Advanced Distributed Wind Turbine Controls Series: Part 2–Wind Energy in Isolated Grids

Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL)

Benjamin Anderson, Ram Poudel, Venkat Krishnan, Jayaraj Rane, Przemyslaw Koralewicz, Jim Reilly, and Ian Baring-Gould

National Renewable Energy Laboratory

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List of Abbreviations and Acronyms

BESS	battery energy storage system
CART	Controls Advanced Research Turbine
DER	distributed energy resource
h	hour
Hz	hertz
IEEE	Institute of Electrical and Electronics Engineers
kV	kilovolt
kVA/kVAR	kilovolt-ampere/kilovolt-ampere reactive
kW/kWh	kilowatt/kilowatt-hour
MIRACL	Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad
MVA	megavolt-ampere
MW/MWh	megawatt/megawatt-hour
NREL	National Renewable Energy Laboratory
PFR	primary frequency response
pu	per unit of the baseline value
PV	photovoltaics
ROCOF	rate of change of frequency
s	second
V	volt

Executive Summary

In an isolated grid, wind turbines are typically deployed to maximize energy production and reduce diesel fuel consumption, carbon emissions, and energy costs. Not only do wind turbines generate energy for the power system, but they can also provide various reliability and resilience services through advanced controls enabled by their rotating masses and inverter-based controls. As part of the Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project, we use desktop simulations to demonstrate advanced wind turbine controls that can be used to support higher contributions of wind energy in isolated grids. We also demonstrate ways that wind energy can support the stability of an isolated grid.

The isolated grid used in our desktop simulations comprises a 600-kilowatt wind turbine, 430 kilowatts of solar photovoltaics, a 1-megawatt/1-megawatt-hour battery energy storage system, a 2-megawatt diesel generator, and critical and dynamic loads. We develop models of the subsystems in MATLAB Simulink and validate them with data from real-world components on the National Renewable Energy Laboratory Flatirons Campus. We then configure the validated models for various case studies. We compare the output of the desktop simulation using a baseline case with the diesel generator. Real and reactive power control of the wind turbine can help improve frequency and voltage responses, respectively, in the isolated grid. By using a small integrated battery energy storage system in the DC link of the wind turbine, we also demonstrate that a wind turbine can help black start a critical load comparable to its rated power and support other renewables (e.g., solar photovoltaics) coming online to pick up an additional load. The simulations and case study applications reported here illustrate the reliability and resilience services that a wind turbine can provide in an isolated grid.

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1 Introduction

The research road map of distributed wind controls for the Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project (Reilly et al. 2021b) includes a literature review of real and reactive power control capabilities of different distributed energy resources (DERs) and develops a road map for the application of such control technologies to distributed wind turbines in four use cases (Reilly et al. 2021a): (1) isolated grids, (2) microgrids, (3) behind-the-meter wind turbine deployments, and (4) front-of-the-meter wind turbine deployments. This report presents simulation results for the isolated grid use case and is Part 2 in a series of reports that cover the four use cases. The first part of the series (Anderson, Poudel, Reilly, et al. 2022) provides details of the MATLAB Simulink models that are used in this report, which are available on GitHub (Anderson 2021).

For many isolated grids, the ability to employ renewable energy sources to offset energy generated from conventional generation sources provides both economic and energy resilience benefits. As higher contributions of renewable energy generation sources are integrated into isolated grids, the ability for these renewable sources to provide additional grid services beyond energy becomes more important. In this report we simulate and document some of the ways that advanced distributed wind turbine controls can improve isolated grid resilience.

Section 2 describes example isolated grids and summarizes grid support functionalities using common controls and opportunities for advanced controls from open literature. Section 3 introduces the National Renewable Energy Laboratory (NREL) Flatirons Campus and its various DER assets. This section examines a significant grid event that necessitated the typically grid-connected Flatirons Campus microgrid to operate as an islanded microgrid, maintaining campus loads and stability by predominantly using renewable energy and storage. Section 4 summarizes simulation results of a wind turbine supporting grid stability in the islanded Flatirons Campus microgrid and discusses the quantitative benefit of wind turbine advanced controls and an integrated battery energy storage system (BESS) in an isolated grid. This section illustrates a distributed wind turbine stabilizing the grid during a step load pickup and voltage fault, and performing black start. Section 5 presents our conclusions and possible future work.

2 Background of Isolated Grids and Controls

To establish a baseline for this research and to align this work with challenges and opportunities in the isolated grids space, we identified several real-world systems with distributed wind turbines. We observed that in many isolated grids, energy is provided by diesel, wind, solar, and BESS resources, while most of the flexibility and essential reliability services come from diesel generators and BESS. In this report we demonstrate and document that flexibility and essential reliability services can be provided by distributed wind turbines using advanced controls.

2.1 Real-World Isolated Grids

There are several examples of remote communities being served by isolated grids, which are electric grids disconnected from main high-voltage transmission networks. In Alaska, with its extreme weather scenarios and remote communities, isolated grids are predominantly served by diesel generators, and the cost of electricity is high. Some isolated grids are geographically isolated, and others are electrically islanded from the main grid for the purposes of resilience and stability. The following are examples of isolated grids:

1. St. Paul Island, Alaska (Mott and Saulnier 1999), has a wind-diesel hybrid system without storage (Reid, Saulnier, and Gagnon 2021) that was commissioned in 1999 by Northern Power Systems (Vermont, United States). This technology was developed by Hydro-Québec to reduce the cost of supplying electricity to remote northern communities. The system at St. Paul Island uses a 480-volt (V), 300-kilovolt-ampere (kVA) synchronous machine (diesel generator), a wind turbine driving a 480-V, 275-kVA induction generator, a 50-kilowatt (kW) customer load, and a secondary load (0 to 446.25 kW) that is varied at 1.75-kW increments.
2. The Alaskan communities of Buckland, Deering, and Kotzebue have a hybrid wind-solar-diesel-BESS. They are isolated northwest Arctic communities with 800–1,000 people (Treinen 2019). The recent addition of BESS helps these grids offset energy from diesel generation while making better use of excess wind and solar energy without spilling. The hybrid wind-solar-BESS can serve the community for at least 6 hours (h) without the need for diesel power, thereby providing emergency support.
3. Kodiak Electric Association (Kodiak Electric Association n.d.) is a rural electric cooperative that generates, transmits, and distributes electrical power in Kodiak, Alaska. The isolated grid in Kodiak is primarily served by the Terror Lake Hydroelectric plant, which provides ~80% of the generation, with the remaining electricity coming from six distributed wind turbines, two flywheels, and a BESS. Diesel generation facilities are used as backup.
4. Igiugig Village, Alaska constitutes an isolated grid with 35 kW of run-of-river marine renewable energy generators and BESS, offsetting diesel use by several thousand gallons, amounting to $68,000–$88,000 savings over 20 years (Burger 2019). Similarly, the Kwethluk hybrid wind-diesel-battery isolated grid in Alaska saves diesel and provide emergency power for a local community for about 1 h serving the peak load, or up to 2.5 h serving an average load of 180 kW.
5. St. Mary's, Alaska, and Mountain Village, Alaska, are examples of remote grids served by Alaska Village Electric Cooperative (which serves about 40% of the Alaskan

population) that are not connected to transmission grids (Flicker 2019). Each of these village grids serves about 100 to 1,000 customers with a load ranging from 100 kW to 3 megawatts (MW). They are supplied predominantly by local fossil-fuel-based generation but are integrating increasing amounts of distributed wind and solar power. St. Mary's and Mountain Village, with peak loads of 600 kW and 500 kW, respectively, have formed a networked microgrid through a 25-mile, 12.47-kilovolt (kV) tie line. A 900-kW distributed wind turbine was commissioned in 2019, and there is a plan for a 500-kW/1-megawatt-hour (MWh) energy storage system with a grid-forming inverter (known as a "grid-bridging system") closer to the St. Mary's isolated grid. The distributed wind turbine and grid-bridging system will help both communities become energy-secure with reduced dependence on diesel fuel, which is difficult and expensive to transport in winter via the Yukon River.

6. At the Ross Island Wind Farm in Antarctica, three 300-kW distributed wind turbines ("Ross Island | Hitachi Energy" n.d.) power the United States' McMurdo Station and New Zealand's Scott Base, where about 1,200 people live during the summer. A microgrid controller helps integrate the wind turbines at two different frequencies (50 hertz [Hz] and 60 Hz) and ensures stable operation. The islanded community is targeted to save approximately 460,000 liters of diesel fuel every year, consequently reducing carbon dioxide emissions and environmental impacts.
7. Located off the coast of California, San Clemente Island holds Naval Base Coronado. The island has a population of about 500 people, with a daily peak demand of less than 2 MW. The isolated grid comprises three 225-kW wind turbines and four diesel generators with 2,950 kW total diesel capacity. Wind power provides 15% of the island's electricity, on average (Energy Central 2020) In 2020, the U.S. government responded to an NREL study by releasing a solicitation to replace the three turbines with larger-nameplate machines, upgrade system power electronics, and add a BESS to increase site resilience (Wood 2019).

In these isolated grids, distributed wind is an integral energy source. However, the majority of isolated grids do not currently employ wind turbines, although many use solar power and batteries. Examples of grids where distributed wind turbines could contribute to energy security and resilience include the isolated grid in Old Crow, Yukon Territory (BBA n.d.), which has PV and battery running in grid-forming mode; the isolated grid at the City of Summerside on Prince Edward Island, which has solar energy, wind energy, diesel generation, BESS, and the possibility of grid supply from the North American mainland; the isolated grid with a solar-diesel-battery hybrid system in Colville Lake, Northwest Territories ("Colville Lake Solar Project" n.d.); and the solar-diesel-BESS in the Gull Bay First Nation, Ontario (Government of Canada 2021).

2.2 Control Focus Areas for Wind in Isolated Grids

The Institute of Electrical and Electronics Engineers (IEEE) standard 1547-2018 (IEEE 2018) provides requirements for robust voltage and frequency ride-through characteristics of DERs. In this report, we demonstrate how distributed wind can provide flexible reliability services to enhance resilience in an isolated grid scenario. The following subsections describe control functionalities from DERs that are gaining more attention and can help improve isolated grid stability in weak grid situations.

2.2.1 Real and Reactive Power Control

Real power control is required to maintain the nominal system frequency by balancing load and generation, and reactive power control is necessary to maintain the nominal voltage. Wind turbines (Type 1 through Type 4) differ from each other in the way they provide real and reactive power. A tutorial (Aho et al. 2012) provides an overview and motivation for real power control in wind turbines.

Real power control can be accomplished through rotor speed control, rotor pitch control, yaw control, mechanical brakes for curtailment, and, in Types 3 and 4 wind turbines, through power-electronics-based vector current control (torque control). Types 1 and 2 wind turbines use a capacitor bank or other auxiliary devices, such as a static volt-ampere reactive (VAR) compensator or static synchronous compensator, to provide or absorb reactive power (i.e., provide leading reactive power to improve low voltage and lagging reactive power to correct overvoltage). Type 3 wind turbines use a doubly fed induction generator along with a power converter that is about one-third the size of the nominal capacity of the wind turbine. The reactive power of a Type 3 wind turbine is documented in Engelhardt et al. (2011). Types 3 and 4 machines can also regulate the real and reactive power independently by taking advantage of their power electronics (i.e., vector control of real and reactive power currents independently within the apparent current limit). Therefore, these power-electronics-interfaced turbines can provide reactive power support even when they are neither operational nor producing real power, such as when wind speed is below the cut-in speed. Wind turbines can follow real and reactive power dispatch commands from a central dispatcher or plant-level controller at the point of interconnection within the forecasted maximum available apparent power, subject to grid service needs. Figure 1 presents the reactive power capability of a co-located hybrid renewable power plant. This example (Gevorgian, Baggu, and Ton 2019) uses a hybrid plant comprising a 1.5-MW doubly fed induction generator wind turbine, a 500-kW PV power plant, and a 1-MW BESS.

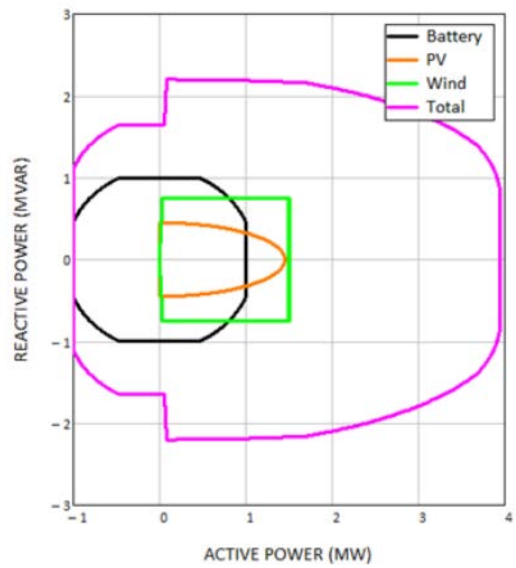

Figure 1. Reactive and real power characteristics of a hybrid power plant (MVAR = megavolt-ampere reactive). ***Image from Gevorgian, Baggu, and Ton (2019)***

To understand the quantitative benefits of real and reactive power control for flexibility services from a distributed wind turbine in an isolated grid, we will use a Type 4 turbine. In this turbine type, real and reactive power is controlled by adjusting the vector components, the d-axis current, Id, and q-axis current, Iq, of the grid-side. The amount of active or reactive power modulation depends on the size of the grid-side inverter and whether active or reactive power is prioritized. For example, if a plant is in active-power priority mode, then the active-power command is given the priority, and the reactive power is limited by the remaining available capacity from the apparent power limit of the grid-side converter. For a plant that is essential for supporting voltage, reactive-power priority is chosen to ensure the maximum use of reactive power modulation for voltage stability.

2.2.2 Frequency Responses

Figure 2 presents a time-domain plot of the grid frequency following a generation loss or a load increase (Wu et al. 2018). For power system balance, controllable resources must adjust their power output to maintain the nominal grid frequency. Conventionally, the response of the power system to a loss of generation or a large change in load is divided into separate control regimes, as seen in Figure 2: inertial response, primary frequency response (PFR), and secondary frequency response, or automatic generation control. These classifications are based on methods for providing each service with conventional generators: synchronous generator inertia for inertial response, generator governors for primary response, and output control responding to system operator power level demands for automatic generation control response (Aho et al. 2012).

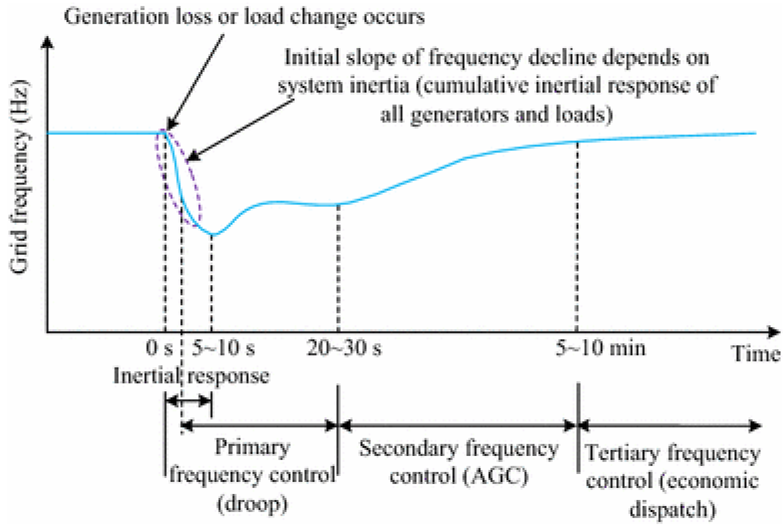

Figure 2. Levels of frequency control and relative time scales of a frequency event (AGC = automatic generation control). ***Image from Wu et al. (2018)***

2.2.2.1 Inertial Response

Inherent system inertia offered by the rotating mass of synchronous generators is key for grid stability—for example, to arrest an immediate change in grid frequency after a sudden generation-load imbalance event (Denholm et al. 2020). Under severe events, the frequency can dip so quickly that underfrequency load-shedding relays trip and shed loads, which compromises grid reliability and stability. In a grid with higher shares of inverter-based resources that are decoupled from grid frequency and lower amounts of inertia from conventional rotating mass (especially in an isolated grid scenario), the grid frequency stability could be at risk. Therefore, inertial response, (also called fast frequency response) (North American Electric Reliability Corporation 2020) from inverter-based resources, including distributed wind turbines, will become paramount for future grids with high shares of renewables. To provide inertial response, generator electrical torque is momentarily increased, which decelerates the wind turbine's rotor to extract kinetic energy and provide a brief surge in power (Wang et al. 2017). If the kinetic energy is extracted at or below the rated speed, the wind turbine goes through a recovery period in which it reduces generator torque (and hence power) to allow the rotor to accelerate back to nominal speeds. The extra burst of power from the rotating mass can be used to arrest declining frequency during a sudden generator loss or load increase event, or to give backup power while auxiliary generators come online. Past studies (Muljadi, Gevorgian, and Singh 2012) used large, utility-scale wind turbines to provide support through either frequency-based methods (in which frequency error or rate of change of frequency (ROCOF) is used to command a commensurate power increase) or torque-based methods (in which a large additional torque increase is injected upon detection of a frequency dip event). The studies showed an improvement in frequency response after a generator loss event in terms of a reduction in the post-event ROCOF and frequency nadir, and an improvement in recovery times. One research question is if a smaller distributed wind turbine can provide adequate inertial response in an isolated grid.

2.2.2.2 Primary Frequency Response

A wind turbine can provide PFR when curtailed (Sonkar and Rahi 2020). Curtailment provides reserve power, or headroom, allowing the wind turbine to ramp up power production when required. Wind turbines are typically curtailed by 5%–10% for PFR. Midwestern utility Xcel Energy has provided PFR for years (Porter, Starr, and Mills 2017). A solar PV plant managed by the California Independent System Operator has been demonstrated to provide many essential reliability services (Loutan et al. 2017). Figure 3 presents a field test of the three-bladed Controls Advanced Research Turbine (CART3) conducted at NREL's Flatirons Campus to demonstrate real power control for PFR. As shown in Figure 3, the power output of the wind turbine is curtailed by 10% before a planned loss-of-generation-frequency event. The wind turbine follows the power command and provides about 25 kW of additional power at about 90 s to support the PFR. Moreover, the turbine tracks the power command very closely after the rapid change in power to provide PFR following the frequency event (Ela et al. 2014).

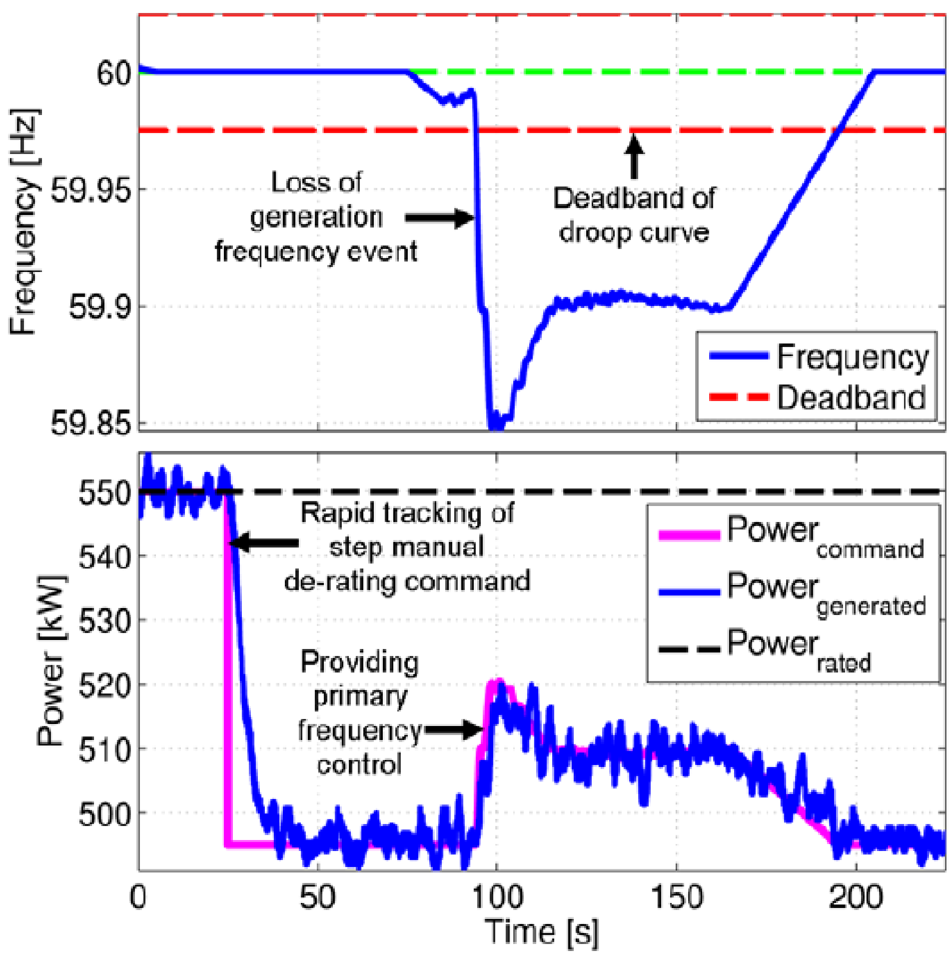

Figure 3. Field test demonstrating primary frequency response with the three-bladed Controls Advanced Research Turbine. ***Image from Ela et al. (2014)***

2.2.3 Voltage Response

Reactive power can be commanded in response to grid voltage deviations; this is known as voltage response or volt-VAR control (Giraldez et al. 2017). Like PFR with its f-P droop, voltage response uses voltage-reactive power (V-Q) droop. In this case, the voltage can be controlled to follow a constant set point (say, 1.05 per unit of the baseline value [pu] or 1.0 pu) or to be within acceptable reliability bands (say, between 0.95 pu and 1.05 pu). During transients such as faults or postfault voltage recovery, voltage response can play an important role in ensuring faster recovery of the voltage and avoiding a trip of the low-voltage protection relay.

2.2.4 Using Wind to Support Black Start

Black start is the first step in restoring a power system after an outage. Some generators are designated to start with the help of a small on-site battery or diesel generator (to start up local auxiliary loads) and then sequentially pick up loads, transformers, high-voltage lines, and other larger generators—eventually stitching the entire grid together for normal operation. An NREL report (Jain et al. 2020) investigated the technical feasibility and potential challenges of an inverter-based resource providing black start support. Typically, the restoration process involves the maintenance of frequency and voltage stability as more loads and transformers are energized, which distributed wind turbines could support with their real and reactive power control capability. However, to be a black start unit, the inverter-based resource needs to support the initial inrush current while energizing components. The NREL study documented the performance of the inverter-based resource while trying to energize an inductive load, using a model developed in MATLAB Simulink. Because inverters are typically designed to provide very small overcurrent, typically about 1.2 times the rated current, their inability to meet the inrush current is seen as a limitation. Accordingly, the time required for the motor to reach a steady state is significantly longer when the source is a current-limited inverter. Soft-start techniques that ramp up the required motor-starting voltage are thought to be useful to limit the increase of the inrush current.

A wind turbine can provide black start capability by employing a grid-forming inverter (i.e., voltage-source converter). An integrated BESS can facilitate the black start process. For instance, in the case of the SMA inverter with the 1-MW BESS at the Flatirons Campus, the black start operation typically proceeds as follows: After closing the DC load-break switch, the inverter checks whether a voltage already exists at the AC terminals. If no AC voltage is applied, the AC disconnection unit is closed, and the configured AC voltage set point is ramped up. The AC voltage set point is usually specified via an external plant control using a Modbus protocol. If an AC voltage already exists at the inverter terminal, the inverter can synchronize with the external auxiliary power supply, close the AC disconnection, and support the power grid in grid-forming or grid-following mode.

In Section 4.3, we evaluate a wind turbine with a hybrid battery connection (either DC- or AC-coupled) and a grid-forming inverter providing black start support to an isolated grid.

2.2.5 Fault Impact Reduction Controls and Interconnection Standards

There are at least two broad sources of faults: the wind turbine itself and the grid it's connected to. Historically, wind turbine controllers have immediately shut down the machine when an operational parameter, such as generator temperature, crosses a fault threshold. The machine remains off until the operator restarts the turbine after dealing with the issue, which often requires a technician to visit the wind turbine. Similarly, when an external fault is detected, inverter-based resources (such as a Type 4 wind turbine) typically trip immediately. With higher contributions of wind energy on electrical grids, such instantaneous loss of key machines can create a large contingency and subsequent operational issues. This is a key problem for isolated grids and is typically mitigated with expensive spinning reserves.

As far as internal wind turbine faults are concerned, a fault controller may allow the turbine to operate effectively under fault conditions and provide more time for a robust grid response than a sudden stop would. Traditionally, wind turbines have fault-detection and isolation logic to detect internal sensor deviations. Some wind turbines also have a fault-tolerant controller, wherein for some smaller or spurious sensor deviations, the turbine is allowed to produce maximum power, overriding the deviating sensors. When a sensor deviation hits a fault threshold, the turbine shuts down. A recently developed fault impact reduction control (FIRC) module, provides additional functionality when a sensor deviates. Depending on the type of deviation as determined by the fault detection logic, the module seeks the highest power that the wind turbine can operate at while limiting the deviation, to reduce the likelihood of faulting and shut down. It communicates the type of fault to the grid operator, when power command changes are predicted, and what that predicted power will be. Fault mitigation by derating and prediction increases energy production over time and reduces the need for expensive spinning reserves and other auxiliary services. This is particularly valuable in isolated, remote systems such as St. Mary's, Alaska. The FIRC module can work in tandem with the IEEE 1547-2018-based inverter controls and external grid fault ride-through logic. Anderson and Baring-Gould (Forthcoming) can be referenced for more details about the proposed FIRC module.

Figure 4 presents an illustration of the working principle of a FIRC module with reference to an isolated grid. Following some sensor deviation, the wind turbine reduces power from its initial set point, P(i), which is the maximum power for a given wind speed (u), to P(t). The grid-level controller provides the complementary power required for stable operation using other generation assets in the system. The FIRC module leads to a more responsive wind turbine that works more closely with the grid or power system controller to enhance system operational integrity and reliability.

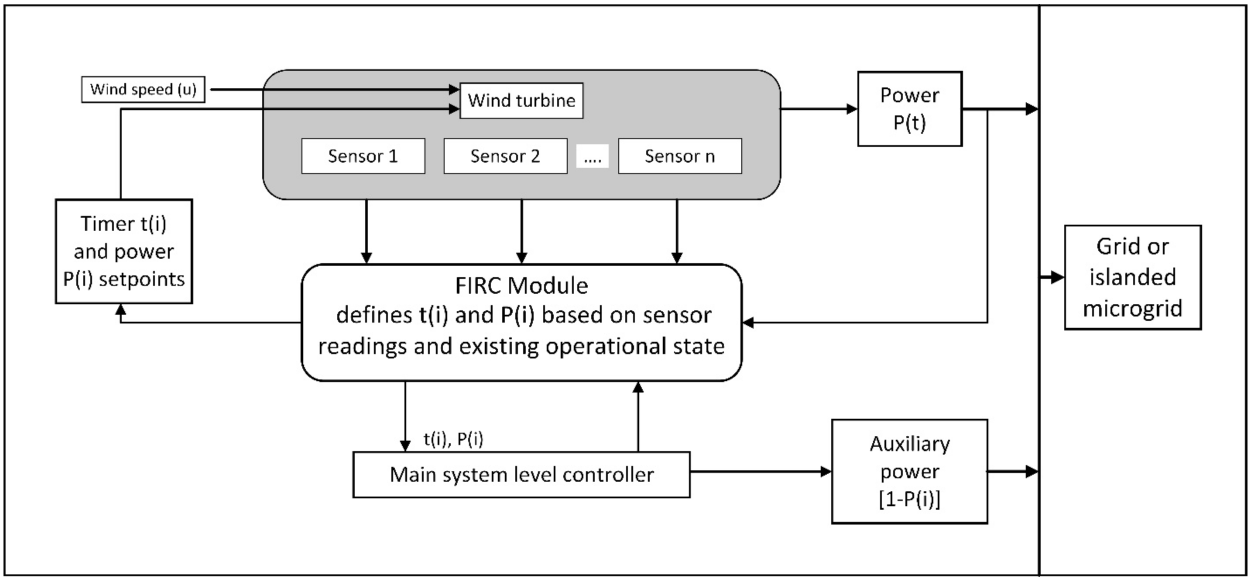

Figure 4. Illustration of a FIRC module integrated into a wind turbine controller

3 National Renewable Energy Laboratory Flatirons Campus

The NREL Flatirons Campus grid has two buses: (1) regular grid (Xcel bus) and (2) controlled grid (CGI bus). Figure 5 portrays the Flatirons Campus grid infrastructure along with the connections to the two buses.

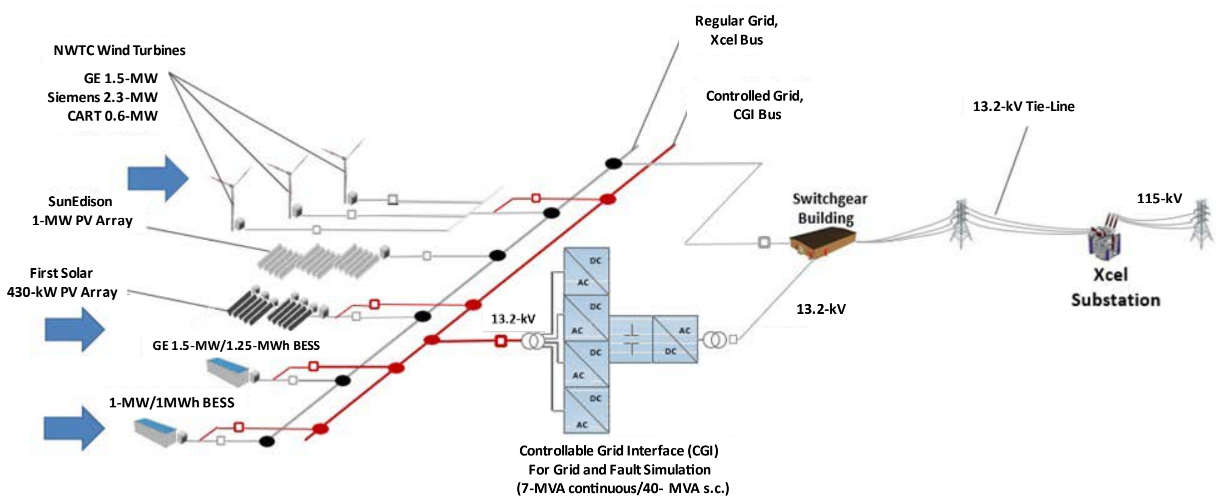

Figure 5. Flatirons Campus grid configuration/infrastructure.

CART = Controls Advanced Research Turbine; GE = General Electric; MVA = megavolt-ampere; NWTC = National Wind Technology Center; s.c. = short circuit

3.1 Grid Configuration

The Flatirons Campus grid simulated in this study comprises the following subsystems, connected via transformers to the 13.2-kV medium-voltage bus:

- Distributed wind at 575 V: 600-kW Controls Advanced Research Turbine
- Solar PV at 600 V: First Solar 430-kW PV plant and SunEdison 1-MW PV plant
- Storage at 400 V: RES Americas 1-MW/1-MWh and GE 1.25-MW BESS
- Critical, dynamic, deferrable, and inductive loads
- Controllable grid interface: 7-MVA back-to-back converter system to simulate grid faults, without impacting the Xcel Energy grid.

More detailed information about the Flatirons Campus grid and both past and ongoing work can be found on the Flatirons Campus website (NREL n.d.). Many of the components at the Flatirons Campus are for research purposes and are not used as power generation sources under normal operating conditions. The distributed generation assets at the Flatirons Campus can be managed using a hybrid plant controller that routes energy generated from wind turbines and solar PV directly to loads while managing deficits and surplus with storage devices such as battery banks or through curtailment of the generation sources. The Flatirons Campus microgrid can be islanded using the circuit breaker in the switchgear building shown in Figure 5.

3.2 Flatirons Campus Islanded Operation Case Study

This section summarizes an unplanned emergency event at NREL's Flatirons Campus. A failure on September 8, 2020, within the substation serving the Flatirons Campus caused an outage from the utility supply for about 6–8 weeks. The event was detected by a voltage-monitoring potential transformer in NREL's newly built 20-MVA substation, which shed the electricity to the entire Flatirons Campus. The grid infrastructure at the Flatirons Campus was not previously configured to run in island mode, so a portable 2-MVA diesel generator was brought onto the campus to continue laboratory experiments. In the first 2 weeks of the outage, the diesel generator provided power to the campus. During this time, NREL staff implemented minor hardware upgrades, controls, and a sequence of operations required to operate the many renewable generation assets on the Flatirons Campus in island mode, disconnected from the Xcel Energy grid.

The Flatirons Campus operated in island mode with communication-free autonomous controls using droop-based logic. Wind turbines, solar PV, and the BESS operated with frequency droop to share power. Any transients in voltage and frequency were supported by the BESS inverter operating in grid-forming mode. A frequency droop set point method was implemented to protect the BESS from overcharging, and a backup generator was used when the state of charge of the BESS dropped below a lower limit (20%). Figure 6 presents a snapshot of the Flatirons Campus operating in island mode for about 24 hours starting at 8 a.m. on Tuesday, October 13, 2020, when the Flatirons Campus grid was run by 100% renewable energy (Koralewicz et al. 2021). The loads in the system were served, and essential reliability services were provided using solar PV and the BESS until sunset. The grid operated on the distributed wind turbine and the BESS from 5:30 p.m. to 8 a.m. The isolated system operated stably, with frequency excursions under 0.4 Hz, for 24 hours with 100% renewable generation.

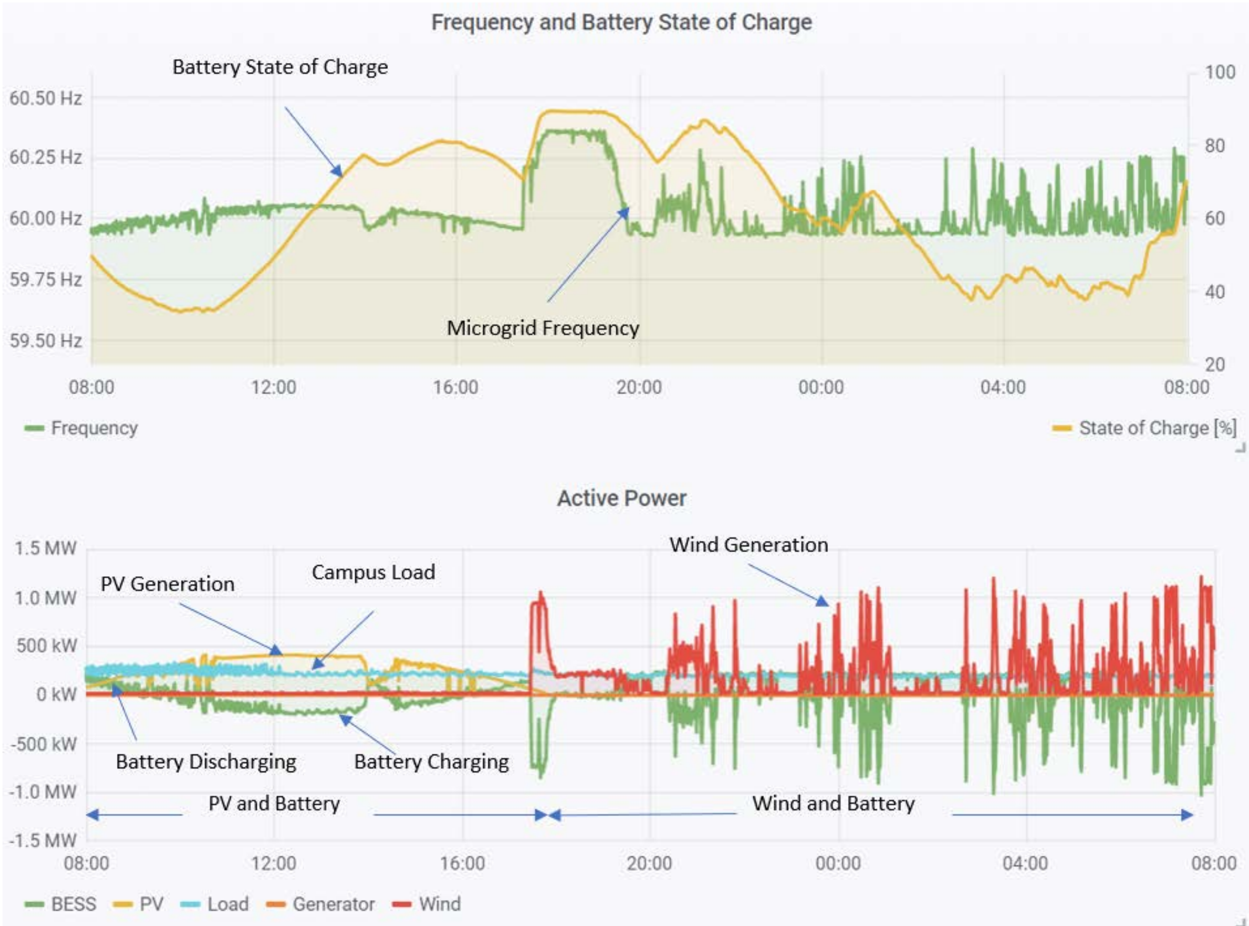

Figure 6. Flatirons Campus islanded operation with 100% renewables (from 8 a.m. Oct. 13, 2020, to 8 a.m. Oct. 14, 2020). ***Image from Koralewicz et al. (2021)***

Typically, communication among various subsystems of an isolated grid is one of the weakest links for resilient controls. The operation of the Flatirons Campus in island mode illustrated autonomous megawatt-hertz droop control without any communication from a centralized plant controller. NREL is working on a series of experiments to demonstrate this communication-free, autonomous control capability for a wide range of operating states and essential reliability services. Another important feature of this operation during the contingency event is the use of the BESS SMA inverter in grid-forming mode, along with the wind turbine and PV to set the grid voltage and frequency. This case study also shows that a smaller-capacity grid-forming inverter can set the voltage and frequency of a larger power system.

4 Simulation Results for an Isolated Grid

This section demonstrates the 600-kW CART using the advanced controls described in Section 2 to provide inertial response, PFR, voltage response, and black start for the Flatirons Campus isolated grid. The simulations for this analysis were performed in MATLAB Simulink. Details on the model used can be found in the Part 1 of this report series (Anderson, Poudel, Reilly, et al. 2022). In the baseline case, the wind turbine and solar PV are in maximum power point tracking mode with no grid forming or support functions. The synchronous diesel generator forms the grid and provides voltage and frequency support in the event of any disturbances, including load changes. It supports grid frequency both with its rotating inertia and with frequency droop control (PFR). The generator is present in the other cases, providing the same support. Renewable resources and load are assumed constant. We demonstrate the improvements to grid stability that the addition of advanced distributed wind controls (described in Section 2) and the integration of a BESS into the wind turbine's DC link can provide. From steady-state conditions, two events impacting frequency (sudden increase of load or loss of generation) and voltage (three-phase short-circuit fault) are introduced to demonstrate the benefit of advanced distributed wind controls and integrated BESS. A black start case is also examined.

4.1 Event 1: Sudden Load Increase

At 40 s into the simulation, a 500-kW step increase in load upsets the generation-load balance, causing a frequency dip. The baseline response is compared against the advanced wind turbine control cases. In all cases, the diesel generator's inertia helps to arrest the frequency, and it steps up its real power output to offset the sudden increase in load, responding with frequency droop. These support the recovery of nominal grid frequency. Also, while the wind turbine goes through fluctuations in its active power output, the diesel generator tries to offset it by changing its generation output to maintain the frequency.

Figure 7 demonstrates the effect of various wind turbine active power control methods on the frequency disturbance, and results are tabulated in Table 1. Note that a turbine providing PFR starts derated to provide headroom. Nadir is the lowest frequency value in a dip, and ROCOF is an average rate of change of frequency from the beginning of the frequency dip to its nadir. These values are important because if they are low enough, protective relays trip on loads to restore system stability and on generators to protect from overexcitation. The 0.1-Hz recovery time is the time from the beginning of the frequency dip until it stabilizes to within 0.1 Hz of nominal. Energy injected and peak power injected are the amount of extra energy and power injected by the wind turbine, respectively.

Table 1. Metrics on Frequency Response for Various Scenarios

Scenario	Description	Nadir (Hz)	Rate of Change of Frequency (Hz/s)	0.1-Hz Settling Time (s)	Energy Injected (kJ)[a]	Peak Power Injected (kW)
1	Baseline	57.77	-4.37	5.5	0.7	20
2	Wind providing inertia	58.17	-3.98	13.4	297	190
3	Wind providing PFR	57.82	-4.54	8.4	146	95
4	Wind providing PFR + inertia	57.99	-4.28	6.2	221	142
5	Wind providing inertia + BESS providing PFR	58.17	-3.73	4.9	121	546

[a] kJ = kilojoule

For this event, two wind turbines were modeled on the grid. In the "IR" case (as labeled in Figure 7), both provide inertial response; in the "PFR" case, both provide PFR. In the "IR+PFR" case, one provides each. In the baseline case, the wind turbines provide no response. The lower plot demonstrates that inertial response provides a faster and larger power response than PFR, but also requires a significant recharge or recovery period, and creates an oscillating power signal for some time after the frequency event. As such, inertial response is more effective in increasing the frequency nadir and ROCOF but has a longer settling time. PFR alone improves the settling time compared to inertial response alone, but the nadir is barely elevated because PFR responds slower than inertial response. A combination of PFR and inertial response both improves the frequency nadir and ROCOF and provides a settling time within 1 s of the baseline case.

Frequency response from a wind turbine is more effective when combined with PFR from a battery, which is faster. In the IR(wind) + BESS case in Figure 7, two wind turbines provide inertial response, and an external BESS is used for PFR. As seen in the lower plot, the BESS smooths the post-disturbance frequency oscillations by absorbing the power oscillations from the wind turbine, reducing settling time.

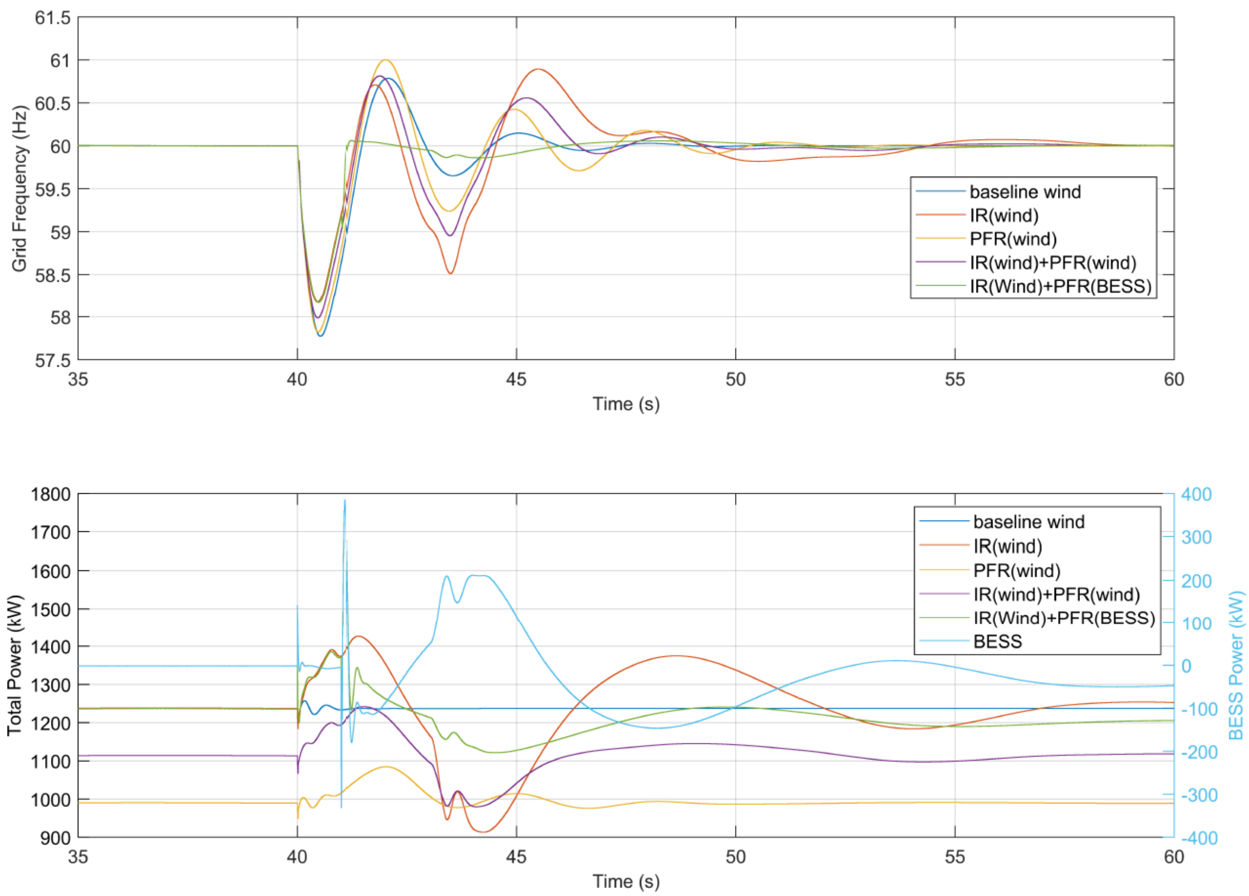

Figure 7. A comparison of real power control methods on frequency response (IR = inertial response)

4.2 Event 2: Voltage Transient

We evaluate how voltage response from the wind turbine improves recovery from a momentary drop in voltage, serving as a proxy for many kinds of disturbances. In all cases, the diesel generator provides some voltage support. In the baseline case, the wind turbine just produces nominal reactive power. In the other cases, voltage response is provided by V-Q droop control. 5% and 10% droop are considered. Figure 8 presents the event. At 10 s, the amplitude of the voltage is reduced to 90% for 5 cycles. The voltage nadir is increased and recovery time is decreased. The 5% droop case provides maximum reactive power from the wind turbine in addition to what the diesel generator provided, and hence has the highest nadir and fastest recovery to nominal voltage.

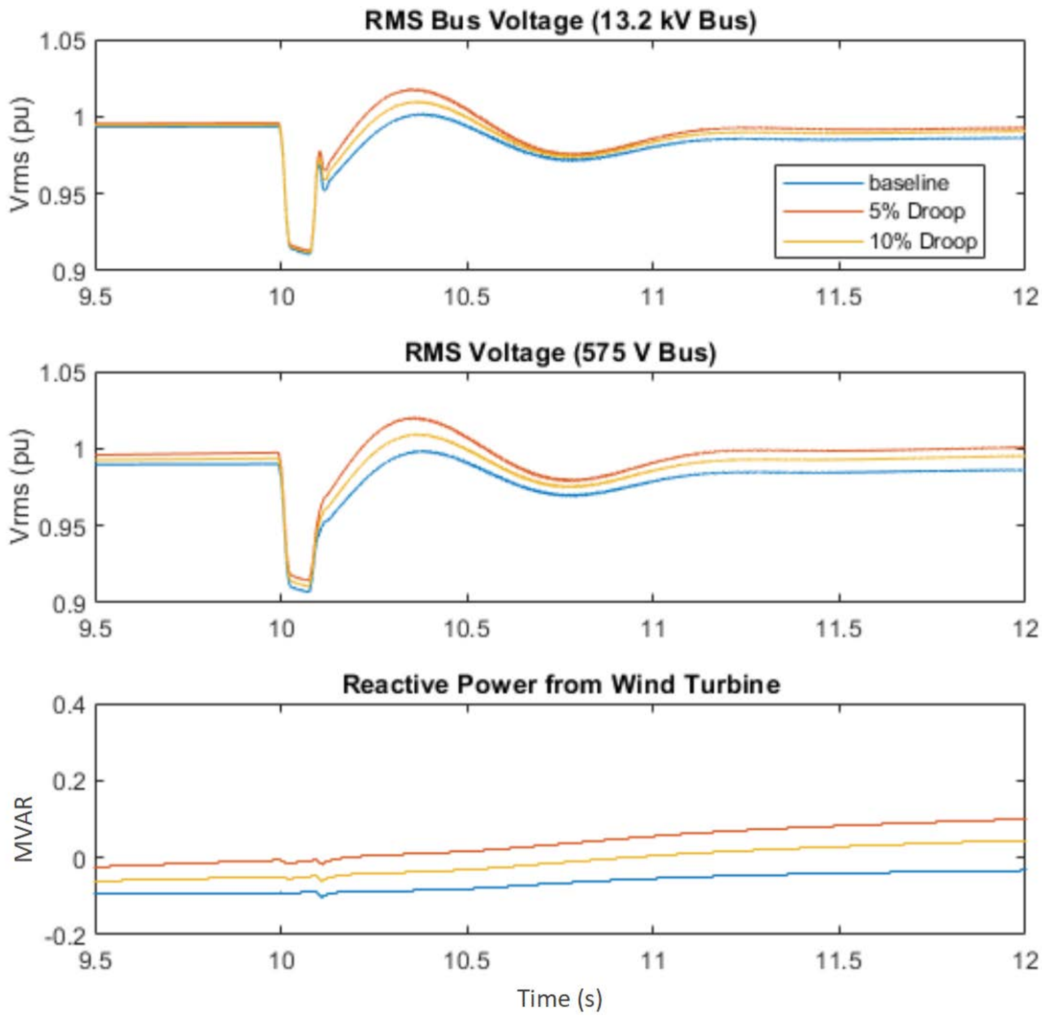

Figure 8. Reactive power support from the wind turbine: baseline case versus 5% and 10% V-Q droop

4.3 Event 3: Using Wind to Support Black Start in Isolated Grids

In the baseline case, black start of a critical load would be performed by the grid-forming diesel generator. Here, we illustrate how a wind turbine integrated with BESS at the DC link could form the grid and perform black start instead. In this case, the integrated BESS provides the capability to start the wind turbine and ensures a stable AC voltage can be provided at the wind turbine's grid-side converter. The BESS maintains the AC voltage while the grid is down, and with that stable AC voltage the wind turbine's energy can be used to pick up the isolated grid's critical load. As shown in Figure 9, at the beginning of the simulation there is a critical load of ~430 kW and 210 kilovolt-ampere reactive (kVAR). The wind turbine comes online at 0.5 s with the help of its integrated BESS and ramps up to pick up the load. At 5 s into the simulation, the solar PV plant is added to the isolated grid, energized by the wind turbine to the nominal voltage of 13.2 kV. To accommodate the solar PV generation, which is in grid-following mode, the wind turbine, which is in grid-forming mode, reduces its own power output, as shown in Figure 9. This ensures that frequency and voltage stability are maintained during system restoration and through the sequential load pickup and additional generation start-up processes. With this additional generation capability, more loads can be picked up. Therefore, the critical load is then stepped up to 100% real power (1 MW) at 8 s. At this point, the wind turbine and BESS combination generates more power to meet the increased load pickup. Figure 9 presents the power output from each of the resources during black start.

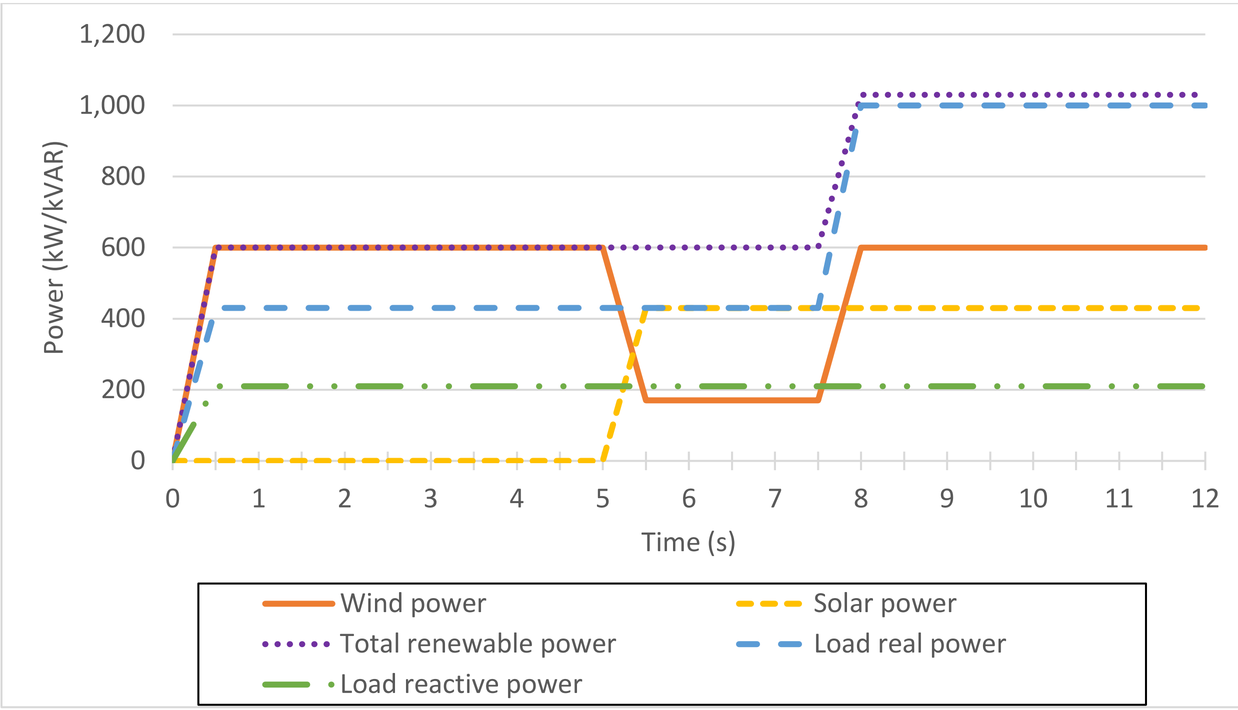

Figure 9. Using wind to support black start and energization of an isolated grid. Purple and green lines are real and reactive load.

5 Conclusion

With increasing renewable resource integration into isolated grids, most operators currently rely on diesel generators and BESS to support essential reliability services, provide flexibility to meet ramps, and provide voltage and frequency support. However, this report demonstrates that distributed wind turbines with advanced control capabilities can provide essential reliability services. To illustrate the possibilities, we model the NREL Flatirons Campus as an isolated grid using MATLAB Simulink and add advanced controls to the CART model to enable the wind turbine to provide frequency and voltage support. The results demonstrate that, during a load pickup, a combination of one wind turbine providing inertial response and the other providing PFR yields a good mix of improving frequency nadir and ROCOF, while limiting settling time. Furthermore, integrating a BESS into the wind turbine provides superior frequency stabilization. During a voltage fault, droop-based reactive power control for voltage response increases the voltage nadir, reduces settling time, and bolsters steady state voltage.

An additional benefit of employing advanced wind turbine controls in a real-world isolated grid is that the burden of providing these services could be shifted away from conventional generation sources or batteries, ultimately improving the battery and diesel generator lifespans by reducing cycling. There is also potential to reduce the amount of storage required, thereby providing further economic incentives for isolated grid operators. These benefits could be furthered by effective coordination with probabilistic renewable resource forecasts, and the utilization of solar PV inverters to provide similar services to those demonstrated by distributed wind here. The benefits of distributed wind with advanced controls in grid-connected and microgrid applications are demonstrated in Part 3 (Anderson, Poudel, Rane, et al. 2022) and Part 4 (Anderson, Rane, and Reilly 2022) of this series, respectively.

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