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From controllable loads to generalized demand-side resources: A review on developments of demand-side resources

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A B S T R A C T

Demand response (DR) is regarded as an important method in the economic and secure operation of the power system, which has attracted great attentions from both industry and academia. With increasing integration of distributed energy resources (DER), demand-side resources become more active and diversified. Moreover, developments of the smart grid (SG) technology provide better environment for DR application. This paper presents an overview of demand-side resource developments from controllable loads to generalized demand-side resources (GDR) including distributed generation (DG) and electric energy storage (EES). Besides, aggregation technologies such as virtual power plant (VPP) and load aggregator (LA) are summarized here. Advantages of GDR application and its development prospects are presented at the end of the paper.

Contents

1. Introduction

In recent years, increasing industrial and residential electricity demand becomes a great challenge to the economic and secure operation of the power system. DR or Demand-side Management (DSM) has proved to be an efficient way to deal with problems like severe peak demand and load fluctuation in such situation. This paper presents an overview of current studies and researches on DR application in different technology and market situations. It also shows the advantages as well as prospects of DR. The paper intends to provide a thorough review of DR developments for researchers interested in this specialized field.

Operation balance of the power system conventionally relies on the adjustments of energy suppliers. Energy utilities expand their generation capacity or purchase reserve capacity in case of emergencies in the system. Such solutions, however, have disadvantages including low response rate, high cost and high carbon emission. New solutions are presented including energy storage

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technologies on the supply side, interconnections with other networks and DSM, among which DSM stands out for its low cost and high reliability [1].

First introduced in the U.S.A in 1984, DSM was originally known as load management and was defined as follows:

“DSM activities are those which involve actions on the demand (i.e. customer) side of the electric meter, either directly or indirectly stimulated by the utility. These activities include those commonly called load management, strategic conservation, electrification, strategic growth or deliberately increased market share” [2].

The core of DSM lies in maintaining the balance of the energy demand and available supply to enhance the stable and economic operation of the system through managements on the demand side. According to previous studies, DSM can be divided into three categories: energy efficiency (using less energy to provide the same services), load management (scheduling the loads to reduce the electric energy consumption or the maximum demand) and DR [3].

As an important branch of DSM, DR (Fig. 1) can be viewed as a new development of DSM with power market and SG technology evolution. According to [4], DR refers to changes in electric use by demand-side resources from their normal consumption patterns in response to electricity price changes, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. Thus DR programs can be classified into incentive-based ones (DLC, IL, DSB, EDR and CASP) and price-based ones (TOU, RTP and CPP). Both kinds have wide application in the power system and will be discussed later in Section 2.

In DR application, residential, industrial and commercial loads are viewed as available resources in system operation rather than energy consumption simply. Taken distributed generation (DG) and electric energy storage (EES) into consideration, demand-side resources are largely diversified. DG can be further divided into intermittent DG and controllable DG. The actual generation capacity of intermittent DG is uncontrollable, like wind or solar photovoltaic generation. Controllable DGs include diesel or gas generators and small CHPs (Combined Heat and Power Plant), etc. As for EES, besides static energy storage (e.g. electric-based heating and batteries), electric vehicles (EV) are also included for its function of bidirectional energy communication with the power grid.

The developments of SG technologies enhance the real-time information communication between different entities in the power system. With updated market information, end-users can adjust their consumption patterns instantaneously according to their own price preferences or contracts. While DR originally focuses on large consumers, intelligent devices enable small consumers like residential loads to participate in the energy market. These consumers, however, are dispersedly located with small capacity and are hard to control directly by the system operator. To deal with these problems, technologies such as load aggregator (LA) and virtual power plant (VPP) are introduced. Thus both the internal operation of the aggregator and the optimal operation of the whole system become research focuses, which are discussed in Section 3.

The application of DR has expanded from the U.S.A to Europe and finally Asia. Taking full advantage of the activeness of demand-side resources, DR has had a profound influence on the power system. Besides DR operation, its policy is also an important research field.

This review is organized as follows. Section 2 presents the application of DR programs without DER involved. Section 3 addresses the coordination of various demand-side resources and the impacts of aggregation technologies like VPP and LA, etc. Section 4 presents the advantages DR has brought to the power system. Section 5 lays emphasis on the prospects of DR by stating the future work in this specialized field. Section 6 gives the conclusion of this paper.

2. Application of DR without DER involved

The main feature of early developments of DR is the absence of power resources on the energy demand side. Thus demand-side resources mainly include large industrial loads. DR is applied through two kinds of DR programs (DRP) in power system, Incentive-based programs (IBP) and Price-based programs (PBP) [5]. The former is provided through interruptible or curtailment contracts, in which large energy consumers are paid to change their energy consumption patterns by load reduction or shifting [6,7]. The latter is provided through electricity price guidance. All consumers voluntarily adjust their energy consumption to the price fluctuation in the power market [8]. Specific classification of DRPs is shown in Fig. 2. In those listed in Fig. 2, DLC, IL, TOU and RTP are the most common DRPs, among which RTP is the most ideal form of DRP. In [9], the specific definition and application methods of each kind of DRP are provided.

In [10], an economic model is presented for the operator to select the most suitable DRP according to specific system situations. A consumer's demand pattern depends on the electricity price or incentive/penalty values of DRP contracts besides its own load characteristic. Thus several problems need to be considered when DR is applied to a certain power system. These problems include:

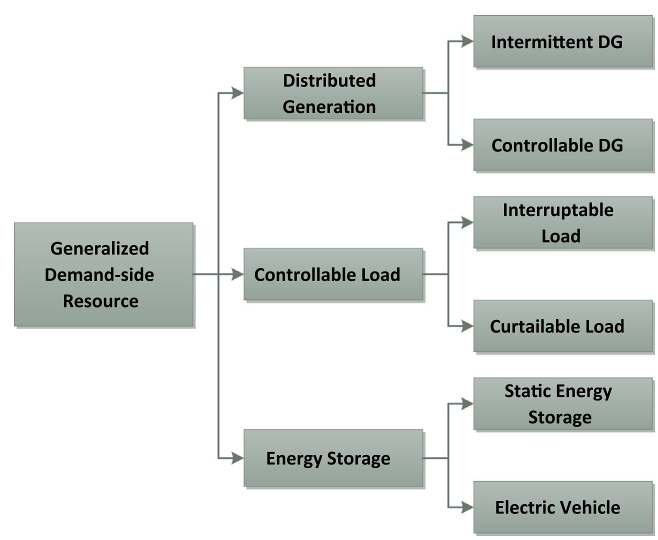

Fig. 1. Classification of generalized demand-side resources.

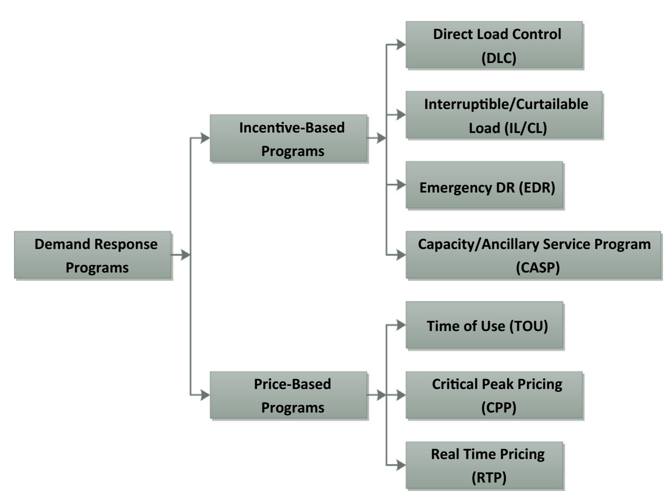

Fig.2. Classification of DRPs.

- DRP type and its parameters.
- The market model DRP is applied to (day-ahead/real-time, energy market/ancillary market/both).
- DRP procurement model (bilateral contract/DRP bidding).
- Pricing model in the auction market (market clearing price (MCP)/pay as bid(PAB)).

In [11–14], DRP applications and policies in America and Europe are reviewed respectively, where DRP was first applied. In [15], DRP developments of these areas in recent years are reviewed. It can be seen that with the evolution of smart meters and communication devices, more households and small nonresidential consumers will be involved in DR. In [16], a DR application plan in India is presented where DR development is still at a nascent stage. Unlike the areas above, main demand-side resources in India come from compact fluorescent lamps instead of industrial loads. [17] presents a history of DR development in China ever since DR was first introduced in the 1990s. Before the Electricity Reform Program in 2002, programs including DLC, TOU and peak-load-pricing were the most widely-used DRPs. Since the breakthrough in 2002, the electricity pricing scheme has drawn more attention and its influence on DR application is reviewed in [18].

The main function of DR in the system operation is peak load shaving. Moreover, the fast response rate of DR enables it to be applied in ancillary service market and provides reserve capacity services of good quality. The study of DR application in ancillary services, however, is still at the beginning stage compared to the wide use of DR in load shaping. In [19], several electricity market situations are analyzed and conclusion is drawn that PJM and ERCOT have the most favorable conditions for DR participation in ancillary service market. Different kinds of load characteristics are studied in [20] to provide suitable ancillary services accordingly. It needs to be pointed out that the system security issue must be taken into consideration when DR is applied to ancillary services.

In the system operation with DR involved, profits of the energy supply utilities, the system operator as well as the DR provider or the consumers should be considered. At first, DR is only used as a tool in economic operation of the system. In [21], DR is paid by direct monetary compensation and the system optimal operation objective is to minimize the operating cost, neglecting the benefit of DR providers. The characteristic and willingness of the load participating in DR are not studied here. Nevertheless, these factors are crucial in risk avoiding of DR application. Response behaviors of energy consumers to different price models are studied in [22]. In [23,24], a price elasticity matrix is employed to capture such demand features. Price elasticity is defined to represent the sensitivity of the load to the electricity price signal. Controllable loads can be classified into deferrable loads and interruptable loads. The former can be shifted to other periods while the latter can only be switched on or off. An interruptable load is represented by self-elasticity in the matrix as a diagonal element and a deferrable load is represented by cross-elasticity as an off-diagonal element. IBPs are carried out in [23], which considers not only the profit of the system operator but also that of the DR provider. In [24], based on the study of load characteristics, TOU is proved to raise the utilization of existing production capacity efficiently. As a kind of PBP, TOU is the combination of flat rate pricing and RTP. The technical demand of TOU for SG devices is easier to realize than that of RTP. TOU, however, tends to bring in payback effect to the system, which means the adverse consequence of the deferrable load recovery causing a new load peak [25,26]. In [27] DR provider's profit is considered in a system employing RTP. Load characteristics are studied to guarantee the minimization of the DR provider's expected payment for the entire day. Time-varying pricing is used instead of fixed rate price in [28] to achieve both the social welfare and DR provider's individual benefit simultaneously.

In a time-varying pricing system, DR implantation has an important influence on the electricity price for it changes the load level. Consumers respond to such price changes, resulting in a different DR performance. An iteration problem is thus created and can be solved by game theory [29]. Games exist not only between electricity utilities and consumers but also among the consumer communities. Equilibriums can be reached assuring benefits of both the energy suppliers and consumers [30].

Integration of renewable energy resources to the power grid like wind power provides DR with new applications. Renewable energy generation is characterized by its uncertainty, which leads to instability of the system such as frequency and voltage fluctuation. Moreover, generation periods of the renewable energy resource often do not coincide with peak load periods, thus imbalance of the system may aggravate with its high penetration.

Conventional solutions include installed capacity increase, reserve capacity purchase, and wind generation tripping. DR is a satisfactory replacement of these solutions for its economic and effective performance in short-term system balance. Electric water heater (EWH) is a common controllable load in DR practice. [31] proposes a DLC program using EWH in Japan through which acceptable wind power generation curve can be acquired. [32] employs a two-stage LP and MILP optimization of a system with an EWH program to improve the voltage quality in the controlled area. [33] proposes three different methodologies of operation optimization of system with DR and wind penetration. It is shown that besides peak load shaving, DR also increases the system flexibility and reduces the weighted average electricity price.

In summary, DR motivates energy consumers to interact with energy suppliers by stimulation of electricity price or contract compensation. It takes advantage of controllable loads to improve the power quality of the system even under rough conditions like the integration of renewable energy resources.

3. Influence of DER and aggregation technologies on DR

DR has proved its advantage of low cost and high efficiency in the economic and secure operation of the power system. DER integration and aggregation technologies provide DR with both challenges and opportunities, which can be summarized as follows.

- Improvements of SG technology reinforce real-time communication between energy suppliers and consumers with advanced infrastructures, thus potentials of the price signal guidance of DR can be fully released.
- Environmental concerns are taken into consideration in power system operation for fossil fuel reduction and population pressure. DR is seen as an economic alternative of high-cost gas-stream turbines in peak load shaving.
- DER integration to the power grid provides the demand side with ability to produce energy. Hence demand-side resources become more active and diversified. Coordinate operation of generalized demand-side resources becomes a research focus.
- Technologies such as VPP and LA provide more small loads with opportunities to participate in system operation.

With DER integration to the energy demand side, generalized demand-side resources mentioned in Section 1 thrive in new application situations and will be discussed in details in this section.

3.1. Generalized demand-side resource

DER refer to electric power generation resources that are directly connected to medium voltage (MV) or low voltage (LV) distribution systems, rather than to the bulk power transmission systems [34]. DER is generally divided into two categories, distributed generation (DG) and electrical energy storage (EES). Integration of DER enables the energy demand side to produce electricity. The unidirectional energy transfer is therefore turned bidirectional and DR application situation becomes more complicated. Fig.3 is a specific description of various kinds of DERs.

DG includes conventional generation units like micro gas turbines and unconventional generation units such as solar photovoltaic and wind generation. Different from the full controllability of conventional generation, generation capacity of renewable energy resources depends largely on the environmental state and is characterized by intermittency, volatility and uncertainty.

EES refers to a process of converting electrical energy from a power network into a form that can be stored for converting back to electrical energy when needed. Basic types consist of mechanical, electrical, chemical and thermal EES [35,36]. Several practical forms of EES are suggested in [37] and such systems can be easily applied to the demand side. As a well-established approach in maintaining the power system reliability and stability, EES serves as mitigation of the system operation in case drastic fluctuation of load or supply occurs. It can be applied to load following, peak shaving, load shifting and standby reserve [38]. While large-scale stationary EES on the energy supply side such as pumped hydroelectric systems (PHS) dominates in EES application, researches on smaller scale EES on the demand side are now in trend. The performance of the stationary EES is determined by multiple factors including size, input energy price and the autonomy level of the network.

EES can be classified into stationary EES and movable EES according to its mobility rather than energy storage forms. Movable EES refers to electric vehicles with V2G (Vehicle to Grid) function. EV includes battery electric vehicle (BEV), hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) [39]. When large numbers of EVs are integrated to the electric network, their random charging or discharging may aggravate the peak supply shortage of a system drastically [40]. Nevertheless, with rational charging/discharging policy and accurate load forecast, EV can provide better DR services for its ability of discharging.

EV is introduced worldwide as an alternative of traditional transport mainly for the environmental concern. Hence energy loss minimization is a common objective of EV charging control optimization [41,42]. Several charging policies and their impacts on the PHEV profile are suggested in [43] according to the types and charging voltage levels of PHEVs. Such research results can be applied to load profile forecast with PHEV involved so that the controllability level of PHEVs can be raised. [44] proposes a DR scheme for proper EV integration aiming at securing financial and energy benefits for end-users. In Queensland, Australia, such

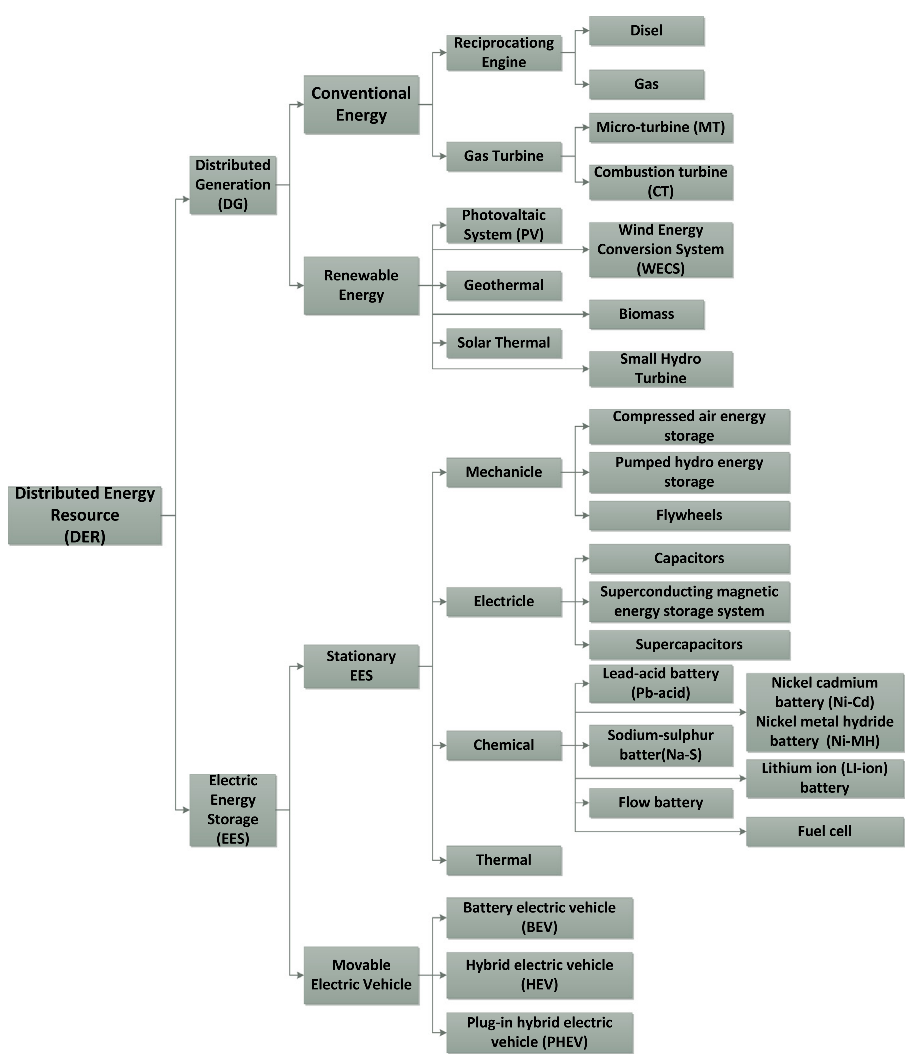

Fig.3. Classification of DER.

scheme has helped improving the utilization rate of the existing electrical infrastructures. Based on queuing theory, a stochastic model of EV charging demand is proposed in [45]. The model contributes to accurate demand forecast with EV involved. Thus better DR policy and price scheme planning for EV can be achieved accordingly. With rational control, EV has a fine performance in not only load profile shaping but also coordinate operation with renewable energies.

EES is regarded as an imperative technology to mitigate the volatile output of intermittent energy, thus coordination of DG and EES in system optimal operation becomes a research focus. Such cooperation brings in environmental benefits to the power system. In [46], it is suggested that renewable energy with co-located EES in an autonomous network can be seen as a promising solution of energy problems in the environment dilemma. Moreover, the integration level of renewable energy can be raised by EES application. Previous studies show that integration of wind and solar photovoltaic energy in a system cannot exceed a limit around 20% or 25% for their inherent intermittence [47]. With EES involvement in the system the percentage can be raised by 25% [48]. Besides those mentioned above, researches on EV prove that EES can also improve the infrastructure utilization efficiency of the power system [49–52].

3.2. Coordination of generalized demand-side resources (GDR) in the power system

GDRs including controllable loads and DER (DG, EES) bring in various technical, economic and environmental benefits to the power network. The energy demand side becomes more active in market regulation and system operation because of DER integration. Therefore the focus of this part is laid on the optimal coordinate operation of different GDRs.

GDR is often integrated to distribution networks. In order to guarantee power quality, it is crucial that the networks operate within certain constrains. Moreover, optimal operation of these networks involves interests of entities including the system/market operator, energy consumers and power suppliers, etc. Individual operation objectives of these entities are different and may even conflict with one another, thus compromise is needed [53]. Developments of smart grid technologies improve the information transfer rate significantly. Real-time interaction therefore is enabled not only between different entities within a single network, but between operators of different networks as well. Moreover, increasing residential and small nonresidential energy consumers are taken in DR and the optimal coordination of GDR is rendered a multi-layered problem.

A schematic of multi-layer control and management of GDRs in power grid is shown in Fig.4. Note that CL is the abbreviation of controllable load. On the secondary layer, an aggregator can be a load aggregator, a VPP or a micro-grid/distribution network operator, and interaction between different aggregators is realized by the system/market operator.

3.2.1. Basic models and algorithms

Model buildings and algorithms are the basics of GDR optimization problems. For controllable loads, the load curve is reshaped according to certain control policies and the standard or forecast load curve. Similarly, energy consumption of EES can be treated as either a regular load or an energy resource according to certain time intervals based on reasonable charging/discharging policies with physical constraints. A study on characteristics of various kinds of electricity consumption is presented in [54], based on which acute load modeling can be acquired.

There are two common simulation methods of renewable energy resources. One is to use classic distribution curve. Taking wind power as an example, its generation capacity depends on wind speed, which can be modeled by distribution functions such as Weibull, Rayleigh, lognormal, normal and gamma distribution. Wind power generation capacity can thus be acquired accordingly [55,56]. The other method is to sample or forecast from real generation statistic data. Such method is applied to solar photovoltaic generation in [57]. Besides, DG can also be regarded as a negative load instead of an energy resource and its generation variation is expressed through the changes in the demand profile [58].

Optimal operation of a network can be either single-objective or multi-objective. Common optimization objectives include economic and environmental ones, taking the security issues into consideration. Due to the complexity of the power system, such optimization problems are often non-linear with high exponents. Therefore it becomes difficult to use traditional algorithms to achieve optimal solutions. Intelligent algorithms like heuristic algorithms, artificial neural networks (ANN) and genetic algorithm (GA) are widely employed to provide not necessarily optimal but satisfactory solutions [59]. As is mentioned in Ref. [53], when interests of different entities are taken into consideration, a single-objective optimization problem becomes multi-objective and these objectives may conflict with each other. For example, reduction in carbon emission calls for DER integration, which increases the investment in reserve capacity and operation, thus

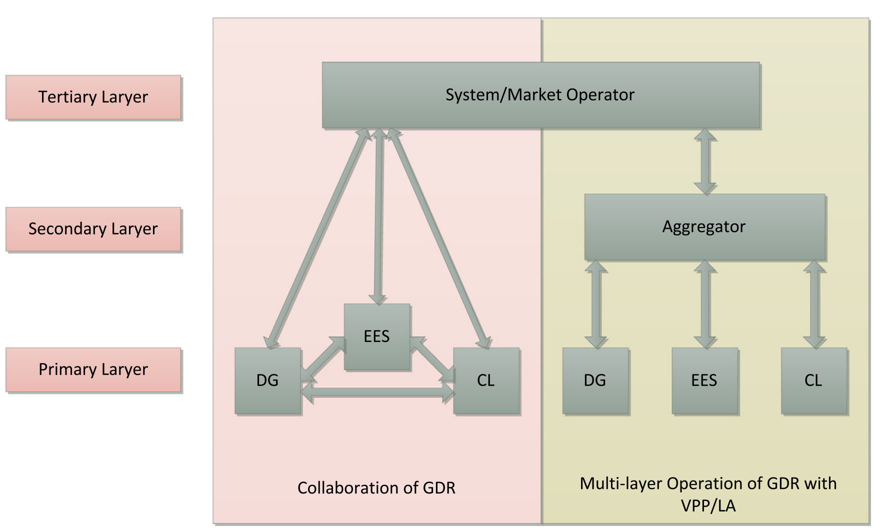

Fig.4. Multi-layer controlling of GDR.

conflict is raised between environmental and economic objectives. If all the objectives of a multi-objective problem can be aggregated to one, weight-sum method can be applied and the problem is reduced to a single-objective problem [60]. Otherwise, the solution that optimizes every objective may not exist, thus they need to compromise and a Prato frontier including a set of non-dominated solutions is acquired, which needs further decision making for the ultimate solution [61].

With appropriate application of models and algorithms, system operation optimization problems with GDR involved can be solved similarly to conventional system optimization problems.

3.2.2. Multi-layer optimal operation of GDR

As mentioned above, resources on the energy demand side are often dispersedly located with small capacity, leading to a single GDR's insignificant influence on the power system operation. When controlled and managed collectively, however, these resources can together provide considerable amount of energy for system operation. This is the embryo concept of the virtual power plant (VPP) and the load aggregator (LA). A VPP aggregates the capacity of many diverse DERs, it creates a single operating profile from a composite of the parameters characterizing each DER and can incorporate the impact of the network on aggregate DER output [62]. A virtual power plant can be a cluster of dispersed generation units, controllable loads and storages systems aggregated in order to operate as a unique power plant [63]. A VPP can be on either the supply side or the demand side in a power system. There are technical VPPs (TVPP) and commercial VPPs (CVPP). The former mainly provides system balancing and ancillary services for the system operation while the latter participates in the energy market. Main attention here is paid to TVPP on the energy demand side. [64] provides such a fine example, in which a profile of over 27,000 scenarios of GDRs is created for the VPP operator to select from according to certain system situations.

A load aggregator (LA), also called load serving entity (LSE) or energy service provider (ESP), was first introduced for the uniform EV control to save the large amount of communication and management work for the system operator. It is mentioned in [65] that with all the driving profiles of EVs known, the aggregator can create a virtue power plant. That is to say a LA is very similar to a TVPP in both its concept and management. For such similarity, VPP and LA are not specifically differentiated in the following discussion.

A VPP/LA is the intermediary between the system/market operator and the large numbers of demand-side resources. It can serve as a technical interface without making its own profit. Otherwise a VPP/LA can be regarded as an independent entity with its own operation constrains, operation costs and bids.

The basic issue here is the internal optimal operation of a VPP/LA. Optimal CL schedules are proposed in [66] for a VPP to optimize load reduction over a certain period. In [67] a VPP is used for EV penetration control to minimize the cumulative cost of the system. Both economic and environmental concerns are taken into consideration in [67]. In [68], an EV aggregator participates in both the energy and reserve market. A management algorithm to minimize the differences between contracted and realized values is proposed. In the above works, a VPP/LA serves as a tool for the system operator to manage GDRs and VPP/LA's profit is not considered.

In [69,70], interest of the VPP/LA is taken into consideration in the optimal operation problem. In [69] the aggregator properly distributes the energy purchased from the wholesale market to PEVs for its own energy trading profit maximization. In [70] the load aggregator minimizes its energy cost by schedule making and determination of the imported power with the application of EES. The strategy proposed in [71] is a bit more complex. An aggregator of shiftable loads and EES creates its optimum profile according to the price forecast and submits it to the operator. If the profile is accepted by the system operator, the aggregator ensures that the profile is fitly carried out to produce economic benefit to end-users. Otherwise LA has to adjust this profile to satisfy the operator's requirements while guaranteeing the participants' profit. In these cases, energy profiles of the aggregators are assumed to have no influence on the electricity price of the system. DR services are provided by bilateral contracts or day-ahead purchase with real-time adjustment. With such strategies, the multi-layer optimization problem of the system with aggregators involved can be reduced to a single-layer one, which is similar to a usual optimal operation problem.

The energy profile of an aggregator, however, represents the demand level of the power system, leading to its influence on both the electricity price and the system balance. The energy schedule of the aggregator and the electricity price thus becomes interactional and the multi-layer optimal operation problem needs to be solved as an iterative one. Such thoughts are carried out in [72]. In [73,74] bidding strategies of aggregators are proposed to maximize the benefit of LA. A LA transaction model based on [72] is shown in Fig.5. The model can be applied to day-ahead energy market or real-time market with intelligent meters and updated information available. Moreover, aggregators can also participate in ancillary service market and sell energy produced by DG back to the system.

A VPP/LA can do more than load shaping discussed above, it can also provide ancillary services to the system like frequency control [75], and economic gains of different operation cases can be quantified [76]. It is proved in [77] that the market regulation has an important influence on the performance of aggregators in DR services. It is suggested that the operator categorizes consumers'

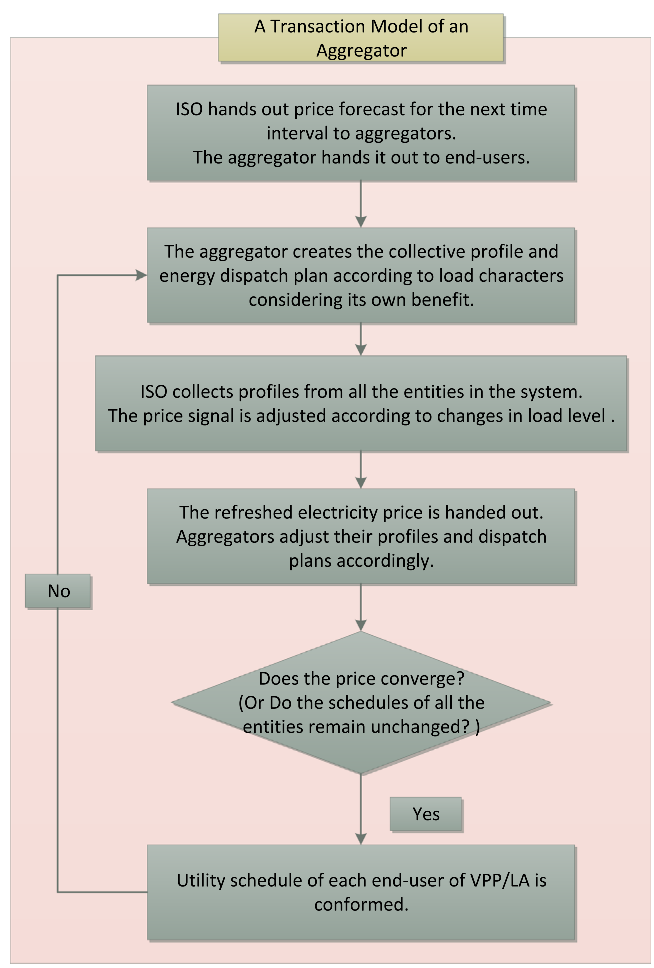

Fig. 5. A transaction model of an aggregator.

behaviors and sign different DR contracts accordingly to avoid the risks of uncertainties from end-users.

Conclusion is drawn that the implantation of VPP/LA can be a fine solution to GDR management and operation. Key issues here include the internal management of the aggregator, the system optimal operation with aggregators involved, the market regulation and the risk management of uncertainties from end-users.

3.2.3. *Management and interaction of multiple networks*

With DER integration to the demand side, the micro-grid is proposed as an original method for DER manipulation. Management of micro-grids is realized through micro-grid controllers, by which a micro-grid can present itself to the system as a single controlled unit due to its inner flexibility [78]. A micro-grid, at this stage, serves as a functional interface between the system/market operator and bottom resources.

The individual operator of a micro-grid or an active distribution network is introduced to guarantee economic operation within the network. It considers the profit of the network while meets the secure and economic needs of the bulk system. The technical process of the optimal operation here is very similar to that of VPP/LA and is not to be discussed again. What is intended to be pointed out is the load feature of the networks.

DER Integration has changed the unidirectional energy transfer between energy suppliers and end-users into a bidirectional one. That is to say, the concept of the load is generalized from a simple energy consumer to an aggregation of a bunch of appliances including loads, generators and batteries. From this point of view, a micro-grid can be treated as a controlled aggregated load, which is mentioned in [79]. Similarly all the aforementioned technologies like LA, VPP and even an active distribution network can be seen as a load to the system. The essential of the thought lies in that with appropriate internal optimal operation, the external characteristic of a network becomes the only concern when it interacts with the system/market operator. The operation complexity of the system with large numbers of GDRs is thus reduced. The thought is carried out in [80]. A DISCO (a distribution company of aggregated DGs and interruptible loads) transacts with the system operator based on its ICF curve which presents the lumped financial model of the DISCO at the connecting point to the transmission system. Furthermore, multi-agent systems with multiple VPP/LAs, micro-grids or active distribution networks can be built based on the external feature of each individual network and the optimal operation problem of the whole system will be simplified [81]. Fig.6 depicts the scheme of the discussion in this section.

4. Advantages of GDR and its relative technologies

DR, as has been proved, has brought much positive influence to the power system. DER integration enlarges the range of demand-side resources, and the evolvement of SG technologies enhances information communication between different entities in the power system. Moreover, technologies like VPP and LA simplify the management of demand-side resources. GDR implantation brings in advantages to the power system, the energy consumers and suppliers as well as the whole society.

From the perspective of the power grid, demand-side resources in the system operation provide effective and economic peak load shifting with fast response rate. DER application enables dispersed energy resources to locate near the load center, which reduces the transmission loss enormously. The energy produced by DER reinforces the ability of demand-side resources to shape the load curve and provide ancillary services. In practical operation, system operators have to pay for long-term reserve in case of major accidents that rarely occur, which is necessary but uneconomic. The dilemma, however, can be solved by signing bilateral contracts with some end-users to curtail or postpone their energy consumption when such accidents happen. DG and EES can also provide such services according to their own generation or charging/discharging features.

From the energy consumers' point of view, being accepted into the electricity market provides them with better guidance of their energy consumption plans. Through the response to the market signals, electricity cost can be reduced. Consumers may even gain economic benefit by providing DR services. With domestic generation available, end-users can even provide the power system with electricity produced by local wind or solar photovoltaic generators to make profit. Moreover, with the help of GDR, energy consumers will enjoy power service of better quality at a lower price.

Advantages of GDR from both the energy supply side and demand side add up to the social benefit. The integration of more renewable energy resources decreases the reliance on fossil fuels. Services from demand-side resources instead of high-cost combustion gas turbines on the supply side raise the energy efficiency and the infrastructure utilization of the whole system, which in turn leads to postponement of new infrastructure investment. The high cost of installation, operation and maintenance of renewable energy resources has always been a concern. Coordinate operation with controllable loads and EES, however, can be a suitable solution. Much of the uncertainty and fluctuation of the intermittent energy resources can be alleviated, which in turn not only reduces the aforementioned cost but increases the renewable resource penetration level as well. More and more end-users can be taken in DR services by the uniform control and management of aggregators. Social welfare is thus achieved by higher energy and

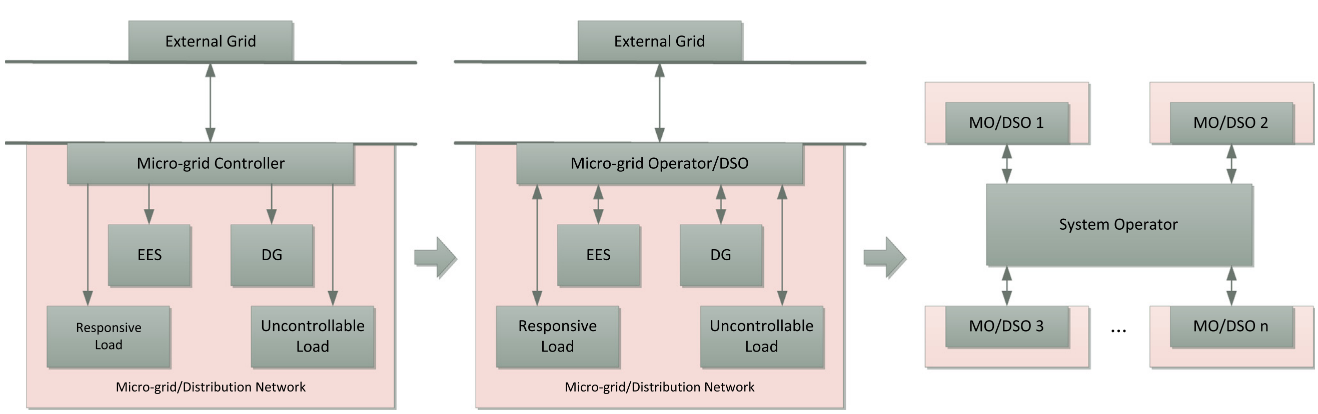

Fig.6. Load character of networks.

infrastructure utilization, lower cost and less environment destruction.

5. Prospects of GDR development

GDR has a promising future in the economic and secure system operation for its huge potential. However, challenges of reliable operation strategies, market frameworks and the lack of experience still pose threat to the development of GDR as is mentioned in [82].

Extensive application of GDR has a lot of obstacles to surmount, which may also be the future research focuses of GDR and its relative technologies. The prospects of GDR can be summarized as follows:

- Though has been studied for years, suitable incentive and pricing mechanisms taking participants' behavior characteristics into consideration may still be an issue in DR application.
- Coordinate operation of controllable loads, EES and DG can be the solution of the high cost of renewable energy integration, thus studies on operation schemes are in need.
- DER integration to the energy demand side changes the unidirectional power flow in a distribution network into a bidirectional one, which results in security and stability problems that need to be solved either at the system planning stage or in system operation.
- Current researches mainly focus on the VPP built for newly-integrated DER. Nevertheless VPP can also serve for the cooperate operation of existing conventional generation plants with unstable output or bad management to create a satisfactory generation output together.
- Most GDR coordinate operation researches now take controllable loads into consideration for their full controllability. The method, however, affects the consumers' energy consumption will and adds to their inconvenience. The alleviation of renewable energy uncertainty through the cooperation of various DERs without affecting the consumers is still an issue to be studied on.
- The transaction mechanism of a multi-layer system or a multi-agent system with aggregators involved needs further researches. The electricity and capital interaction in real-time market as well as generation/utility schedule making call for fast iteration algorithms. The problem will be even more complex if the entities on the demand side bid for the energy they produce.
- Though characteristics of different kinds of loads have been well studied, the risks that consumers do not obey the contracts or follow the price signals still exist. Such risks pose threats to both the benefit of the aggregators and the system. Thus risk management needs to be considered in the operation of demand-side resources. To categorize the consumers according to their response behaviors and sign different contracts accordingly may be one of the possible ways to reduce risks.
- Researches now mainly focus on the curtailment and shifting of the controllable loads. The pay back effect, namely the recovery of these loads postponed, however, may cause new peak demand, leading to issues in stable and economic operation of the system.

6. Conclusion

This paper presents an overview of the developments of demand-side resources from controllable loads to generalized demand-side resources with DER involved. GDR performs functions ranging from load shaping to ancillary services in the power system. The involvement of aggregators and network operators reduces the system operation complexity while taking in more end-users to participate in DR. GDR has brought multiple benefits to the system operation and its development prospects are presented at the end of this paper. It is assured that GDR and its relative technologies have a lot in store for the power system.

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