

Sources of grid reliability services[☆]

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ABSTRACT

The bulk power system is undergoing a digital revolution. With the recent and continuing growth of inverter-based generation, primarily wind and solar energy, the industry has begun exploring the implication of these new resources on power system reliability and resilience. This paper provides an overview and description of grid services that key resource types are able to provide, showing that new resources can provide many of the required grid reliability services.

1. Introduction

The bulk power system (BPS) is undergoing a digital revolution. With the recent and continuing growth of inverter-based generation, largely from wind and solar energy, the power system industry has begun exploring the implication of high levels of wind and solar energy on power system reliability and resilience. In 2014, the North American Reliability Corporation (NERC), the recognized reliability authority on the BPS, formed the Essential Reliability Services Task Force (ERSTF).¹ The objective of the ERSTF was to examine the implication of the changing resource mix, including the trends toward use of less coal, more natural gas, more demand response, and higher levels of variable energy resources (VER) with regard to the provision of essential reliability services (ERS). This task force changed to a working group, but its focus has remained the same.

Recently, the Federal Energy Regulatory Commission opened a proceeding on grid resilience, terminating the United States Department of Energy Notice of Proposed Rulemaking that proposed new market rules for resources capable of stockpiling fuel supplies. At the heart of the U.S. DOE concern was the changing nature of the BPS power supply.

As these and other efforts have moved forward, it has become apparent that there is no widespread understanding of the grid services

that can be provided by alternative resource types. In some cases, there were unfounded claims that traditional resources could provide all of the required ERS and that new resources cannot. However, it is difficult to make such generalizations, and so the objective of this paper is to provide an overview and description of grid services that key resource types are able to provide. We begin with a brief summary of these services, and base this discussion on the emerging expert work of the NERC ERSWG (and ERSTF before that).

2. What services are important, and how can they be provided?²

There are several prerequisites for a resource to provide a grid service: (1) physical capability of providing the service, (2) be in an appropriate operating state to provide services when needed, (3) have an economic incentive, and/or no economic disincentive, to provide the service.³

Reliable grid operation depends on ensuring that the aggregate demand and supply are matched at all times. To accomplish this balance, grid operations have various processes that operate on multiple time scales so that the needed equipment can be in place and available when needed. Some of these grid services, such as primary frequency response, operate in very fast time scales and help to ensure that system frequency is held at nominal values (within small allowable

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¹ [https://www.nerc.com/comm/Other/Pages/Essential-Reliability-Services-Task-Force-\(ERSTF\).aspx](https://www.nerc.com/comm/Other/Pages/Essential-Reliability-Services-Task-Force-(ERSTF).aspx).

² NERC Essential Reliability Services Concept Paper. Available at <https://www.nerc.com/comm/Other/essntlrbltysrvscstskfrDL/ERSTF%20Concept%20Paper.pdf#search=erstf>.

³ The ownership of a resource can significantly affect its deployment. Resources owned by the grid operator can be deployed whenever they are needed to support reliability. Other resources may be available via a tariff or other operational agreement, with some form of payment for service. It is important that institutional constraints don't drive physical capability/response constraints that can compromise reliability (or economics, when a more expensive solution is needed).

differences). Other grid services such as frequency regulation and ramping, operate more slowly, but are also used to maintain system balance. These services are not provided uniformly; a resource may respond quickly or slowly, be capable of providing the given service for long or short time periods, be able to provide a limited quantity of a given service, or be able to provide the service only if the resource is in certain state(s).

During normal grid operations, supply and demand must be kept in balance.

The discussion below focuses on selected key resources, including coal-fired, gas-fired, nuclear, hydro, wind, and solar generation. Additionally, we provide information about generic battery storage, and some discussion of emerging demand-response. The objective of this paper is to provide a short, yet comprehensive, summary of the grid services that can be provided from key resource types, helping to inform the wide range of decision-makers regarding the potential source of these important grid services.

2.1. Grid reliability services

The ability of different resources to provide grid services is being driven by a “digital revolution” that is occurring in the electric power sector.⁴ Wind, solar, and battery storage are electronically coupled to the power system. Because the power electronics devices that couple DC to AC power offer very fast response, it is now possible to use software to control how the resource interacts with the power system, subject to physical constraints. This has profound implications on how current and future wind, solar, and battery resources will provide grid services, and may also have a significant impact on the way that some grid services are defined, offered, and procured (Fig. 1).

2.2. Grid services during normal operation

Demand and supply must be balanced at all times. Grid operators carry out an economic dispatch function, normally every 5 min in most of the U.S., that instructs resources to generate a given level of output based on an economic optimization function. Demand fluctuates between these dispatch intervals, and therefore the frequency regulation service is used to ensure balance between successive dispatches. Computers monitor the grid frequency/balance and send signals to regulating resources to increase or decrease their output, nominally every 4 s; the process is often called automatic generation control (AGC). This frequency regulation service compensates for the constant, small variations in demand and supply. This is illustrated in Fig. 2.⁵ The upper part of the figure contains a table that briefly describes the differences between the need for frequency regulation services and the need for flexibility/dispatch. The graph shows demand fluctuations over a one-month period in blue, and the daily demand cycles are apparent. This represents the load-following changes in demand, which are met by units on economic dispatch. Although it is not discernible in the blue trace on the graph, there are many very small changes in the load. These are calculated separately and shown on the graph by the red trace, which has a separate scale on the right. This red trace represents the frequency regulation needs of the system, provided by AGC.

Demand response

Demand response is not a single technology; rather, it is a combination of technologies that allow the customer to alter consumption patterns, with the possibility of selling services to the grid operator via established electricity markets. In principle, DR can deliver several services to the grid: (1) energy efficiency, which reduces electricity consumption and often reduces peak demand, (2) price-responsive load, which can shift usage from high-value time periods to low-value time periods, (3) peak shaving, which does not reduce total energy consumed but shifts some demand to off-peak periods, (4) reliability response that includes a fast frequency response that can respond quickly to system contingency, (5) frequency regulation service. Although there is a very large technical and economic potential for DR, it has generally been slow to develop in the U.S. With recent improvements in electricity market design, communication, instrumentation, and control technology, DR appears to be emerging and may in the future capture a significant market presence.

Currently there is interest in developing new DR products that illustrate its forward potential. PJM has undertaken a pilot program to help develop and adopt a regulation signal that could be used to help integrate grid-scale batteries, flywheels, and water heaters.^a Mosaic Power utilizes a fleet of hot water heaters to supply frequency regulation into the PJM market.^a There are recent grid interconnected water heating (GIWG) pilots at Portland General Electric (PGE), Arizona Public Service (APS), and Green Mountain Power (GMP).^a Programs like this depend on the diversity of demand coupled with the thermal storage capability residing in the hot water heater so that a response fast enough to provide frequency regulation can be obtained. Because DR encompasses a wide variety of resources, pooling these alternative responses can result in the provision of grid services that is not necessarily apparent. Multiple individual resources, such as compressors, aerators, grinders, HVAC, and others can be combined to provide accurate frequency regulation signals, as shown in Fig. 1.^a In ERCOT, DR provides up to 50% of the required contingency reserve.

Demand response market development and technology are poised to change rapidly, and it is not clear how much of this capability will be developed. DR can provide frequency regulation, may be able to shift loads from peak to off-peak, and may be able to function in a short-term dispatch market. For the discussion that follows, we include DR capabilities as they appear to be effective today; however, this is a rapidly changing technology/market.

^a Ela, E; Milligan, M.; Kirby, B. (2011) Operating Reserves and Variable Generation. Available at <https://www.nrel.gov/docs/fy11osti/51978.pdf> page 46.

Economic dispatch has two components of grid services that will be discussed below: (1) flexibility and (2) ramping. Together, dispatch and regulation services are key to preserving system balance. They are used in routine operations, and as will be seen later, are key components of grid recovery after a large disturbance.

2.2.1. Reactive power and voltage control

2.2.1.1. Description. The supply of reactive power provides the ability to regulate voltage, which in turn prevents equipment damage from voltage that is outside of nominal design limits. As with real power, maintaining an active reserve for reactive power helps promote system reliability and resilience.

⁴ Ahlstrom (2018) “Digital Transformation of Power Systems: Implications on Reliability, Operations, and Markets.” IEEE Transmission and Distribution Conference and Exposition. April 17–19. Denver, CO.

⁵ Adapted from Shiu, Milligan, Kirby, Jackson (2005) California Renewables Portfolio Standard Renewable Generation Integration Cost Analysis: Multi-year Analysis Results and Recommendations. Available at <http://www.energy.ca.gov/2006publications/CEC-500-2006-024/CEC-500-2006-024.PDF>.

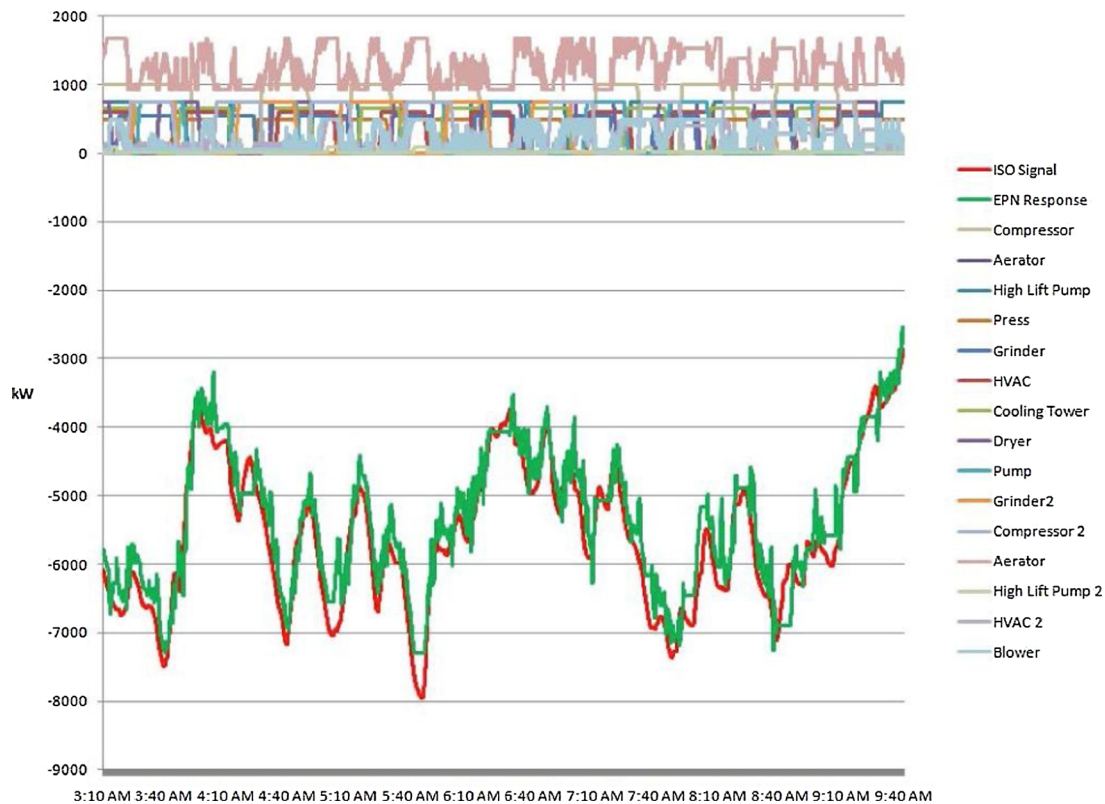


Fig. 1. Example of DR aggregation to provide frequency regulation.

2.2.1.2. Resources that can provide reactive and voltage control. Large thermal plants—coal, nuclear, and natural gas—can provide this service if they are generating real power, as can hydro power. Wind and solar plants can provide reactive and voltage control through power electronics-based controls, and they can therefore supply the service even if they are not generating.⁶ Battery with power electronics can provide this service similarly to wind/solar because the connection characteristic is the same.⁷

2.2.2. Voltage/voltage ride-through

2.2.2.1. Description. Devices that are interconnected into the BPS are designed to operate at nominal voltages within a range of design limits. A grid disturbance, which may be caused by a transmission line or generator tripping offline or other faults, may cause the voltage to vary so that other resources may go offline. In many cases, the original fault does not in itself threaten grid stability; however, if other resources or loads trip offline, the cascading disconnections may, in extreme cases and if not arrested, cause a blackout. To prevent this type of cascading outage, generators can be designed to ride through voltage fluctuations within a given limit.

2.2.2.2. Resources that can provide voltage ride-through. Wind generators are required to ride through voltage faults⁸ and can ride through these events better than most other generators. Solar plants are physically capable of riding through voltage disturbances, but until the recent

FERC Order 828, were not always required to do so. Order 828 requires that newly connected solar facilities subject to the Small Generator Interconnection Agreement (SGIA) must ride through abnormal frequency and voltage events without disconnecting.

For many years distributed solar resources were required to disconnect and remain offline after a voltage event. Recent changes in the IEEE 1547 requirement will now require new DER resources to ride through the event. Because batteries are connected to the grid via a converter like wind and solar, they can, with proper controls, ride through a voltage excursion.⁹ Presumably, they would also be subject to the same ride-through requirements as solar plants.

Not all resources can provide this service.¹⁰ Gas-fired generation is often taken offline by grid disturbances, and therefore has not always provided substantial voltage ride-through.¹¹ Similarly, coal plants often go offline during voltage faults because some combination of the generator or critical plant equipment such as pumps and conveyor belts cannot ride through the disturbance.¹²

Nuclear plants can go offline for similar reasons.¹³ The inability of

⁹ P1547/D7.3, Dec 2017 - IEEE Approved Draft Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. Available at <https://ieeexplore.ieee.org/document/8233447/>.

¹⁰ I describe voltage ride-through as a service, but I note that this is not a NERC requirement. Instead, NERC's PRC-024 refers to the setting of voltage protection relays.

¹¹ TRC Solutions (2015) Revisions to NERC PRC Standards Have Significant Implications for Utility Compliance Programs. Available at <https://www.trcsolutions.com/writable/images/Regulatory-Update-NEERC-PRC-Standards-Changes-Nov-2015-FINAL.pdf>.

¹² NERC (2015) Standard PRC-024-2 – Generator Frequency and Voltage Protective Relay Settings. Available at <https://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-024-2.pdf>.

¹³ Electric Light and Power (2015) Both Calvert Cliffs nuclear units go offline due to D.C. area disruption. Available at <https://www.elp.com/articles/2015/>

⁶ NERC (2009) Special Report: Accommodating High Levels of Variable Generation. Available at https://www.nerc.com/files/ivgtf_report_041609.pdf.

⁷ Tan, J., Zhang, Y. "Coordinated Control Strategy of a Battery Energy Storage System to Support a Wind Power Plant Providing Multi-Timescale Frequency Ancillary Services." IEEE Transactions on Sustainable Energy, Vol 8, No. 3, July 2017.

⁸ FERC Order 661 <https://www.ferc.gov/CalendarFiles/20051212171744-RM05-4-001.pdf>.

some large generators to ride through a disturbance contributed to recent blackouts in Washington, D.C. and Florida.¹⁴

2.3. Grid services responding to contingency events

To describe several of the grid services it is helpful to refer to a graphic representation of the various types of response (Fig. 3). Our discussion centers around the key time periods and their relevant responses starting with the contingency event and ending with frequency recovery:

- 1 Contingency event occurs. This is often a large generating unit or transmission line¹⁵ that disconnects unexpectedly as a result of mechanical or electrical failure
- 2 Frequency begins to drop from its nominal rate of 60 Hz. The rate of decline is a function of system inertia—the rotating mass of large generators. This inertial response can slow the rate of change in frequency (RoCoF) but cannot by itself arrest the decline. Combined with resources that provide fast frequency response (FFR), the frequency decline is slowed, and then arrested by FFR resources. In the diagram this point of arresting is identified as the “nadir” of the frequency drop. It is important that the nadir occurs before frequency falls far enough to trigger under-frequency load shedding events (UFLS), which has the potential to exacerbate the situation. FFR can be provided by several resource types, including wind/solar and storage. Fig. 3 shows this as the “arresting period.”
- 3 Primary frequency response (PFR) helps improve frequency, and occurs when governors respond to the frequency decline by speeding up, thereby helping to increase frequency towards its nominal value. Power electronics on wind/solar and storage can often contribute to PFR. This is shown in Fig. 3 as the “rebound period.”
- 4 A combination of frequency regulation (automatic regulation control, AGC) and economic dispatch increase power output (or reduce demand, or both) so that the frequency reaches its pre-disturbance level. This is shown in the graph as the “recovery period.”

Grid reliability services contribute to (a) helping to arrest the initial frequency drop, (b) contribute to the rebound period, increasing frequency after the nadir occurs, (c) inject energy during the recovery period, helping to restore frequency to pre-disturbance levels. These are discussed further below.¹⁶

2.3.1. Arresting frequency drop: inertial and fast frequency response

2.3.1.1. Description. Inertial response comes from large rotating machines, and it is an attribute of the entire interconnection.¹⁷ Immediately after a disturbance, system inertial response sets the rate

(footnote continued)

04/both-calvert-cliffs-nuclear-units-go-offline-due-to-d-c-area-disruption.html.

¹⁴ Reuters (2008) FPL cites human error as cause of Florida blackout. Available at <https://www.reuters.com/article/us-florida-blackout/fpl-cites-human-error-as-cause-of-florida-blackout-idUSWNAS318320080229>.

¹⁵ As noted early, most transmission line outages are not contingency events, and therefore have different impacts on the grid than the loss of a large resource. Key reliability services will likely still be required, although at a lower level than the loss of a large resource.

¹⁶ Special protection systems (SPS), also known as remedial action schemes (RAS) can also be considered as reliability services. RASs detect abnormal system conditions, and respond via pre-determined actions so that operational reliability is maintained.

¹⁷ Traditionally, the fastest form of frequency response is the inertial response of large, rotating machines. In the past few years, power electronics have made it possible for wind and solar power to provide an extremely fast frequency response that operates in a similar time scale as inertial response. We distinguish these as inertial response and fast frequency response, FFR, respectively.

of decline of frequency; by itself, it is not capable of arresting frequency. FFR injects power into the grid, which contributes to slowing the frequency decline, and then arresting the decline. Thus the frequency drop is arrested by a combination of inertial response and FFR. The action of FFR occurs prior to the frequency nadir.

2.3.1.2. Resources that can provide this service. Inertial response is provided by large rotating generators, such as coal, nuclear, or gas. FFR can be supplied by coal and gas plants, and it is not provided by nuclear plants because governor response has been disabled in the U.S. FFR can be supplied by VER and batteries that have sufficient controls and incentives to do so, and if they are operating in a partially curtailed state.^{18,19} In many cases this FFR is much faster than that provided by thermal generation and can have a beneficial impact on the initial rate of frequency decline immediately after a disturbance.²⁰ In ERCOT, DR provides up to one half of the contingency response obligation for the market, and thus DR can contribute to arresting the frequency.

2.3.2. Primary frequency response

2.3.2.1. Description. Primary frequency response (PFR) is an automatic response to frequency decline, and it begins within seconds following a disturbance. Governors respond to the frequency drop by increasing power output.

2.3.2.2. Resources that can provide this service. PFR can be provided by natural gas, coal, and nuclear plants although in practice approximately 10% of these plants actually provide this response.²¹ Not all resources respond at the same rate: some resources can respond more quickly than others. In some cases, a higher response is required before the frequency drop is arrested. The level and speed required for PFR to arrest the frequency drop can also be influenced by some of the attributes of AGC. “Improvements in the full AGC control loop of the generating resource, which accounts for the expected Primary Frequency Response, have improved the delivery of quality Primary Frequency Response while minimizing secondary control actions of generators. Some of these actions can provide quick improvement in delivery of Primary Frequency Response.”²² PFR is generally slower than FFR.

2.3.3. Frequency regulation

2.3.3.1. Description. Generation that responds to computer signals

¹⁸ Gevorgian and Zhang (2016) “Wind Generation Participation in Power System Frequency Response,” 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Vienna, Austria. Available at <https://www.nrel.gov/docs/fy17osti/67287.pdf>.

¹⁹ Milligan et al. (2015) Alternatives No More. IEEE Power and Energy Magazine, October. Available at <http://iesi.org/assets/pdfs/ieee-power-energy-mag-2015.pdf>.

²⁰ Over-frequency events, such as loss of load, can be provided by VER any time they are generating power. In future power systems with limited inertial response, it is likely that FFR, along with suitable controls, will be able to replace much of the potentially retiring inertial response. See for example https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2017/2017-03-10-GE-FFR-Advisory-Report-Final-2017-3-9.pdf.

²¹ Comments of the North American Electric Reliability Corporation Following September 23 Frequency Response Technical Conference. Docket Nos. RM06-16-010 and RM06-16-011 available at https://www.nerc.com/files/FinalFile_Comments_Resp_to_Sept_Freq_Resp_Tech_Conf.pdf. Also see Miller et al (2013) “Eastern Frequency Response Study” shows the impact of alternative levels of participation in frequency response by large thermal plants. Available at <https://www.nrel.gov/docs/fy13osti/58077.pdf>.

²² See NERC: Frequency Response Standard Background Document, Nov. 2012. Available at https://www.nerc.com/pa/Stand/Project%20200712%20Frequency%20Response%20DL/Bal-003-1_Background_Document_Clean_20121130.pdf

	Regulation	Load Following
Patterns	Random, uncorrelated	Largely correlated
Generator control	Requires AGC	Economic dispatch
Maximum swing (MW)	Relatively small	10-20 times more
Ramp rate (MW/minute)	5-10 times more	Relatively slow
Sign changes	20-50 times more	Relatively few

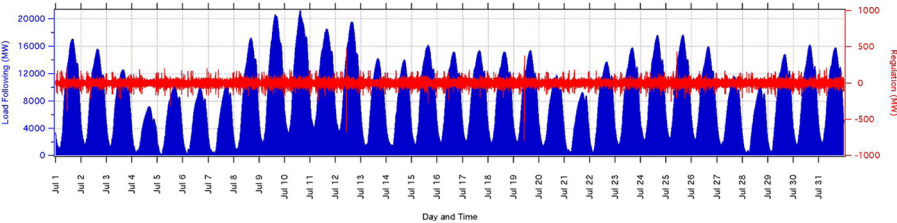


Fig. 2. Relationship between frequency regulation ("regulation") and economic dispatch (load following).

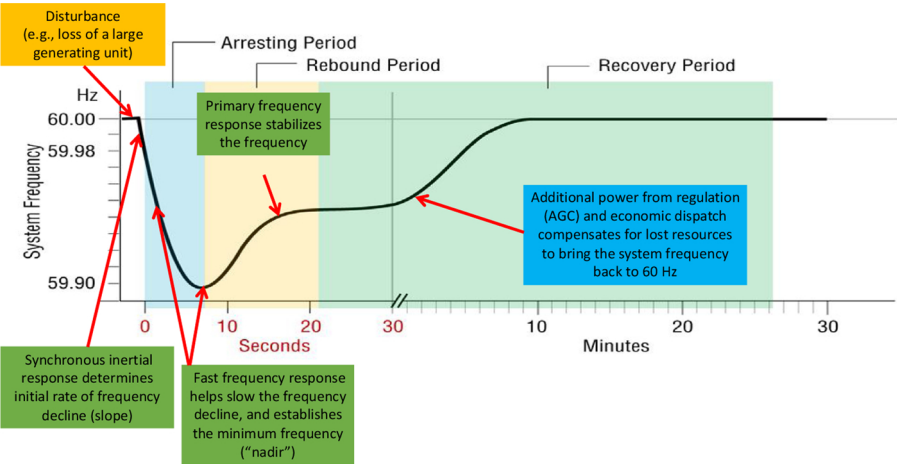


Fig. 3. Grid services immediately following a contingency event.

Table 1
Grid Services Summary.

	Inverter-Based			Synchronous				Demand Response
	Wind	Solar PV	Storage/Battery	Hydro	Natural Gas	Coal	Nuclear	Demand Response
Disturbance ride-through	Excellent	Very Good	Good	Excellent	Limited	Limited	Limited	Limited
Reactive and Voltage Support	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Limited
Slow and arrest frequency decline (arresting period)	Limited	Limited	Limited	Limited	Limited	Limited	Limited	Limited
Stabilize frequency (rebound period)	Limited	Limited	Limited	Limited	Excellent	Limited	Limited	Limited
Restore frequency (recovery period)	Limited	Limited	Limited	Excellent	Excellent	Limited	Limited	Limited
Frequency Regulation (AGC)	Limited	Limited	Excellent	Excellent	Excellent	Limited	Limited	Excellent
Dispatchability/Flexibility	Limited	Limited	Excellent	Excellent	Limited	Limited	Limited	Limited

These services also contribute to frequency restoration, but are also considered essential reliability services on their own.

● Excellent ● Very Good ● Good ● Limited ○ Incapable

(automatic generation control, AGC), commonly at intervals of one to four seconds, to ensure frequency is in nominal range. AGC service is utilized at all times, but it is also useful during the recovery period after a contingency event (see above). It is a slower response than FFR and PFR.

2.3.3.2. Resources that can provide frequency regulation. Although the system needs to have access to up-regulation and down-regulation, individual resources can provide either, or both of these responses. A resource can provide down-regulation when it is operating above minimum output, and it can provide up-regulation and down regulation when it is operating between min-gen and max-gen with

sufficient foot room and/or head room to provide service. Wind and solar resources are no different: they can provide upward frequency regulation only if (a) they are “pre-curtailed,” running at less than maximum output for the given wind/solar fuel input, and (b) only if there is sufficient wind/sun for the resource to respond.²³ They can provide downward regulation whenever they are producing power. Obtaining this service from variable energy resources (VER), such as wind and solar power, may be costly because a more expensive resource from the dispatch stack must be called upon to make up for the energy lost by the VER providing frequency regulation. Batteries can supply frequency regulation if the state of charge is sufficient, or if charging is in process during the time the services is called upon.²⁴ Gas generators can generally provide this service efficiently and accurately. Nuclear plants in the U.S. do not provide this service, whereas coal plants can do so, but often do not have the capability for accurate response.²⁵ Hydro generation and DR can also provide this service.²⁶

2.3.4. Flexibility/Dispatch

2.3.4.1. Description. Although several definitions of flexibility have emerged, they generally describe the ability of the resource—or portfolio of resources—to have the ability to react to changes in the power system, both anticipated and unanticipated.²⁷ Flexibility that is inherent in a particular resource depends on its design objectives and operational modes, along with the type of fuel it uses.

2.3.4.2. Resources that can provide this service. Controllable hydro plants, some combined-cycle gas, aero-derivative gas turbines, and reciprocating engines are very flexible. Some plants that are somewhat inflexible can be made more flexible by “strategic modifications, proactive inspections and training programs, among other operational changes to accommodate cycling, can minimize the extent of damage and optimize the cost of maintenance.”²⁸ Wind and solar plants can easily provide this service in a downward direction if they are generating, and can perform very quickly and accurately. They can also provide upward ramping if they are operated in a pre-curtailed mode. Although wind and solar have very flexible technological attributes, it may be more economic to obtain this flexibility from other resources.

2.3.5. Ramping/ramping reserve

2.3.5.1. Description. Ramping—changing the output of a generator or other resource in a given time period—has been identified as an essential reliability service by NERC²⁹ and is receiving renewed

attention following CAISO’s adoption of it as a market-based product, and MISO’s ramp capability product development.³⁰ Ramping is an inherent part of power system operation because resources must change their output to match fluctuating demand. As the BPS evolves to higher levels of VER, additional ramping will be needed to maintain system balance. Although some RTOs/ISOs have developed ramping products, others are able to utilize the fast, 5-minute economic dispatch to find sufficient flexibility in the operational time frame. Without ramping products, inflexible resources may be rewarded for their inflexibility if they are paid the market-clearing energy price during ramp-constrained periods when combustion turbines (or other costly resources) are on the margin.³¹ Ramp products, which may be in fact ramping reserve products (holding back some capacity so that it can be ramped up/down if needed) can separate the ramping service from the energy product, providing incentive to flexible resources that can ramp. There is some evidence that a look-ahead dispatch that locks in advisory prices may result in the same dispatch and revenue as an energy market with ramp product.³²

2.3.5.2. Resources that can provide ramping/ramping reserve. Wind and solar plants can both provide very fast and accurate dispatch/ramping response. However, this may be costly to the system because these plants typically have the lowest marginal cost for producing energy and therefore incur the largest lost opportunity cost if they are backed down to retain headroom for ramping, so may not be utilized often. Most, but not all, natural gas generators have the potential to ramp and are often the resource of choice to do this because they have reasonably good flexibility and are often marginal units in the dispatch stack. Many coal plants have limited ramping capability because of a combination of thermal inertia, operating practice, and design, and therefore may have difficulty ramping as quickly as needed in some situations. Nuclear plants do not provide ramping service in the U.S. because of a combination of regulations, economics, and technical challenges, but can be more flexible in other countries.³³ Batteries can ramp up or down very quickly, depending on the state of charge. Controllable hydro power can normally ramp quickly, but it may be subject to water flow constraints or other regulations that may inhibit this response³⁴. DR can potentially provide this service, but it may be limited in the energy component that it can provide.

2.3.6. Other facets of flexibility

2.3.6.1. Description. Although resource flexibility is often thought of as fast-ramping, there are additional flexibility components:

(a) Fast startup time: ability to move from non-operational state to operational state.

²³ ERCOT: Demonstration of PFR Improvement September 2017. ERCOT Operations Planning. <https://www.pjm.com/-/media/committees-groups/task-forces/pfrstf/20171009/20171009-item-04-ercot-frequency-response-improvements.ashx>.

²⁴ Battery-supplied regulation does not require up-down charging, but can also be provided by variable/intermittent charging or discharging, separately.

²⁵ Chen, Leonard, Keyser, Gardner, “Development of Performance-Based Two-Part Regulating Reserve Compensation on MISO Energy and Ancillary Service Market. IEEE Transactions on Power Systems, Vol 30, 1, Jan. 2015.

²⁶ Examples can be found in Milligan M, et al., Integration of Variable Generation, Cost-Causation, and Integration Costs Electr. J. (2011), doi:<https://doi.org/10.1016/j.tej.2011.10.011>, and in Milligan et al. (2011) Cost-Causation and Integration Cost Analysis for Variable Generation, NREL. Available at <https://www.nrel.gov/docs/fy11osti/51860.pdf>.

²⁷ Examples include Cochran et al. (2014) Flexibility in 21st Century Power Systems. Clean Energy Ministerial and National Renewable Energy Laboratory. Available at <https://www.nrel.gov/docs/fy14osti/61721.pdf>, and Milligan et al. (2015) Advancing System Flexibility for High Penetration Renewable Integration. NREL. Available at <https://www.nrel.gov/docs/fy16osti/64864.pdf>.

²⁸ Cochran et al. (2014) Flexible Coal: Evolution from Baseload to Peaking Plant. NREL. Available at <https://www.nrel.gov/docs/fy14osti/60575.pdf>.

²⁹ NERC ERSTF *ibid*.

³⁰ MISO (2016) Ramp Capability Modeling in MISO Dispatch and Pricing. Presented at FERC Technical Conference on Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software, June 27–29. Available at https://www.ferc.gov/CalendarFiles/20160629114652-1%20-%2020160621%20FERC%20Technical%20Conference_MISO%20Ramp%20Product.pdf.

³¹ Milligan, M., Kirby, B. (2010) Market Characteristics for Efficient Integration of Variable Generation in the Western Interconnection. NREL Technical Report. P 17. <https://www.nrel.gov/docs/fy10osti/48192.pdf>.

³² Ela, E.; O’Malley, M. (2016) Scheduling and Pricing for Expected Ramp Capability in Real-Time Power Markets. IEEE Transactions on Power Systems, Volume: 31, Issue: 3, May.

³³ Utility Dive (2016), “How market forces are pushing utilities to operate nuclear plants more flexibly.” Oct. Available at <https://www.utilitydive.com/news/how-market-forces-are-pushing-utilities-to-operate-nuclear-plants-more-flex/427496/>.

³⁴ U.S. Department of Energy Hydropower Vision: A New Vision for United States Hydropower. <https://www.energy.gov/eere/water/articles/hydropower-vision-new-chapter-america-s-1st-renewable-electricity-source>.

- (b) Fast shutdown time: ability to go off-line; may be to a cold state or warm state
- (c) short min up/down times: Minimum length of time that the plant must stay in an operational state before being taken offline, or minimum length of time that a plant must be in a non-operational state before it can be started again.
- (d) Minimum stable generation level: The minimum output level that the plant can sustain, often expressed as a percentage of rated power. This is also an indicator of the plant's operating range: the difference between rated capacity and minimum stable generation. The ramp rate measures how quickly a resource can move across its range of output.

2.3.6.2. Resources that can provide other facets of flexibility. Coal, nuclear, and some gas plants generally have slow startup and shutdown times, and relatively long minimum uptimes and downtimes. Nuclear plants in the U.S. do not cycle or ramp, and therefore have undemonstrated minimum generation levels that are significantly below rated power.

Coal plants' minimum generation levels are dependent in part on plant design, but they are often in the 65–75% of rated capacity range. The high minimum generation constraints limit flexibility and limit the ability to efficiently utilize wind and solar energy.³⁵ This inflexibility causes more wind and solar energy to be curtailed. Thermal plant startup and shutdown times are generally long, as are minimum uptime and downtime.

Some gas plants have similar flexibility attributes as some coal plants. However, newer combined-cycle gas plants can be quite flexible, and some can be operated either in combined-cycle mode or single-cycle mode, providing additional flexibility compared to only combined-cycle mode operation. Peaking plants that use aero-derivative gas turbines or reciprocating engines can be very flexible, with minimum generation levels that may approach as little as 1% of rated capacity, short up/down minimums, fast starting and shutdown, and fast ramp rates.³⁶

Hydro plants can be very flexible from a technical point of view. Their main constraints, if any, relate to a combination of water supply and water regulations, including water delivery schedules and minimum/maximum flow constraints to mitigate environmental damage. Thus, there is no one-size-fits-all characterization; however, this resource has the potential to be very flexible.³⁷

Wind and solar plants can ramp very quickly in both directions, depending on the generators' current state, and can both achieve a very low minimum generation level even when the wind is blowing or the sun is shining.

Batteries have similar characteristics as wind and solar, but subject

to the battery's state of charge.

DR does not have specific minimum up/down times in the same sense as conventional generators. However, there are limits as to how much/how often a DR resource may be called upon, and this may provide a similar constraint. However, the quick potential response of DR makes it a valuable contributor to ramping capability over short time frames.

3. Grid services summary

All resources discussed herein can provide at least some reliability services. The speed of provision, depth of provision, and machine type and state will all play a role in determining the physical capability of each resource type. Market and reliability rules may limit response in some cases; however, rules should be revised if that is the case. Table 1 summarizes the discussion of the reliability service capabilities from different resources.

3.1. Recommended policy directions

As this summary shows there are many sources of grid services. As technology changes, it becomes important to avoid placing unintentional limits that constrain the types of resources that can provide it. Any resource that is capable of providing a grid service should not be prevented by reliability rules or market rules from doing so. Instead of binding technology type with grid service, the latter should be carefully defined so that individual resources can demonstrate their ability to provide the relevant service(s). Not all resources will perform equally, and therefore grid service definitions should be constructed in such a way that resources can be distinguished; this also makes it possible for grid experts to assess whether there is a sufficient level of reliability services to avoid problems. Specific attributes may include (a) speed of response and (b) depth of response; other characteristics should be investigated as appropriate.

After rigorous definitions of these various services is put in place, a certifying process could then be used so that new resource types (or configurations) could then be recognized as valid contributors to BPS reliability.

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³⁵ Lew et al. (2013) The Western Wind and Solar Integration Study Phase 2. National Renewable Energy Laboratory. Available at <https://www.nrel.gov/docs/fy13osti/55588.pdf>. See also Cochran et. al (2017) Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. I—National Study. National Renewable Energy Laboratory. Available at <https://www.nrel.gov/docs/fy17osti/68530.pdf>.

³⁶ Milligan and Kirby (2010) Utilizing Load Response for Wind and Solar Integration and Power System Reliability. Presented at WindPower 2010. National Renewable Energy Laboratory. Available at <https://www.nrel.gov/docs/fy10osti/48247.pdf>.

³⁷ See Chapter 2 of the U.S. D.O.E Hydro Vision report <https://www.energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-Chapter-2-10212016.pdf>.