

Review

A review on control systems for fast demand response for ancillary services

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Abstract: To solve the climate change problem every country should use renewable energy sources for power generation. However, present renewable sources such as wind and solar are intermittent sources. So, to integrate these intermittent sources into the power grid the capacity of ancillary services (AS) must be increased. Fast demand response (Fast DR) has the potential to be used as an AS in a power system. This paper first reviews the progression of demand response (DR) as an AS. From this, it is shown the concept of Fast DR emerging in the literature. Then the literature is categorized into economic studies, experimental studies, and control system studies. The economic studies done by several contexts in several countries show that using Fast DR for AS is viable. Then the technology used to implement Fast DR is reviewed using the experimental studies and using existing technologies to implement Fast DR is shown to be viable. The literature on control system studies for Fast DR is categorized based on the type of the load. The paper is focused on highlighting the types of loads that can be used for Fast DR for AS and the requirements of a Fast DR program. The authors are conducting research on using Inverter Air Conditioners (Inverter ACs) to provide Fast DR which looks promising. A project to implement a Fast DR program in a building is being planned.

Keywords: smart grid; microgrid; ancillary services; fast demand response; demand response; control systems

1. Introduction

Renewable energy is essential for a sustainable future for mankind. UN Sustainable

Development Goal 7 [1] expresses the necessity of substantially increasing the share of renewable energy in the global energy mix. Because of this many countries plan to turn to higher capacity of renewable energy soon [2,3]. However, with the increasing share of renewable energy, the reliability of the utility grids will be at risk due to the intermittent nature of renewable sources [4]. To mitigate this issue, the capacity of ancillary services should be increased.

Ancillary services (ASs) are services that support the power system in maintaining power quality, reliability, and security. The main ancillary services are regulation, load following, spinning reserve, and non-spinning reserve. The ancillary services provide the utility with several resources that can be used in an emergency or in control which increases the power systems' capability to handle more renewable energy sources. These resources are traditionally supplied by generators. With more AS capacity needs, using DR to supply AS is studied.

Table 1. Ancillary services for fast demand response participation.

Service	Response speed	Duration	Market cycle
Regulating reserves	<1 min	30 min (real-time)	Hourly, every 15 min
		60 min (day ahead)	looking ahead 2 hours
Load following or fast energy markets	~10 min	10 min to hours	5 min
Spinning reserves	Instant response: <10 min	30 min	10 min
Non-spinning reserve	<10 min	30 min	10 min

Demand response (DR) has been identified as a viable method to provide ancillary services (ASs) to power systems [1,5,6]. DR programs are a set of programs or activities that introduce changes to the power consumption patterns of consumers as a response to the price of the electricity over time or incentives provided by the utility at certain high-cost periods or when the system reliability is at risk. DR programs, DR program types and taxonomy, DR program participants, and challenges are widely reviewed in the literature [7,8]. Automated demand response (ADR) is identified as a type of DR program in which the DR signals of the utility are received by control equipment on the consumer side and the necessary preprogrammed control is done automatically without human assistance. Automating the DR programs is required for the advancement of the DR programs and smart grid technologies will permit the ADR programs to thrive in the future. Also, intelligent control of DR programs such as using Multi Agent Systems will be favorable in future [9]. For an overview of ADR architecture, standards, case studies, and research challenges, see [10].

Introducing DR or ADR to provide AS in the power system paved the way for a fast time scale demand response. Fast time scale demand response, fast automated demand response, and fast demand response (Fast DR) are used to describe the same concept in the literature over the years.

However, Fast DR is yet to be properly defined. There are many similarities between DR for AS and Fast DR and in many cases, DR for AS can be categorized under Fast DR. In [11] Kiliccote shows that regulation services, load following, spinning reserves, and non-spinning reserves are the AS for Fast DR participation. This understanding is the basis for this review paper. To justify this, these AS and their features are summarized in Table 1 [11].

The goal of this review paper is to identify the progression of research on using DR for ancillary services and Fast DR. The focus is on the technology used and the economics and policy involved. As the review progress towards the technology used, the term Fast DR will be used to refer to all the programs.

This paper is organized as follows. Section 1 is the introduction. Section 2 covers the progression of the research on Fast DR and research areas. Section 3 summarizes the research on the economic value of Fast DR for AS programs and inquire about the status of the related policy. Section 4 summarizes the experimental studies conducted. Section 5 summarizes the simulated studies and control system studies. Section 6 is the quantitative analysis of Fast DR capacity and time delay. Section 7 is the conclusion.

2. Research progression and areas of research

The earliest notable mention of using DR for AS dates to a report published in 1999 [1]. In [1], the possibility of using loads as a bulk power system reliability source is discussed. This white paper has reviewed the market structures for the future grid in which customer participation in ancillary markets is discussed. After this many researchers from several institutions have researched on providing AS from DR. However earliest mention of providing AS from demand-side management is in [4], which is just a short account of providing demand-side services to NGC Transmission Services in the UK.

2.1. Earliest research

The research before 2010 is considered early research since this research is mostly done only in the USA. Oak Ridge National Laboratory (ORNL) and Lawrence Berkeley National Laboratory (LBNL) are the main institutes that led the research with industry collaborations [12–22].

2.2. After 2010

After 2010 the research interest can be identified globally. Researchers from many institutions are researching various aspects of providing AS from DR by this time. In this period, the new set of names such as fast automated demand response, fast timescale demand response, and fast demand response is used in literature. Also, there is little research on applying Fast DR in Isolated Power System (IPS) which is a novelty [23,24].

2.3. Research areas

The research areas are economics-related, policy-related, and technology-related [1]. Some research may overlap in the areas they touch while others are more focused. The trend is that while economics and policy-related work are done together, and technology development is more focused. Also supporting experiments are almost always present in economics and policy-related work. There are subcategories in technology-related literature. They are experimental studies and simulated studies. Typically, simulated studies are used for control development. There are several other notable research areas such as required communication [19,25,26,27] and baseline estimation for telemetry [28].

Also, there are some other approaches such as using both DR and electricity generation for AS [29,30]. Furthermore, in [31] DR and the existing spinning reserve are used for frequency restoration. Also, in [32] primary voltage is controlled using DR. The main research areas can be

summarized as in Figure 1. Classification of the literature available on Fast DR for AS is given in Table 2.

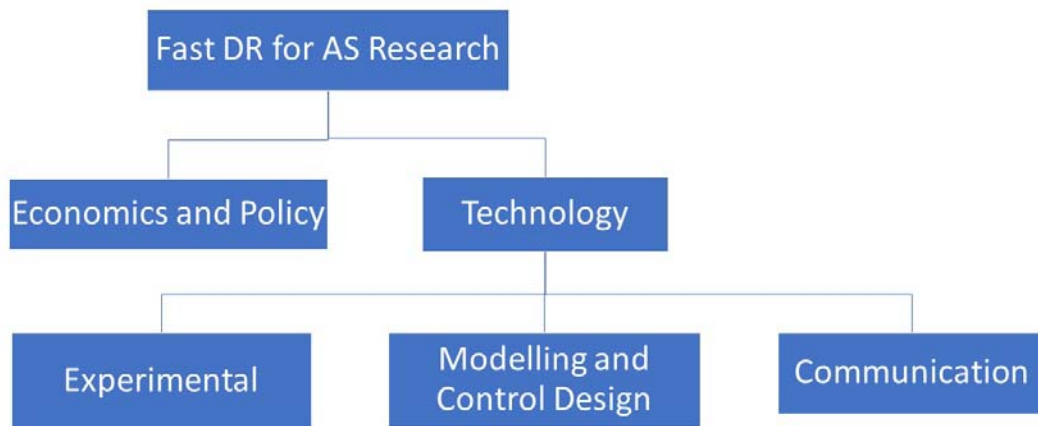


Figure 1. Classification of the research areas on fast demand response for ancillary services.

Table 2. Classification of literature on fast demand response.

Type of study	Research
Economics and policy related	[12–15,17,21,33,34,35,36,37,38,39,40,41]
Technology related: experiments	[12,16,20,42,43,23,44,45,46,47–49]
Technology related: control	[50–61,62,28,63–70,71,72,29,31,73,74,32,75,76,38,24,39,77,30]
Technology related: communication	[19,25,26,27,12]

3. Economic and policy studies

The early research addresses the economics of implementing DR for AS. The studies, [12,13] are the beginning of a series of research and reports to introduce the idea of AS using DR in the USA. In [13] authors have conducted a study to analyze the potential of providing ancillary services to the grid using pump loads. Their results were encouraging, and the authors have reported over \$11 million in revenues annually and pointed out the policy and rule changes needed to give AS using load response. In [14] the authors argue on the costs of using generation for spinning reserve and points out that using DR for AS will reduce costs of all power system customers. Kirby answers some important questions regarding the concept and the economic value it possesses as well as rule and policy changes needed to adopt DR for AS in [15]. In [17], authors have analyzed the capability of providing DR through its manufacturing and aluminum smelting facilities. There is a market analysis done to obtain the exact financial benefits of the implementation. Also, a comparison is done to compare the different markets in the USA in [17] as well as in [34]. Similar market analysis regarding the UK, Australian, Nordic, Pennsylvania, New Jersey, Maryland Interconnection LLC (PJM) and Electricity Reliability Council of Texas (ERCOT) is conducted in [21]. Also, several international feasibility studies in Canada [37] and Italy [40,41] is done. In [33] an interesting economic study is done to compare the costs between batteries and DR in the context of renewable energy. Also, in [35] a study is conducted to identify the mix between DR and renewable energy to minimize the cost of operating wind energy.

All the studies [12–15,17,21,33,34,35,37,40,41] give positive results on the economic value of implementing DR for AS. The negative results are from the authors of [36,38,39]. In [36] it is concluded that immediate financial benefit to run a Fast DR type program on small domestic thermostatically controlled loads (TCLs) is negative. They also stress the fact that there are limitations of the models used and there are indirect benefits and other types of markets that are not included in the study. In [38,39] the researchers point out that the overall efficiency of the system is adversely affected because of the short timescale changes in the system and later compensating for them.

The research areas of the economic studies can be summarized as follows,

- Preliminary feasible studies
- Studies specialized for different customers/loads
- Studies based on different market structures
- Studies in the context of renewable energy

4. Control systems of experimental studies

After and during the preliminary studies researchers began experimenting on the concept of providing ancillary services through Fast DR. Several notable experiments are,

- a. SCE experimental study [20,42,47]
- b. PG&E experimental study [22,78]
- c. LBNL experimental study [79]
- d. An experimental study by Mitsubishi Electric Building Techno-Service and Kyushu Institute of Tech. [44]
- e. LISCOOL energy project [45]
- f. King Island Smart Grid project [23,49,80]
- g. SYSLAB at Technical University of Denmark [46]
- h. An experimental study by Cardiff University [71]

In these research studies, few approaches can be seen and there are a lot of similarities. The features of the study that is focused on this review are, the control structure, telemetry, and communication technologies. However, the communication aspect is integrated into the control structure and telemetry. So, it is not considered separately.

4.1. Control structure

The control structure is quite similar in most of the studies except for the study by Cardiff University researchers [71]. So, two main control structures can be identified. Also, these two control structures can be categorized as centralized and distributed structures. The criterion for determining a control structure is centralized or decentralized is based on the whether the DR signal originated from the utility or from a local controller. If the DR signal originated from the utility the control system is taken as centralized and if it originated from a local controller the control system is taken as distributed.

The distributed control structure is used in [71]. This research on providing secondary frequency control using local load control. The researchers have used smart meters to measure the grid frequency and control the loads using a control algorithm. They have implemented the local

control system to determine the control scheme delay. The researchers have used a simulation of the Great Britain power system to assess the capability of the system. The control structure is shown in Figure 2.

The centralized control structure can be simplified in to three sections. Namely, central controller, communication, and load controller. In some cases, there are additional components like data aggregators, databases, data managers, and data forecasters. These additional components enhance the reliability and accuracy of the overall system. However, most of these additional components are highly integrated to the system. Figure 3 summarizes the structures of all the centralized control structures.

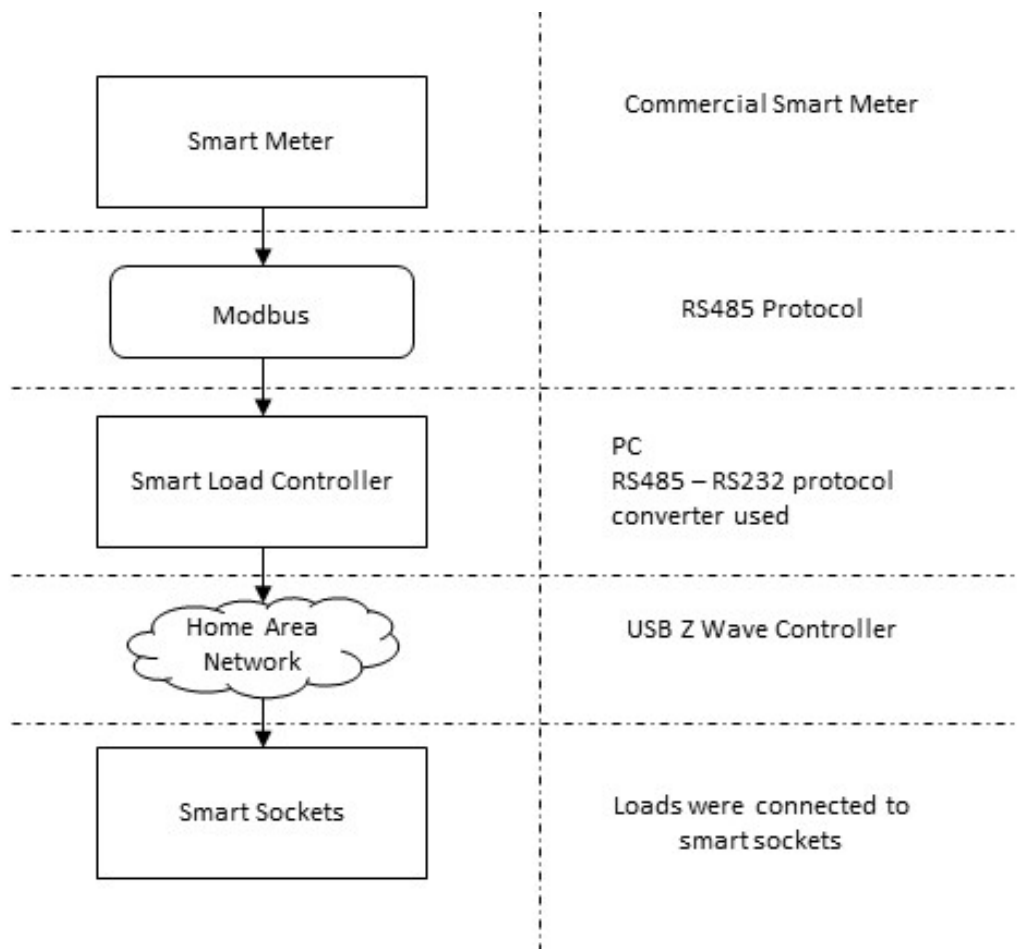


Figure 2. Distributed control structure using smart meters.

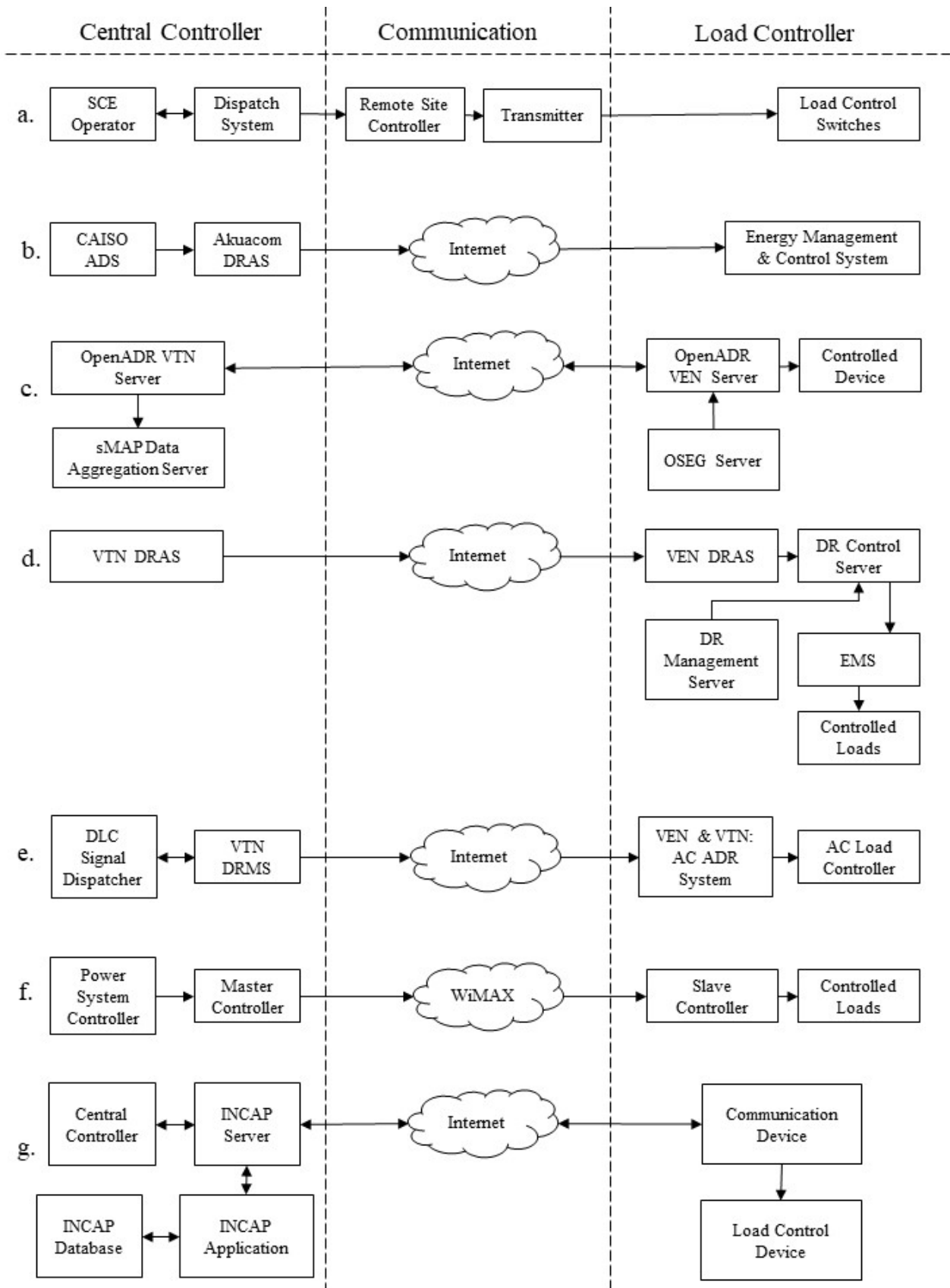


Figure 3. Summary of centralized control structures in experimental studies.

4.2. Telemetry

Telemetry is an important part of a DR program. Telemetry allows utility companies to measure the incentives to be provided for the customers who participate in the program. Also, telemetry data provides the necessary insights that determine a successful DR program. In the experimental studies considered in this review, a wide variety of technologies have been used for telemetry purposes. However, using internet for the implementation is visible in every case. The motivation for this is the cost effectiveness of the internet technologies.

4.3. Overview

After establishing that DR can provide AS in an economical way, researchers began studying the technology needed to achieve it. There are several basic technology components of the DR for AS programs. Since these components are also available in all Fast DR programs, these technologies are identified as the technologies required for Fast DR programs. Tables 3 and 4 summarizes the technologies used for control and the technologies used for telemetry in the experimental studies respectively.

Table 3. Summary of technology used in experimental studies for control.

Study	Control		
	Central control	Communication	Load control
SCE experimental study [20,42,47]	SCE control center (SCADA system sends DR signal to loads)	Radio tower using VHF waves	Load control switches with ACP (VHF receiver takes the signal and control loads using relays)
PG&E experimental study [22,78]	DRAS	Internet	EMCS controls the loads using CLIR box
LBNL experimental study [79]	Cloud-based server with Ubuntu Linux	Internet	BeagleBone black controller Wi-Fi thermostat Dimmable LED bulb With OpenADR 2.0b
Fast DR for small buildings in Japan [44]	DRAS	Internet	EMS with OpenADR 2.0b
LISCOOL energy project in Portugal [45]	DRAS in a DRMS	Internet	AC local controllers or HEMs with OpenADR 2.0b
King island smart grid project [23,49,80]	DR master controller	WiMAX antennas are used to transmit the signal	Slave controller box with smart switches (WiMAX modem takes the signal and given to smart switches using ZigBee module)
Secondary frequency control based on DR [46]	Project INCAP server	Internet	Smart relay controller (Communication using the internet)
Experimental load control scheme: UK experiment [71]	Laptop PC (IntelTM Core 2 Duo T7250 2 GHz processor)	HAN	Smart sockets with HAN

All the controllers except [71] in experimental studies use a central controller and local load controllers. In every case considered in this review, the central controller hardware is a server computer. Many types of load controllers are used in different studies. Some of these controllers are commercial components [12,16]. Smart switches and relays are widely used as load controllers. For the communication different technologies are used in each experiment. The use of existing technologies can be seen in many experimental studies that were done on large scales. VHF communication in large distances is done in SCE experiment [20,42,47]. WiMAX is used in the KISG project [23]. Another major communication infrastructure is the internet. For a more detailed study on communication for Fast DR see [13]. Several software applications and protocols to implement load control and telemetry are used in experimental studies. The use of OpenADR 2.0b is prominent in the experiments. Other protocols include ACCP, CDMA, Modbus, and ZigBee which are used for communication.

Apart from these research studies, there are some experiments on grid-based Fast DR programs, and some are done for IPSs. The most notable experiment on Fast DR in IPS is done in [23,49,80] studies. The IPS in these studies is the King Island Smart Grid.

Table 4. Summary of technology used in experimental studies for telemetry.

Experimental study	Technology used for telemetry
SCE experimental study [20,42,47]	Web-based ACCP
PG&E experimental study [22,78]	Smart Meter with CDMA chip Network provider (Bow Networks)
LBNL experimental study [79]	USB radio adapter (Rainforest RAVEn adapter) OpenSEG
Experimental load control scheme: UK experiment [71]	Commercially available smart meter
Fast DR for small buildings in Japan [44]	EMS
LISCOOL energy project in Portugal [45]	Not specified
King island smart grid project [23,49,80]	Not used
Secondary frequency control based on DR [46]	Measurement using the same controller used for load control

5. Model based control system studies

Table 5. Classification of research on control logic based on load type.

Load type	Research
Central HVAC	[50,51,52,55–59,61,62,28,63–70,75,38,39]
Distributed air-conditioners	[73,74,81]
Thermostatically controlled loads	[53,72,74,82,81]
Inverter ACs & Variable speed heat pumps	[84–88]
Pool pumps	[54]
Data centers	[77]

The simulated studies are done to develop the control logic for different loads. The control logic depends on the control load type as different loads show different power consumption characteristics. Mainly there are three types of loads considered in previous studies and they are, Thermostatically Controlled Loads (TCL), distributed air-conditioners, and central HVAC systems. Also, there are pool pumps [54] and data center loads [77] that are used in the studies. Finally, research on using

Inverter ACs and variable speed heat pumps for providing frequency response in a power system is reviewed. Classification of control logic research based on the type of load is given in Table 5. Main types are used for the categorization.

5.1. Central HVAC studies

Studies on using Central HVAC systems for Fast DR is done by several research groups. Their research focuses on building models, developing control systems, and providing ancillary services without effecting the occupant comfort.

In [50,51,55,56] the researchers have gradually improved the model, control, and results. In these kinds of literature, a model based on input-output measurements is used to develop a controller. In [50], providing regulation to the grid is converted into a Linear Quadratic Regulator (LQR) problem which has a simple closed-form solution. In [51,57], a feedforward control architecture is proposed. In both this literature, the controlled load is a Variable Frequency Device (VFD) equipped fan in an Air Handling Unit (AHU). In the studies fan power is used for regulation and the regulation signal can be tracked in the frequency band $f \in \left[\frac{1}{3 \text{ min}}, \frac{1}{8 \text{ sec}} \right]$ without affecting the indoor temperature. It can be derived that approximately 6.6 GW regulation capacity can be provided using all the VFD equipped fans in commercial buildings in the USA. In [55,56], the research is expanded to include chillers. It used the Variable Air Volume (VAV) HVAC system with onsite chillers. The main idea presented in this literature is the bandwidth limitation of the regulation signal. It can be derived that approximately 47 GW regulation can be provided, and the regulation signal can be tracked in the frequency band $f \in \left[\frac{1}{60 \text{ min}}, \frac{1}{3 \text{ min}} \right]$ without affecting the indoor temperature. Also, all these systems meet the ISO/RTO standards for regulation. Further studies on providing a faster response are given in [58].

In [59] fine time granularity fast demand control of building HVAC system is studied. A novel scheme is proposed for building a Variable Refrigerant Flow (VRF) HVAC system. An Auto-Regressive (AR) model of 5-minute interval power consumption of the entire building HVAC facilities was obtained using data. The trial calculations show that the new scheme implementation will be successful. In [61,62] an emulation system is developed to reproduce and analyze the behavior. A neural network model is developed from actual time series data. It was found that step responses of Fast DR sometimes oscillate depending on control.

In [63] Fast DR control strategy is presented which uses shutting down chiller(s) of an HVAC system. Also, active and passive cold storage is used in this strategy to improve indoor thermal comfort and to alleviate the post-DR event spike in demand. The advantages of using chillers to reduce demand are that the demand reduction is immediate and considerable. However, there are some problems such as the uneven distribution of water flow and air temperature unevenness caused by shutting down essential operating chillers. These issues are addressed in [64,65,67]. The paper [66] presents a control strategy based on Model Predictive Control (MPC). In [68,69] the control strategy for the cold storage is discussed and the complete research is presented in [70] in detail. In [28], studies on multi type air conditioners in a building are conducted. The research is focused on estimating base line estimation for Fast DR. In [75] the researchers develop a model for commercial HVAC systems and in [38,39] they use it to design controllers to provide ancillary services. However,

their economic study gives negative results when the overall efficiency is considered.

5.2. *Distributed air conditioning units*

In [73] load control of heterogeneous populations of ACs using a novel parametric Linear Time-Invariant (LTI) model is presented. This LTI model is used to design the controller using the parameters of the AC population. The control is done by introducing offset to the user's temperature set-points. The study in [74] presents Thermostatically Controlled Appliances (TCA) which controls the Air Conditioners. A centralized load controller is developed to control TCAs for Continuous Regulation Reserves (CRRs). The logic for setting up baseline load, generating priority lists, issuing dispatch commands is given in [74]. The TCA load controller is successful in providing robust, high-quality CRRs with reduced cost for communication and load controllers. In [81] parameter section of the controller is discussed.

5.3. *Thermostatically controlled loads*

These studies are similar to controlling distributed ACs, but a wide range of appliances can be used with these controllers. In [82] modelling is done using existing data of TLCs as well as other loads such as ACs. In [53] a generalized battery model is used and in [72], bin transition modeling technique is used for the control design. In [83] regulation service is provided using DR of TCLs. Also, researchers have considered providing regulation services in different seasons and providing "regulation raise" services from the network of different sizes.

5.4. *Distributed inverter air conditioning units*

There is some literature on using Inverter ACs and variable speed heat pumps for DR. However, they are limited to providing frequency response to power systems which can be extended to provide ancillary services. The researchers have modeled [88] and developed control systems to provide frequency regulation in a power system [84–88]. This research can easily be extended as a Fast DR program.

6. **Quantitative analysis of fast demand response programs**

There are many approaches that can be taken for a quantitative analysis on the literature studied. They are,

- Fast DR capacity analysis
- Time delay analysis

These approaches show the various aspects to be considered to execute a successful Fast DR program.

6.1. *Fast demand response capacity analysis*

Fast DR capacity can be identified as the amount of power which can be used for Fast DR purposes in the different experiments and studies. Since the studies are not structured this parameter

is not given in a typical format in the studies. Also, there are several external conditions that effect this parameter. However, Fast DR capacity is important because it gives an idea on the usefulness of the Fast DR program.

When considering different loads, there are several studies for different loads. In [13], an experiment was conducted using packaged through the wall air conditioners (PTAC). It was found that approximately 1.1 kW of spinning reserve is available per PTAC during maximum load demand times. In [14], studies were done on supplying spinning reserve for the California Independent System Operator (CAISO) grid using water pumps of California Department of Water Resources (CDWR). It was found that CDWR has the potential to supply 62% of the CAISO spinning reserve requirements under specific conditions. Also, the responsive water pumps had enough capacity to supply 100% of the spinning reserve requirements for 3292 hours. In [15], studies were conducted to use central control of air conditioning systems using smart thermostat to supply spinning reserve. The controlled load consisted of 23400 smart thermostats. It was found that roughly three times the load reduction capacity is available for spinning reserve. In this case the load reduction capacity was 25 MW and spinning reserve capacity was 75 MW and two thirds of the spinning reserve capacity, 50 MW was still available for spinning reserve when the loads are already curtailed. In [16], it was shown that load can be curtailed by 22%–37% depending on the outdoor temperature and time of the day for a hotel load. In [17], studies were done to use an Aluminum smelting plant to provide spinning reserve. The average load of the plant is 500 MW and 15 MW of spinning reserve was successfully provided to the grid. In [52] and [55–57], a team of researchers have studied providing regulation services using a building HVAC system. They have increased the HVAC system regulation capacity from 11 kW which only use AHU fans to 100 kW using chillers with AHU fans. Also, they have studied about RegD type regulation services which is the fastest regulation reference signal provided by PJM. It was found that fans in AHU provide 40% of their nominal power for ancillary services.

In [73] researchers have used a population of 60 distributed air conditioners to supply load following services where the generation is supplied by wind turbines. The generation was assumed to be 6, 20 kW wind turbines and the study shows that the proposed controller can make the total demand tightly follow the varying generation output with a maximum change in temperature setpoint of 1.5 °C. A similar research is [74] where approximately 1000 HVAC units were considered rated at 6 kW and it is shown that 24 hours of intra-hour balancing services which amounts to 1 MW of bi-directional signals can be achieved by the proposed control scheme.

In [82], researchers have studied providing regulation services in different seasons. For 30 houses, the average possible regulation during winter is 28.83 kW, 17.74 kW in fall, 25.58 kW in summer and 22.57 kW in spring. Also, the study is done for network sizes of 120 and 960 houses. The error percentage is reduced when the number of houses increased. For example, at 12.30 hours, in 960 house network the error percentage is 0.17% and in 30 house network the error percentage is 4.77%.

Baseline estimations is a must for metering purposes and to determine the Fast DR capacity. In [28], the researchers have developed a model in which the root mean square error of baseline estimations from 18 weekdays of Fast DR trials was 1.68 kW, i.e., 13% of rated power consumption.

In [49], researchers present Fast DR as an enabling technology to support high renewable energy penetration in an IPS. The simulated results show that renewable energy penetration increased by 2.5% without added renewable energy generation or decreased consumption for 50% Fast DR capacity.

6.2. Time delay analysis

Time delay is a major concern in a Fast DR program. The maximum time delay for load following, fast energy markets, spinning reserve, and non-spinning reserve is given as 10 minutes and the maximum time delay for regulation service is 1 minute in USA [11]. A Fast DR program must adhere to these constraints to be implemented.

In [15], researchers claim that the tie delay was 90 seconds. Improved results are given in [16], where researchers have achieved 12–60 seconds time delay. In [20] the time delay is lower than 20 seconds and in [79] it is approximately 20 seconds. In [34] the average time delay is reported as 24 seconds. In [23] researchers are reporting that they have achieved sub second DR capacity of more than 100 kW. These experiments show that necessary time delay for a Fast DR program can be achieved.

In [71], a distributed control system using smart meters is developed and it is shown that if the time delay is more than 1s, there is no effect from the controlled loads. Also, it is shown that the maximum primary response can be obtained if the delay is less than 200 milliseconds.

7. Conclusions

Using Fast DR to provide AS is reviewed in this paper. Fast DR is becoming more applicable and relevant in the modern utility grid with high penetration of intermittent renewable sources. This paper reviews Fast DR programs in terms of economic feasibility and technology.

Many studies show that Fast DR is economically viable with few exceptions. However, these exceptions also point out that Fast DR can be improved or that all the factors are not considered in their research scope.

The technology used in Fast DR programs is considered in the context of experimental studies and control development. Most of the studies consider central HVAC systems, Distributed ACs, and TCLs. Also, Inverter ACs are considered for DR which can be directly applied to Fast DR programs. Apart from using Fast DR in the main utility grid, some researchers have experimentally used it in IPSs successfully. All these findings show that Fast DR is a viable technology to provide ancillary services to main utility grids and IPSs. When considering the control structure, central control and distributed control can be identified. There are very few studies on using distributed control in the Fast DR context so it's still unclear what would be the more suitable structure. However, the centralized control looks promising and reliable hindering the need for distributed control. The only study on distributed control structure is done as a single load in a grid and if it is scaled to a grid wide implementation, the practical impacts are yet to be determined. Time delay and capacity are two most important parameters that decide the effectiveness of a Fast DR program. The state-of-the-art implementations have accomplished time delays of few seconds and capacities that can provide substantial ancillary services to the grid.

Future of Fast DR programs depends on implementing them in the real world. More implementations are needed to solidify the technology used in the programs. The authors are currently conducting research on using Inverter ACs to provide Fast DR which looks promising. As a future project, implementing Fast DR in a building using Inverter ACs is being planned.

Acknowledgments

This work was supported by the Indo-Sri Lanka Joint Research program, by Department of Science & Technology (DST), Government of India and Ministry of Science, Technology & Research (MSTR), Government of Sri Lanka under the Grant: MSTR/TR/AGR/3/02/13.

Conflict of interest

The authors declare no conflict of interest.

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