Advanced Distributed Wind Turbine Controls Series: Part 4–Wind Energy in Microgrids

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

Benjamin Anderson, Jayaraj Rane, and Jim Reilly

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
IEEE	Institute of Electrical and Electronics Engineers
kV	kilovolt
kW/kWh	kilowatt/kilowatt-hour
MIRACL	Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad
ms	milliseconds
MW/MWh	megawatt/megawatt-hour
NREL	National Renewable Energy Laboratory
PFR	primary frequency response
PV	photovoltaics
V	volt

Executive Summary

In recent years, the technical capabilities and requirements for distributed wind turbines to provide ancillary services beyond maximum energy production has increased. Ancillary services, leveraged through advanced wind turbine controls, can support grid stability, reliability, and resilience. In the context of a microgrid, wind turbines can provide ancillary services that are useful in both islanded and grid-connected modes, as demonstrated in previous parts of this report series. This report focuses on how wind turbines with advanced controls and power electronics can support the stability of the microgrid during transitions from grid-connected to island mode, and back.

This report documents simulation results from a model of the National Renewable Energy Laboratory (NREL) Flatirons Campus containing NREL's 600-kilowatt Controls Advanced Research Turbine. Using this turbine, we demonstrate through desktop simulation how a wind turbine can support the voltage and frequency of a microgrid during transitions—from making planned transitions seamless to keeping all loads online during some unplanned transitions to supporting black start in the event of an open transition (blackout).

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1 Introduction

Recent trends show an increasing interest in developing microgrids with higher contributions of renewable distributed energy resources (DERs). Such trends will ultimately lead to the need for variable resources to move beyond providing energy to providing grid-stabilizing benefits. This report provides an overview of distributed wind's ability to provide grid support, or ancillary, services to support microgrid stability in islanded mode, grid-connected mode, and in transitions between the two. We discuss some of the power system stability requirements of a microgrid and perform desktop simulations to understand how a wind turbine's advanced controls can support those requirements. This report is the final report in a four-part series. The first report, *Advanced Distributed Wind Turbine Controls Series: Part 1—Flatirons Campus Model Overview* (Anderson, Poudel, Reilly, et al. 2022), details the Simulink model used in the series. The second report, *Advanced Distributed Wind Turbine Controls Series: Part 2—Wind Energy in Isolated Grids* (Anderson, Poudel, Krishnan, et al. 2022), describes the benefit of wind in isolated grids (corresponding to an islanded microgrid in this report). The third report, *Advanced Distributed Wind Turbine Controls Series: Part 3—Wind Energy in Grid-Connected Deployments* (Anderson, Poudel, Rane, et al. 2022), describes the benefit of distributed wind in grid-connected settings (corresponding to a grid-connected microgrid in this paper).

This report is structured with respect to the two main operating modes, grid-connected (or grid-tied) and island (or stand-alone), and considerations for a smooth transition between the modes. In grid-connected mode, the microgrid shares a common voltage waveform with the utility grid. We assume that the utility grid acts as an infinite bus, which is orders of magnitude larger than the microgrid, and can absorb fluctuations in load that the microgrid produces while keeping the microgrid stable and maintaining its voltage, frequency, and overall stability. In island mode the microgrid is disconnected from the utility grid and utilizes its grid-forming assets to energize connected loads with no support from an external utility grid. In island mode the DERs should contribute to the stability of the microgrid.

The significant change in configuration that occurs with the microgrid transitions between grid-connected and island modes often causes voltage and frequency fluctuations. In a closed transition, all the critical loads and generation will stay online when the voltage and frequency deviations remain within the protection-setting parameters. In an open transition, all the assets will disconnect, or trip, from the microgrid and will then reconnect later as the microgrid is formed. In this report we describe how distributed wind can ride through and even stabilize the transitions by supporting frequency and voltage within the microgrid.

1.1 Benefits of Wind Power in Microgrids

Wind power can bring several key benefits to microgrids, which are particularly relevant when the microgrid is in island mode. Adding wind power to a microgrid typically diversifies the generating assets, which may provide the microgrid with redundancy and may avoid single points of failure. When paired with fossil-fuel-based generation, such as diesel generators, wind generation can offset fuel use. This is particularly impactful in remote microgrids with expensive and potentially unreliable supply chains for imported fuels that may need to be transported over long distances. When paired with other types of renewable generation, such as solar photovoltaic (PV) generators, wind provides resource complementarity, which spreads the generation profile across a given day, reducing the mismatch between load and generation. In many locations, solar resource dominates during the day, and a complementary wind resource dominates during the night; Jurasz et al. (2020) provide a detailed review of renewable energy complementarity. Wind can be coupled with energy storage systems, such as battery energy storage systems (BESS), to smooth out the generation profile to match the required daily load demands. In times when the wind resource exceeds the load, excess wind energy can be stored and later released when the load ramps up beyond the available wind power. Energy storage can also smooth the momentary fluctuations in both load demand and wind generation. Figure 1 demonstrates how the combination of wind, solar and storage can smooth out the cumulative generation curve (Clark et al. 2022). Finally, wind can provide ancillary services to support microgrid voltage and frequency and can support microgrid stability during transitions between grid-connected and island modes.

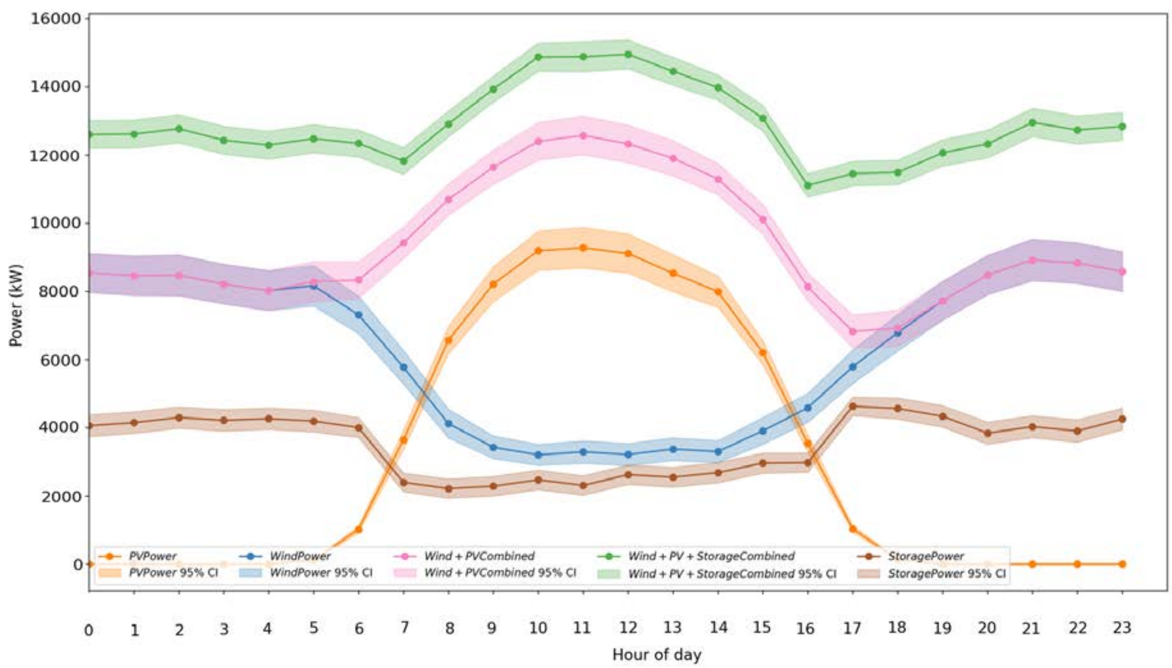


Figure 1. Complementary generation using wind, solar photovoltaics (PV), and storage. **Image from Clark et al. (2022)**

1.2 MIRACL Flatirons Campus Model

A MATLAB Simulink model of the National Renewable Energy Laboratory's (NREL's) Flatirons Campus was developed for this report series and is available on GitHub (Anderson 2021). The Flatirons Campus is a microgrid that can be operated in either grid-connected or island mode. The main Flatirons Campus components modeled are the 600-kilowatt (kW) Controls Advanced Research Turbine (CART), a 430-kW solar photovoltaics (PV) array, a 1-megawatt (MW)/1-megawatt-hour (MWh) BESS, a 2-MW diesel generator, and building loads. A one-line diagram and Simulink graphic of the NREL microgrid are shown in Figure 2 and Figure 3, respectively. The details of the microgrid's components and implementation are given in the first report in this series (Anderson, Poudel, Reilly, et al. 2022). In this model, the grid connection, BESS, and diesel generator are manually switched. This will be automated in future work by developing an autonomous microgrid controller.

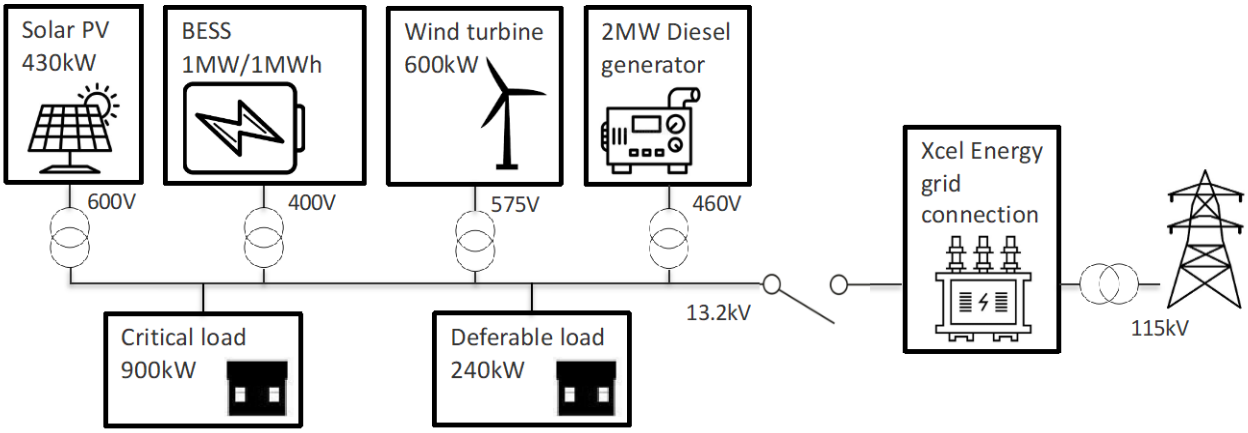


Figure 2. One-line diagram of the Flatirons Campus microgrid under study

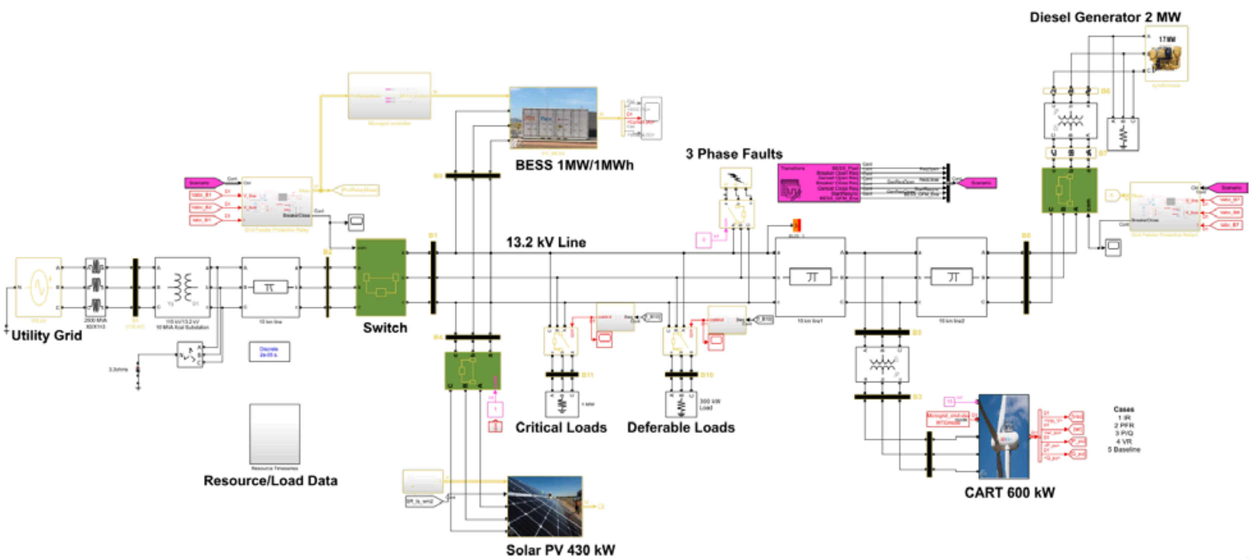


Figure 3. MATLAB Simulink model of the Flatirons Campus

2 Wind in Microgrids: Island Mode

2.1 Microgrid Support Services

Beyond power production, wind turbines can quickly ramp their real and reactive power production up and down, allowing them to support an islanded microgrid's frequency and voltage stability. Some essential ancillary services for isolated grids, corresponding to islanded microgrids, are discussed at length in Part 2 of this report series (Anderson, Poudel, Krishnan, et al. 2022). Two main services, frequency response and voltage response, are briefly summarized here.

2.1.1 Frequency Response

Microgrid frequency deviations occur when an imbalance in generation and load occurs due to relatively large load steps, generation variations, or electrical faults in the system that cannot be managed by ramping generation up or down. Islanded microgrids are particularly susceptible to such fluctuations, because individual loads or generators may make up a large fraction of total load or generation. If frequency drops below a specified threshold, loads will trip offline to help restore the system frequency (typically programmed in an underfrequency load-shedding scheme). If frequency deviations reach certain thresholds, protection devices and generators may trip offline to protect themselves and the system, which will typically result in an entire microgrid blackout.

A Type 4 (full converter) wind turbine can support microgrid frequency in two main ways when equipped with intelligent power electronics. The first is synthetic inertial response: a wind turbine can extract energy from the inertia of its rotor to provide a surge in power to stabilize microgrid frequency. It does this by momentarily increasing generator electrical torque to decelerate the rotor. However, the wind turbine needs to reaccelerate its rotor after the power surge, which it does by reducing its power output for a time. It is synthetic because the converters isolate the generator from the microgrid—they will not automatically respond to frequency deviations as a synchronous machine would. So, intelligent controls are required to harness the rotor's inertia. The second is primary frequency response (PFR): a wind turbine can use a frequency-real-power droop controller to ramp its power up or down to respond to deviations in microgrid frequency. To perform PFR, the wind turbine needs to operate in a curtailed state to provide headroom, or reserve available capacity, for it to ramp up when frequency dips. However, no recharge time is needed because the wind turbine will not produce more than its maximum power.

Part 2 of this report series demonstrates a wind turbine providing the required synthetic inertial response and PFR to maintain the frequency stability of an isolated grid (Anderson, Poudel, Krishnan, et al. 2022). Figure 4 is the simulation result of utilizing two wind turbines and a BESS to provide frequency response and inertial response. In the baseline scenario (blue line) the wind turbines produce maximum power and no services, and there is no BESS. Inertial response has a faster response time than PFR, so it elevates the frequency nadir more. However, inertial response causes a longer settling time due to fluctuations during its recharge period. Providing PFR and inertial response from one turbine each elevates the nadir while retaining a lower settling time. Providing inertial response with a wind turbine and PFR with a BESS provides superior performance: it is as effective at elevating the frequency nadir as providing inertial response with two wind turbines, but significantly reduces the settling time by smoothing frequency fluctuations. The high ramp rate of the battery allows the highest peak power injection, crucial for an event of such a short time scale. Integrating BESS support is discussed in Muljadi et al. (2003) and Poudel et al. (2021). Such a hybrid approach holds significant potential for maintaining microgrid stability while integrating DERs into isolated systems.

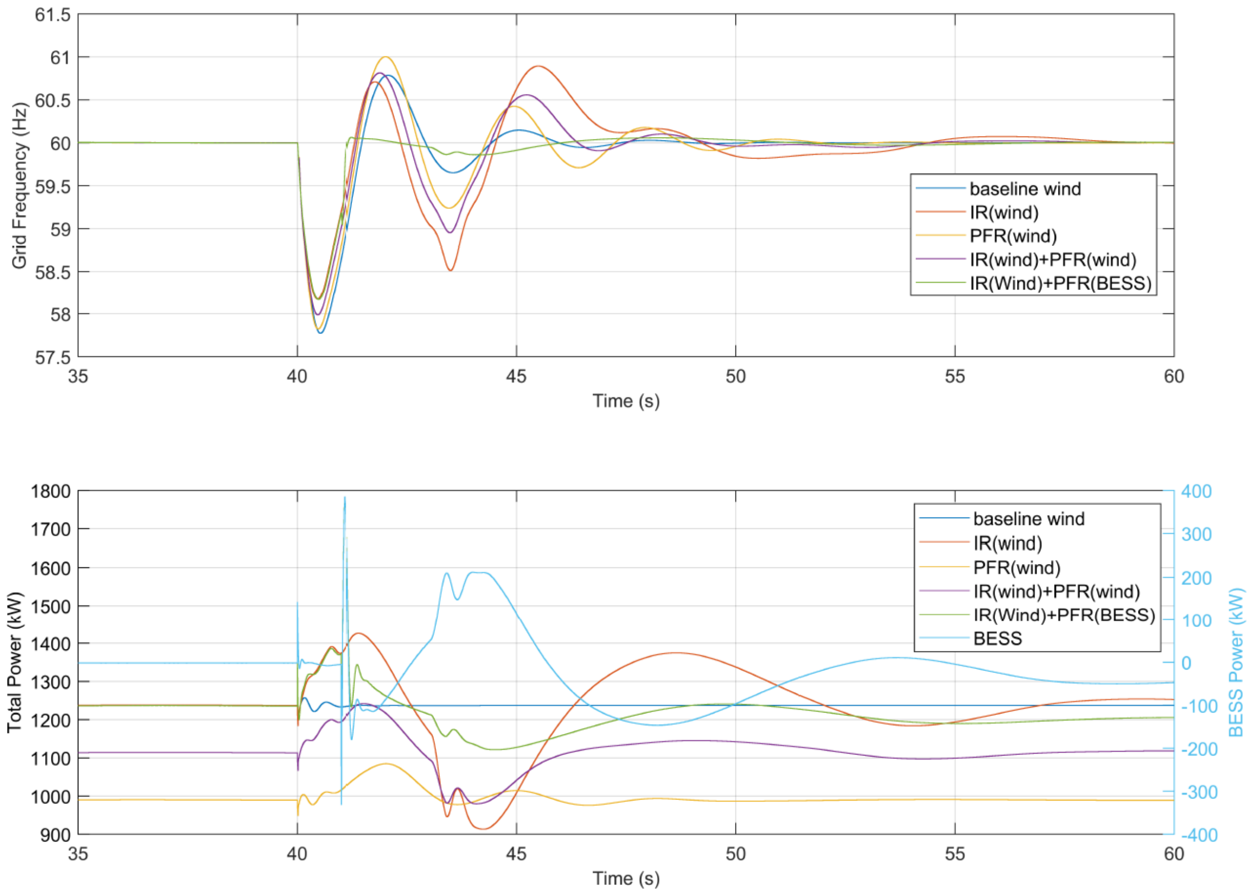


Figure 4. Frequency response by different methods. Blue: baseline, wind turbines producing maximum power. Red: two wind turbines providing inertial response (IR). Yellow: two wind turbines providing primary frequency response (PFR). Purple: one wind turbine providing inertial response, the other PFR. Green: one wind turbine providing inertial response and a BESS providing PFR. Cyan, second plot: the power that the BESS provides in the IR (Wind) + PFR (BESS) case.

2.1.2 Voltage Response

Just as a wind turbine can support microgrid frequency with real power, it can support microgrid voltage with reactive power, which we refer to as voltage response. Reactive power is the component of the power output wherein the voltage and current are out of phase with each other. These two components are interrelated and are controlled by power plants or the grid in various ways. Typically, unity power factor (injecting all real power and no reactive component) is preferred in many markets to maximize the utilization of real power generated and maximize on energy sales per kilowatt-hour (kWh). Reactive power can be commanded in response to voltage measurements at the point of interconnection (or another location on the grid). In this case, the voltage can be controlled to follow a constant set point (for example, 1.05 per unit nominal value [pu]) or to be within an acceptable range,[1] often voltage is served between 0.95 pu and 1.05 pu (Giraldez et al. 2017).

Like PFR, the wind turbine can use a voltage-reactive-power droop controller to support voltage. Part 2 of this report series demonstrates a wind turbine injecting reactive power to maintain the voltage stability of an isolated grid (Anderson, Poudel, Krishnan, et al. 2022). Like frequency, voltage can fluctuate when loads and generators turn on/off or ramp up/down, or when faults occur in an electrical circuit (in the microgrid or utility grid). Figure 5 illustrates a three-phase fault example that occurs at 10 s with a duration of five cycles, short-circuiting the system on the 13.2-kilovolt (kV) bus. In the baseline case, only the diesel generator provides reactive power to support voltage. In the voltage response case, wind also injects reactive power into the fault. The voltage nadir, rate of recovery, and voltage oscillation are improved by the wind turbine's injection of reactive power.

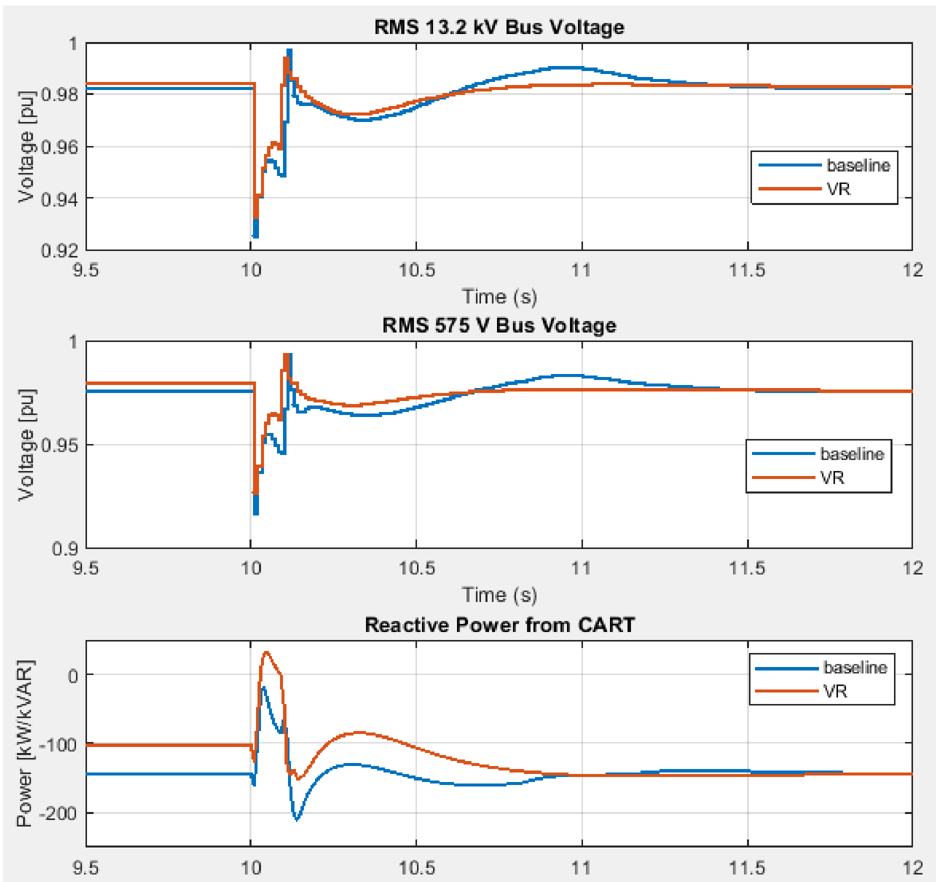


Figure 5. The CART supports microgrid voltage. Baseline: wind turbine provides no voltage response. VR: wind turbine provides voltage response. The wind turbine is on the 575-volt (V) bus. (kVAR = kilovolt-ampere reactive)

[1] In 60-hertz (Hz) systems, the standard ANSI C84.1 specifies Range A as ideal, in the +/- 5% pu voltage range.

3 Wind in Microgrids: Grid-Connected Mode

3.1 Grid Support Services

For an introduction to grid services and the feasibility of wind power providing them, refer to Denholm, Sun, and Mai (2019). Part 3 of this report series (Anderson, Poudel, Rane, et al. 2022) demonstrates a wind turbine providing support in a grid-connected context, analogous to a grid-connected microgrid. In this setting, a single distributed wind turbine will not have a significant effect on the entire utility grid but may influence its local distribution circuit. Also, if enough DERs act in concert, then they can provide significant support to the utility grid, and ultimately the bulk power system. This report demonstrates a distributed wind turbine acting as a Category B/III DER (the categories with the highest functionality for grid support) according to the Institute of Electrical and Electronics Engineers (IEEE) standard 1547-2018 (IEEE 2018). Some results from this report are summarized here. Please refer to the full report for more details.

3.1.1 Frequency Response

Per IEEE 1547-2018, a frequency deviation resulting in a power change of less than 5% of the rated real power requires a maximum open-loop response time of 5 s (IEEE 2018) to settle to the new real power output. The new real power output is given by a droop equation specified in IEEE 1547-2018. Figure 6a presents a test case of a small high-frequency condition, beyond the deadband, at 1 s. The wind turbine, utilizing the droop function, reduces its power accordingly by 5% and settles to the new real power output in about 4.6 s, exceeding the minimum requirement. Per IEEE 1547-2018, for larger frequency deviations (requiring >5% change in power), the DER does not need to ramp faster than 20% per minute (IEEE 2018). Figure 6b presents a test case of a low-frequency event at 1 s. The wind turbine increases its available real power accordingly by 20% and settles to the new mode of operation within 9 s, far exceeding the requirement. A droop of 5% and deadband of 0.036 hertz (Hz), the default values from IEEE 1547-2018, are used (IEEE 2018). For a demonstration of frequency response to the rate of change of frequency, refer to Part 3 of this report series (Anderson, Poudel, Rane, et al. 2022).

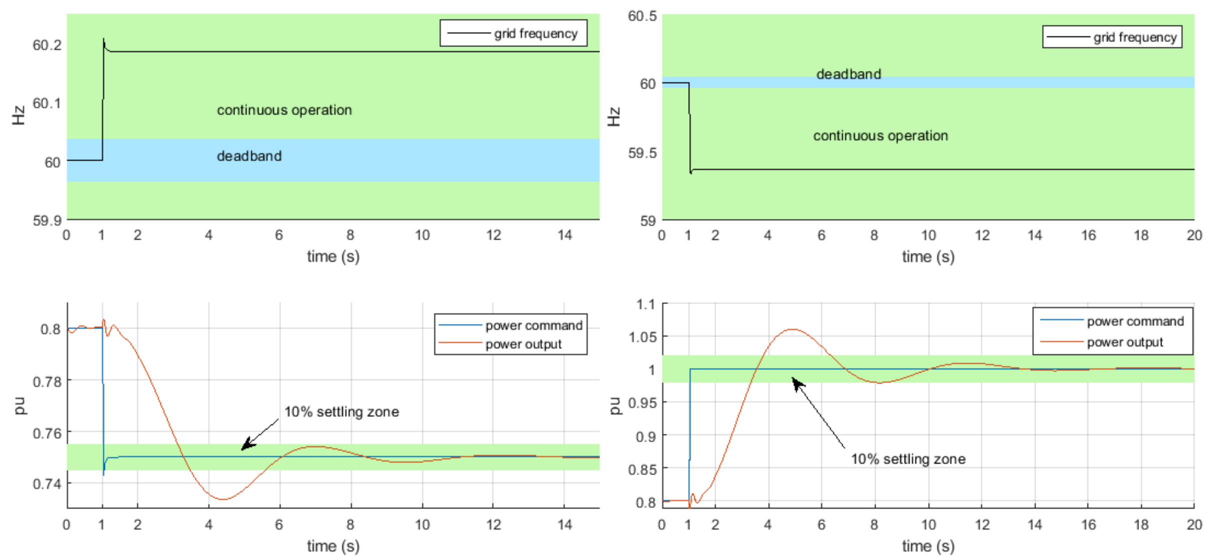


Figure 6. (a) Wind turbine's power response to a small overfrequency event and (b) Wind turbine's power response to a large underfrequency event

3.1.2 Voltage Response

In a grid-connected system, wind power can provide a reactive power response to local voltage deviations. Figure 7 demonstrates the wind turbine navigating various IEEE 1547-2018 voltage regions. In the deadband, it provides no support. At 1 s, when the microgrid voltage drops to 0.9 pu in the continuous operation region, it provides increased reactive power via the droop control function. When the microgrid voltage drops to 0.7 pu in the mandatory operation region, it rides through and does not provide extra reactive power, although its real current increases to stabilize its real power output given the voltage drop. Finally, after 20 s, it enters the trip region and trips offline. The wind turbine uses a voltage droop of 13.6% and deadband of 0.02 pu, the default values from IEEE 1547-2018. For a demonstration of undervoltage ride through, refer to Part 3 of this report series (Anderson, Poudel, Rane, et al. 2022).

IEEE 1547-2018 defines momentary cessation as follows: When grid voltage or frequency strays outside of certain thresholds, a DER must temporarily cease to provide real power to the grid while staying connected, and immediately restore power when voltage or frequency return to within the thresholds. This is demonstrated in Figure 8. Initially, the wind turbine operates at nominal real power and zero reactive power while the microgrid voltage remains within the deadband. Voltage dips into the momentary cessation zone at 5 s, and real power drops to zero in about 31 milliseconds (ms). The wind turbine remains connected to the microgrid but provides no real power. Voltage returns to the deadband at 10 s, and real power steps up back to its nominal value. At 12 s, voltage rises into the upper momentary cessation zone, and real power again drops to zero in 27 ms, staying connected but providing no real power. Voltage returns to the deadband at 17 s, and real power ramps up back to its nominal value. Reactive power is slightly elevated during the faults. The response times exceed the IEEE 1547-2018 requirement of 83 ms.

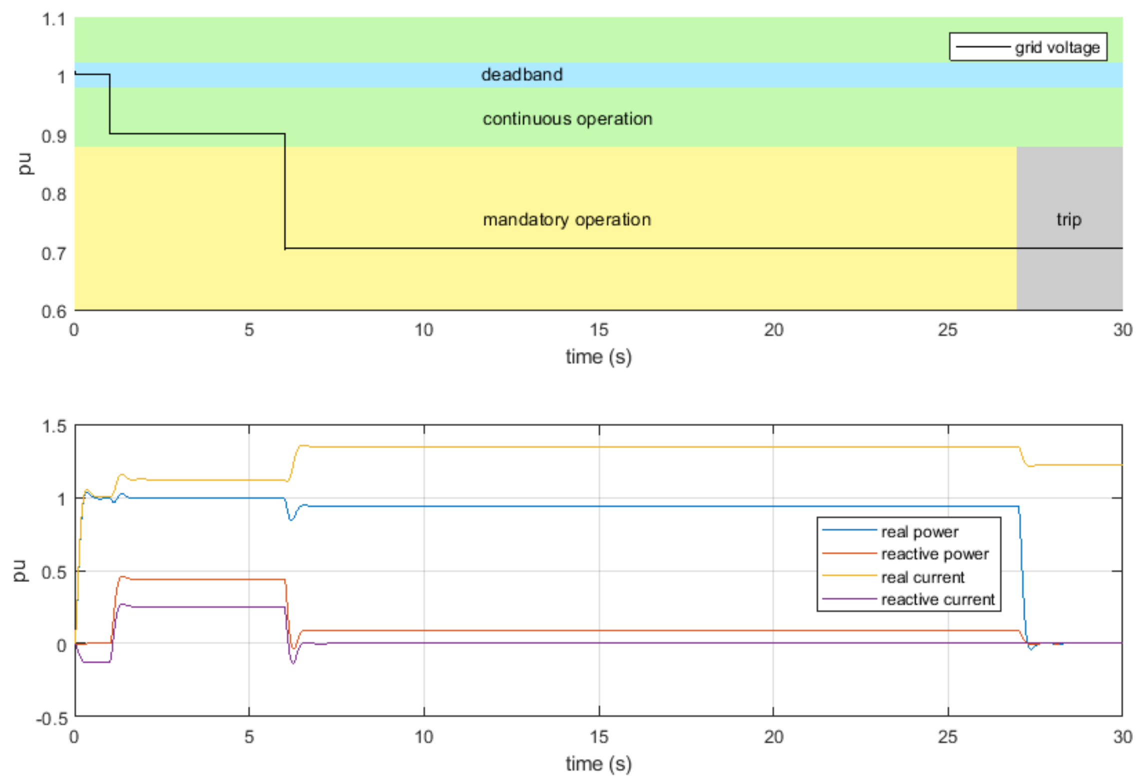


Figure 7. Wind turbine demonstrating voltage response and trip

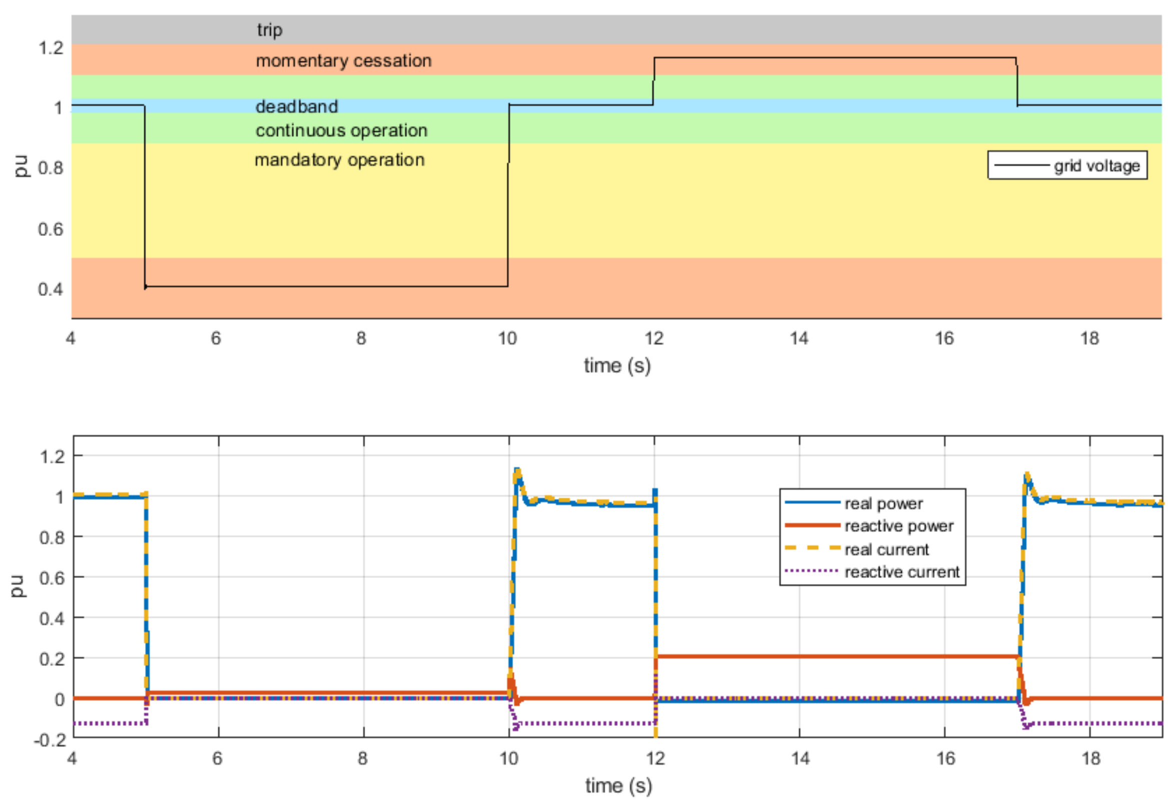


Figure 8. Wind turbine demonstrating momentary cessation during undervoltage and overvoltage

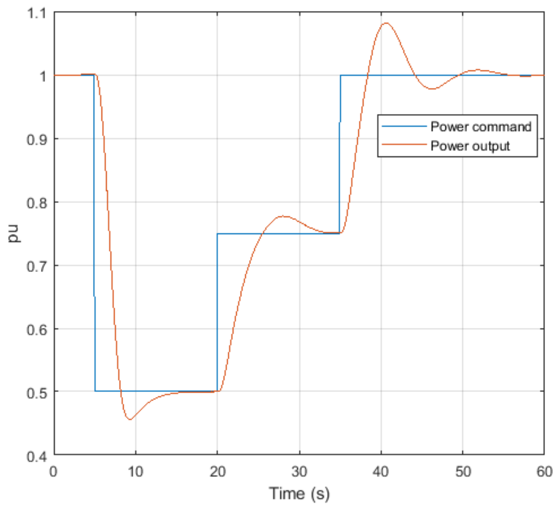
3.1.3 Real and reactive power command tracking

A generator can provide frequency support services by adjusting its real power output and voltage support services by adjusting its reactive power output, in real time. The electricity market classifies frequency support services as ramping, regulating, and contingency reserves. Some of these services are procured in a day-ahead market and others in real time. A day-ahead market is based on projected hourly load/generation or real time based on current system conditions. The real-time market supplements the day-ahead and hourly planning process. Ramping reserves follow a forecast-based dispatch, so they do not need to respond rapidly to commands. Regulating reserves balance the difference between the ramping generation and the total load, typically requiring a response time in the 1-min range. Contingency reserves are used to restore system frequency right after an outage, typically requiring a response time in the 10-min range. From the wind turbine's perspective, these appear as real power commands.

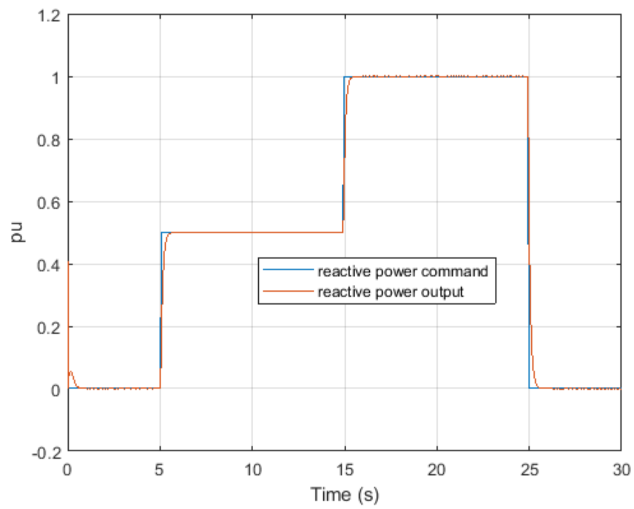
Reactive power support is required to provide reactive power to loads, to support voltage (depending on the utility methodology), and with some utility tariffs, to avoid a surcharge applied against the demand portion of the electric utility bill.[2] From a wind turbine's perspective, this looks like a reactive power command.

Figure 9a demonstrates the wind turbine tracking an external real power command. The wind turbine responds faster to the step-down commands than to step-up commands. The slowest of the three responses shown is to rated power, at the limit of the machine's ability. However, this is still fast enough to participate in ramping, regulating, and contingency reserve services. Figure 9b demonstrates the wind turbine tracking an external reactive power command. All responses occur within 1 s. The reactive power response is faster than real power because increasing real power requires the wind turbine to generate more torque and its blades to pitch, whereas increasing reactive power just requires increasing the reactive current command, solely within the power electronics. This is orders of magnitude faster than the response time required by reactive power support. For a demonstration of inertial and reactive power support, refer to Part 3 of this report series (Anderson, Poudel, Rane, et al. 2022).

[2] The reactive power component of a utility bill is typically metered in 15-min increments but is accounted for in a monthly average of power factor or a sum of reactive power purchased (if a utility charges for reactive power at all).



(a)



(b)

Figure 9. Wind turbine following an (a) real and (b) reactive power command

4 Wind in Microgrids: Transitions

4.1 Grid-Connected Mode to Island Mode

This section investigates the considerations of a wind turbine operating as a generation asset within a microgrid during transitions from grid-connected mode to island mode. It examines three types of transitions: closed planned, closed unplanned, and open. Each of these transition types depends on the amount of microgrid generation online and available to support the transition, as well as whether the infrastructure and generation is designed to synchronize microgrid generation and loads with the external grid. A one-line diagram of the microgrid is displayed in Figure 2.

4.1.1 Closed Planned Transitions

During a closed planned transition, the utility grid seamlessly hands off power production to the local generators, so that local generation and load match closely before opening isolation devices. This prevents significant voltage and frequency deviations, which keeps generators or load from tripping offline. This requires the generators to ramp their real and reactive power to the appropriate level before the transition, or for a sufficiently large BESS to be present to cover the generation deficit during the transition because BESS can respond much faster than conventional generators such as diesel or natural gas internal combustion engines.

To demonstrate the value of distributed wind in microgrid transitions, the first option of generator ramping is simulated here. This is the best-case scenario for transitioning, with minimal voltage and frequency deviations. In this scenario, shown in Figure 10, the generating assets used within the microgrid are diesel, wind, and solar PV, with no energy storage used. At 30 s, in preparation for the transition, the wind and diesel generators begin to ramp up from their initial, curtailed power production to their rated power production, displacing the power provided by the utility grid. At 40 s, once net power across the incoming utility meter is zero and local load is being met by local generation, the microgrid disconnects from the utility grid. Because power from the utility grid was previously ramped down and loads were being met locally before the transition, the transition results in relatively minor voltage and frequency deviations, and all assets remain online. Wind and diesel are given manual ramp commands in this model. This could be automated by incorporating a microgrid controller into the system.

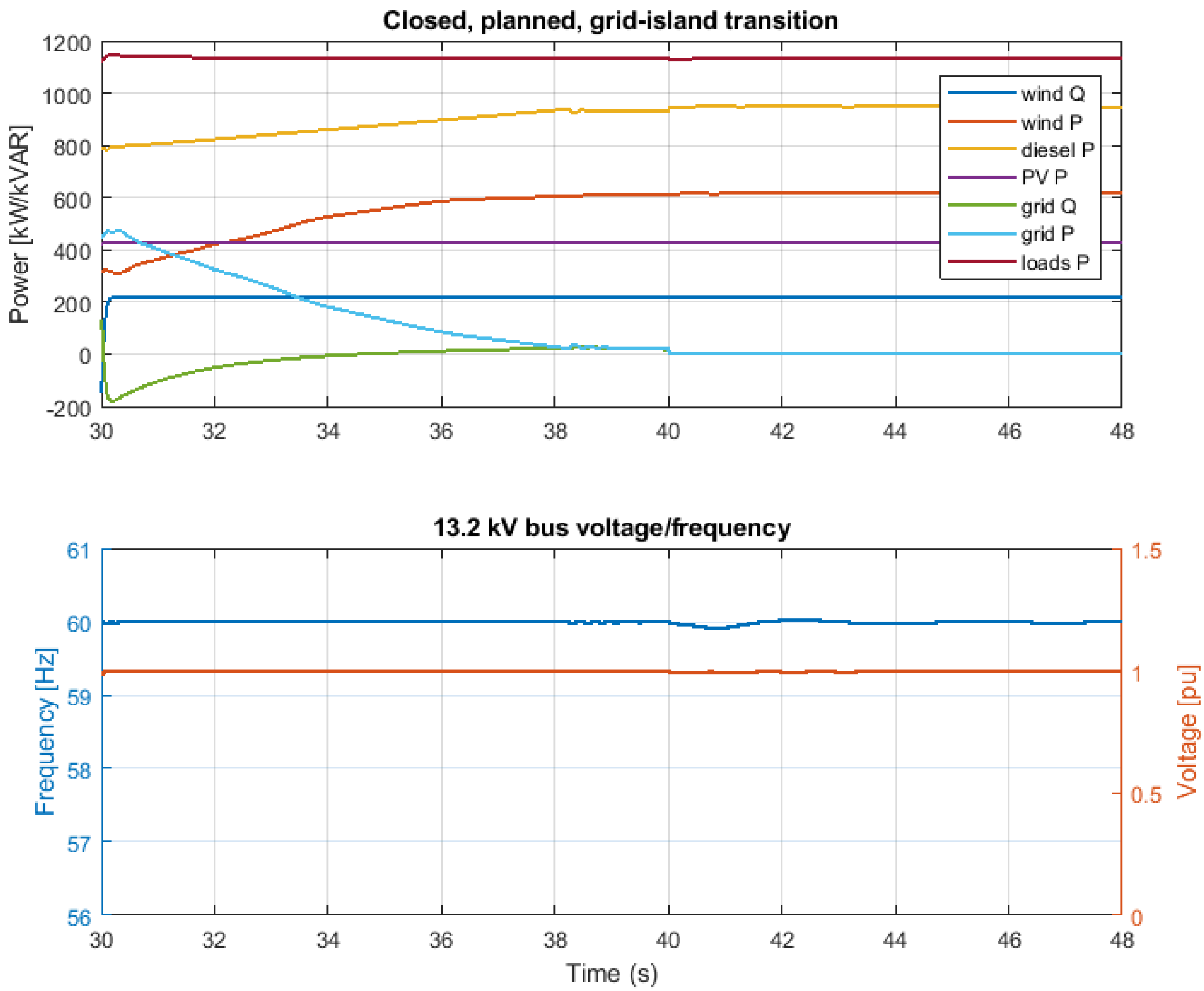


Figure 10. Local wind and diesel ramp up to displace power provided by the utility grid to allow a seamless disconnection. (P = real power; Q = reactive power)

4.1.2 Closed Unplanned Transitions

During an unplanned transition, the microgrid disconnects from the utility grid without warning. This abrupt change will cause significant voltage and frequency deviations. To maintain a closed transition, these deviations must be small enough for local generation and critical loads to remain online and sufficient local generation must be online already. Otherwise, a blackout will occur. Deferable loads, which have more stringent frequency thresholds than critical loads and generators, may trip offline. The system operator or transmission organization sets the trip thresholds, so they will vary depending on the location of the system. In this model, the deferrable load under/overfrequency thresholds are set to 58/61.8 Hz (North American Electric Reliability Corporation n.d.), and the critical load thresholds are set to 57/63 Hz. If generators begin to trip offline, a cascading frequency dip will occur, likely resulting in all assets tripping offline and a blackout occurring. Not only can Types 3 and 4 wind generators ride through short-duration closed transitions, but they can also support microgrid voltage and frequency to prevent tripping during transitions. Trip thresholds for DERs are defined in the IEEE 1547-2018 standard. The wind turbine's frequency zones are shown in Figure 11, taken from IEEE 1547-

2018 (IEEE 2018). For this report, the default frequency trip thresholds of 56.5 Hz and 61.8 Hz are used. For more information on wind operating in the IEEE zones, refer to Part 3 of this report series (Anderson, Poudel, Rane, et al. 2022). Because this microgrid model tends to experience frequency deviations relatively larger than voltage deviations, frequency will be the focus here.

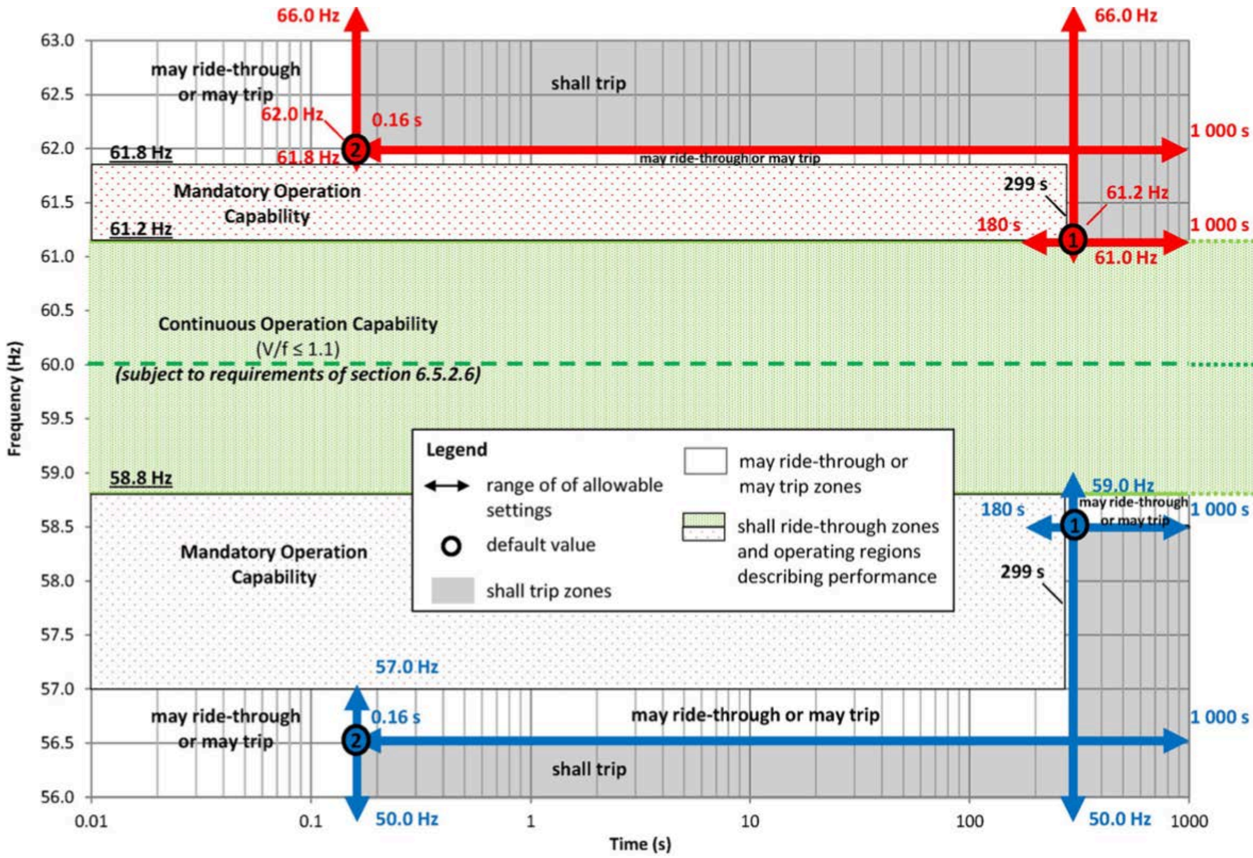


Figure 11. Frequency ride-through and response requirements for distributed energy resources. Image from (IEEE 2018, Figure H.10)

Two closed unplanned transition scenarios, shown in Figure 12, are modeled to demonstrate the support that wind can provide. In these scenarios, energy storage is not used; the generating assets are a diesel generator, wind, and solar PV.

In the first scenario of Figure 12, wind power rides through the transition at 10 s. The frequency deviation is large enough to cause the 240-kW deferable load to trip offline momentarily at 10.5 s, before the diesel generator ramps up sufficiently to raise the frequency and the load comes back online. In the second scenario, wind power provides inertial response during the transition: the rotor is decelerated to inject extra power into the microgrid, which counteracts the frequency dip, elevating the frequency enough to prevent the deferable loads from tripping. However, there is a second, smaller frequency oscillation that occurs when the wind turbine drops its power output to reaccelerate after decelerating its rotor, which begins around 14 s. In this system, the frequency nadir occurs within half a second of the utility grid disconnection. The wind turbine's inertial response takes about 1 s to ramp up, so its effects on the frequency nadir are small. In a system with a larger delay between the disconnection and the frequency nadir, the inertial response would have a much larger effect. In both cases the diesel generator, which tracks a reference microgrid frequency, responds in a matter of milliseconds to the frequency dip upon disconnection at 10 s. This rapid response is in line with the simulation and experimental validation results for an induction generator from Ion and Serban (2019).

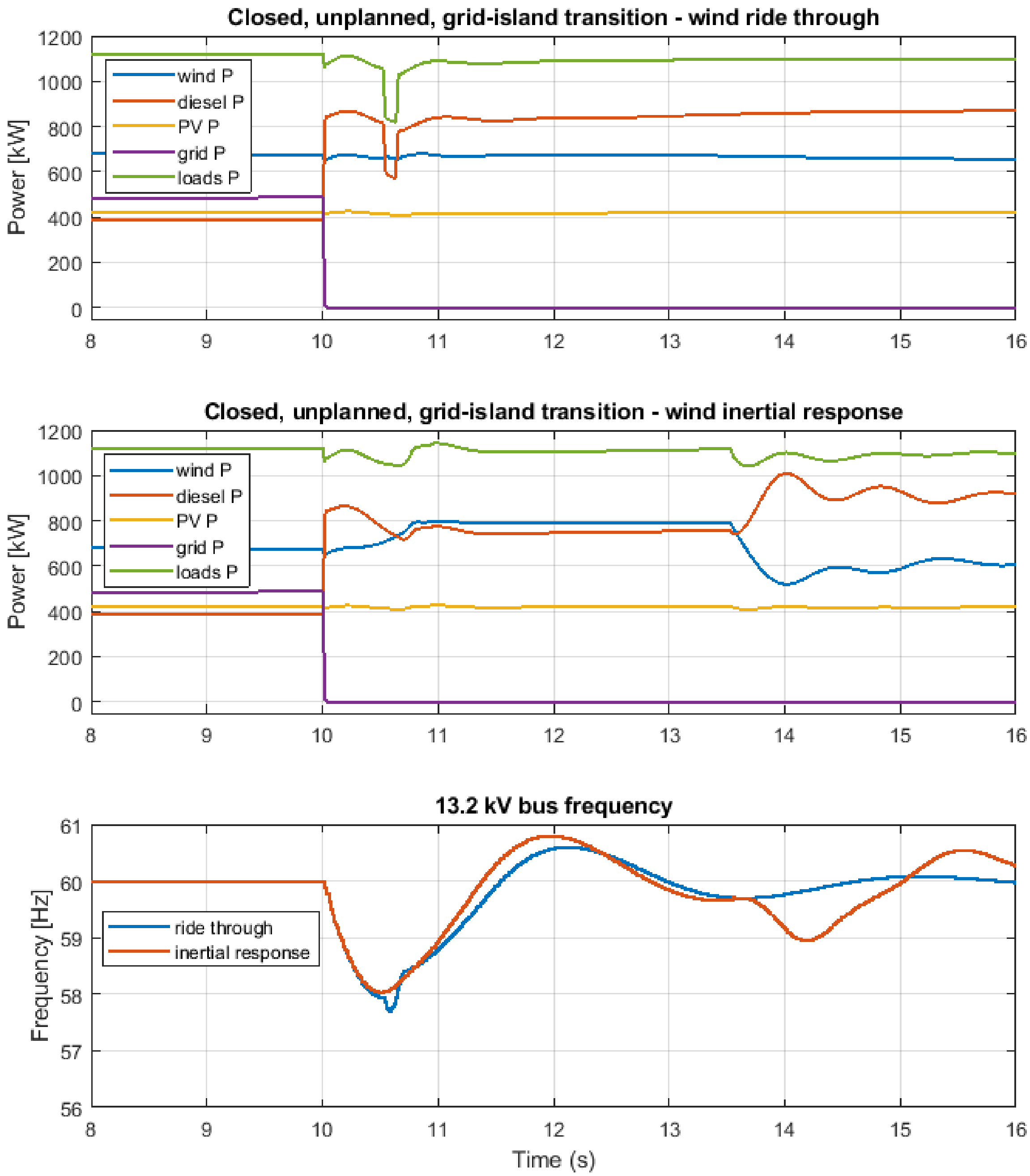


Figure 12. When wind power provides inertial response during an unplanned transition, it elevates the frequency nadir enough to prevent deferable loads from tripping offline

4.1.3 Open Transitions

If the frequency and voltage deviations are significant enough to cause all assets to trip offline during a transition, the microgrid will experience a short-duration outage. This is called an open transition, which depends on the local generation and storage assets present and their initial conditions. Future modeling efforts may include a study that examines the tipping point between closed and open transitions in terms of the types and sizes of the local generation and storage assets and their initial conditions. An open transition may be deliberately done if the local generators do not have the ability to ramp sufficiently to maintain a stable microgrid during a transition. After the outage, the grid-forming assets will black-start the microgrid and bring other generators and loads back online in a balanced way to prevent significant fluctuations in voltage and frequency. Traditionally, the wind turbine would trip offline and shut down when the blackout occurred, and later reconnect after the microgrid was black started and stable. In this case, the wind turbine would remain disconnected from the microgrid for a significant period, typically a few minutes, as it went through its shutdown and startup sequence.

A wind turbine equipped with momentary cessation capability per IEEE 1547-2018 (via UL 1741 SA or SB) can provide more support to the microgrid during black start: Instead of tripping off completely, the wind turbine stays spinning and electrically connected to the microgrid during a very short outage but provides near-zero real power. This maintained connection allows the wind turbine to quickly ramp its power output back up once the microgrid is formed by the grid-forming assets, in about 1 s. IEEE 1547-2018 requires a 1-s momentary cessation duration, but the wind turbine here is capable of longer-duration cessations.

In the open transition scenarios, illustrated in Figure 13, the microgrid uses a BESS, wind, diesel, and solar PV. All except for the diesel are initially connected. When the microgrid disconnects from the utility grid at 3 s, microgrid voltage drops precipitously, causing the wind turbine to enter momentary cessation. The BESS is disconnected during the transition for demonstration purposes (if connected, it would prevent an open transition). As the microgrid frequency falls, deferable loads trip off at 5 s, and critical loads trip off at 6 s. Soon after, the grid-forming BESS is reconnected and black-starts the microgrid, allowing the solar PV, wind turbine, and diesel generator to produce power. The BESS can form the microgrid but cannot produce enough power to support the loads, so other generation is required to bring the loads back online. The rapid ramping up of the wind turbine supports the recovery of voltage and frequency during black start and shortens the duration of the loads being offline. It reduces the amount of power that the battery needs to deliver (which could be a constraint in the event of a small battery or a battery with a low state of charge) and reduces the amount of time needed for the diesel to synchronize with the microgrid and come back online, from ~2 s to ~0.5 s. Without wind, the diesel generator takes longer to match the microgrid's frequency and phase. We note that the solar PV absorbs power during the blackout. This is an artifact of the model, which experiences small amounts of current flowing through the microgrid during blackout. Keeping the PV connected is required to keep the model stable during blackout. In a real system, the PV array would trip offline and would neither absorb nor produce power. Grid-forming inverters like that used by the BESS may have harmonics issues during open transitions, creating voltage waves outside of IEEE 1547-2018 limits. Such high-frequency harmonics were not considered in this report but warrant future research with high-fidelity models.

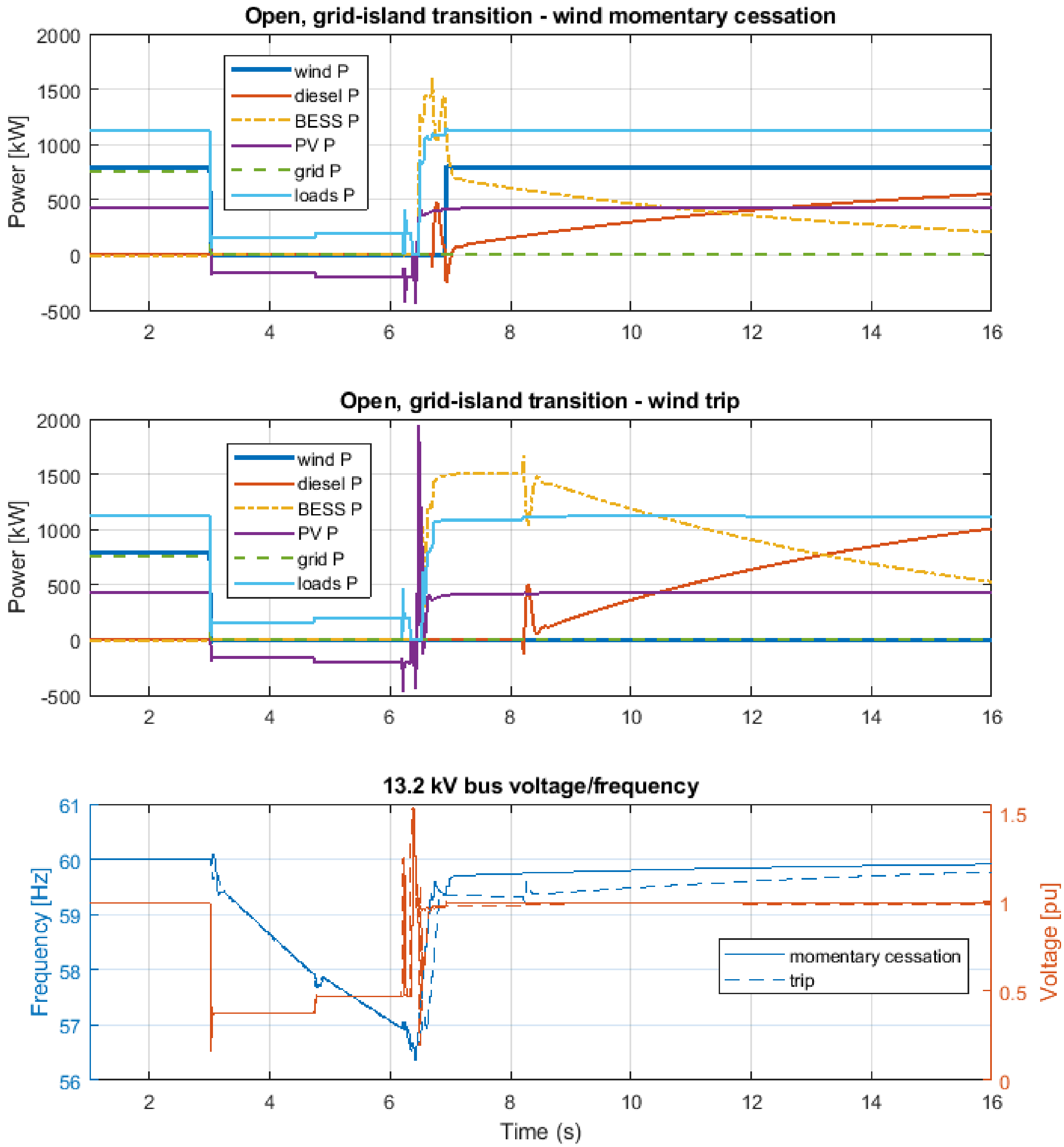


Figure 13. When wind performs momentary cessation during a blackout, it supports microgrid recovery: elevating frequency, reducing battery discharge, speeding diesel generator synchronization, and reducing load loss

If equipped with a grid-forming inverter and depending on the current wind resource, a distributed wind turbine could black-start the microgrid, as the BESS does with its grid-forming inverter in this scenario. Siemens Gamesa has developed black-start technology for its utility-scale wind turbines (Siemens Gamesa 2021). At the distributed wind/microgrid scale, this is a topic for future research, as the wind turbine's grid side converter in this model is not grid forming.

4.1.4 Closed Transitions: Return to Grid-Connected Mode

The transition from island mode to grid-connected mode may be open closed, depending on the configuration of microgrid assets and the inclusion of a protection system that can synchronize microgrid generation sources with the utility.

In an open transition from island mode back to grid-connected mode, all generation and loads would be turned off, the utility grid switch would be closed, and load and generation would come online as the utility grid reenergized the microgrid. Although undesirable, this method does not require an expensive synchronizing switchgear configuration.

A closed, planned transition returning to grid-connected mode would have a reverse process relative to the closed, planned transition from grid-connected to island mode discussed in Section 4.1.1. The first step would be for the two sources, local generation within the microgrid and the external utility grid, to be synchronized across the point of common coupling. Once these sources are synchronized, the second step would be for the point-of-common-coupling isolation device to close, connecting the two formerly separate power systems. The third step would be to reduce the local microgrid generation, as the local loads are increasingly served by the external grid. The voltage and frequency deviations during this transition would likely be minimal, but the wind turbine can still dampen any deviations that do occur, if the turbine is configured to do so. Two return-to-grid scenarios are simulated in Figure 14 to demonstrate the benefit of wind supporting microgrid voltage during a closed, unplanned transition from island to grid-connected mode. In these scenarios, the generating assets are wind, solar PV, and diesel, and there is no BESS.

In the first scenario in Figure 14, the wind turbine just rides through the transition and does not provide support. There is a momentary voltage dip to 0.8 pu at 10 s when the microgrid synchronizes and connects to the utility grid. In the second scenario, the wind turbine responds to this voltage dip by injecting more reactive power into the system, elevating the voltage dip to about 0.85 pu. The voltage dip occurs so quickly and is so brief (milliseconds) that the wind cannot respond quickly enough to have a larger effect. In both cases, voltage fluctuations are very small when the diesel disconnects at 13 s, as the utility grid ramps up almost instantaneously to displace its generation. Frequency fluctuations are very small in both cases, so are not shown.

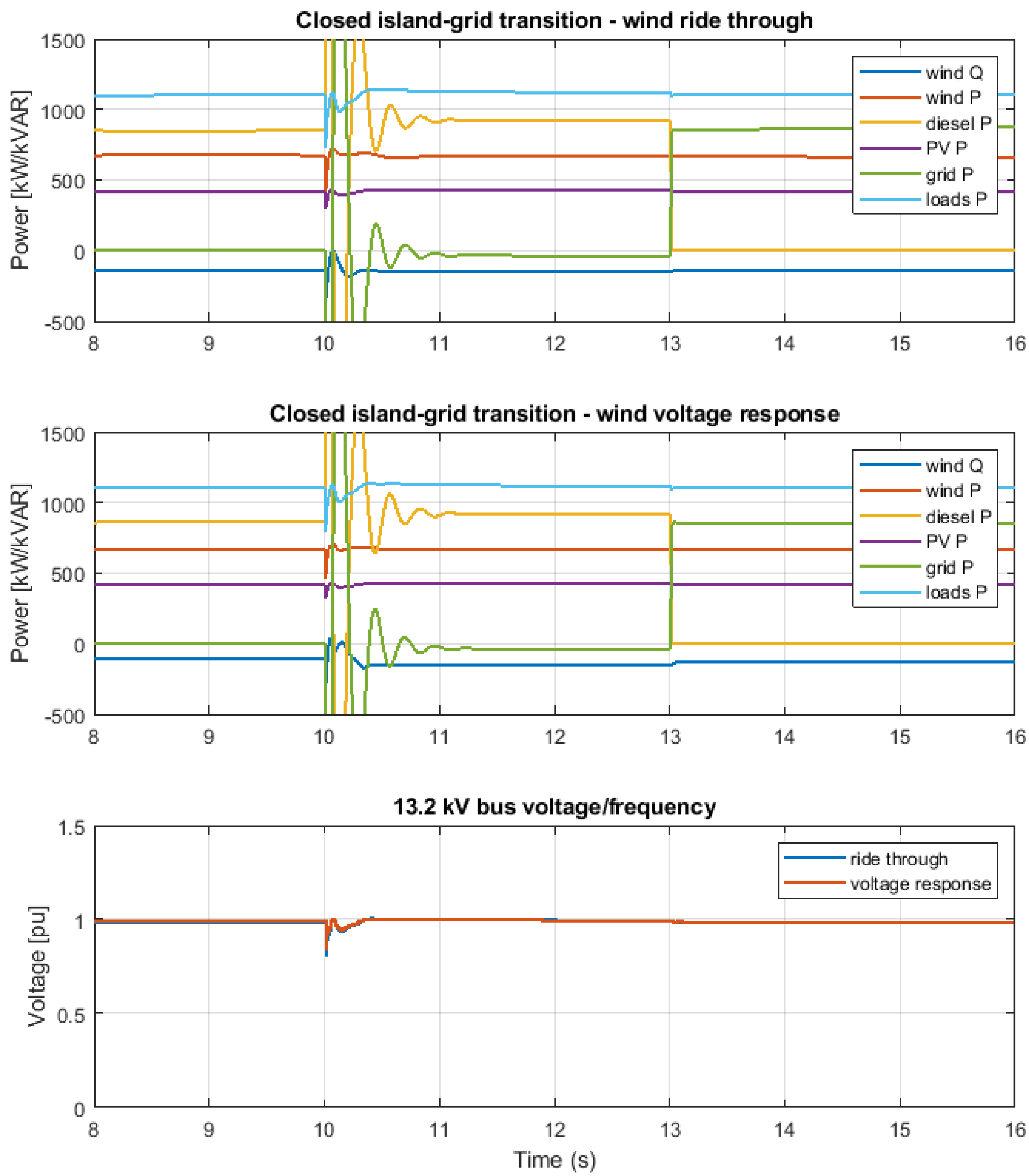


Figure 14. The wind turbine can inject reactive power to support voltage during an island-to-grid-connected transition (P = real power; Q = reactive power)

5 Conclusion

Distributed wind turbines can provide a host of benefits to a microgrid. When in island mode, wind turbines can support resilience by providing redundancy and complementarity with other renewable generation. This can increase total renewable output, decrease dependence on fuel supply chains, and decrease the required amount of local energy storage. Wind turbines can also provide the islanded microgrid with fast voltage and frequency response. When in grid-connected mode, wind turbines can provide regulation services as well. Wind turbines can further support transitions between modes: in a closed, planned transition, wind turbines can ramp up real and reactive power to displace the power that the utility grid is providing locally so that the transition occurs seamlessly. In a closed, unplanned transition, wind turbines can ride through voltage and frequency fluctuations and help reduce them, preventing deferable loads from tripping offline. In an open transition, wind turbines can ride through brief blackouts using their momentary cessation capability, which allows them to support microgrid black start and bring loads and generation back online faster. If equipped with a grid-forming inverter and the correct controls, wind turbines have the potential to perform black start themselves; this technology is under development. There are several topics for future research: (1) examining the tipping point between closed and open transitions, in terms of the types and sizes of the local generation and storage assets, and their initial conditions; (2) modeling a distributed wind turbine with black-start capability in an open transition scenario, and considering any harmonic issues caused by grid-forming inverters during black start; (3) automating microgrid control functionalities and dispatch, including switching, ramping for transitions, and integrated forecasting; and (4) validating the microgrid model with a hardware-in-the-loop system.

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