Load Control for Frequency Response – A Literature Review

Benjamin Anderson, Jim Reilly, and Venkat Krishnan

National Renewable Energy Laboratory

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Table of Contents

List of Figures

List of Tables

1 Introduction

This paper reviews the literature documenting physical simulations and real-world systems that employ load control for frequency response and other grid services. As electricity grids employ greater fractions of renewable energy such as distributed wind, which introduce additional variability and uncertainty in the net load, balancing electrical load and generation becomes more challenging. A failure to quickly balance the power system can result in unwanted frequency excursions and expensive operational mitigation strategies that require the quick start of non-spinning generators. This reality is amplified in distribution systems, islanded microgrids, and isolated grids, where individual loads and variable renewable generation sources like distributed wind make up a much greater fraction of energy generation or consumption. Traditionally, variable renewable generation has been curtailed or conventional generation has been ramped up to support grid frequency stability. Currently, in larger grids, during frequency dips automatic under-frequency load-shedding (UFLS) relays drop entire feeders. This is problematic, causing widespread blackouts and cutting off distributed energy resources (DERs) in the dropped feeder, which can exacerbate the frequency dip. As such, there is increasing interest in using alternative methods to support grid stability such as actively and intelligently controlling loads.

To simplify the relationship between frequency and load, note that a sudden increase in load will decrease the system frequency, and a sudden decrease in load will increase the frequency. Using this principal, loads can be used to control and improve grid frequency regulation and stability, if they are large enough and can be quickly controlled. Apart from academic and simulation studies, few sources exist on large-scale lab hardware testing or actual real-world physical systems that employ load control for frequency response, and we review them here. Four areas that we consider are: 1) laboratory-based load control experiments, 2) isolated microgrids that employ load control, 3) larger grids that employ load control, and 4) vehicle-to-grid (V2G) technology, using electric vehicles (EVs).

The size of the grid and the type of devices supplying that grid have a significant impact on frequency regulation. For example, smaller microgrids with limited inertia and large potential swings in energy flows from variable renewables, such as distributed wind, will require more rapid frequency response than larger grids with higher inertia. Larger grids often contain generation reserves and large numbers of distribution circuits and loads, making frequency control less granular and more generation-centric. They are typically designed to shed entire distribution circuits during underfrequency events and are controlled by utilities at the substation level using pre-programmed, autonomous relay controls. Such controls could be improved by a more granular approach that accounts for the various DERs dispersed throughout the grid. Loads could be controlled by intelligent internal control systems, or by external protection and switching devices. This work is performed under the under the U.S. Department of Energy Wind Energy Technologies Office's Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project, which aims to demonstrate the benefit of distributed wind in various contexts and illuminate pathways to increase distributed wind benefit and deployment. We believe that leveraging the capability of controllable loads to support grid stability could ease the integration of wind in distributed applications.

2 Load Control Use Cases and Demonstration

2.1 Research Systems

Laboratory-based experiments have been performed to validate load control algorithms for frequency regulation. They are the first physical step in demonstrating load control methods that can benefit real-world systems with distributed wind. Fatheli et al. (2017) developed a load control algorithm and validated it in an islanded-grid setup. The islanded microgrid comprised solar photovoltaic (PV) generators, an inverter, light bulbs, and a controlled load bank. Their threshold algorithm disconnected the load bank from the grid when the difference between the load current and the PV current exceeded a threshold value, thereby ensuring generation-load match and addressing frequency and voltage violations caused by variations in solar irradiance. Current fluctuations occurred because of a lack of synchronization between data acquisition system hardware timing and software timing, but these fluctuations were minimized by adding a time delay to the software.

Samarakoon et al. (2012) developed a load control system for grid-connected homes in the United Kingdom (UK). They used smart meters to measure the frequency dip and switch a variety of types of loads off/on as necessary to keep the grid frequency within 1% of its nominal value. The loads were divided into different categories, with different reasonable switching constraints (e.g., a dryer was switched off at a smaller frequency excursion and for a longer time than a lightbulb). They noted that, if smart meters are to be involved in grid primary frequency response, then they must measure system frequency quickly (within 200 milliseconds (ms) in their setup). They used commercial-off-the-shelf components to demonstrate a feasible system.

Pandiaraj et al. (2001) developed a novel microcontroller to monitor system voltage and frequency. They preferred to use a level crossing detection (LCD) algorithm to detect frequency excursions, as it performed multiple frequency estimates and multiple use of voltage samples per cycle. They tested this algorithm at an 18-kilowatt (kW), 230-volt (V), 50-hertz (Hz) single-phase microhydropower system located at Polmood, UK. Even with heavily distorted waveforms, the algorithm had a maximum frequency measurement error of 0.04-Hz, with a response time of 175-ms. To stabilize the system frequency, they used a fuzzy load control algorithm that bypassed two common issues with threshold-based load controllers: unequal load service and difficulty finding set points, which typically create oscillations or require additional controls for stabilization. The fuzzy logic controller achieved +/- 0.2-Hz frequency regulation at the same microhydro site, although it struggled to maintain system frequency in another system powered by a single 60-kW wind turbine. This was likely a result of the relatively larger wind power plant size and highly variable wind ramps during testing, along with a coarse level of load control (the system had only six controllable loads).

Lundstrom et al. (2018) demonstrated fast primary frequency response using coordinated distributed energy resources and flexible loads at the residential scale. Instead of deferrable loads acting independently to provide frequency support, they controlled individual loads by a centralized master controller that commanded an optimal dispatch decision for distributed energy resources and deferrable loads. This allowed for a much faster frequency regulation (within 10 alternating current (ac) cycles, down from 1-3-s). The control objective was to minimize the total load deferred while hitting a frequency response target to a grid frequency disturbance, although other objectives could be supported. They performed a physical demonstration comprising an inverter and four household appliances at the National Renewable Energy Laboratory's (NREL's) megawatt-scale power and controller hardware-in-the-loop testing facility in the Energy System Integration Facility in Golden, Colorado. The appliances were a 120-V fridge, a bank of fifteen 120-V lightbulbs, a 120-V electric heater, and a 240-V oven. Frequency disturbances were found with a quadrature phase locked loop (QPLL) algorithm, tuned to provide reliable, settled measurements within 1–3 ac cycles for all test cases. As the latest study examined in this report, they asserted that QPLL is currently the best method to measure frequency, as supported by Karimi et al. (2004). Frequency anomalies were responded to within 143-ms for all cases. Future work will include using this system at a larger scale and coordinating with synchronous generators to provide ancillary services.

2.2 Real-World Isolated Systems

There are real-world, operating, islanded microgrids that employ load control for frequency response, some of which contain distributed wind resources. As such, they demonstrate the resilience benefits of load control in high-renewable-penetration systems. Mitra et al. (2008) detailed one such microgrid, located on the Greek island Kythnos in the Aegean Sea. The German Institut für Solare Energieversorgungstechnik e.V., the Greek Centre for Renewable Energy Sources, and the German company SMA Technologie AG, are the main partners for this project. The systems were installed in 2001 under the framework of European projects PV-MODE and MORE. They were co-funded by the European Commission. The microgrid consists of 10-kW of solar PV, a 53-kilowatt-hour battery bank, a 5-kW diesel generator, an inverter for each battery/PV array, and 12 houses equipped with load controllers. The loads are controlled to protect the batteries from deep discharge. When battery charge is low, grid frequency decreases, and the battery is unable to provide the needed discharge to improve the frequency. At such times, the load controllers trip the loads off, thereby enabling generation-load balance and timely improvement in the frequency. Alternatively, the diesel could be switched on when the battery charge reaches a critical level instead of or in addition to the load control, but this was not explored in the documentation of this real-world system.

Outside of distribution system based UFLS, control of frequency using limited load control has been deployed in Alaska-based isolated systems since the early 2000s. Most systems have used dedicated thermal load devices, typically heating systems, to provide under frequency support by decreasing the thermal load and over frequency support by increasing thermal load at times of excess generation. In early systems, such as the high-wind-contribution system designed for Wales, Alaska (Drouilhet 1999; Drouilhet and Shirazi 2002), thermal loads for fast frequency response were located at the diesel plant to dissipate excess power, sometimes incorporated into the diesel plant heating system. Additional heating elements were also added at the village school that could be switched on during times of excess renewable energy. These thermal loads were not used to control system frequency but consumed excess wind energy generation, allowing the local deferable load and battery storage system to manage frequency while the diesel generators were not operating (Baring-Gould 2009).

A similar high-contribution, wind-based power system was installed in St. Paul, Alaska (Baring-Gould 2009). In this case, staged resistive elements, essentially a fast-acting controlled dump load, was embedded in an electric boiler to consume excess wind energy and manage system frequency when the wind turbine was producing more electrical energy than was needed at the facility. The boiler heated an industrial facility, allowing long periods of operation without external dispatchable generation. The St. Paul power system did not include electrical storage so it would only turn off the diesel engines and use the electric boiler for frequency regulation when there was a large excess of wind-based power generation, representing a wind energy contribution well above 100% of the electrical load. A synchronous condenser was used to control system voltage and reactive power when no dispatchable generators were operating. The Alaska Village Electric Cooperative has also developed load control devices to support power systems with higher wind contributions, again focused largely on thermal loads and not to provide direct frequency regulation. A high contribution wind project using two simple type III wind turbines and diesel engines was developed in Kokhanok, Alaska, through the Alaska Renewable Energy Fund. This project was designed to use large dispersed thermal loads, combined with battery-based energy storage, to provide frequency regulation. Technical issues kept the system from operating successfully, but the technical concept was fully vetted with additional analysis conducted on the potential to expand the system to include community heating as a dispatched load to address times of high renewable generation (Baring-Gould et al. 2017).

More recent work on frequency regulation in operating small-scale isolated power systems has focused on the use of distributed thermal energy systems to provide frequency regulation. Electric thermal storage (ETS) space heaters have been deployed in three high-contribution, isolated microgrid power systems in the Alaskan communities of Kongiganak, Kwigillingok, and Tuntutuliak by Intelligent Energy Systems. In each system, the ETS units are installed in homes around the community to serve the dual purposes of providing a fast-acting, highly controllable, interruptible, dispatchable load and to displace imported heating fuel with a local energy resource. Active control of the ETS units allows for the balancing of wind energy and electrical load, thereby supporting the regulation of grid frequency, which is largely driven by the variable wind resource. Energy flow to each of the ETS units is regulated using a specialized controller developed by Intelligent Energy Systems that receives a utility broadcast activation signal every ¼ to ½ seconds. The grid-interactive controller adjusts the ETS duty cycles to balance the output of a wind system, allowing for frequency regulation by adjusting the electrical load to meet generation from variable energy sources. Figure 1 demonstrates the direct result of the use of ETS powered by wind energy to provide thermal energy needs for the month of January 2016 in the community of Tuntutuliak. Initial work was begun to see if frequency regulation would be possible using these dispersed thermal loads in combination with wind turbines alone, as had been done with centralized thermal loads, but the relatively slow control and communication speeds combined with the fast response needs of small microgrid systems proved unworkable. Battery storage was then deployed to provide fine frequency support when the communities' dispatchable generators were turned off. Based on dialog with the project developer and system operator, with the implementation of faster control and communication hardware and the use of localized, low-frequency disconnects, it should be possible to achieve active frequency regulation without the need for additional battery storage.

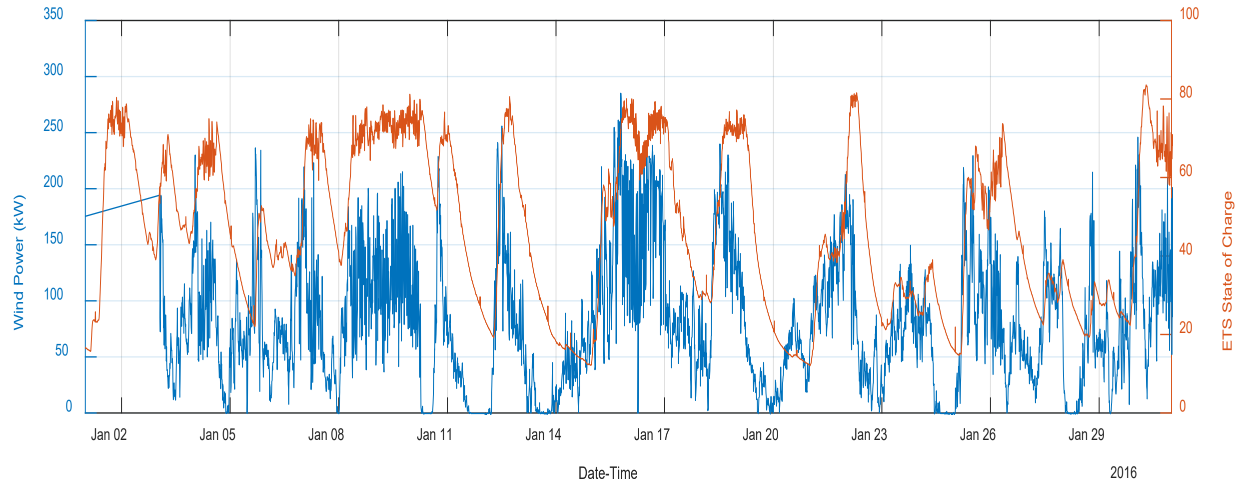

Figure 1. Wind power and electric thermal storage (ETS) state of charge for January 2016 in the Tuntutuliak wind-diesel grid. The plot indicates the ability of ETS to use wind energy to meet home heating needs. Note that between January 3 and the 12, ETS units were able to capture and use significant amounts of wind to meet heating needs. Data provided by Intelligent Energy Systems.

2.3 Grid-Connected Systems

Large utility grids have also employed load control for frequency response. Although frequency swings in such large grids are attenuated due to their inertia, as more variable renewable resources such as distributed wind are integrated, maintaining frequency stability is expected to become more challenging. Power constraints on local feeders is another concern that load control can ameliorate. The Olympic Peninsula Project was a field demonstration of smart grid (GridWise) technologies led by the Pacific Northwest National Laboratory (PNNL) (Hammerstrom et al. 2008). The peninsula, located in Washington, was fed by a 750-kW feeder, and had two diesel generators for backup when demand eclipsed the feeder rating. Using real-time market pricing and price-responsive contracts, which deferred customer heating, ventilating, and air conditioning (HVAC) loads (to a level that they determined), peak load was reduced, the feeder power balance was met, and feeder power constraints were not violated. This also allowed the diesel generators to easily meet the demand when it briefly eclipsed feeder capacity. The process was easy for customers to participate in and well-received: featuring automatic internet-based control, flexible participation, and ease of control override on the customer side. Customers had a "shadow market" account credited with their electricity savings, adding a visible financial incentive.

PNNL also performed the Grid Friendly Appliance (GFA) project (Hammerstrom et al. 2007). Fifty residential water heaters and 150 residential dryers were modified to respond to underfrequency signals from load-shedding appliance controllers. These modified appliances were distributed among residences in several communities in the Pacific Northwest—Gresham, Oregon; and Yakima, Port Angeles, and Sequim, Washington. When grid frequency fell below 59.95-Hz (60-Hz nominal), within 250-ms the controllers requested the appliances to shed electrical load. Note that this threshold is far from the underfrequency load shedding threshold of 58-Hz ("PRC-006-NPCC-2 - Automatic Underfrequency Load Shedding" n.d.). Responding to this shallow frequency dip could prevent larger dips from occurring in a grid, thus preventing underfrequency load shedding of whole distribution feeders. This is possible in a grid-connected setting where the vast number of loads and generators creates a highly stable system. Control at such a stringent threshold would be less feasible in a microgrid setting, with frequent swings crossing this threshold. The controllers also responded to peak-shaving demand-response requests and notified their customers via an indicator on the machines. Customers could easily override curtailment requests. Appliances did not shed all of their load, which allowed them to remain operational and return to full functionality when frequency moved into the normal range, as opposed to shutting off and requiring customer restart. Participant surveys indicated that they did not notice the load control and were not inconvenienced by it, and that they would purchase appliances equipped with the grid-friendly appliance controller. In contrast, traditional substation relay action created outages for many customers on entire feeder circuits, which such grid-friendly appliances could help prevent. GFA offers other benefits over traditional methods: curtailment could smooth the response to system frequency dips, and could better mitigate disturbances if distributed throughout the system such that some were near the disturbance source. Finally, GFAs could respond to demand-response requests.

Figure 2 shows the results from the aforementioned study. Whenever the frequency dip crossed the trigger point of 59.95-Hz, load control was initiated to bring the frequency back to greater than 59.95-Hz. As shown in the plots, the amount of load control varied depending on the frequency drop size beyond the trigger point and the rate of change of frequency (ROCOF) measured. Larger events required greater amounts of load curtailment and for a longer duration.

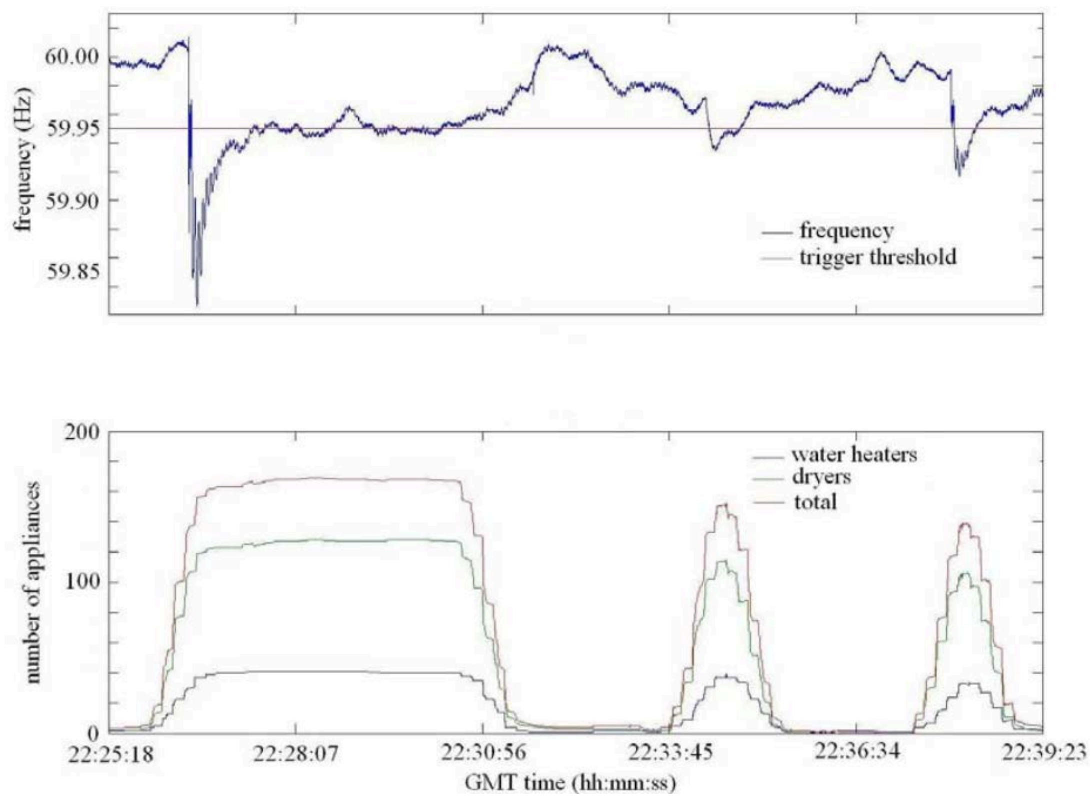

Figure 2. Frequency response from load control to several consecutive underfrequency events (Hammerstrom et al. 2007)

2.4 Vehicle-to-Grid

Electric vehicles (EVs) contain large batteries, which can provide ancillary services such as frequency response to the grid, with some constraints (i.e., customer's permission to access and communicate with the battery, cybersecurity, the customer's use of the vehicle, and the limitations that customers' mobility needs place on the use of stored energy). Recruiting EV batteries to provide ancillary services is known as vehicle-to-grid (V2G). Looking beyond some of the nontechnical and infrastructure reasons, from a technical perspective ancillary services require large capacity and quick response time, but low total energy. EV batteries (several of them distributed) are well-suited to provide these ancillary services, specifically regulation via automatic generation control (AGC), short-term ramping, and oscillation damping services; all of which are important for frequency response. If there is appreciable penetration of EVs, significant combined capacity and an aggregator, they can provide both spinning reserve in response to grid contingencies or outages, and longer-term energy storage for renewables (Kempton et al. 2009), which helps to avoid curtailments and meet large ramps. With its capability of injecting power back into the grid in addition to controlling power draw, V2G has the potential to be a more powerful tool than regular controllable loads. Although no examples of V2G in microgrids or isolated grids were found, V2G's frequency-stabilizing capabilities will be even more critical in these systems, as their stability is more difficult to maintain. Given the omnipresence of vehicles, as EVs expand throughout the vehicle market, they will likely be present in such systems and could contribute.

Brooks (2002) evaluated the feasibility and practicality of EVs providing frequency response on a utility grid. This work was performed in California as a collaboration between AC Propulsion, Inc., NREL, and a variety of other individuals and organizations. The EV engaged in frequency response by charging when the grid frequency was above nominal and discharging when it was below nominal (up/down regulation). In this study, power dispatch commands were sent to the vehicle at 4-second intervals, which were within the independent system operator's (ISO's) automatic generation control and frequency regulation system requirements. Significant physical modifications were required for the EV to provide power back to the grid: the installation of a second generation AC150 drive system which was equipped with a bidirectional grid interface, and the installation of a wireless modem to allow remote dispatch of V2G functions. On a web-based platform, users could set when they wanted the EV to be available for regulation and the minimum battery state of charge (SOC) desired at the end of the service period (based on individual customer's transportation needs). Daily energy throughput resulting from regulation was at the same order of magnitude as that caused by daily driving, and battery heating was negligible. Brooks noted that providing ancillary services could also create a significant financial incentive for EV owners (on the order of $1,000–$5,000/year [2001 dollars]) However, this value fluctuates with the market value of ancillary services.

Kempton et al. (2009) led an experiment with a custom EV connected to the PJM system for regulation, with a team of engineers from Pepco Holdings Inc., PJM, and the University of Delaware. They determined frequency regulation to be the most valuable ancillary service in terms of its market value, as it is typically higher than that of energy and spinning reserves. In frequency regulation, the grid operator provides a power command to the generating asset to stabilize the frequency, instead of the generating asset calculating the required power directly. They noted that the local distribution network must be equipped to handle the extra load from the EV, or the EV controller must recognize distribution capacity limits (on the other hand, the EV will decrease the network load when generating power). They noted the importance of anti-islanding to protect power electronics and line workers during grid failure and the systems passed all IEEE 1547 anti-islanding tests. Results showed the EV battery responding well to frequency regulation signals, as shown in Figure 3. The power modulation from the vehicle's battery closely followed the regulation signal at 4-s from AGC (primary y-axis). Given the size of the service (~ +/- 10-kW), the impact on the battery SOC was not appreciable in the 4-hour study time frame (as observed from secondary y-axis), and the study successfully demonstrated the ability of V2G to follow AGC signals to provide frequency regulation service. We note that, as with any large, new load or source, it will be imperative for system operators and distributors to coordinate when using V2G for frequency response, as the rapid charge/discharge cycling has the potential to disrupt the power quality of the distribution feeder. The distribution feeder must be upgraded as necessary to handle the large power swings that V2G performs during frequency response.

Over a 24-hour span, the EV provided adequate up regulation (providing power), but was sometimes limited in down regulation (absorbing power) by being at its maximum SOC limit (as shown in Figure 3). Inversely, if the SOC became too low, the battery could not provide up regulation. To mitigate this issue in the future, if many EVs were in the market, an aggregator could dispatch them to match battery SOC with regulation needs, EVs could have default charge/discharge rates, and a separate regulation signal (i.e., similar to typical disaggregation of total regulation signals into fast variation [REG_D] and slow variation [REG_A] signals, as done by the PJM markets) could be issued by the ISO to the EV batteries, which is much faster but more balanced than traditional regulation signals.

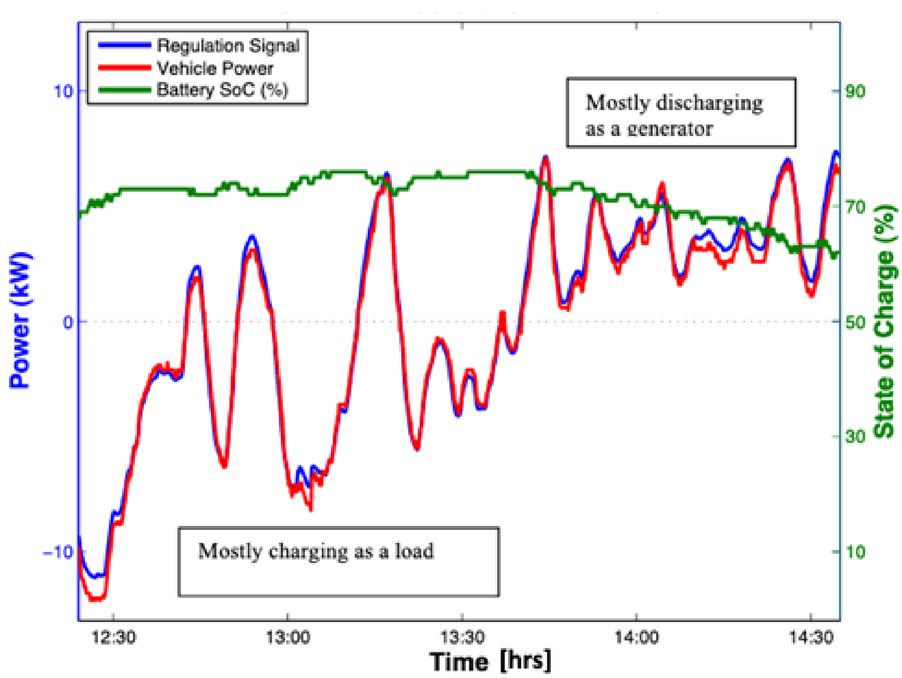

Figure 3. Regulation service supply from V2G over 4 hours: successful AGC signal tracking (Kempton et al. 2009)

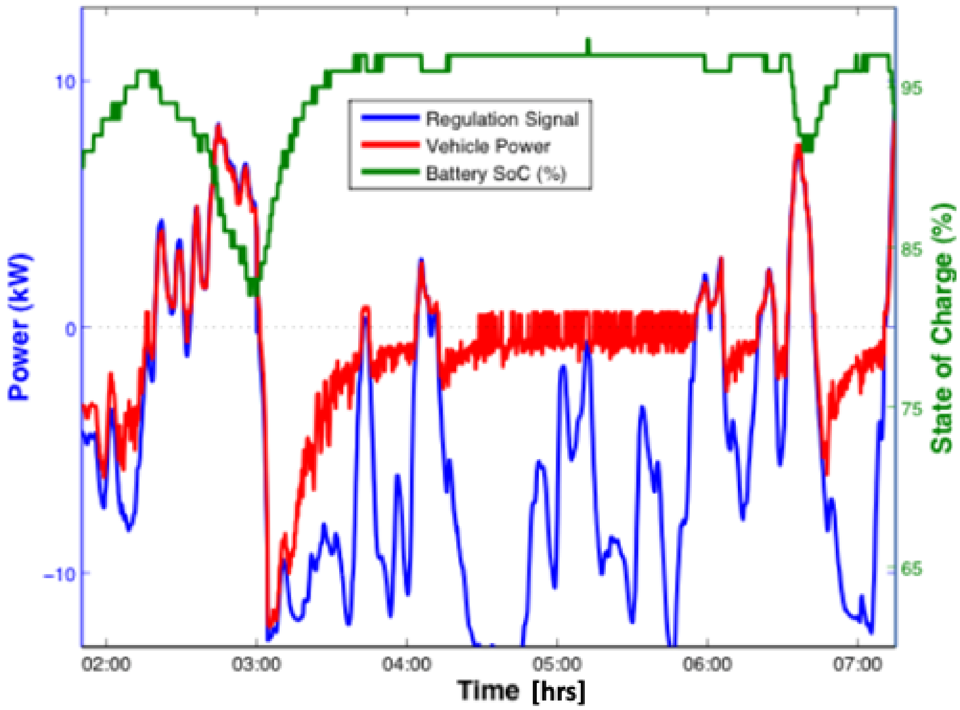

Figure 4. Regulation service from V2G over a 24-hour span limited by battery SOC (Kempton et al. 2009)

A recent study led by the Electric Power Research Institute (EPRI) and performed in California Independent System Operator (CAISO) at the University of California San Diego (Chhaya et al. 2019) implemented an electric vehicle V2G technology that meets cybersecure, end-to end requirements from industry standards associations. They verified the EV's standards requirements and performance under a variety of use cases, including peak load shaving and reduction of customer peak demand charges, overgeneration mitigation, and ramping power support. This study did not consider frequency response or regulation services but focused on flexible ramping services that allowed generation to meet the net-load ramps, which typically result in high real-time price spikes and the starting of expensive gas-fired generation plants or load shedding. Therefore, EVs may have a significant role in providing ramping service during ramp-limited scenarios. Such ramping services promote grid stability by bolstering generation to match demand. Results are displayed in the following figures. Figure 5 displays simulation results where the EV dispatch is used to mitigate the infamous "duck curve" observed in California. The duck is derived from the unusual shape of the net-load curve that is caused by abundant solar generation during the day, and higher load at night when solar generation drops to zero. The belly of the duck is increased by charging the batteries, thereby leveling the net load, as well as mitigating the morning and evening ramps by charging and discharging EVs, respectively. Here, EVs reduce the belly of the duck curve from –21 kW to –10 kW.

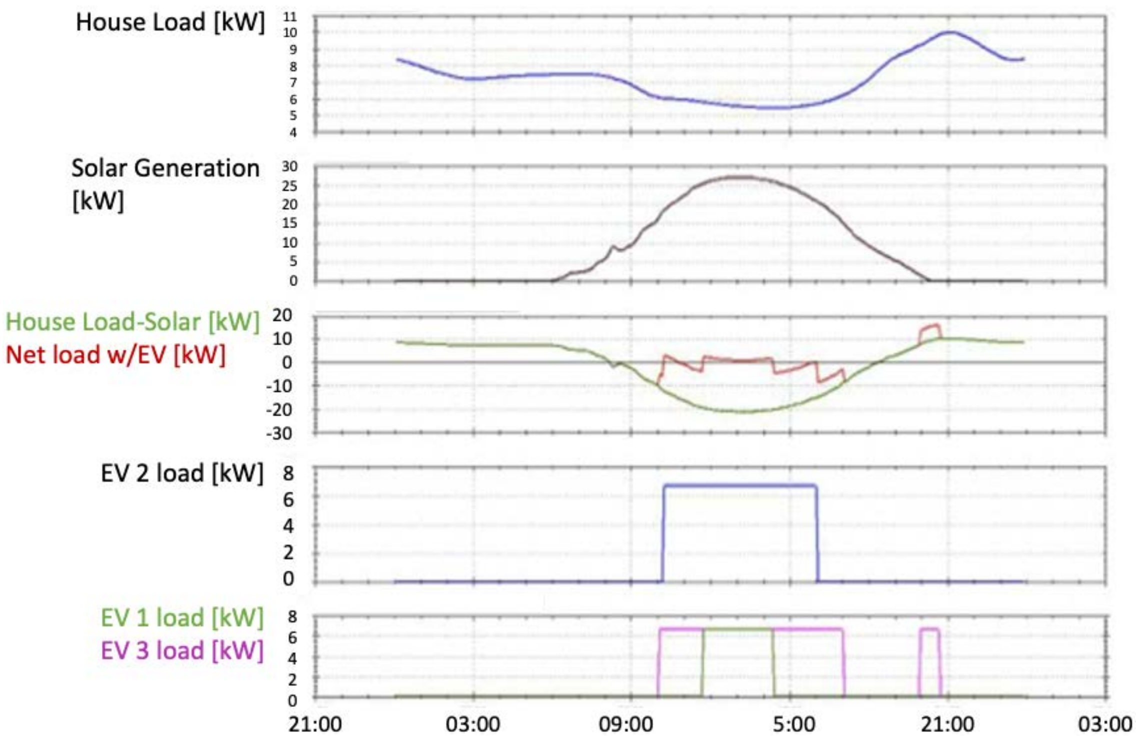

Figure 5. Duck curve modification and providing ramp capability by a three-vehicle schedule over a 24-hour period (Chhaya et al. 2019)

Figure 6 demonstrates simulation results where the EV dispatch for three distinct EVs united to ensure that charging happens within transformer capacity limits (15-kVa in this case). Without the dispatch, the transformer limit would have been exceeded by 7.1 kW.

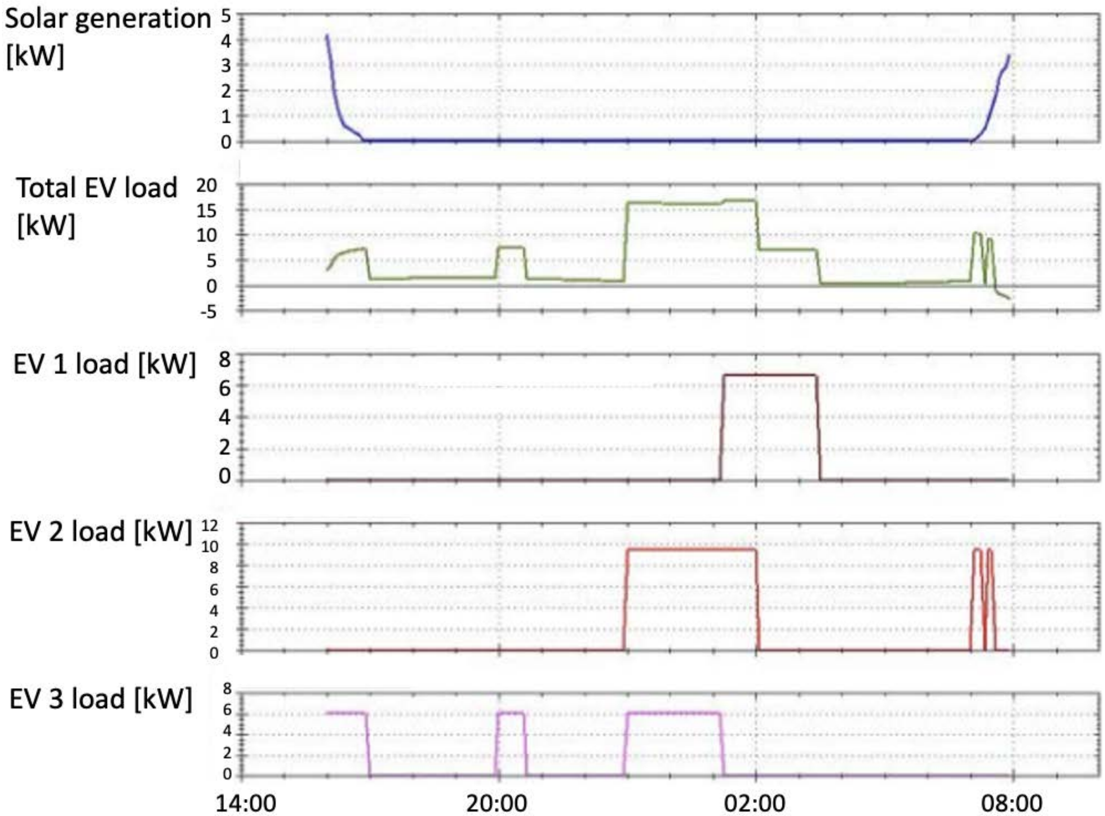

Figure 6. Transformer protection by a three-vehicle charge/discharge schedule and management (Chhaya et al. 2019)

Figure 7 shows two EVs providing staggered peak shaving during high-load evening hours, controlled by battery SOC requirements. The dispatch chose Vehicle 2 to support first based on its higher initial SOC. It finished grid support when reaching the lower SOC limit of 25%. Vehicle 3 began support later, and also finished upon reaching 25% SOC.

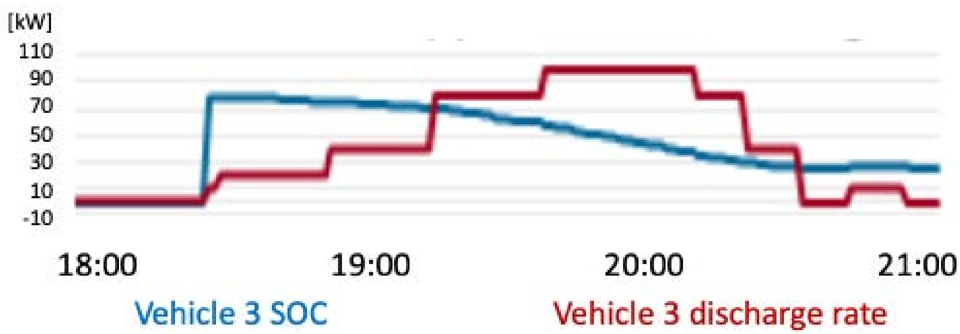

Figure 7. Vehicle (dis)charge peak shaving profiles (Chhaya et al. 2019)

Results suggest that EV-grid communication needs refinement, as there is a disparity between standards and current methods. However, the hardware is capable of providing grid services. They noted that if VAR and frequency regulation are required, the control loop time would need to be ≤ 4 s, per ISO standards for AGC and frequency response.

For V2G to become a viable solution for frequency response and other ancillary services, its impact on battery degradation must be accounted for. Although this is a continued topic of research, requiring further testing, it appears that V2G algorithms that don't consider battery degradation will exacerbate it. However, V2G algorithms that have the objective of maximizing battery longevity can extend battery life (Uddin et al. 2018). For V2G to be viable and enjoy widespread participation, such algorithms must be implemented, EV owners must be compensated for both the full value of the ancillary services they provide and any negative effects on battery life, standards and legal frameworks must be established for privacy, data protection, and liability, and two-way communication between EV and grid must be established to account for the EV owners' charging needs.

3 Conclusion

As renewable energy contribution increases in energy grids, and microgrids grow in popularity, granular load control, rather than shedding entire circuits, becomes an important method to support grid frequency stability. Intelligent protection and disconnection devices, along with smart devices, will further enable the ability to control individual loads more granularly. There is a host of theoretical and simulation-based research on load control techniques that show promise, yet far fewer studies with physical demonstrations. The documentation of real-world systems employing load control is even more sparse, although V2G validations are gaining significant traction, especially in highly populated regions with good markets for EVs (such as California and the East Coast) and high value for frequency regulation and ramping services. Most studies have been performed in utility grids, rather than isolated microgrids, although microgrids may have more early applications because of their relatively higher renewable energy contribution and need for frequency response services. As load control grows in the energy industry, we have four main recommendations: 1) encouraging system operators to engage in granular UFLS methods rather than dumping entire feeders, which is current standard practice, 2) encouraging system operators who use load control to publish system characteristics and lessons learned, 3) transitioning more load control techniques from theoretical/simulated systems to physical experiments, and physical experiments to real-world pilot systems, 4) demonstrating load control to support isolated systems with high contributions from variable renewables. The national laboratories have, and are expanding, the resources and infrastructure needed to demonstrate the value of load control for frequency response in experimental, isolated, and grid-connected contexts. They are also building capabilities that could validate V2G systems in both isolated and grid-connected contexts. This paper establishes a baseline for future research opportunities that could be pursued within the distributed wind portfolio, and more broadly, to support grid stability of high-contribution variable renewable energy in power systems. For instance, NREL has developed simulation models of distributed wind turbines providing ancillary services in various contexts (isolated grids, microgrids, and utility grids), and plans to run hardware-in-the-loop (HIL) simulations using equipment at NREL's Flatirons Campus to validate these models. Controllable loads and V2G could be integrated both into the simulation models and the HIL simulations. NREL's Flatirons Campus also has the capacity to install physical controllable loads/V2G systems to run regular validation experiments. Furthermore, NREL's new Advanced Research on Integrated Energy Systems (ARIES) platform uses supercomputing to model the effects of various devices such as EVs on the modern power system. Controllable loads could be one such device researched.

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Appendix

Table A-1. Summary Review of Experiments

Study and Site/Independent System Operator	Distributed Energy Resources Involved	Control Objective	System Type	Method of Control	Major Findings
Fatheli et al. 2017	Solar photovoltaics (PV)	Frequency regulation	Experimental; isolated microgrid	Frequency sensor; threshold algorithm	Algorithm addressed frequency and voltage fluctuations caused by variable solar irradiance
Samarakoon et al. 2012: United Kingdom (UK)	n/a	Frequency response	Experimental; grid-connected	Smart meters	Need to measure frequency within 200-ms for successful control
Pandiaraj et al. 2001: Polmood, UK	Microhydro, wind	Frequency regulation	Experimental; isolated microgrid	Frequency LCD algorithm; fuzzy logic algorithm	LCD was successful; algorithm was successful for microhydro but struggled with highly variable wind
Lundstrom et al. 2018: National Renewable Energy Laboratory, Golden, CO	Solar PV	Frequency response	Experimental; grid-connected	Quadrature phase locked loop (QPLL) frequency sensor; master load control over various types of loads	QPLL produced fast, reliable measurements; controller produced fast frequency response
Mitra et al. 2008: Kythnos, Greece	Solar PV	Prevent battery deep-discharge	Real-world; isolated microgrid	Battery charge sensor Frequency sensor. Threshold algorithm.	Load control operates in a real-world isolated microgrid
Drouilhet et al. 1999&2002: Wales, Alaska	Wind, dispatchable diesels	Frequency regulation, high renewable contribution	Real-world; isolated microgrid	Frequency sensor, supervisory control, and central	With storage, able to operate with high wind contribution and no

Study and Site/Independent System Operator	Distributed Energy Resources Involved	Control Objective	System Type	Method of Control	Major Findings
				thermal loads	dispatchable generation
Baring-Gould et al. 2009: St. Paul, Alaska	Wind, dispatchable diesels	Frequency regulation, high renewable contribution	Real-world; isolated microgrid	Frequency sensor, supervisory control, and central thermal loads	Without storage, able to operate with high wind contribution and no dispatchable generation
Kongiganak, Kwigillingok, and Tuntutuliak, Alaska	Wind, dispatchable diesels	Frequency regulation, high renewable contribution	Real-world; isolated microgrid	Frequency sensor, supervisory control, and dispersed thermal loads in homes	With storage, able to operate with high wind contribution and no dispatchable generation
Hammerstrom et al. 2008: PJM	n/a	Peak-shaving demand response	Real-world utility grid	Smart heating, ventilating, and air-conditioning control; demand pricing	Peak load reduced without inconveniencing customers
Hammerstrom et al. 2007: PJM	n/a	Frequency response; peak-shaving demand response	Real-world utility grid	Smart appliances	Fast frequency response without inconveniencing customers
Brooks et al. 2002: California Independent System Operator (CAISO)	Electric vehicle (EV)	Frequency response	Real-world utility grid	EV-grid controller	EVs suitable for frequency response
Kempton et al 2009: PJM	EV	Frequency response	Real-world utility grid	EV-grid controller	EVs suitable for frequency response; require advanced controls for optimal regulation
Chhaya et a. 2019: CAISO	EV	Peak shaving, overgeneration mitigation,	Real-world utility grid	Transformer management system	EVs suitable for tested grid services;

Study and Site/Independent System Operator	Distributed Energy Resources Involved	Control Objective	System Type	Method of Control	Major Findings
		ramping power support, transformer load reduction			communication needs refinement to meet industry standards, but hardware is capable