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Demand response for sustainable energy systems: A review, application and implementation strategy

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ABSTRACT

The growth of advanced metering infrastructure, enhanced communication infrastructure in power grids, and the ability of end-user consumer to actively participate helps in realizing vision of sustainable energy systems. Demand response (DR) programs are developed in order to deploy this ability and make power grids more efficient, environmental friendly, and reliable. This paper presents a review of DR, existing application and a possible implementation strategy in a smart grid environment. Furthermore, classification and status of DR programs in different U.S. electricity markets have been also discussed.

Contents

1. Introduction

According to ‘Grid 2030’ vision report by the US Department of Energy, power disturbances and power quality issues cost $119–$188 billion annually to other industries [1]. A paradigm shift is needed to maintain high system reliability with ongoing changes in power grid. One of the mechanisms to maintain or improve reliability is enabling the consumers to actively participate directly or indirectly and act as a resource [2]. Active participation of consumers in the electricity market could be achieved through appropriate demand side management programs (DSM). Demand response can be broadly defined as one of the mechanism within demand side management and possible with ongoing smart grid activities.

Federal Energy Regulatory Commission (FERC) defines DR as changes in electric usage by end-use consumers from their normal consumption patterns in response to changes in the price of

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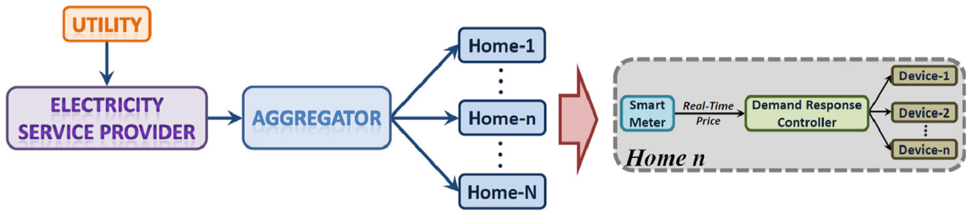

Fig. 1. An illustration of the information flow between utility and customers within smart grid network.

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 [3]. Recently, DR has become more attractive to consumers and system operators because of many factors such as, problems in restructured electricity markets (e.g. the electricity crisis in western state power markets in 2000–2001), price volatility and reliability concerns during the system peak demand conditions [4]. Potential peak reductions via demand response increased to 25% during 2010 to 2012 [3]. In order to fully exploit the potential of DR for peak reduction, integrated distributed generation (DG) and renewable energy resources (RES) (such as wind and solar), DSM programs and communication framework are required. An illustration of price information flow between utility and consumer within a smart grid network is presented in Fig. 1. Residential consumers would be interested in minimizing their own load consumption based on the received price or incentive. Optimal operation can be developed at multiple levels, including the designed automatic DR controller based on smart meter data. DR opportunities may exist in residential homes when the operations of home appliances during peak periods can be shifted to off-peak times [2].

This paper presents an overview and classification of DR resources that could be implemented within smart grid framework. Section 2 provides an overview of existing types of DR programs. In Section 3, a review of the literature available on existing DR models is presented. Section 4 presents various DR activities under existing Independent System Operators (ISO's) and Regional Transmission Organizations (RTO's). Existing DR programs in the US electricity markets are explained in Section 5. A new implementation framework for DR incorporating RES is proposed in Section 6. Finally, Section 7 concludes this paper.

2. Demand response programs

Penetration of advanced metering infrastructure (AMI) in the United States reached approximately 22.9% in 2011, which enables more consumers to participate in DR programs. According to estimates provided by FERC, the annual potential contribution of DR resources that are available in United States is nearly 72,000 MW or equivalent to 9.2% of the forecasted U.S. peak demand during the year 2012 [3]. Influencing the electricity consumption behavior of the consumer through an integrated DR approach into the smart grid is the best possible avenue to achieve energy conservation [5]. There are many types of DR products available depending on the way of utilization [6]. Currently, various available DR schemes that are offered to both commercial and residential consumers are shown in Fig. 2 where we can observe two major categories of DR, dispatchable and non-dispatchable [7,8].

In dispatchable DR programs, the consumers will participate voluntarily into certain schemes by allowing the system operators to control some of their electric appliances directly such as heat ventilating air conditioners (HVAC's) during the peak or emergency periods. DR schemes such as direct load control (DLC) and interruptible/curtailable service (I/C) have been used by the utilities for a long time. The participants who are enrolled in these

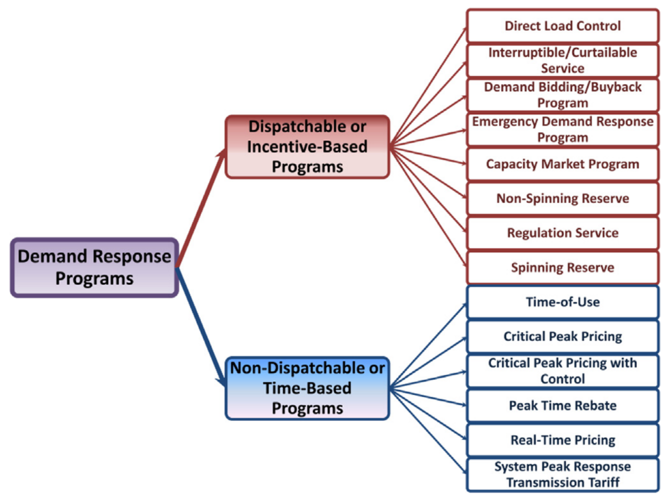

Fig. 2. Classification of demand response schemes.

programs are offered some incentives in exchange to the reduction of their loads to some pre-defined values. Also, those participants, who are not responding, might be penalized. In case of emergency DR program (EDRP), the participants get paid only during the emergency conditions for their measured load reductions [9]. In capacity market program (CMP), the participants are the ones who could offer pre-specified load reductions when system contingencies arise [9], whereas in demand bidding, consumers bid specific load reductions in wholesale electricity markets [10]. DR in ancillary service markets allows the participants to bid for load curtailment only in spot market as operating reserves. Time-Sensitive pricing programs, also called price-based programs (PBP), include three different DR programs; these are time of use (TOU), critical peak pricing (CPP), and real time pricing (RTP). In general, these programs are based on dynamic pricing rates in which the main objective is to flatten the demand curve by offering higher price during peak periods and lower prices during off-peak periods [10]. The design process of TOU program, which is a part of PBP, is described in [11]. CPP has a different rate structure during a CPP event when the electricity usage rates are very high and the price information will be informed early before the event to the participants or consumers. In general, a CPP is implemented only during contingencies. When it comes to RTP, which is also called 'Hourly Pricing (HP)' [12], participants are informed about the prices on day-ahead or hour-ahead basis, and many economists convinced that RTP programs are the most direct and efficient DR programs for competitive electricity markets [13]. Few examples of existing dispatchable DR programs in which the participants receive load control signals includes PG&E SmartAC program [14], the energy smart thermostat program by Southern California Edison [15] and the smart thermostat program at San Diego Gas & Electric Company [16]. Similarly, few existing time-sensitive DR pricing programs are the PowerCentsDC program [17] and the voluntary time-of-use pilot rate offered by the Sacramento Municipal Utilities District [18].

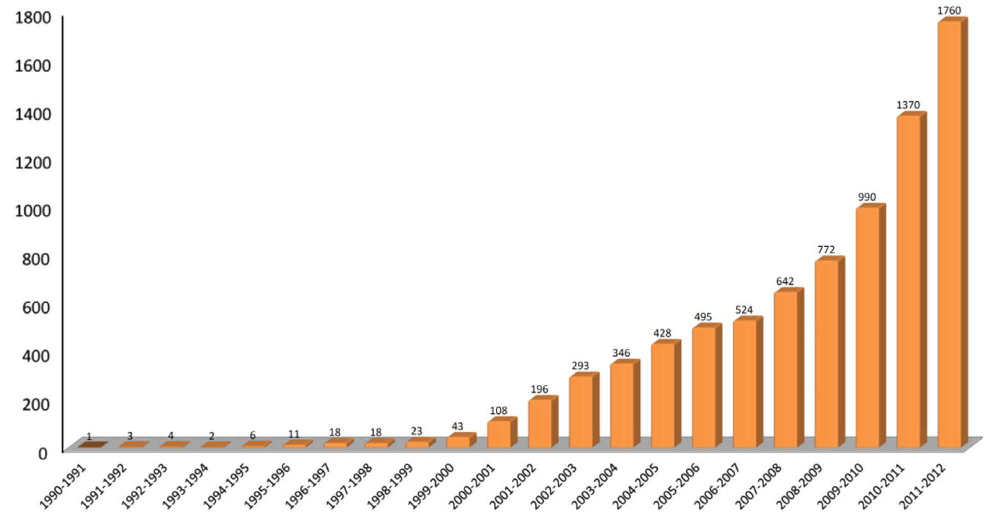

Fig. 3. Number of publications on demand response topic during the last two decades.

3. Demand response experiences within smart grid environment

In recent years, more numbers of researchers have shown interest in this area. As seen in Fig. 3, after 2000–2001, numbers of publications in the DR have drastically increased.

Use of DR in the past several years has shown a significant impact on the wholesale electricity market prices. However, this type of change has led to intensive research and development of various aspects of DR in wholesale market concept such as reliability, DR modeling, and models for scheduling or dispatching DR that can be extended to either wholesale or retail markets. Few of these concepts are discussed in this section briefly. Reliability improvement has been considered as one of DR direct impact. Modeling the behavior of consumers in the presence of DR has been done in [19]. Authors defined self- and cross-elasticity matrix and discussed on the structure of elasticity matrix for various types of consumers. Elasticity matrix has been implemented in pool-based market such as Electricity Pool of England and Wales (EPEW). Elasticity of price affects both the price of electricity and unit commitment. Five types of consumers have been described based on the ability of consumers to react to unusual prices and this ability varies with respect to time of day. Elasticity of load in response to price changes is a pivotal feature of demand response modeling.

The effect of elasticity and participant's share are investigated on the performance of two types of DR programs: DLC and dynamic pricing [20]. This work has shown increasing number of price-responsive load leads to more savings in electricity cost and relation is nonlinear. Including price-elastic load and solving optimal power flow (OPF), it has been shown that price-responsive load causes lower LMP at the buses and bigger social welfare in the system [21]. Another similar simulation has shown that volatility of nodal spot price is reduced and reliability of power systems is improved in the presence of demand response in the system [22]. Implementing programs with non-vital residential loads generally stabilize distribution network and prevented blackout [23]. In [24], the concept of DR exchange is proposed which is pooling the consumers with similar interests in their demand reduction to be bought by various buyers of DR like the retailer, transmission system operator (TSO) and the distribution system operator (DSO). A method for clustering DR participants into small industrial, small and medium commercial and residential loads has been proposed to investigate the potential of different clusters in implemented day-ahead market (DAM) and real-time pricing market (RTPM) [25]. Controllable industrial bulk loads in a proposed load scheduling strategy have been studied to minimize electricity cost under real-time pricing (RTP) [26]. Results showed that concave load profiles could participate more actively in DR program leading to more cost saving. Participation of industrial buildings in a DR program has been studied in [27,28]. This study modeled generation companies (GENCOs), load-serving entities (LSEs), commercial building aggregators (CBAs), and ISO as agents in the agent-based electricity market model. Results have shown that higher penetration of DR leads to less volatility in price. A market optimization method for microgrids in islanded mode was proposed which minimizes electricity cost and changes in the demand [28]. Consumers have been modeled using price elasticity matrix (PEM) and proposed method improves microgrid efficiency and reduces generation cost. "Smart Grids Model-Region Salzburg" project has studied DR as two main parts: Building-to-Grid (B2G) and Consumer-to-Grid (C2G) [29]. B2G is about physical aspects of DR such as voltage regulation and DR implementation. However, C2G focused on human behavior in DR programs. Role of DR in demand side management (DSM) system to deploy significant amount of variable energy resources (VER) has been analyzed in future of UK power system [30]. The impact of DR as reserve balancing capacity in Germany's electricity market on forecasting of wind and load is reported in [31]. Simulating German power grid at 2020, study showed that DR program reduced cost by 20%. It has been shown that implementing DR via DLC program is able to prevent overload in the volt/Var control scheme [32]. Topology of power grid has been taken into account for DR program implementation, in the sense that DSO should determine distribution grid topology based on aggregator data [33]. Also, it has been shown that decrease in demand can cause congestion in the system for specific topology [34]. A field survey in Japan for demand bidding program (DBP) and critical peak pricing (CPP) has showed that implemented DR program in the market is highly dependent on consumer acceptance [35]. In spite of incentives in CPP, surprising results were seen during a survey as DBP was chosen by 35% of the participants and CPP has been chosen by 14%. More details about the RTP with possible ways of implementing this kind of DR in wholesale electricity market conditions have been provide in [36,37]. A stochastic model to schedule reserves provided by DR is presented to demonstrate the benefits of consumers' response to ancillary service demand response (ASDR) programs of ISO [38]. Many ISOs have certain ASDR programs like the ICAP/SCR program developed by NYISO for the purpose of utilizing it during reserve shortage events [39], and day-ahead scheduling reserve market (DASR) program developed by PJM interconnection with an intention to provide day-ahead scheduling resources by giving incentives for demand resources [40]. Also, the Electric Reliability Council of Texas (ERCOT) program designated as load acting as resource (LAAR) program to provide the operating reserves [41]. In [42], effect of DR program on Iranian Power Grid market has been investigated. Authors proposed a combined model of time-of-use (TOU) and EDRP based on load elasticity matrix using test data from 2006. Virtual power player (VPP) that aggregates market entities, namely generators and consumers, and curtailment service provider (CSP) that aggregates small residential or commercial loads into a minimum amount of kW (e.g. 100 kW) to be able to react effectively, have reduced LMP in day-ahead and real-time market in the presence of distributed generation (DG) and storage energy [43]. Benefit of DR in day-ahead market has been analyzed for two cases as fixed and variable unit commitment [44]. This showed that fixed unit commitment can cause undesirable and high LMP in other nodes. In [45], end-user load was divided into two types of responsive and unresponsive loads. HVAC system, which is able to adjust the set-point of temperature based on feedback price signal from the market, has been assumed as responsive load to lower the price and consumption. A settlement mechanism for market clearing price (MCP) proposed in case of DLC for home temperature [46]. In a pilot study in Norway, it is shown that electricity consumption in households is more dependent on habits than electricity price [47]. DR has been suggested as solution to overload problem due to plug-in hybrid electric vehicles (PHEV) and avoid unnecessary changes in the grid [48]. It is also found that retail market level based DR programs are more active than the DR programs in wholesale level [49]. Thus, necessary architectural needs that are required to enhance the competition of different DR programs are addressed in [50,51]. An approach based on game theory has been proposed to find the optimal hourly consumption level of a particular number of consumers when served by a single utility [52]. Another approach similar to this is proposed in [53] for scheduling the power usage by various home appliances throughout the 24-h horizon.

4. Pilot demand response programs for residential customers

First experiments with time varying pricing methods for residential consumers have been done between the late 1970s and early 1980s, under the auspices of the U.S. Federal Energy Administration. In these experiments, focus was on measuring consumer response to static time-of-day and seasonal prices [54]. Static pricing methods determines electricity prices for all the pre-determined period and can change only by changing electricity tariffs. Static price includes flat rate and TOU pricing methods. On the other hand, dynamic rate provides change options on short notice for utilities. CPP and RTP are two common dynamic rate types of pricing methods. However, from the late 1990s, several experiments have been carried out based on dynamic rates in order to investigate impact of DR programs on peak reduction for residential consumers.

In this paper, brief results of some of those experiments are presented in Table 1. Most of these experiments consider two categories of daytime: critical peak time and non-critical times. It is noticeable that in most of these experiments consumers are divided into treatment group with dynamic pricing rate or control group with existing/static rate, and for simplicity these categories are not listed in the table. As is shown in Table 1, CPP program can cause load increase in non-CPP times.

5. Demand response activities at different ISOs/RTOs in the USA

Currently, DR programs are offered by many ISOs/RTOs, such as Pennsylvania–New Jersey–Maryland (PJM), California ISO (CAISO), ISO New England (ISO-NE) and ERCOT as well as a large number of utilities such as Pacific Gas & Electric (PG&E) and Southern California Edison (SCE). An overview on present status of DR contribution by different markets present in the U.S. is shown in Fig. 4 where it can be observed that the PJM has provided higher amount of DR during the years 2011 and 2012. Except ISO-NE, other markets have improved their DR contribution during the year 2012. In this section, various DR activities at different ISOs are summarized.

5.1. ISO New England (ISO- NE)

ISO-NE offers three incentive based DR programs: real-time demand (RT-Demand), real-time price (RT-Price) and day-ahead load response (DALRP) program. In DALRP the consumers are given the opportunity to participate in the ISO-NE's day-ahead energy market indirectly [4]. While in RT-Price, the consumers can reduce their load in real-time once the prices goes beyond a specific point. However, for consumers under ISO-NE's emergency (RT-Demand) DR program has three options. The first two options requires the participants to send their real-time meter data for every 5-min interval to the ISO based on which the participants are paid an energy price for the curtailments offered, but the third option doesn't require any of the communication or telemetry device to participate in it.

5.2. PJM interconnection

PJM interconnection has separate energy, capacity, and ancillary services markets. PJM offers its consumers with three different incentive-based programs: emergency, active load management (ALM), and economic load response programs. The first two programs are utilized for dispatching under emergency conditions. In ALM, the consumers are required to commit prior to the summer period so it was possible to reduce the power consumptions for at least 10 days up to 6 h for each day [67]. Consumers under economic pricing can choose among direct or indirect scheduling of their loads, in order to participate in Real-Time energy market, and also a qualified economic DR resource can provide ancillary services to the wholesale market with appropriate infrastructure. Economic DR resource can participate in three ancillary services markets [68]: synchronized reserves (reducing electricity consumption within 10 min of PJM dispatch), day ahead scheduling reserves (reducing electricity consumption within 10 min of PJM dispatch), and regulation (reducing or increasing electricity consumption within 2 min of PJM dispatch through a frequency response signal or PJM's regulation). In PJM, minimum acceptable capacity of participant in any DR program is 100 kW and CSP is responsible for providing DR to its own electricity consumers.

5.3. New York Independent System Operator (NYISO)

In NYISO, currently five DR programs are offered [69,70,71]: emergency DR program (EDRP), special case resource program (SCR), targeted DR program (TDRP), day-ahead DR program (DADRP), and demand side ancillary service program (DSASP). Out of these EDRP, SCR and DADRP are incentive-based DR programs. EDRP program pays strictly for energy. Although, consumers under SCR are provided with a payment for their load reductions, but it can also penalize the consumers when they do not obey their submitted load curtailment. Participants under DADRP have the opportunity to submit bids into NYISO's day-ahead market (DAM) only when they offer a load curtailment above a certain bid price [72].

In addition, all these three ISO/RTOs have developed new opportunities that will enhance the participation of DR in ancillary service markets for example, DSASP program offered by NYISO which allows the DR to provide regulation, synchronous reserve, and non-synchronous reserve services to NYISO ancillary service

Table 1
Pilot demand response programs with dynamic pricing for residential loads.

Utility name	State/province	Year	Number of participated consumers	Types of demand response program	Percentage peak reduction due to DR program	
					Critical peak time	Other times
APU [55]	California	2005	123	PRT[1]	12%	–
PG&E, SCE, SDG&E [56]	California	2004	2500	CPP w/o Tech[2]	13%	5%
				CPP w/Tech[3] 5 h	25%	−7%
				2 h	41%	13%
PG&E, SCE, SDG&E [56]	California	2004	226	CPP	51%	–
				TOU	–	32%
PG&E, SCE, SDG&E [57]	California	2005	199	CPP	43%	–
				TOU	–	27%
Xcel Energy[4] [58]	Colorado	2006–2007	3699	CPP	44.8%	0.1%
				TOU	–	10.6%
				TOU+CPP	52.2%	10.6%
Gulf Power [59]	Florida	2000–2001	2300	CPP	44%	22%
Idaho Power Company[5] [60]	Idaho	2005–2006	860	TOD[6]	–	1.84%
				EW[7]	about 50%	–
Commonwealth Edison[8] [61]	Illinois	2003–2006	1500	RTP	15%	3%
AmerenUE[9] [62]	Missouri	2004–2005	545	TOU	12%	–
				TOU+CPP	12%	–
				TOU+CPP w/ Tech	35%	–
GPU [63]	New Jersey	1997	Not available	TOU+CPP w/ Tech	50%	26%
PSE&G[10] [64]	New Jersey	2006–2007	1286	CPP	26%	–
				TOU	21%	–
Hydro Ottawa [65]	Ontario	2006–2007	498	TOU	5.7%	2.4%
				CPP	25.4%	11.9%
				CPR[11]	17.5%	8.5%
BPA, Clallam County PUD, The City of Port Angeles, PGE, PacifiCorp [66]	Washington and Oregon	2005	112	RTP	17%	–
				TOU+CPP	20%	–

[1] PRT is for peak rebate time which means utility is willing to pay incentive to consumers on critical peak time to reduce their consumption. RPT is one kind of CPP program.
[2] CPP w/o Tech is for critical peak pricing DR program, which is enabling with communicating technology.
[3] CPP w/Tech is for critical peak pricing DR program without enabling technology.
[4] In this project, different enabling technologies and consumer categories have been studied for each DR program and Table 1 reports only maximum peak reduction for each program.
[5] Ref. [65] reports peak reduction in kW and approximation of maximum peak reduction. Also, EW program was carried out for four hours a day over the period of ten days, and there is no recorded data for other time of day to provide saving.
[6] TOD is for time-of-day program, which is a conventional TOU program where the participants were charged different rates by time of the day.
[7] EW is for energy watch, which is a CPP pilot where the participants were notified of the CPP event on a day-ahead basis.
[8] In this project, maximum percentile reduction for reported day has been considered as critical peak time reduction and average reduction during whole summer is reported for other time.
[9] This project has been done in two years and the reported values are for maximum reductions for the year of 2004. Also, it was reported that for other times, load reduction for implemented DR programs were insignificant.
[10] Participants in this project have been divided into two categories as central air conditioning ownership and without central air conditioning, and here only maximum reductions are reported.
[11] CPR is for critical peak rebate.

markets. As of 2007 [73], most of the DR resources are increasingly being integrated into the organized markets and the level to which these resources can now participate in various ISO/RTO's which is dependent on their participation in the markets. Hence, an overview of DR participation in different RTOs and ISOs is required. Table 1 gives an overview of DR participation in different markets like energy, ancillary services, and capacity markets [73]. From the table it is interesting to identify that almost all ISO/RTOs are biding DR in real time market operations. Hence, the real time price information flow to the consumers could be through either web enabled service or by smart metering infrastructure given to participating residential consumers. Finally, from Table 2 it can also be observed, except MISO, almost all the ISOs and RTOs are participating in both energy and ancillary services markets. However, it is already understood that the ultimate goal of a DR program is to reduce the peak demand. Successfulness of DR programs completely depends on the weather and the type of suitable DR program that is implemented by an ISO/RTO or by any utility. In order to understand the impact of DR programs that could affect the shape of demand curve, few practical experiences are considered as explained.

5.4. ISO-NE

New England has initiated a load response program (LRP) during the year 2001. LRP provides incentives for New England Power Pool (NEPOOL) participants in exchange to the energy demand reductions during the peak periods. The program took place on June 1, 2001 and continued until May 31, 2002. ISO-NE has offered two separate programs [74]: The DR program (also called Class-1) and Price Response Program (also called Class-2). Consumers under class-1 are required to commit mandatory energy reductions (100 kW to ~5 MW) in exchange to some incentives for their ongoing participation and also for saving their energy consumption.

Consumers under class-2 are volunteer participants, and they are allowed to participate for a particular period of time as specified by ISO-NE. In this program, the consumers will receive payments for reducing their actual amount of energy consumption voluntarily and the amount of energy reduction must be between 100 kW and 5 MW. Usually, these programs are implemented on a 30-min prior notice given to consumers by ISO-NE. The LRP for class-1 participants took place only on August 9th, while for class-

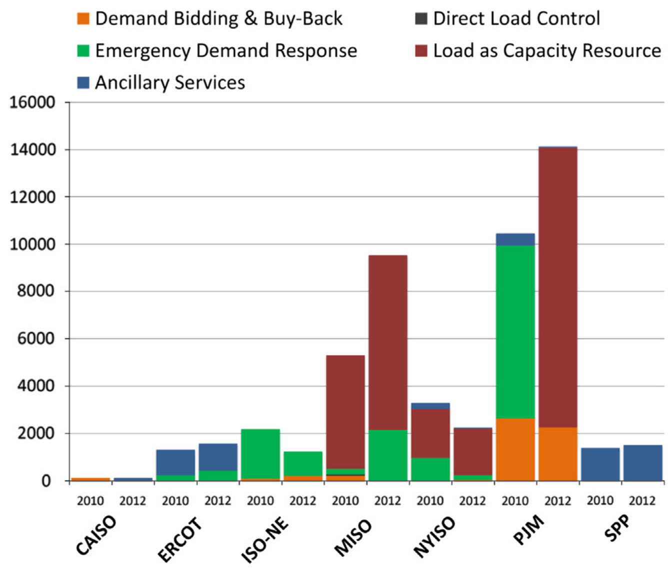

Fig. 4. An overview of DR contribution by different electricity markets in the U.S. utilizing various DR programs [3].

Table 2
Demand response status in the U.S. RTOs and ISOs.

Market DR program type	NYISO	ISO-NE	PJM	CAISO	MISO[a]	ERCOT
DR Program	✓	✓	✓	✓	✓	✓
Emergency DR program	✓	✓	✓			✓
Real time DR bids	✓	✓	✓	✓	✓	✓
Day-ahead DR	✓	✓	✓			✓
Capacity market DR Participation	✓	✓	✓			✓
Ancillary service	✓	✓	✓	✓		✓

[a] MISO is Midwest Independent System Operator.

2, the program took place on July 24, 25 and again on August 7, 8, 9, and 10 [75]. Participants under class-2 can choose when to reduce the load based on the forecast/actual energy clearing price (ECP) of electricity market.

5.5. California statewide Critical Peak Pricing (CPP) pilot program

The California energy commission and the California public utilities commission have jointly started a statewide pricing pilot project during 2003–2004 [76]. This project is implemented by three investor-owned utilities in California: Pacific Gas and Electric Company, Southern California Edison, and San Diego Gas and Electric Company. The pilot program has about 2500 residential and small commercial consumers. The main objective of this program is to test the response of the residential consumers to CPP DR program. A CPP tariff is offered to the consumers by the utilities companies in which the electricity prices were discounted during the "normal" days in return to higher electricity prices that are to be dispatched during high peak periods when the system conditions are jeopardized.

6. Proposed hierarchical framework for control and management of smart distribution systems

Incorporating DR programs into smart distribution systems could leverage economic, reliability and sustainability opportunities, but the major challenge here is to have an efficient integration of DR and RESs. Thus, an attempt has been made in this paper to formulate a DR model along with the integration of renewable resources, mainly wind and solar and smart grid technology into optimization problems as shown in Fig. 5.

This model works on the basic assumption that both the consumer and supplier are bound to a contractual agreement that allows the consumer to receive hourly price information like several minutes prior to the corresponding hour. Practically, this helps the consumer to respond to the price signals that he receives in look-ahead manner, which in turn allows him to manage his electricity consumption accordingly [77,30]. However, real time pricing options are already available for industrial and commercial consumers [78], for domestic consumers, such schemes have only existed with limited implementations for example [79–83]. In the proposed framework, renewable resources such as wind and solar power are considered at two levels of local or building level and system level. Recent studies show that renewable resources will increasingly contribute towards meeting the system load demand [84]. Although published research attempted to integrate VERs with DR, one of the primary limitations for efficient integration is a fully automatic technology with minimum consumer intrusion that can increase the participation of DR. In the proposed framework, DLC technology is adopted as it has the potential to provide accessibility to every individual consumer in the system and reach the economical and environmental goals. The DR implementation suggested in this paper utilizes a pricing scheme in the day-ahead market scenario so that the residential consumers are able to see the MCP ahead and may change their usage behavior accordingly. In this model, electrical home appliances have been divided into two categories as controllable and uncontrollable. Controllable appliances can communicate with controller and change their consumption based on control signals such as a refrigerator, water heater, and HVAC. Consumption change in these appliances would be in the acceptable range and does not cause any inconvenience to the consumer. On the other hand, uncontrollable appliances are based on instant decision of consumers such as lights, furnace and oven. As this part of load is

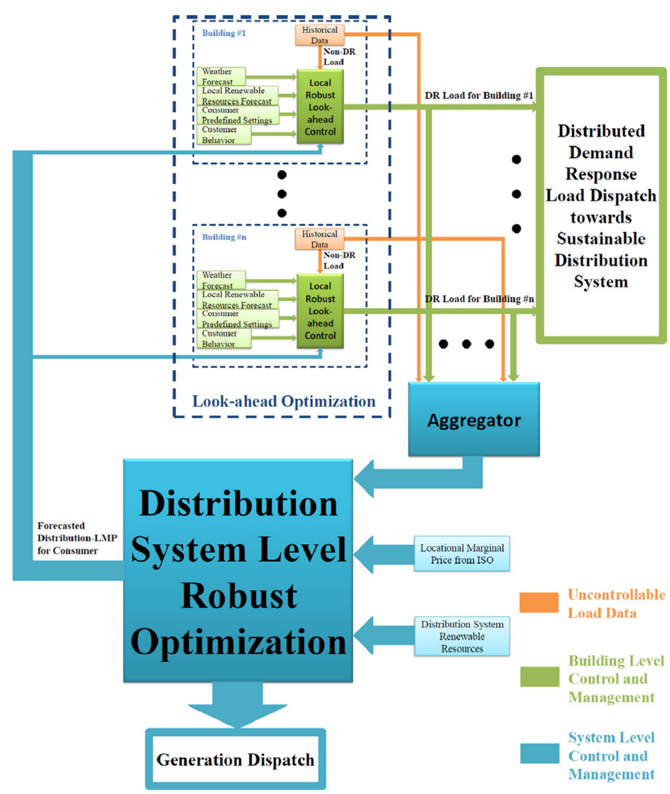

Fig. 5. Framework of demand response and renewable energy integration into smart distribution system.

unpredictable, historical load profile can be considered as a useful data. Since it is unreasonable to expect the consumers to continuously monitor the price, the proposed model will adopt with the controllable appliances of buildings. Consumer pre-determined settings, weather condition forecast, local VERs forecast, prediction of consumer behavior as uncertainty, and price signal are major inputs for local control, therefore, control approach should be able to take these into account to generate a control signal. The goal is to optimize load consumption based on availability of local VERs, so every building will demand lower level of energy from distribution system by maximizing local resources. Controllers have pre-determined comfort levels by the consumer that can operate the system with different electricity consumption, so in the presence of renewable energy and/or lower price, the system can operate at highest comfort level, and in reverse, during the absence of renewable energy and/or higher price, the system would operate at highest energy saving mode. Suggested approach can lead to a more reliable and sustainable grid. Utility also gains benefit from the local controller by load shaving and increased reliability. Also, look-ahead ability in the controller can lead to smarter decisions and more benefit. As all forecasted values have some degree of uncertainty, the local controller should be robust against defined uncertainty. One of the most distinctive features of distribution systems is unbalanced load. In this framework, a proposed three-phase OPF at distribution system level can deal with unbalanced three-phase load and generates price signal for each phase in real-time. Although MCP is implemented at zonal level, for future smart distribution systems, smart grid investment needs more precise and fair pricing system. Proposed OPF problem in this framework can adopt generated LMP by ISO and existing RESs in distribution system into optimization problem. One of advantages of the suggested approach is that it requires a very minimum change in order to adapt with the current management system. RESs have been integrated into proposed OPF to minimize exchange between distribution system and main grid by maximizing RES usability in the distribution system that can avoid congestion on transmission lines as well. Three-phase OPF creates fair opportunities for consumers to participate in DR programs and gain most possible benefit. Note that uncertainties associated with price and others such as consumer behavior and weather forecast uncertainty could be considered via robust optimization model as these are particularly suited to address uncertain but bounded parameters [85,86]. Using proposed framework, surplus renewable resources of distribution system would be reported as available generation to ISO. Finally, this type of DR framework, which is combination of look-ahead and real-time computations, would cause a transition of a centralized functioning of the grid to a distributed control of smart grid.

7. Conclusions

Demand Response (DR) is playing a greater role in the electricity industry and has opened up new avenues for residential electricity consumers to participate in grid operations within the framework of ongoing smart grid activities. Different types of DR programs are deployed to make power grids more efficient and reliable. DR can improve reliability through load profile shaping. DR programs such as, EDRP, interruptible/curtailable service, CMP, and CPP are able to shed or shift load to reduce the peak load. Also, using ASDR, TOU, and RTP programs, helps in similar efficiency and reliability goals. Penetration of these programs is dependent on consumers and diverse DR programs needs to be introduced to encourage end-user consumers to participate. However, studying DR participation shows significant growth in recent years in U.S. ISO/RTO and it has grown about 10,000 MW from 2011 to 2012 [3]. Several ISO/RTO's in U.S. have implemented DR programs in order to reduce peak load and save energy.

It is also anticipated that the efficiency of the RESs adopted in the proposed framework might be dependent on the regions or on different seasons during a year. The amount of solar radiation and wind speed may vary based on the regions; however, adaptive look-ahead approach is expected to deal with the intermittent nature. Controllable loads have the capability to assist with the local renewable energy sources and also provide ancillary service to distribution system. Our recommendation for the future work is to allow higher penetration of RES into a smart grid environment by simultaneously including large number of local controllers and new pricing schemes appropriate for distribution systems.

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