Review

Controllable Load Management Approaches in Smart Grids

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Abstract: With rapid smart grid technology development, the customer can actively participate in demand-side management (DSM) with the mutual information communication between the distributor operation company and the smart devices in real-time. Controllable load management not only has the advantage of peak shaving, load balance, frequency regulation, and voltage stability, but is also effective at providing fast balancing services to the renewable energy grid in the distributed power system. The load management faces an enormous challenge as the customer has a large number of both small residential loads and dispersed renewable sources. In this paper, various controllable load management approaches are discussed. The traditional controllable load approaches such as the end users' controllable appliances, storage battery, Vehicle-to-Grid (V2G), and heat storage are reviewed. The "broad controllable loads" management, such as the microgrid, Virtual Power Plant (VPP), and the load aggregator are also presented. Furthermore, the load characteristics, control strategies, and control effectiveness are analyzed.

Keywords: controllable load; load management; renewable energy; microgrid; active distribution system; demand response

1. Introduction

In recent years, controllable load management has become an active area of new research. Normally, the consumers manage their own loads to reduce their consumption during peak hours. It is possible to shift consumption to optimize the load curve of the system managing "peaks" and "valleys" [1].

By assessing the active participation of distributed energy resources using the questionnaire survey data from Tokyo, Japan during summer 2009, it showed that a controllable load strategy could reduce about 10% of peak demand of a distributed power system [2]. Meanwhile, controllable load management can provide other ancillary services to the grid. For example, the controllable loads, such as heat pump and electric vehicles, are also used to control system frequency and distributed voltage in the power system based on the smart grid [3,4].

In the distributed power system, the popular controllable loads such as refrigerators, freezers, air conditioners, water heaters, and heat pumps are controlled by the load management programs including direct load control (DLC) [5–8] and interruptible load management (ILM) [9–12]. Other controllable loads such as battery storage, Vehicle-to-Grid (V2G), heat storage, *etc.*, are more and more active to take part in the load management programs [13]. Traditionally, the customers sign the interruptible load contracts with the utility companies and then reduce demand at the fixed time when the system is at the peak load period or at any time requested by the power utility. In the smart grid environment, however, these controllable devices can communicate with the upper control system or the distributor operation company, and the bi-level mutual information is communicated in real-time. Measurements from the controllable loads are sent to the management center through a two-way communication network, and the customers provide various ancillary services with demand response management (DSM) [14].

With the development of smart grid technologies such as smart meter and smart control technologies, a lot of distributed generation and renewable energy sources (RES) are conveniently connected with the distributed grid [15,16]. Traditional technologies such as diesel generators are difficult to smooth the distributed grid. It is necessary to develop other flexible solutions to manage the electric distribution network when integrating large amounts of small and dispersed renewable sources. Recently, two types of approaches were studied. One is a microgrid, which provides a solution to manage local generations and loads as a single grid level entity [17–20]. A microgrid can connect and disconnect from the grid to enable itself to operate in both grid-connected or island mode. The other is the Virtual Power Plant (VPP) which composes various distributed small size generating units and controllable or flexible loads [21]. Unlike the microgrid, the VPP is always connected with the main grid. VPP combines the distributed generation in different geographical sites and mainly focuses on communication and market participation. There are small/medium-scale RES in both microgrid and VPP. However, the impact of RES can be evaluated by considering them as a source of demand reduction, instead of a source of generation [22]. From the grid point of view, both the microgrid and VPP are mainly regarded as loads in grid-connected mode. As a result, the microgrid and VPP may be regarded as the new types of loads—"the broad controllable loads".

This paper focuses on using controllable loads to provide fast balancing services to the system in the active distribution system. In this paper, the controllable loads are divided into the passive controllable loads and active ones. The passive controllable load management approaches, including direct load control and interruptible load, are reviewed. The active controllable load management approaches such as battery storage, V2G, heat storage, *etc.*, are also discussed. It is shown that the controllable load management approaches are more and more important in a smart grid with high penetration level of renewable energy.

This paper is organized as follows. Section 2 gives the definition of controllable loads. Section 3 introduces the passive controllable load management approaches. Section 4 reviews the active controllable load management approaches. Section 5 discusses the difference and relation of these controllable loads

management approaches. Section 6 discusses the broad controllable loads management and effectiveness. Section 7 discusses the trend development of controllable load management. Section 8 gives the results and conclusion.

2. Definition of Controllable Loads

In this paper, the controllable loads include a wider range than the traditional ones. Various types of controllable loads are defined as follows:

Type I of controllable loads: this type of controllable load includes various residential loads, such as fridges, washing machines, air conditioners, space cooling/heating, water heating, *etc.* [23]. These loads are interrupted or shifted by the load's utilities monitor. The load curve can be reshaped by reducing demand. This type of load cannot inject power to the grid at any time. In this paper this type of load is defined as a passive controllable load.

Type II of controllable loads: this type of controllable loads includes battery storage, Vehicle-to-Grid, the combined cooling heating, and power (CCHP), *etc.* Compared with the type I of controllable loads, this type of controllable loads can inject power to the grid. These loads can be charged from or discharged to the grid. In addition, this type of load has greater flexibility to be scheduled as controllable loads to accommodate grid needs. In this paper this type of controllable loads is defined as an active controllable load.

Type III of controllable loads: this type of controllable load includes the microgrid, VPP, *etc.* Although the microgrid and VPP have distributed generators, battery storage, renewable energy, *etc.*, the loads take a great proportion in these systems. They are mainly loads and demand power from the grid in the connected-grid mode. As a result, in this paper the microgrid and VPP are defined as "the broad controllable loads". Figure 1 shows the definition methods of controllable loads.
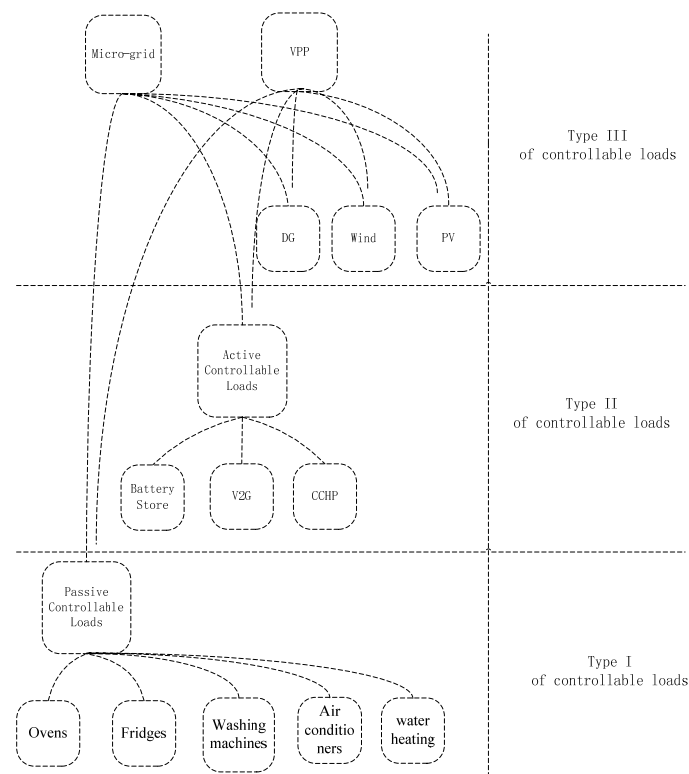

Figure 1. Definition method of controllable loads.

3. Type I Controllable Load Management Approaches

In the distributed power system, direct load control (DLC) and interruptible load management (ILM) are the most common load management programs. By cycling the end users' large current drawing appliances, such as refrigerators, freezers, air conditioners, water heaters, and heat pumps, DLC can reshape the load curve easily. Traditionally, the customers sign the interruptible load contracts with the utilities and then reduce the demand at the fixed time when the system gets its peak load period or at any time requested by the power utility. In the smart grid environment, more and more customers respond favorably to an incentive interruptible load program. The interruptible customers can curtail their load flexibly during peak hours and receive monetary returns.

3.1. Loads Characteristics

In general, DLC can be controlled without a noticeable impact on consumers' life styles. However, interruptible loads are noticeable when being controlled. The load monitors utilities and directly sends an on/off command to the smart appliances, such as fridges, washing machines, air conditioners, *etc*. The optimal time shifts for the utilities are scheduled to provide peak shaving and cost reduction over a limited time horizon [23]. Other loads such as space cooling/heating and water heating are controlled automatically to satisfy the set temperature value [24]. With the development of smart meter technology, the bi-level mutual information between the distributor operation company and the smart devices can be communicated in real time. Therefore, the customer can actively participate in demand-side management (DSM) with the help of energy management systems (EMS). As a large number of small residential loads participate in DSM, the load management presents new development trends. The controllable loads characteristics are as follows:

- Most controllable loads are small-scale and dispersed. A single controllable load has almost no market value. Normally, many types of loads are in one residential home. It is difficult to manage them by traditional control methods.
- Real-time information is possible. The controllable loads receive the control demand from the upper controller or utility and send back the measured information in real time. The traditional forecast dispatch is replaced by iterative control in real-time.
- The active demand-side response by the customer will be more popular. Traditional DLC mainly focuses on peak shaving and load profile smoothing. With smart home and smart grid development, the end users have more chances to schedule the controllable loads. Cost reduction, revenue maximization, renewable energy high penetration, and customer satisfaction will be included in the control strategy.
- The controllable loads are usually controlled together with distributed renewable energy in a microgrid. How to optimize the controllable loads in the hybrid power system is worth researching. In the DLC model, the impacts of control variables such as appliances, minimum turn-off times, response delays, and forecast errors are studied. The influences of load uncertainty, energy payback, the customers' willingness, and instantaneous reserves are also discussed.

3.2. Control Strategies

Many strategies of type I controllable loads have been proposed in the past three decades [6–10]. While transitional DLC strategies often focus on peak shaving applications during high demand period, recent DLC paradigms are mainly for real-time coordination of demand response and renewable energy, such as wind and solar power [25–28]. The control strategies are summarized as follows:

- ➢ Central/Bi-level control: if the controllable loads are of the same type and in one distributed area, a central control strategy is suitable and simple [29,30]. As the loads have the same controllable characteristics, the energy management system (EMS) just decides which part of the loads will be curtailed and which part will be served to achieve the objective value. A microgrid may include different types of controllable loads. Bi-level control strategy is also effective. The bottom level control strategy is similar to the central control, and the upper level control strategy mainly focuses on coordination and optimization operation.
- ➢ Aggregator: controllable loads of the same type can converge to an aggregator. An aggregator serves as a central control node which collects information from both the power grid and connects controllable loads. A load aggregator can also act as an interface between the controllable loads and the grid operator to provide the regulated management with joint consideration for benefits of both users and the grid. The aggregator models for the appliance-level loads are developed to generate load profiles for a distribution circuit [24].
- ➢ Hybrid coordination control: in the distributed power system, controllable loads, storage devices, renewable energy sources, and electric vehicles are integrated [31–33]. Operating in a coordinated way is challenging because some loads and energy sources are always fluctuating. The coordination control includes load balance, frequency regulation, voltage stability, peak shaving, and ancillary services.

In [34,35], the DLC program was focused on improving the operation economics and reliability through peak load management. In [36,37], the minimum disruption objective was proposed. A forecast control approach was presented by Ning Lu and Yu Zhang [29]. The forecaster models tuned by measurement data were proposed to reduce the computational complexity in the controller feedback loop with a system consisting of 1000 heating, ventilating, and air-conditioning (HVAC) units. In the hybrid system including controllable loads, the bi-level programming is effective to optimize coordination control. A simplified forecast model is suitable for the central controllable loads in the lower level control programming. The upper control model focuses on coordination control. The coordination between DLC dispatch and unit commitment was discussed and the integrated problem was solved through a dynamic program (DP) in [34,35]. A hybrid DLC and interruptible load management (ILM)-based approach was presented to remove the energy payback phenomenon of DLC and provide instantaneous reserves for ancillary services in [6].

3.3. Control Effectiveness

The optimal control strategies of DLC and ILM achieved a fruitful benefit for both the end users and the grid operator. In recent years, several optimal load control schedules which are based on linear

programming or dynamic algorithms are used mainly for peak shaving, load shifting, or contingency reserves to minimize production cost or meet reliability requirements over a limited time horizon [38–40].

In [29], A centralized controller with 1000 HVAC units provided 24 h of intra-hour continuous balancing services by the proposed control scheme. Another gradient descent optimization technique based on the Taylor series acquired 20% peak reduction and 5% cost savings [23]. The author in [41] summarized the results from a PG and Epilot including nearly 2000 residential households to use air conditioner direct load control to provide ancillary services. It shows that air conditioner load control programs started resources quickly, typically, within 60 s and roughly 80% of the available demand reduction began to be delivered in less than 3 min. The author in [27] presented a demand-side management system based on the centralized direct control of electric water heaters (EWHs). The optimal dispatch of the EWHs made clear that average power export peak reduced about 45% and average power import peak reduced about 25%.

4. Type II of Controllable Load Management Approaches

There are other types of controllable loads in the distributed power system, such as battery storage, V2G, CCHP, *etc.* Unlike type I controllable loads, these loads can supply energy. Consequently, they are active controllable loads. There are new characteristics and management approaches with the active controllable loads.

4.1. Loads Characteristics

4.1.1. Battery Storage

Since battery storage can buffer the power output of renewable energy by storing excess energy throughout times of high availability and inject it to the power system during a power shortage, it is paid great attention as one of the load management components [42,43]. Due to controllable and flexible charging and discharging operation, battery storage is one of the best ways to reduce the renewable energy fluctuation and enhance system stability. Compared with other controllable loads, battery storage is safe, noiseless, extendible, low maintenance, and of easy operation that does not depend upon landform or physiognomy.

4.1.2. Vehicle-to-Grid (V2G)

Vehicle-to-grid (V2G) describes a system in which plug-in electric vehicles, such as electric cars (PEVs) and plug-in hybrids (PHEVs), can be charged from or discharged to the grid. It can provide power system ancillary services in the form of power balance reserves to support the large-scale integration of variable renewable energy sources like wind power. Unlike traditional demand response schemes, V2G has greater flexibility to be scheduled as a controllable load to accommodate grid needs.

4.1.3. Combined Cooling Heating and Power (CCHP)

Another option for balancing fluctuations of renewable energy is using the CCHP in district heating systems [44]. The stored heat is used in different end users, including space heating and cooling,

industrial process heat, commercial heating and refrigeration, as well as household hot water usage. Like V2G, CCHP can also discharge to the grid. The power consumption can be changed during water heating and, therefore, heat storage presents a large potential for power system flexibility.

4.2. Potential Benefits in a Smart Grid

The active controllable loads have several benefits and advantages in the smart grid, such as short term power supply, ancillary service, power quality improvement of renewable energy, and facilitating integration.

As controllable loads, battery storage adds significant flexibility to the grid. It is used to store excess electricity energy at off-peak hours and then deliver it at peak hours. Battery storage can also be used to provide ancillary services; for example, reactive power, voltage, frequency control, and emergency power during a power outage to maintain the security and reliability of the system.

- PHEVs can charge at night when wind resources are abundant and provide ancillary services as virtual powers during peak hours. V2G supports the renewable energy and increases the penetration of renewable energy as follows.
- Storing excess energy when the wind blows strongly or the sun shines, and sending it back to the grid during peak load.
- Optimizing the load profile—"valley filling" (charging at night when demand is low) and "peak shaving" (sending power back to the grid when demand is high).
- Providing spinning reserves (meet sudden demands for power).
- Providing regulation services (reactive power and voltage control, loss compensation and frequency stability).

There are many effective application approaches for the heat storage. Heat pump water heater (HPWH) is one of the energy efficient-use appliances which takes in heat from the atmosphere into a refrigeration cycle [45]. The detailed HPWH model was depicted in [46] which consisted of three units including control unit; start unit and thermal storage unit. As a controllable load, heat storage is also combined with a battery energy storage system (BESS) [45], power plant [47], pumped hydro accumulation storage, underground pumped accumulation storage, and compressed air energy storage [48].

4.3. Hybrid System with Renewable Energy

Various storage battery technologies have been developed with high penetration of renewable energy. Daneshi H. and Srivastava A.K. discussed the impact of battery energy storage on power system with high wind penetration [49]. Case studies based on an eight-bus system demonstrated the effectiveness of the proposed model, and also the advantage of battery storage. It is shown that battery storage reduced wind curtailment as wind penetration increased in a system, thereby reducing the operation costs. Results also show that battery storage impacted the peak load reduction, system operating cost, transmission congestion, commitment, and dispatch of the units. Several other works investigated the optimal store battery size. Maja Etinski *et al.* [50] proposed an algorithm to optimally size a hybrid energy storage taking into account different technology costs and round-trip efficiencies. They also designed a control strategy for the hybrid storage operation. Hiroyuki Amano *et al.* [51] proposed the

utilization of battery storage load frequency control toward large-scale renewable energy penetration. The results suggested that the effect of required store battery capacity reduction tended to be strong when the fluctuation of renewable energy generation had unpredictable large slow-varying components.

The hybrid system of V2G and renewable energy can be implemented by connecting to the end of the distribution grid when parked. The electric grid operator controls specific times of discharge or charge. Since V2G was first introduced by Willet Kempton in 1996 [52], various V2G technologies have been researched on increasing renewable energy penetration. Uwakwe *et al.* [53] analyzed the economic value of V2G considering four ancillary services: base-load, peak-load, spinning, and regulation. The results showed that using the V2G for peak-load and regulation services had more economic value than when used for other ancillary services. However, the authors did not analyze which choices of ancillary service application depended on the types of V2G. The frequency regulation of V2G was studied in more detail in [54] and a new reliability index was derived and named failure rate for frequency regulation (FRFR). Then the allowable penetration level of wind power was studied with the impact of the V2G based on FRFR. From the results, V2G played an important role in mitigating the uncertainty of the grid. As is known, the role of a single V2G is unobvious. The V2G aggregator was proposed by Taraneh Ghanbarzadeh in [55]. The V2G aggregator's role was to effectively collect EVs into a single entity that could act either as a generation/storage device or as a controllable load. The result showed that this method was effective to maintain the output of the wind power under a typical variation of wind speed using actual wind histograms of the Sotavento wind farm in Spain.

It is important to control the hybrid system with heat storage and other storage energy. Information and communication technology (ICT) [48] is an effective method to solve the problem. Each local control center collects the information of the field heat storage or other storage energy and sends it to the central load dispatching center. Based on the information, the central load dispatching center generates a control signal for the whole network and dispatches the signal to each local control center. Then each local control center sends the signal to its local unit equally. The mutual information may be in real-time. This bi-level control technology is also applied in other controllable load problems and will be discussed in the following section.

5. Comparison of Controllable Load Approaches

In the current work, comparisons of DLC, interruptible load, store battery, V2G, and heat storage are summarized in Table 1. All the controllable loads in the table are effective to increase the renewable energy penetration with peak shaving, valley filling, and meeting sudden demands. The cost of the controllable loads is low except battery storage. However, battery storage is the most effective way to improve the renewable energy penetration, usually in conjunction with the solar and wind energy [56].

Normally, DLC technology is mainly focused on the family devices such as air-conditioning load management. Single V2G and heat storage are also effective in a small system. The aggregator model and multilayer control technology are suitable for these loads [57]. However, interruptible load management technology can be applied to controllable load large capacity with bilateral contract. Battery storage technology is widely used together with renewable sources.

Table 1. Summary of the Controllable Loads.

Item	DLC	Interruptible Load	Store battery	V2G	CCHP
Power	Passive	Passive	Active	Active	Active
Store excess energy	No	No	Yes	Yes	Yes
Send energy to grid	No	No	Yes	Yes	Yes
Peak shaving	Yes	Yes	Yes	Yes	Yes
Valley filling	Yes	No	Yes	Yes	Yes
Meeting sudden demands	Yes	Yes	Yes	Yes	Yes
Voltage &frequency control	Yes	Yes	Yes	Yes	Yes
Effectiveness to increase penetration	Good	Kind	Better	Better	Good
Controllable loads cost	Low	Low	High	Low	Low

Notes: Direct load control (DLC), Vehicle-to-Grid (V2G), Combined Cooling Heating and Power (CCHP).

6. Broad Controllable Loads Management and Effectiveness Analysis

When the controllable load is integrated in distributed generation, this load can be called "the load with the power". We call "the broad controllable loads management" for the management of the load or load aggregator with the power. For example, in a microgrid, the demand response capability via the controllable loads and the applications such as the photovoltaic (PV) panels and the storage units would be a power producer or a consumer—known as a "prosumer"[58]. Similarly, the VPP which includes the controllable loads, DG, renewable energy sources (RES), conventional power plants (CPP), and energy storage systems, also promotes a new vision for distribution systems operation, where a "grid customer" is a load or generation resource (or a mix of the two: a "prosumer") [59]. The load aggregator is also a market entity to maximize the demand response potential by scheduling a large number of medium-sized and small controllable loads [55]. From the view point of the distribution systems operation, the microgrid and VPP are also regarded as the loads. However, these loads may include based loads, controllable loads, renewable resources and other diesel generators. In this paper, this kind of load is called "broad controllable load". Normally these "broad controllable loads" absorb power from the main grid. The "broad controllable loads" can inject power to the main grid by optimizing the schedule the inner controllable loads and the distributed generators. Compared with traditional controllable loads, the broad controllable loads management has more flexible and suitable approaches in smart grids.

Figure 2 shows the configuration of the load with the power in IEEE14-bus system. A new broad controllable load is connected to the bus 13, which includes the based loads, diesel generators, and other renewable resources.

6.1. Loads Characteristics

Since the broad controllable load contains different types of generation resources, storage devices, and controllable loads it has new characteristics. The controllable load characteristics are as follows:

- Integrating the power. Containing different micro-generators, renewable resources and storage devices.
- Control flexibility. A broad controllable load can be operated connected to the main power network or autonomously, in a controlled and coordinated way.

- Power injected at low voltage, distribution levels.
- Providing ancillary services to the main grid.
- Challenge of managing a large number of complex broad controllable loads.
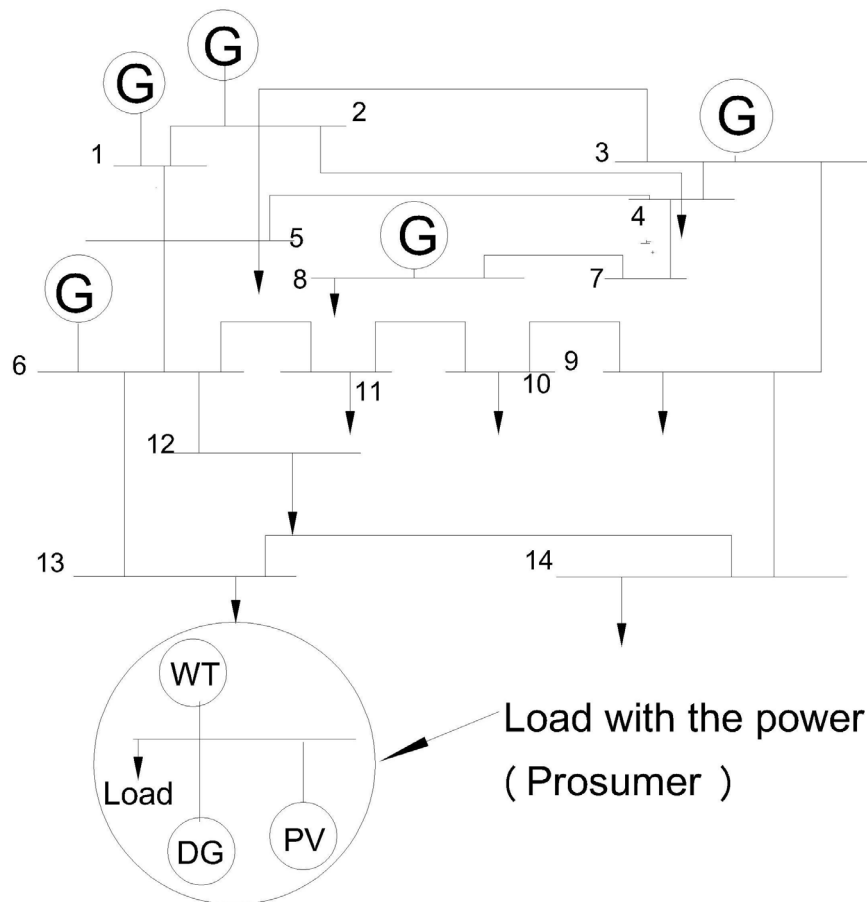

Figure 2. Load with the power in IEEE 14-bus system.

6.2. Management Approaches and Effectiveness

Compared with traditional controllable loads, the broad controllable load management has more flexible and suitable approaches in smart grids. In [60], a double-layer coordinated control approach for microgrid energy management was proposed which consists of the schedule layer and the dispatch layer. The coordination control method was studied in both grid-connected mode and stand-alone mode. In [61], the author developed a virtual power plant-based (VPP) distributed control strategy for multiple distributed generators, which had advantageous coordination control without central station collecting global information. Pierluigi *et al.* [62] presented a comprehensive dedicated framework to analyze distributed multi-generation systems for the purpose of identifying and quantifying their potential to participate in real-time demand response programs.

The flexible management approaches of broad controllable load can achieve more benefits and supply more ancillary services to the main grid. The management effectiveness of broad controllable loads is summarized in Table 2.

Table 2. Summary of the management effectiveness of broad controllable loads.

Item	Microgrid	VPP	Load aggregator
Minimizing the production cost	Yes [63]	Yes	Yes [55]
Reducing the grid peak consumption	Yes [64]	Yes [65,66]	Yes
Mitigating fluctuation of the tie-line	Yes [64]	Yes [67]	Yes
Congestion management	No	Yes	Yes
Increasing the renewable energy penetration	Yes	Yes	Yes [57]
Voltage &frequency control	Yes	No	No
Market management mode	No	Yes	Yes

With the development of the smart grid technologies, thousands of small distributed generators and dispatchable loads are connected to the grid. The challenge of the coordinated management of the flexible loads comes into being [68].

7. Trend Development of Controllable Load Approaches

With the development of microgrid control approaches, active loads, and demand response approaches, the new controllable load management approaches are being researched. Firstly, new control strategies may include more controllable loads. A hybrid control model [69,70] may be popular in practical applications, including the main power system, renewable sources, and many different kinds of controllable loads. The aggregator model [71], bi-level, and multilayer control models will be studied in detail. Secondly, as more and more meter information is confirmed for the controllable loads and transmission lines in real time, the traditional optimized dispatching model will be replaced by the real-time optimized control strategy [72]. The spot price in microgrid and distributed power system would then be realized. Finally, the customer physical behaviors and customer habit formation will attract high attention in the demand response model [73]. The controllable load management approaches will be quickly developed with the research on smart grid and actively distributed.

8. Conclusions

This paper reviews the controllable load management approaches, including DLC, ILM, V2G, battery storage, and heat storage. The optimal management strategies are reviewed and the control models are discussed. Comparison and development trend of controllable load approaches are also studied in this paper. It is concluded that the controllable loads management approaches are effective to provide fast balancing services to the system in the active distribution system. It is also helpful for future research on renewable energy penetration. Future work will be focused on the penetration level of each controllable load and coordinate the optimal operation of hybrid renewable energy and controllable loads.

Acknowledgments

Author Contributions

Chuanwen Jiang contributed to the conception of the study. Jingshuang Shen contributed significantly to analysis and manuscript preparation. He also performed the data analyses and wrote the manuscript. Bosong Li edited English language.

Conflicts of Interest

The authors declare no conflict of interest.

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