Review of Demand Response under Smart Grid Paradigm

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***Abstract*—Demand response (DR) has an important role to play in the electricity market for maintaining the balance between supply and demand by introducing load flexibility instead of only adjusting generation levels, at almost all operational time scales. There are many players in the market who benefit from DR, like the TSO, DSOs, retailers and end-customers themselves. The recent advent of smart grid technologies advanced the integration of DR by providing the needed information and communication infrastructure to the existing grid. Available literature on DR talks about the concept and definitions of DR, possible DR models for various region-specific market structures along with few DR implementation experiences in a system with ever increasing levels of loads along with evolution of innovative technologies like renewables, micro-grids, PEVs, etc. In this paper, the available literature on DR is categorized into general concept papers and papers on DR models applicable to the wholesale or retail markets, and are presented in a precise manner.**

***Index Terms*—Demand Response, Smart Grid, Wholesale Electricity Market, Retail Electricity Market**

I. Nomenclature

AMI	Advanced Metering Infrastructure
ATC	Available Transfer Capacity
CPP	Critical Peak Pricing
CSP	Curtailment Service Provider
DER	Distributed Energy Resources
DG	Distributed Generation
DMS	Distribution Management System
DR	Demand Response
DRP	Demand Response Provider
DRX	Demand Response Exchange
DSM	Demand Side management
DSO	Distribution System Operator
$EDRP$	Emergency Demand Response Program
$EENS$	Expected Energy Not Supplied
EMS	Energy Management System
$HVAC$	Heating Ventilation and Air Conditioning
$I\&C$	Interruptible and Curtailable Load
IL	Interruptible Load
MO	Market operator
$NSGA$	Non-Dominated Sorting Genetic Algorithm
PEV	Plug-in Electric Vehicle
PTR	Peak Time Rebate
RTP	Real Time Pricing
$SCUC$	Security Constrained Unit Commitment
TOU	Time Of Use
TSO	Transmission System Operator

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II. Introduction

DEMAND Response is going to become a part of the system operations in the smart grid driven restructured power system around the world in the near future. DR implementations are more active at the retail level than the wholesale level. To enhance competition at the retail level, separate entities called retailers have also come into the scenario. The increased retail level competition is associated with a variety of problems which can be categorized as market based and network based problems [30]. The former problems occur when the generators or the retailers face financial risks caused by spot price volatility in the wholesale electricity market. The latter problems occur when TSO and DSOs have to maintain reliable power supply during times of peak demand or low operating reserves or when constrained networks are operating at their limits. Traditionally, problems of the latter type have been handled single sidedly, by the generating utilities who have to either ensure a security margin of generation to be always available to be dispatched when asked to do so by the ISO or in the opposite case have to reduce generation to bring the network from a constrained state to the normal state. A resource which is left unused is the demand side resource which can also be helpful in such situations.

Demand Side Management was introduced by Electric Power Research Institute (EPRI) in the 1980s. DSM is a global term that includes a variety of activities such as: load management, energy efficiency, energy saving, etc. The problems mentioned above can be categorized as short term problems whereas problems such as environmental effects of burning coal to produce electricity can be categorized as long term problems. DSM schemes like energy efficiency and energy saving schemes are potential inhibitors of such problems whereas the short term problems can be tackled by efficient load management programs which are collectively referred to as Demand Response. According to Federal Energy Regulatory Commission, Demand Response (DR) is 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." The end-use customers can also be the customers who are participating in the wholesale market operations.

Based on how the changes in electric usage are implemented the DR can be classified as shown in the Fig. 1. This paper presents the review of available literature on various aspects

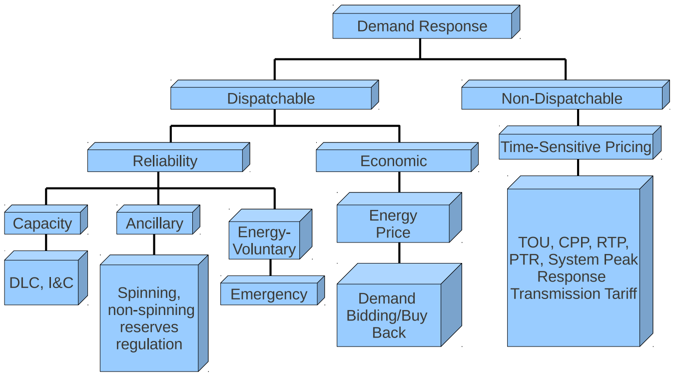

Fig. 1. Classification of DR schemes

of modeling, implementing and issues in realizing Demand Response at various market levels in a smart grid scenario.

The organization of the paper is as follows: Benefits of DR are summarized in Section III. Section IV presents the review of the literature available on Demand Response based on the market levels. The challenges involved in DR realization are pointed out in Section V and Section VI concludes the paper.

III. Benefits of DR

Besides the motivations as to why involve demand side into the operational aspects of the system other benefits of DR are listed below:

- DR can reduce system peak load in the long term and therefore postpone the need for building new power plants, leading to considerable environmental impacts.
- TSO can benefit from DR by being able to improve reliability of the transmission network. Improved network reliability results from reducing the probability of forced outages when system reserves fall below desired levels. By reducing electricity demand at critical times (e.g. when a generator or a transmission line is unexpectedly lost), DR dispatched by the TSO can help to return system reserves to pre-contingency levels. Moreover DR can be dispatched in less than 5 minutes, whereas a peaking power plant can take up to 30 minutes to ramp up to full capacity.
- DSO can use DR for managing network constraints at the distribution level- [16]
  1) Relieving the voltage constrained power transfer problem
  2) Relieving congestion in the distribution substations
  3) Simplifying outage management and improving the quality of supply

  During incidents of congestion or peak periods DR relieves the components of the network from the undesirable stress. This way a gain in service quality and reliabilty is achieved. The load curtailment during incidents is expected to reduce the monetary global value of the non-supplied load.
- Retailers buy electricity from the wholesale market and sell it to their consumers at a flat rate. So they are exposed to the financial risks involved with the spot price volatility in the real-time horizons. In order to cover most of these risks they can ask their consumers to reduce their consumption during the times when spot prices are most volatile and reach their peaks, provided the customers can receive financial reward for such decrease in consumption.
- The short term impacts of DR on electricity markets leads to financial benefits of both the utility and the consumers.
- Deployment of new technologies like, distributed generation (solar, small wind, geothermal) and storage (stand-alone, PHEV) also motivate the inclusion of DR as a key component for the smart grid. For example during times of high wind speeds, the generation is quite in excess. A curtailment in wind generation proves to be inefficient for the wind farm, making its payback period quite high. So DR can be used to increase the demand during such periods.

IV. Literature Review

The classification of papers on DR is made based on the generic models and literature, direct applicability of algorithms to wholesale and retail markets. Fig. 2 gives an overview of the papers classified on the basis of aforesaid notion. The number

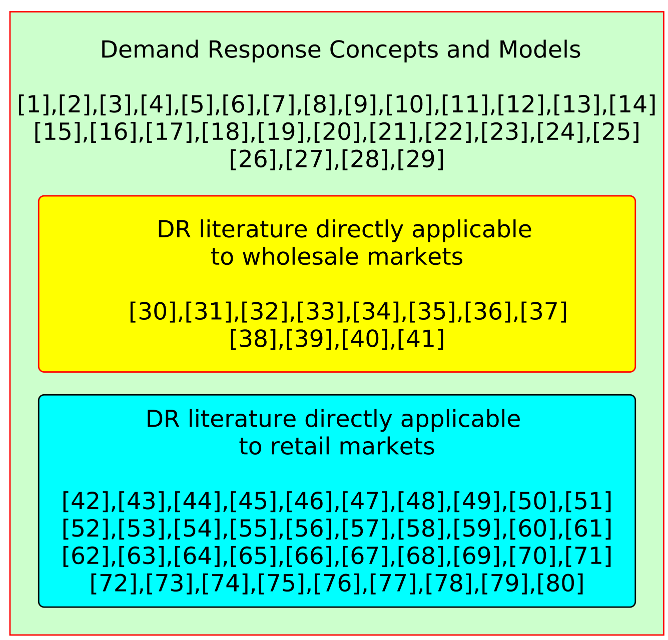

Fig. 2. Available publications classification

of major journal and conference publications from year 2000 to till July 2011 is shown in the Fig. 3. It is estimated that a total of 250 publications on DR can be available by the end of year 2011. The available literature on Demand Response at present can be broadly categorized into:-

A. Literature on DR concepts and models

The literature in this category mainly talks about the concepts which guide incorporation of DR into the system

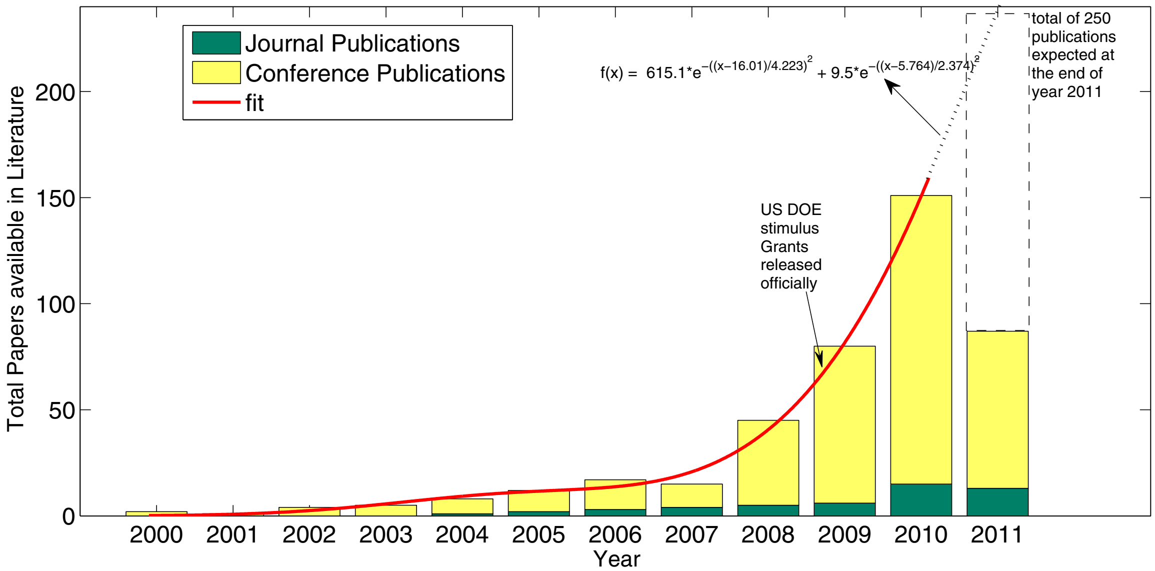

Fig. 3. Journal and conference publications chronology

operation at all operational time-scales. Various models for scheduling or dispatching DR which can be extended to either wholesale or retail markets are presented. Some papers also present measure of the effects of inclusion of DR into system operation. Reference [1] introduces the economics theory of the electricity industry. The old "vertical integration model" (where central planners set the generation capacity levels, which is an inefficient solution) and the new market-based ones are presented. The problems related to transitioning to the new model are analyzed. The market-based model relies on energy prices to achieve reliability (expressed as outage probability) and short-run efficiency in production and consumption. To work properly, effective DR mechanisms are needed: consumers must be charged on an hourly basis and vary consumption with a certain level of responsiveness according to marginal prices (active demand side). If DR is inadequate, socialized reliability solutions (such as installed reserve margins) become necessary. In reference [2], a review of DSM techniques and a list of future challenges are presented. Regarding dynamic pricing, the authors states that "if prices are not sufficiently different, it will be difficult to justify investments on DSM". More details about the real-time electricity pricing with the possible avenues for their implementation are discussed in [3], [4]. Authors in reference [5] have carried out mathematical analysis of the side-effects of DR apart from the desirable result of reducing the local market price of electricity on a simple 3-bus power system. The importance of simultaneous plant production and demand reduction scheduling for the establishment of a fully competitive market is emphasized in [6]. A shift of thought from demand response being negative generation to redistributable demand is proposed. The optimization problem is formulated based upon the cost of producing electricity which consists of the sum of cost of generating it and the cost of demand reduction. The constraints involved are limits on generator capacities and demand reduction amount, the total available energy reduction from a particular Demand Side Bidder (DSB), and the supply and demand balance for every scheduling period. But the paper fails to address the network operating constraints. In reference [7], authors proposed a method for optimally selecting the locations of DR alongwith their capacities to achieve a number of objectives like maximizing ATC, minimizing EENS, minimizing active power loss and minimizing total DR program capacity. In case of such multiple objectives which are conflicting in nature, the NSGA II algorithm is used to obtain pareto optimal solution, for a given domain of possible solutions.

In reference [8] an attempt is made to evaluate the effects of implementing demand response on system variables like total cost of energy and market clearing price by formulating a unit commitment problem. Reference [9] proposed a method of load control based on the price elasticity of consumers. The load control event is triggered by the need of the supplier to reduce the load. The optimization problem is minimization of the cost to the consumers subject to constraints like maximum load reduction for a particular customer, maximum increase in electricity price, and the load and generation balance. A simulation model involving the model of the grid incorporating the aggregate generator inertia, governor action, and load-frequency dependence, model of large number of refrigerators (as frequency responsive loads) and the model of a dynamic demand controller (DDC) has been developed in [10] for investigating whether frequency stability could be provided by incorporating DDC into consumer appliances. Such a concept of frequency responsive load shifting can be extended to the network level of a distribution or transmission network and hence has been categorized under the category of "generic concept".

Authors in [11] examined the use of real-time electricity pricing in the domestic sector in supporting the penetration of wind generation. The basic idea being that during periods of low wind generation i.e. when only thermal generation is available and the forecasted load is close to the supply capacity, then the real-time price signal will be high as per the pricing model and thus bring in DR. Authors in [12] discuss the viability of a reliability based rather than a price-based DR program as the Korean electricity market is an incomplete market as price signals are not informed to the customers. Moreover the demand bidding market is settled after the generation scheduling plan is done. The incentive to the participants of the proposed reliability based DR programs comprises of an energy reward, a reserve reward and a capacity reward which must be set so as to fully compensate the participants of their cost of load reductions.

Reference [13] proposed the modeling and integration of the Distribution system topology into the DR scheduling process. This allows calculation of DR available at the nodes of the transmission thus helping in better monitor and verification of requested DR. This paper also proposes the addition of a Distribution System Operator to analyze the effects of DR events on the distribution grid. Reference [14] proposed the implementation of DR from the DMS level instead from an aggregator or DRP or substation level in order to achieve the additional benefits of DR like efficient congestion relief in the distribution network, satisfying the voltage constraints of distribution system buses while achieving load reduction which may be violated otherwise. Reference [15] explored the various issues related to the two forms of demand response namely, reliability based and price based demand response. It claims that neither of them can individually maximize the benefits out of demand response.

DR can be considered as a virtual resource which can be exchanged between two groups of participants, retailers, DSO, TSO and MO on one hand and the aggregators and consumers on the other. In this respect two business models are proposed in [16] namely, bilateral and pool based. Authors in reference [17] investigated the performance of centralized and decentralized approaches for DR on a modified IEEE 34 bus system with detailed household load models including dynamic models for air-conditioners, water heaters as well as an aggregated load profile for other loads. The effects of these lower level distribution loads on the transmission level operations can be easily derived after reading the paper. A small islanded microgird with 3.125 MW, 2.4 KV diesel generator, equipped with speed governor and exciter, as a DG alongwith fixed active and dynamic loads are modeled in MATLAB/simulink environment in [18] for simulating frequency and voltage regulation events and observing the recovery due to the response from flexible loads which are centrally controlled by a controller based on Adaptive Hill Climbing technology (AHC). Simulation results show that such control actions improve the transient part of the frequency profile under sudden load disturbances.

A primary step in DR implementation is the detailed knowledge of customer potential through customer aggregation and the characterization of the demand clusters. For example customers whose demand follow the day ahead or the real-time prices are the ones who are more suitable for DR programs selection from the view point of both the customers and suppliers. So, the effective contribution of these classes of customers needs detailed knowledge of customer potential through customer classification and their characterization. Clustering provides the typical load pattern of each customer class which can then be used for applications like choosing suitable DSM programs, tariff structures, etc. and demand characterization or modeling provides an effective tool to estimate the potential demand reduction, loss of service cost and the impact of DR programs on demand. In literature there are a number of clustering techniques like K-means, self-organizing maps, modified follow the leader, etc. [19] presented a modification on the K-means and the fuzzy average K-means to make it more suitable to DR applications. Clustering Dispersion Indicator is proposed as a measure of adequacy of the methods on the basis of which these methods are compared after implementing them on the data of 316 load curves of non-residential customers of Tehran Distribution network. In reference [20], the use of the ISODATA algorithm for customer classification is proposed which also includes temperature dependency correction and outliers filtering. The applicability of the algorithm on practical data is questionable. Reference [21] proposed the integration of tools like self-organizing maps and physically based load modeling to achieve the above mentioned requirements. [22] presents the lessons learned from the relation between networks and consumer electronics, and higher-layer requirements for network infrastructure regarding interoperability and standardization. References [23]–[26] provide an introduction on the smart grid talking about the problems of the actual grid, the requirements for the future smart grid, the components, benefits, and the entities involved in the development process, framework to classify different types of Energy Management programs and a case against the smart grid. Reference [27] proposes the nanogrid paradigm as an alternative to the Smart Grid top-down approach that adopts the point of view of the grid. Reference [28] illustrates the characteristics of building networks and their relation with the smart grid. Reference [29] presents a set of guiding principles for DR, for each of the domains of utility, customer and energy management.

B. Literature on DR frameworks directly applicable to wholesale markets

Reference [30] proposed the concept of a Demand Response Exchange in which the demand reduction of interested customers is pooled into the exchange to be bought by various buyers of DR like the retailer, TSO and the DSO. The main idea behind this concept is that the traditional retailer based, TSO based and distributor based DR schemes are only partial solutions to an effective DR program as they focus on benefits of only a particular set of participants. This method aims to optimize the overall benefit of DR and moreover reward customers better by allowing them to deal with multiple DR-involved players. The summary of the DR implementations in wholesale markets are presented in [31]. The usefulness of DR in balancing the high penetration of renewables is presented in [32]. In [33], combined day ahead scheduling of energy as well as reserve from both generators and ILs using a probabilistic approach is presented. Authors in reference [34] have devised a complex-bid day-ahead market clearing mechanism in which the DR is scheduled along with the generators energy. Reference [35] proposed a method of congestion management based on the traditionally followed method of congestion management (in decentralized market structures) in which the generators are redispatched after the auction-based dispatch (ignoring network congestion). The generation redispatch may cause additional costs and consequently increase the cost of electricity production. This paper proposes the redispatch of demand alongwith generation to handle congestion as an effective solution to mitigate the same in a cost-effective manner.

Reference [36] discussed about the role of a curtailment service provider called Ener NOC bidding DR into the synchronized reserve market in the PJM. The authors in [37] proposed a short-term stochastic SCUC model for scheduling the generating units energy and spinning reserve as well as the reserve provided by the demand response providers (DRPs) simultaneously. Reference [38] presented a non-simplex algorithm to solve an optimization problem in which the objective function is to minimize the production cost of a storage type industry in a scenario in which the electricity price varies over time periods. In reference [39] a short term physically based load model of the demand of a group of air conditioners as a function of outside temperature, air conditioning system parameters and the average thermostat setting. The formulated problem is a linear programming problem, the solution to which provides the optimal schedule of electricity usage given the predetermined electricity price schedule.

References [40], [41] discuss various means for the real-time scheduling of ILs using OPF, dynamic programming, priority-based heuristics inference rules and probabilistic models. Reference [40] presents real-time scheduling of ILs along with generating units by the solution of OPF problem. The conventional OPF is modified to consider a range of ILs at load buses of different power factor and duration of curtailment. Reference [41] propose optimal scheduling of IL portfolios as well as modulating the schedule in the real time owing to influence of load variation and forecasting errors. The customers' requirements are dealt with by fuzzy variables and the optimal or near optimal schedule of ILs are obtained through dynamic programming (DP) search scheme. A priority-based heuristics inference rule (PBHIR) is employed as a regulator in the real-time. The proposed method is called as the model reference adaptive control (MRAC) strategy.

C. Literatute on DR frameworks directly applicable to retail markets

Most of the papers reported on DR, point to the retail market implementations. The architechtural needs of the DR esp., for promoting end-consumer participation are addressed in references [42]–[44].

Scheduling of ILs to achieve a system requirement of hourly curtailments is considered in [45]. This objective alongwith requirements like minimizing payment to the ILs, minimizing frequency of interruptions on ILs form a multi-objective optimization problem which is complex, non-linear and non-continuous problem, solved using binary particle swarm optimization technique. Authors in reference [46], based upon concept of a virtual power plant which comprises of a large number of customers with thermostatically controlled appliances propose an algorithm to determine the optimal control schedules of these appliances or the optimal load reduction bids that an aggregator should present in the electricity market. Reference [47] presented the vision of a home electrical system which consists of solar PV modules, stand-alone energy storage system, electric vehicle, small wind turbine, a bio-fuel burning micro- turbine, set of controllable (TV, lights, etc.) and uncontrollable appliances (HVAC systems). Assumptions involving a day-ahead forecast of the local energy production from wind and solar systems based on weather forecasts, a dynamic pricing signal over the next day and availability of a module to forecast the non-controllable appliances consumption based on the home grid history data are made. The objective is to minimize the cost of energy used over a time horizon. In reference [48] an approach to solve the energy cost minimization problem to find out the optimal hourly consumption level of a number of customers served by a single utility is proposed. In other approaches, the optimization problem is solved centrally and accordingly the consumption levels of customers are centrally controlled, that requires high level interactions between the utility company and the customers. Here, the authors propose an Energy Consumption Scheduler (ECS), which can be coupled to the smart meter at each customer premise to solve the optimization problem locally and autonomously using a game theoretic approach.

Authors in [49] proposed an optimization model to adjust the hourly load level of a given consumer in response to hourly electrical prices. The objective is to maximize the utility of the consumer subject to minimum daily energy consumption levels, limits on hourly load levels and ramping limits on such load levels. In [50] a DR model based on TOU and EDRP methods, using single and multi-period load models is proposed. The paper shows that the demand and load shape can be changed by the SO by implementing such programs. The effect of TOU prices, incentive rates and demand elasticities on shaping the load curve are analyzed. An optimal load scheduling strategy for participating industrial loads is formulated in [51], in a scenario in which DR is implemented through Real-Time Pricing scheme. The objective function is minimization of energy cost (linear function of consumption over periods) with a set of linear constraints such as, amount of electrical energy required to reach production target, bounds on energy consumption in an hour. Rigorous mathematical analysis is done to obtain relationship between cost savings and the parameters like plants installed consumption capacity, plants storage capacity, and terms which describe the structure of the RTP tariff. The approach can be challenged on the grounds of the assumptions made such as that of adequate spare consumption capacity. Authors in [52] proposed a method of scheduling power usage by various appliances in a home in a real-time pricing scenario in which real-time price signals are sent from the utility to the customer end. The proposed method considers scheduling of both- only schedulable as well as both schedulable and real-time appliances over the 24 hours horizon and can be implemented on home area networks (HAN) that may support other applications such as sharing internet access, etc. with a common control channel.

The idea of integrating DR as a source of primary frequency control alongside that from dedicated generators is proposed in [53]. Reference [54] provided an approach called Event-Driven (Emergency) Demand Response in which given a particular type of credible system contingency, particular load reductions are activated, with an objective to restore the operating reserves to a desired level. Authors in [55] proposed the modeling and simulation of commercial building loads especially the HVAC loads in order to estimate the control margin achieved for a certain load control event. The architecture consists of a central controller who calculates the optimal control actions according to the constraints introduced by the retailers/distribution company and the control strategies programmed in the local controllers at the EMS of each consumer building. Reference [56] focused on the business case for a consumer portal demand response functions. Consumer portal acts as a gateway between the utility and the consumer and facilitates many energy service functions including flexible pricing, remote equipment diagnostics, interfacing with building EMS (BEMS), remote energy use monitoring and control, etc. In reference [57], aspects of grid modernization that affect consumer-end activities are addressed, which can be categorized into information and infrastructure, instrument and technology and intelligence and automation. In [58], a framework for jointly controlling regulation from the supply and demand response as a resource for regulation in the real-time imbalance scenario is proposed. The approach is based on a multi-rate model predicting control to capture the varying complementary dynamics of the two resources. In [59] development and validation of physically based load model of electric heating loads is done. A duty cycle model of the demand for evaluating impact of load control strategies is presented in [60]. Reference [61] talks about a discrete time continuous state stochastic model of the temperature of a house having AC/heater regulated by a thermostat. Reference [62] presents a probabilistic model for aggregate storage heating loads taking into account the uncertainty in the external temperature forecasts and the cycling effects of the reduced rate period determined by the utility. In [63] different aggregation techniques for estimation of probability distribution function of thermal and electrical variables of aggregated thermostatically controlled loads whose behaviour is modeled as stochastic differential equation system based on perturbed physical models. A state-queuing model of thermostatically controlled loads is presented to simulate the response of aggregated loads to the electricity prices in [64]

Authors in [65] present experience on a pilot DR project implemented at Malvik Everk, a DSO in Central-Norway involving 40 household customers. The project involved smart metering, real-time pricing with a time-of-day network tariff and a token provided to the customers indicating peak hours. Specific concepts for DSM involving end-consumers are discussed in references [66]–[78]. A distribution network perspective of reducing losses by using DR for load shifting is presented in reference [80].

V. Challenges in DR implementation

There are several challenges in implementing DR in a smart grid paradigm. DSM and DR implementation has the potential for making the grid more flexible, self-healing, and also includes societal benefits, the regulators will always warrant extensive proof before authorizing investments [81], [82]. Moreover, the utility industry may not be able to support a financial roll out to fund new technologies without the help of government incentive programs. The older equipments for example electromechanical electricity meters need to be replaced by new smart meters and other smart technologies. This may pose a problem for the utilities and the regulators since early retirement of equipments may not be financially acceptable to the end users. Lack of policies, standards and required ICT infrastructure call for the need of faster development to realize DR in many countries. Moreover, the distribution companies have limited experience with ICT technologies and therefore management of smart grid components becomes difficult. In this regard partnership with leading ICT companies need to be fostered to realize smart grid concepts. One of the most important challenges in DR implementation is educating the customer about the benefits and implementation issues. Such programs should also be aimed at regulators, policy-makers and financial institutions. Sufficient market analysis and studies on product design must be made to ensure fair acceptance of the technology by the consumer side. The issues of standards and protocols regarding the design and operation of AMI are still not settled. Any investment made in such a situation may be subject to the risk of obsolescence. A cost benefit analysis considering these issues and also including an estimate of the cost of the equipments the customer will deploy to automate response has to be made to reduce the investment risk. A proper rate should be designed not only to ensure that the investment made in the new technology is recovered in fair amount of time, but also to be acceptable to every customer class. The absence of robust empirical evidence regarding the performance and economics of new technologies and tariff-design (for example AMI and dynamic pricing) on a system-wide basis and over time pose a question of uncertainty over the real potential of such schemes in regard to their technical performance and the benefits in terms of improvement in grid health in the long run.

VI. Conclusions

The paper has reviewed the demand response programmes reported in the literature. A projection on the future research growth in the demand response is made. The classification of the papers on demand response is made on the basis of applicability to the wholesale and retail markets. It is observed that DR can play a major role in the smart grid implementations and the end-consumer participation in the energy supply chain can be promoted by the means of DR programmes. The design of DR programmes is dependent on the prevailing market conditions of a particular region. Most of the DR models reported in the literature are academic in nature which can be extended and moulded according to the prevailing market conditions and nature of market participants of a particular region. The practical viability of implementation of such schemes on a system wide basis does require ample amount of research.

ACKNOWLEDGEMENT

The authors would like to thank Crompton Greaves Limited for providing support to this research.

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