a DB event.

4. DEMAND RESPONSE BENEFITS

Ancillary support - DR can be used to perform frequency (and in some cases voltage) regulation. Ref [10] investigated the potential benefits of using DR for ancillary services while [11] discussed the opportunities and challenges for using DR for ancillary services.

Grid expansion deferrer - DR can also help defer planned grid transmission and distribution expansion [12].

Grid efficiency increase - DR also helps to increase grid efficiency and use less fossil fuel plants [13],[14].

More economical operation –DR offers USOs opportunity to supply power at a more economically sustainable way.

Enabler for Smart Grid paradigm – DR is crucial to the true realization of the smart grid paradigm.

DR helps to reduce curtailment of renewables [15].

5. REQUIREMENTS AND CHALLENGES OF DR

There are certain elements that are required for the true realization of widespread DR participation.

Communication infrastructure - One of the enablers of DR in smart grid is the deployment of advanced ICT. There are several DR solutions that require short latency communications infrastructure. Ref. [16] discussed the benefits of DR and also detailed the challenges facing the implementation of DR including the communications infrastructure. Ref. [17] discussed smart grid applications for integration of distributed generation (DG) and the associated communications requirements for the deployment of these smart grid applications. The deployment of several DR solutions will inherently require several components such as sensors, control devices, advanced metering infrastructure (AMI) and the communications layer (operated by the USOs) by which these devices communicate.

Smart meters/AMI – According to the U.S. Energy Information Administration [18], an AMI is one that uses meters that measure and record electricity usage at a minimum of hourly intervals and that provide the data to both the utility and the utility customer at least once a day. Smart meters/AMI are required in order for DR programmes to be realized in a smart grid.

Energy management System (EMS) – The EMS is an important part of the smart grid system and it is crucial to the execution of DR. The EMS' function is to determine the optimal control actions for the optimal operation of the smart grid for safety, reliability and efficiency of the grid. The AMI transmit consumption data to the EMS through supervisory control and data acquisition (SCADA) and remote terminal units (RTUs) and the EMS uses state estimation algorithms, generation and load forecast system to determine the optimal control actions for the operation of the smart grid [19]. DR programmes are integrated into the load forecast system or to put it simply, the forecasted load can be adjusted using DR programmes to reach a more efficient, reliable and economic operation of the smart grid. The development of a robust EMS for the smart grid is a subject of intensive research by many authors. Ref. [20] reviewed the various aspects of EMS for smart grid and the current challenges.

Regulatory Framework – The implementation of DR programmes need the development of regulatory frameworks and policies in order for their deployment by USOs and high consumer participation to be realized. Many power markets in China [5] and several states in the US do not have the regulatory framework that support the deployment of DR programmes. As a result of this a lot of DR programmes are deployed in pilot programmes in order to evaluate the potential benefits and compile reports that will encourage authorities to initiative frameworks and policies for more DR deployment.

Privacy Concerns - The privacy concerns of DR programmes due to data collection through smart meters and DLC is one of the underlining issues that limit the level of DR participation by consumers. The TOU and CPP tariff plans have less privacy concerns compared to RTP and other incentive based DR programmes. However, most DR programmes depend on collection of consumer usage data. In many cases, users have to be incentivized in order to share their information with utilities for DR participation [21]. Presently, most DR programmes are designed for large consumers (commercial and industrial). Ref. [22] and [23] proposed a privacy-preserving DR scheme for the smart grid. More work needs to be done to address these privacy issues in order for DR to be widely deployed across all consumer categories because the true potential of DR will never be reached without widespread participation of residential consumers.

5.1 Distributed Energy Resources/Virtual Power Plant

DERs are independent energy sources that can range from micro-energy sources such as residential energy system to large scale grid-connected micro-grids. Virtual Power Plants (VPP) are geographically located DERs that are pooled together to operate as a single power facility. VPPs facilitate integration of DERs into the grid and DERs are one of the core features of a smart grid as it reduces the power flow through the transmission lines and fosters a more decentralized grid control. VPPs needs to be optimally scheduled in coordination with DR of DERs in the VPPs. A scalable and affordable wireless communication technology is used for DSM to aggregate geographically sparse DERs into a single VPP using ant colony optimization (ACO). The VPP communication supports centralized, decentralized or fully distributed controlled VPP's DER [24].

5.2 Energy Storage System and Vehicle-to-Grid

For effective DSM, the control and monitoring techniques need to be introduced to offset price variations, distributed generation (DG) power intermittency and associated network safety problems [25]. As such, the consideration of electric vehicles (EV), energy storages and their integration in a DG DSM [26] is important. EVs have proven to help mitigate the demand-supply variations often accompanying distributed resource allocation and management. A number of studies have shown the benefits of energy storage system (ESS) and vehicle-to-grid (V2G) in DSM. An optimal strategy for home energy management system (HEMS) integrating solar power, energy storage, and V2G capability was used by [27] to address the DR of RTP, emergency load curtailment and V2G operation. The HEMS operates in the vehicle-to-home mode ensuring supply continuity. The control algorithms are experimentally implemented on a created hardware platform of EV and home batteries, solar power, and household loads with preset priorities. The HEMS simultaneously optimizes the scheduling of charging and discharging of EVs and home battery. A three packed result of smoothening of load profile, minimization of load shifting, and fair charging rate is validated using a representative case study in [28]. The work introduces the concept of Distributed Resource Allocation (DRA) approach for incorporating a large number of Plug-in EV (PEVs) with the power grid utilizing the concept of achieving output consensus. The core aim of the work is to obtain a favorable charging strategy for each grid-connected PEVs in such a way that it satisfies both grid objectives in terms of load profile smoothening and minimizing of load shifting as well as economic and social interests of vehicle owners.

6. SoA REVIEW OF SMART GRID TECHNOLOGIES FOR DR

The use of Multi-Agent systems (MAS) in smart grid for DR is important to coordinate the response of DR participating consumers for a more predictable DR outcome. Ref. [29] proposed an agent-based decentralized DR to solve the problem of new load peaks created by a centralized DR programme such as RTP. Ref. [30] also used MAS for coordinating the response of participating consumers to achieve the best DR that would otherwise not be possible without autonomous agents. Thus, DR needs to take advantage of the decentralized control of smart grid using MAS in order for its full potential to be realized. Thus more research in the use of MAS is needed.

A lot of works in literature have also considered DR for renewable integration because it is a more economical option compared to ESS. The challenge with DR is that it is hard to control the response of participating DR consumers to achieve the same level of control as ESS [15], [31]. Research into a more decentralized control of participating DR consumers using MAS is made all the more important. The true potential of DR for renewable integration still needs to be assessed. Authors in Ref. [31] are one of the few researchers that have investigated the potential of DR for increasing wind energy adequacy. We believe a lot more feasibility (technical and economical) studies of DR for renewable integration still need to be done to truly encourage utilities to use DR for this purpose.

Given the very limited participation of residential consumers in DR, research in smart home EMS with DR becomes even more important to increase residential DR participation. Ref. [32] overviewed the major smart home EMS optimization techniques for minimizing energy utilization and reducing peak-to-average demand ratio. Given the need to protect consumers' privacy and ensure energy transactions in the smart grid are secure, block chains have emerged as a secure way to execute energy transactions for DR in smart grid. Ref. [33] proposed block chain for energy trading in DR management. We believe more research into the use of block chain for DR is needed because the privacy and cyber-security of the future smart grid is paramount.

Finally, hardware-in-the-loop (HIL) simulation using digital twin of smart grid system for DR is needed for reliable implementation of DR in the smart grid. This is an emerging research area and [34] used HIL simulation to demonstrate DR. More research in HIL simulation of DR in smart grid for evaluating grid stability is paramount to ensure safer and wider deployment of DR in the future smart grid.

7. REVIEW OF RECENT DEMAND RESPONSE MATHEMATICAL MODELS IN LITERATURE

Ref. [35] introduced a DSM model in which a DR aggregator act as an intermediary between utility and customers. The utility seeks to minimize cost of operation and give part of its revenue to the DR aggregator as bonus. The DR aggregator then pays the customers compensation for participating in DR programs. The authors formulated a multi-objective optimization problem to minimize utility's cost of operation, maximize the net benefits (bonus received from utility minus compensation payments to customers) to the DR aggregator and to maximize the customer social welfare (received compensation minus dissatisfactory level). The authors proposed an artificial immune algorithm for maximizing the benefits of all participants. This proposed method addresses the inherent intermittent problems of renewable energy sources. Result of this proposed method shows that benefits for all participants (utility, DR aggregator and customers) are maximized.

To prevent formulating incomplete energy models that affect energy prices, it is pertinent to account for asymmetric price responses. As such, at any time slot t, the supply and demand must be balanced at each bus k on network such that the A.C power flow with power from DGs and curtailed power from renewable energy sources (RES) gives the demand response. The nodal voltage is given by [36] in Eqn. 1.

$$E_k = \sum_{m \epsilon \mathcal{N}(k)} V_k(t) V_m(t)^* y_{km}^*; k \epsilon \mathcal{N} \qquad (1) \quad [36]$$

where V_k represent the complex voltage at bus k at time t, V_m represents complex voltage at bus m, y_{km} is the admittance of line (k, m), $\mathcal{N}$ is set of nodes.

This then presents an optimization problem of minimizing the cost function of power generation cost by utilities, cost of curtailed power of RES and price elastic demand costs by the customers. Other optimal function can be the control of the power demand fluctuation through the regulatory of the total violation existing between reactive power demand and average power demand.

Overtime, electricity systems have moved from matching available supply with dynamic demand to matching dynamic supply with dynamic demand. This has given rise to significant mismatch problem such as in periods of high supply and high demand, shifting method of accessing energy resources for electricity generation from procure, store and generate when needed to generate when available, continuous struggle to match variable supply with variable demand, and installed capacity redundancy. As such this creates a need for effective demand-side solutions that will manage variations in both supply and demand. This further presents an optimization solution to model for implementing and validating emergency and economic demand responses.

As an example, it is economical to ensure consumers (m) participate in DR policies by formulating objective function around load blocks (n) to maximize incentives Z paid to consumers for their participation. The objective function is made up of penalties for rigid loads (l) and incentives for curtailment in short, medium, and long-term loads in time T. This is expressed by [37] in Eqn. 2.

$$max(\mathrm{Z}) = \sum_{r=1}^{l} \sum_{t=1}^{T} \sum_{i=1}^{m} \sum_{j=1}^{n} \left[\left(ILC_i \times CL_{r,t,i,j} \right) + \left(ISTSE_i \times STSL_{r,t,i,j} \right) + \left(IMTSE_i \times MTSL_{r,t,i,j} \right) + \left(ILTSE_i \times LTSL_{r,t,i,j} \right) - \left(PRE_i \times RL_{r,t,i,j} \right) \right] \qquad (2) \quad [37]$$

where ILC is incentive for load curtailment, CL is curtailable loads, $ISTSE$ is incentive for short term shifted energy, $STSL$ is short term shifted load, $IMTSE$ is incentive for medium term shifted load, $MTSL$ is medium term shifted load, $ILTSE$ is the incentive for long term shifted load, $LTSL$ is long term shifted load, PRE is price for rigid energy and RL is rigid loads.

8. FUTURE TRENDS FOR DR IN SMART GRID

Some of the technology paradigms that are crucial to the full realization of the potential of DR in smart grid are internet of things, block chain, internet of energy autonomous cloud management of smart grid, self-controlled DR and smart city.

CONCLUSIONS

This paper discussed the various DR programmes, the benefits of DR and the requirement/challenges of DR. We reviewed the use of smart grid technologies such as MAS, block chains and VPPs for aiding DR. Also discussed are the needed regulatory frameworks to facilitate DR, integration of DERs/VPPs and the need to aggregate DR participants using MAS for reduced curtailment of renewable sources. Finally, we reviewed recent DR mathematical models.

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