Advanced Distributed Wind Turbine Controls Series: Part 3–Wind Energy in Grid-Connected Deployments

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

Benjamin Anderson, Ram Poudel, Jayaraj Rane,
and Jim Reilly

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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List of Abbreviations and Acronyms

ANSI	American National Standards Institute
CART	Controls Advanced Research Turbine
DER	distributed energy resource
Hz	hertz
IEEE	Institute of Electrical and Electronics Engineers
kV	kilovolt
kW	kilowatt
MIRACL	Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad
ms	millisecond
NREL	National Renewable Energy Laboratory
PFR	primary frequency response
pu	per unit of the baseline value
s	second
V	volt

Executive Summary

As the share of generation from variable renewable resources on the grid increases, it becomes increasingly important for them to provide ancillary services to support grid stability, because of both the variable nature of renewables and the lower fraction of traditional, dispatchable generators. In recent years there has been an increase in both the technical ability of and requirement for distributed energy resources to provide ancillary services beyond maximum energy production. Large wind turbines have been shown capable of providing grid services. Conceptually, smaller wind turbines in distributed settings have been shown capable of providing these services. As part of the Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project, we take this a step further by using desktop simulations to demonstrate the use of advanced distributed wind turbine controls to provide ancillary services, supporting grid reliability and resilience. The next steps would be to demonstrate these capabilities with hardware-in-the-loop experiments and finally with operating systems.

Using a stand-alone model of the 600-kilowatt Controls Advanced Research Turbine connected to the National Renewable Energy Laboratory's Flatirons Campus grid, we establish that the wind turbine model exceeds fault ride-through performance requirements stipulated in the Institute of Electrical and Electronics Engineers (IEEE) standard 1547-2018 regarding interconnection and interoperability of distributed energy resources. One of the test cases under study is a Category III voltage fault defined in IEEE 1547-2018 and derived from California Rule 21. Some distributed wind turbines were unable to connect to the grid following the Rule 21 enforcement in California because they lacked advanced controls. Even if similar requirements are not enforced elsewhere, grid codes will likely evolve in this direction. We also demonstrate that the wind turbine is capable of tracking external power commands that utility grids use to maintain grid stability and that local smart metering systems use to maintain a power balance in behind-the-meter applications. This study illustrates how distributed wind turbines can provide services that enable a pathway toward a higher contribution of renewable energy in a grid-connected context.

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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, Poudel, et al. 2021) documents a literature review of real and reactive control capabilities of different distributed energy resources (DERs) and develops a road map for the application of such control technologies for distributed wind turbines. The road map envisions the development of advanced controls for distributed wind turbines in four use cases, as defined by the multilaboratory MIRACL team (Reilly, Gentle, et al. 2021): (1) isolated grids, (2) microgrids, (3) behind-the-meter wind turbine deployments, and (4) front-of-the-meter wind turbine deployments. Part 1 of the MIRACL Advanced Distributed Wind Turbine Controls Series—Flatirons Campus Model Overview—provides details for the MATLAB Simulink models that simulate the research wind turbine and various subsystems at the National Renewable Energy Laboratory (NREL) Flatirons Campus (Anderson, Poudel, Reilly et al. Forthcoming). Part 2 of the series focuses on isolated grid deployments (Anderson, Poudel, Krishnan et al. 2022), and Part 4 focuses on microgrid deployments (Anderson, Rane, et al. 2022). This report is Part 3 of the series and focuses on the application of advanced wind turbine controls for the last two use cases, which are grid-connected. We demonstrate a set of advanced controls that have been developed and validated to provide grid support services stipulated in industry electric grid standards.

Some manufacturers and providers of distributed wind turbines have reported concerns over not being able to connect to certain high-renewable-contribution utility grids, such as the Southern California Edison market, because of evolving grid standards (Guasti Solar 2021). California Rule 21 (known as CA Rule 21)—especially the fault ride-through capability requirement—is a challenge for some original equipment manufacturers of small-scale distributed wind turbines that typically have a rated power of less than 500 kilowatts (kW) (California Public Utilities Commission n.d.). Distributed wind turbines of all size classes are increasingly required to deliver the full integration and interoperability functionalities of utility-scale wind turbines (IEEE 2018). Also, tax incentives and rebates for DER deployment are gradually tapering in many markets, so alternative revenue sources would greatly benefit DERs.

Section 2 of this report describes the behind-the-meter and front-of-the-meter wind turbine deployments and introduces the NREL Flatirons Campus and its various DER assets configured in grid-connected mode. Section 3 describes the grid services a distributed wind turbine can provide to support grid stability, along with fault ride-through requirements. Section 4 demonstrates, through simulation, how a distributed wind turbine can provide these services.

2 Grid-Connected Wind Turbine Deployments

2.1 Wind Turbine Deployment Configuration

In a grid-connected system the wind turbine can be connected in one of two configurations: front of the meter or behind the meter. Figure 1 presents a sketch of these two configurations. The following subsection illustrates the two configurations of a grid-connected wind turbine system and the value that each configuration adds to the distribution system and the owner/customer.

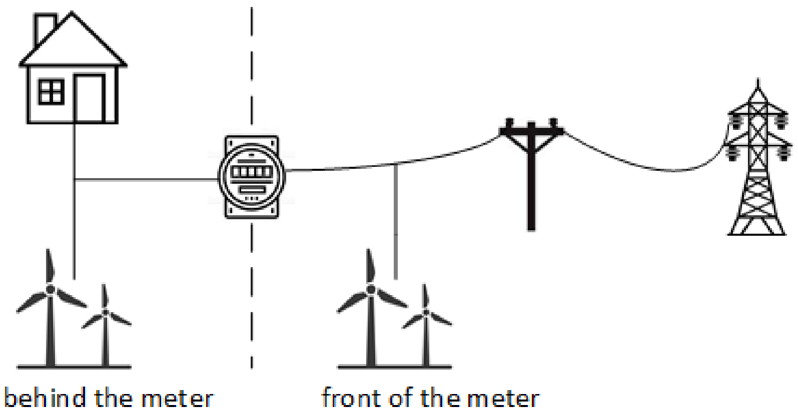

Figure 1. Wind turbine connected to the distribution system in front-of-the-meter and behind-the-meter configurations

2.1.1 Behind the Meter

Behind-the-meter distributed wind systems capable of many gigawatts are expected to be installed by 2050 (Lantz et al. 2016). In a behind-the-meter configuration, the wind turbine resides on the customer side of the utility meter and is typically owned by the customer. It is used to offset load behind the customer's meter and can provide active and reactive power support locally. Value from a behind-the-meter system largely comes from serving the local loads and can be supplemented by the provision of grid services. Although not the focus of this work, systems that combine active load control, other DERs, and storage would be better equipped to provide grid services and limit demand charges to the customer.

2.1.2 Front of the Meter

In a front-of-the-meter configuration, the wind turbine is deployed on the utility side of the meter and is typically owned by an electric utility, electric cooperative, or a power producer. In a front-of-the-meter configuration, the focus of the wind turbine control is more on the reliability and resilience of the larger power system. A front-of-the-meter wind turbine may be connected to the area electric power system at typical primary or secondary distribution voltages. Depending on the voltage it connects to, the wind turbine can have varying impact on the local or regional grid. In this configuration and especially when combined with storage, a wind turbine can help support a weak grid or a grid toward the end of the distribution line, where voltage and frequency are very sensitive to changes in load. Value from a front-of-the-meter system largely comes from the sale of wholesale power and grid services.

Table 1. Common Grid Services

Scenario	Common Grid Services	Grid-Connected Wind Turbine	
		Front of the meter	Behind the meter
1	Fault Ride-Through	√	√
2	Voltage Support	√	√
3	Frequency Support	√	
3.1	Arrest Frequency Decline (Inertial Response)	√	
3.2	Stabilize Frequency (Primary Frequency Response)	√	
3.3	Restore Frequency (Contingency Reserves)	√	
3.4	Frequency Regulation (Regulation Reserves)	√	
3.5	Dispatchability/Flexibility (Ramping Reserves)	√	
4	Emergency Support (Black Start)		√

Table 1 illustrates common grid services (Driscoll 2019) that a wind turbine can provide and notes their relevance for front-of-the-meter and behind-the-meter configurations. A wind turbine can help arrest frequency decline by using its rotor inertia. Primary frequency response helps stabilize the frequency, and secondary frequency response helps restore the frequency in general. Emergency support services from a wind turbine may make more economic sense in the behind-the-meter configuration. The Pacific Northwest National Laboratory, a member of the MIRACL team, is investigating the valuation aspect of advanced controls for various grid connection configurations.

2.2 MIRACL Flatirons Campus Desktop Simulations

2.2.1 Grid-Connected Wind Turbine Model

There are five main types of wind turbine electrical configurations, referred to as Type 1 through Type 5 (Camm et al. 2009). Here, our focus is on the inverter-based control functionality of a wind turbine specific to the Types 3 through 5 configurations, which have the most flexible power output and are the most common for modern distributed wind turbines. We use a model of a Type 4 wind turbine that employs a full-sized power converter, which is most capable of providing grid services (Anderson, Poudel, Reilly, et al. 2022).

We model NREL's Controls Advanced Research Turbine (CART) for this study (Fingersh and Johnson 2002). The 600-kW, Type 4 CART generates power at 575 volts (V) and is located at NREL's Flatirons Campus (NREL n.d.), a microgrid that virtually always operates in a grid-connected model. The power generated is connected to the 13.2-kilovolt (kV) Xcel Energy bus using a step-up transformer. The Flatirons Campus is connected to the Xcel Energy Eldorado substation by a 13.2-kV tie-line. The stand-alone grid-connected CART Simulink model is presented in Figure 2, which captures this physical reality. We omit the other assets at the Flatirons Campus for this study to focus on the utility grid–wind turbine connection.

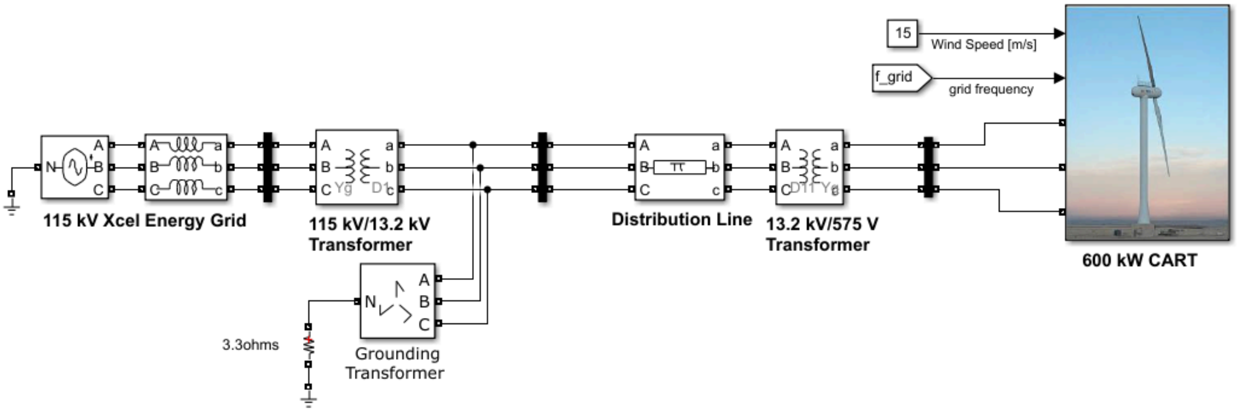

Figure 2. Simulink model of the Controls Advanced Research Turbine (CART) connected to the Xcel Energy 13.2-kV bus

Pitch-regulated wind turbines like the CART control their apparent power by controlling blade pitch and generator torque. Because the CART is a Type 4 machine, it also controls the real and reactive power of its inverter through power-electronics-based vector current control real power can only be generated, not absorbed, but reactive power can be both generated and absorbed. The amount of real or reactive power modulation depends on the size of the grid-side inverter and whether real or reactive power is prioritized. For example, if the CART is in real power priority mode, then real 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 allow maximal reactive power modulation for voltage stability. The CART can provide reactive power support even when the rotor is not spinning, such as when the wind is below the cut-in speed. The CART can also be set to run at a certain power factor (for example, at 0.9 or 0.95 leading or lagging), thereby delivering some reactive power while operating.

3 Ancillary Service Opportunities for Grid-Connected Distributed Wind Turbines

3.1 Ancillary Services Required by the Grid

A grid operator must balance demand and supply to maintain grid parameters such as frequency and voltage at their nominal values, which requires ancillary services. The mass inclusion of variable renewable resources heightens this requirement. Examples found in literature often use "ancillary service" and "essential reliability service" interchangeably. The time scales of ancillary services may vary from milliseconds (ms) to hours and beyond. Figure 3 illustrates time scales of the main grid services procured in the U.S. power system (Denholm, Sun, and Mai 2019), overlaid with the services that distributed wind can provide to fulfill these needs. Inertial response and primary frequency response (PFR) cover "Frequency Responsive Reserves"; real power command tracking covers "Regulation Reserves," "Contingency Reserves," and "Ramping Reserves"; voltage response and reactive power command tracking cover "Voltage Support"; and wind turbine "Black-Start Capability" is currently under development. The following subsections describe how distributed wind can provide these services.

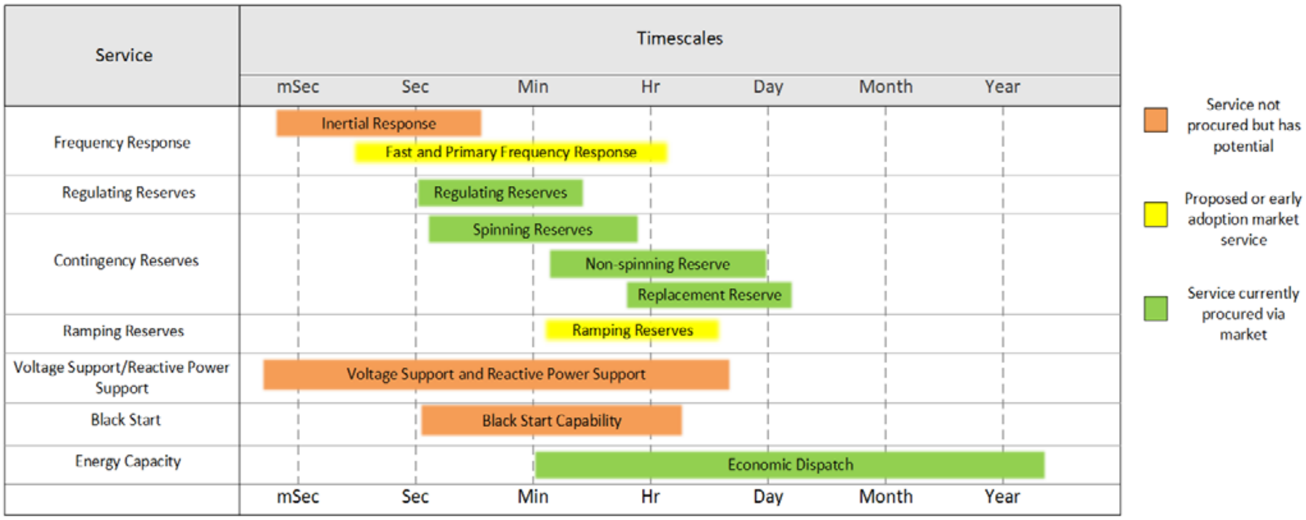

Figure 3. Main services procured in the U.S. power system and their time scales. ***Figure from Denholm, Sun, and Mai (2019)***

The rise of wind energy in the power generation mix suggests that wind turbines may be increasingly required to provide these grid services at the distribution-grid level. In fact, standards already require certain categories of DERs to provide PFR, voltage response, and fault ride-through capabilities. Institute of Electrical and Electronics Engineers (IEEE) standard 1547-2018 presents two categories of DERs based on area electric power system performance expectations. Category A includes the minimum requirements for DERs with a power output not subject to frequent large variations. Category B requires supplementary capabilities where the DER penetration is higher or where the DER power output is subject to frequent large variations. For area electric power system fault ride-through requirements, IEEE 1547-2018 presents three categories of DERs (separate from the prior categories A and B). Category I and Category II require the DER to ride through two momentary drops in voltage spaced 20 seconds (s) and 10 s apart, respectively. Category III requires ride-through capability for three sets of disturbances at consecutive fault events occurring 5 s apart. Category III is the most advanced, as it is "based on both bulk power system stability/reliability and distribution system reliability/power quality needs and is coordinated with existing interconnection requirements for very high DER penetration" (IEEE 2018). Category III also encompasses all the capabilities of Categories I and II. Our wind turbine models adhere to the advanced categories B and III. Figure 4 presents a sequence of voltage faults a Category III DER should be able to ride through according to IEEE 1547-2018. In addition to grid faults, a wind turbine must be able to handle internal faults while maintaining maximum power production and reducing the risk of turbine shutdown or damage (Anderson, Rane, et al. 2022).

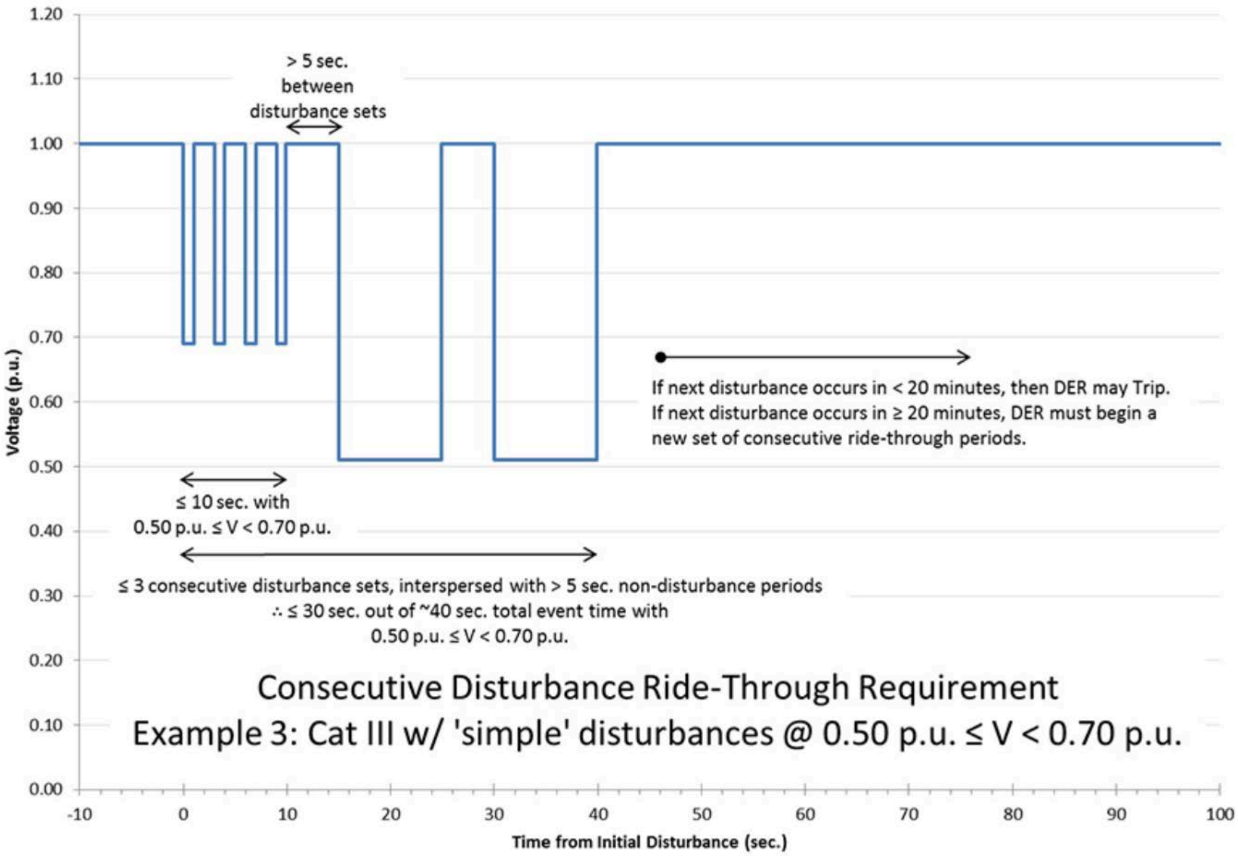

Figure 4. Voltage ride-through requirement for a Category III DER (p.u. = per unit of the baseline value). ***Figure from IEEE 1547-2018 (IEEE 2018, Figure E.3)***

3.2 Frequency Support

A distributed wind turbine can provide the frequency support discussed in the following subsections. Inertial response and PFR are the first line of defense to frequency deviations and are calculated internally by the wind turbine's controller. The other reserve commands are calculated by the grid and sent to the wind turbine as real power commands.

3.2.1 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 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-interfaced 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. We use advanced controls to momentarily increase generator electrical torque, 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.

3.2.2 Primary Frequency Response and Fault Ride-Through: IEEE 1547-2018 Requirements

IEEE 1547-2018 provides requirements for PFR and fault ride-through. Per IEEE 1547-2018, a wind turbine must provide PFR to support the grid during faults using droop control; depending on the magnitude and length of the frequency event, there are four regions. Figure 5 outlines these regions in a frequency–time plot, and we demonstrate operation in each:

1. Continuous operation: provide droop control outside of the deadband, indefinitely
2. Mandatory operation: provide droop control for a time
3. May ride through or may trip
4. Shall trip.

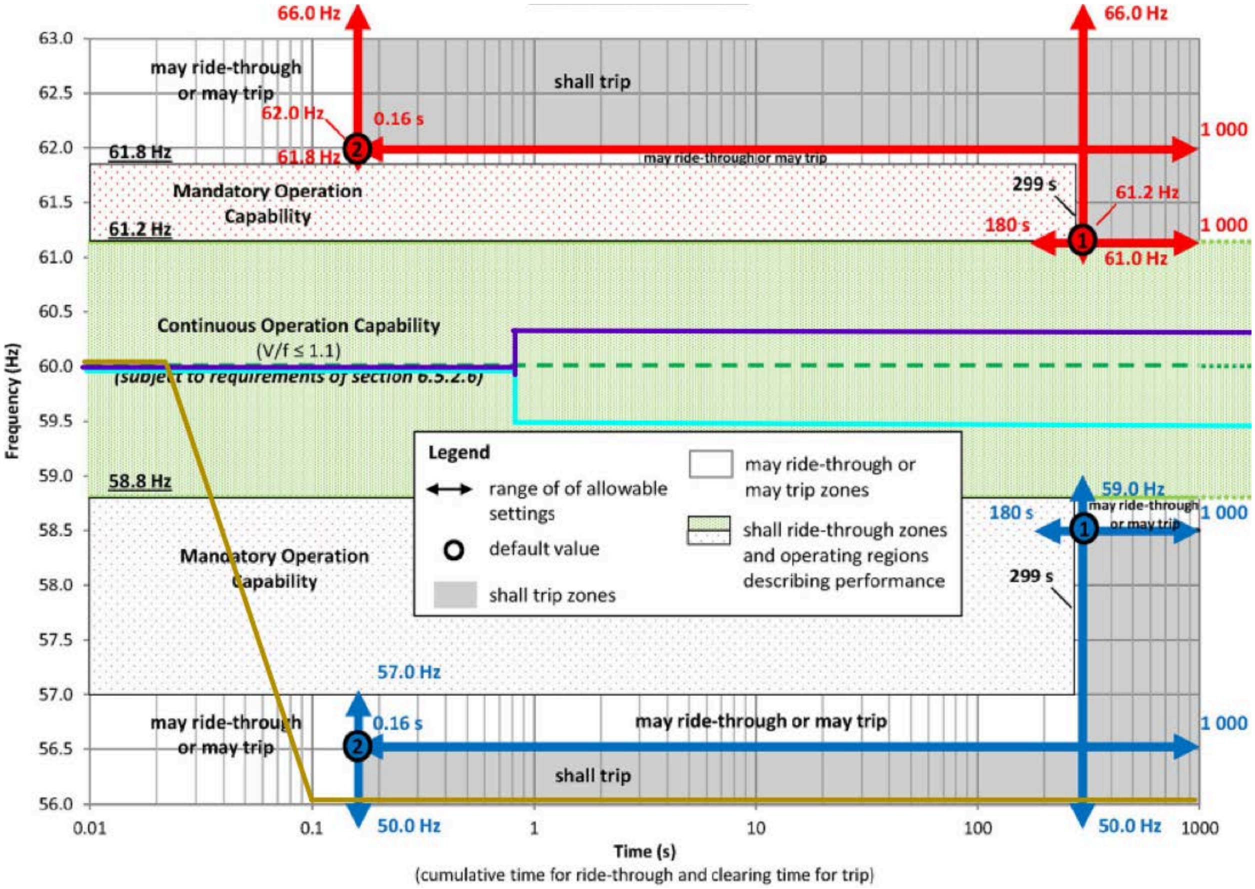

Figure 5. DER response to abnormal frequencies and frequency ride-through requirements for a DER. ***Figure from IEEE 1547-2018 (IEEE 2018, Figure H.10)***

Our first fault ride-through demonstration case is a small frequency-deviation response, our second is a large frequency-deviation response, and our third is response to a frequency ramp which leads to trip. There are three lines overlaid in Figure 5 that correspond to the frequency fault cases displayed in Section 4.1.2. The purple line belongs to Case 1, the cyan line to Case 2, and the dark yellow line to Case 3. We use the deadband and droop parameters to reflect the requirements in IEEE 1547-2018: 0.036-hertz (Hz) deadband, 5% droop, and 5-s settling time to reach within 10% of the steady-state frequency value.

3.2.3 Real Power Command Tracking

A wind turbine can participate in a variety of reserves to support grid frequency. Ramping reserves are economically dispatched to meet the load forecast, but there will always be a mismatch between forecasted and actual loads. The difference between actual load and the ramping component is handled by regulation reserves. Figure 6 shows the morning ramp-up decomposed into total load, ramping, and regulation (Kirby 2005). Ramping and regulation ensure that, under normal operating conditions, a control area accurately balances generation with load. The grid operator converts the area control error to automatic generation control commands and divides it among the generators participating in the regulation market. A generator participating in the regulation market should be able to quickly increase or decrease its power output; typical regulation response times are on the order of seconds to a few minutes.

Regulation is a net-zero-energy service from the operator's perspective, matching generator and supply in real time and maintaining frequency at the nominal value. Contingency reserves restore system frequency immediately after an event. They can be spinning, (typically begin producing within seconds, ramp up to full response within ~10 minutes, and stay there for ~60 minutes) or nonspinning (typically begin producing within ~10 minutes and provide energy for hours). Wind can ramp up quickly enough to provide all of these services but is most suitable for regulation because (1) regulation is usually the most lucrative service and (2) resource variability hampers wind's ability to provide a set amount of power over longer time scales.

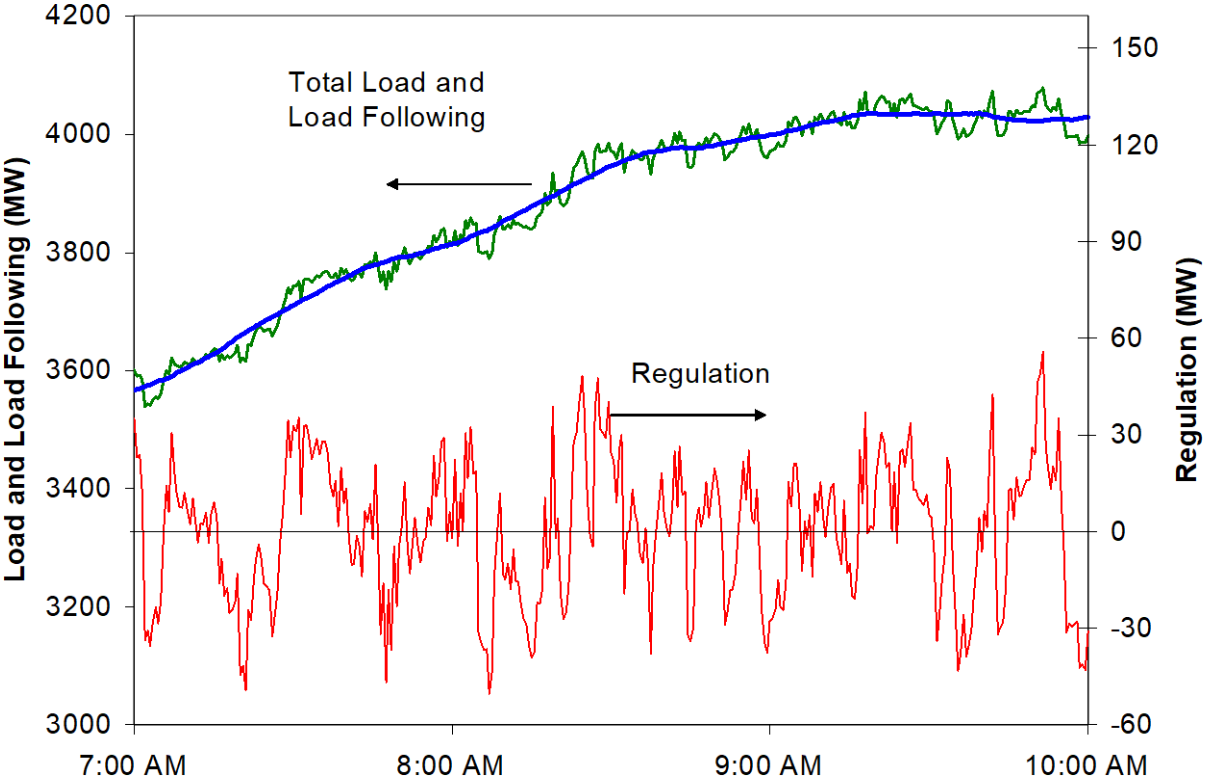

Figure 6. Frequency support services: ramping and regulation. Regulation (red) supplies the difference between total load (green) and ramping (blue). ***Figure from Kirby (2005)***

A study of a single Type 4 wind turbine providing regulation services in a front-of-the-meter, grid-connected deployment was conducted in Regina, Saskatchewan, Canada (Rebello, Watson, and Rodgers 2020). This wind turbine operated with 10% headroom for regulation. The regulation command was processed by the LabView software and fed to the wind turbine controller through the Modbus communication protocol. The Saskatchewan study illustrated that a single wind turbine can provide regulation. The study also presented a financial analysis and found that annual income when providing regulation is greater than the income from providing bulk energy alone. The findings indicated that despite the project-specific limitations of the work, there is potential for even a single wind turbine to participate profitably in frequency regulation. However, this assertion is specific to the control methodology, and assumptions may not hold true for all distributed wind turbines.

3.3 Voltage Support

A distributed wind turbine can provide voltage support either with internal droop control (which we refer to as voltage response) or in response to external reactive power commands from the grid. Unlike frequency, voltage varies locally, so voltage support capability may be required in each distribution feeder.

3.3.1 Voltage and Fault Ride-Through: IEEE 1547-2018 Requirements

A voltage fault occurs when the voltage swings outside a specified range (1 ± 0.02 per unit of the baseline value [pu], per IEEE 1547-2018). Figure 7, reprinted from IEEE 1547-2018, presents performance expectations for a Category III DER. Our first fault ride-through demonstration case is of voltage response and tripping, corresponding to the purple line in Figure 7. Our second case is of momentary cessation, corresponding to the cyan line. Our third case is of fault ride-through, specified in Figure 4. Depending on the magnitude and length of the voltage event, the voltage trajectory may span various regions. The American National Standards Institute (ANSI) standards suggests a nominal 60 Hz frequency, like the IEEE 1547-2018 standard, but the voltage operation region allows a deviation of 5%. The IEEE 1547-2018 operation region is much narrower for increased safety and requires more control. The five voltage regions defined in the IEEE 1547-2018 standard are listed as follows and are marked in Figure 6:

1. Continuous operation: droop control outside of the deadband, indefinite operation
2. Mandatory operation: must operate at nominal power for required time
3. Momentary cessation: must disconnect momentarily, with the ability to reconnect quickly upon voltage recovery
4. May ride through or may trip
5. Shall trip.

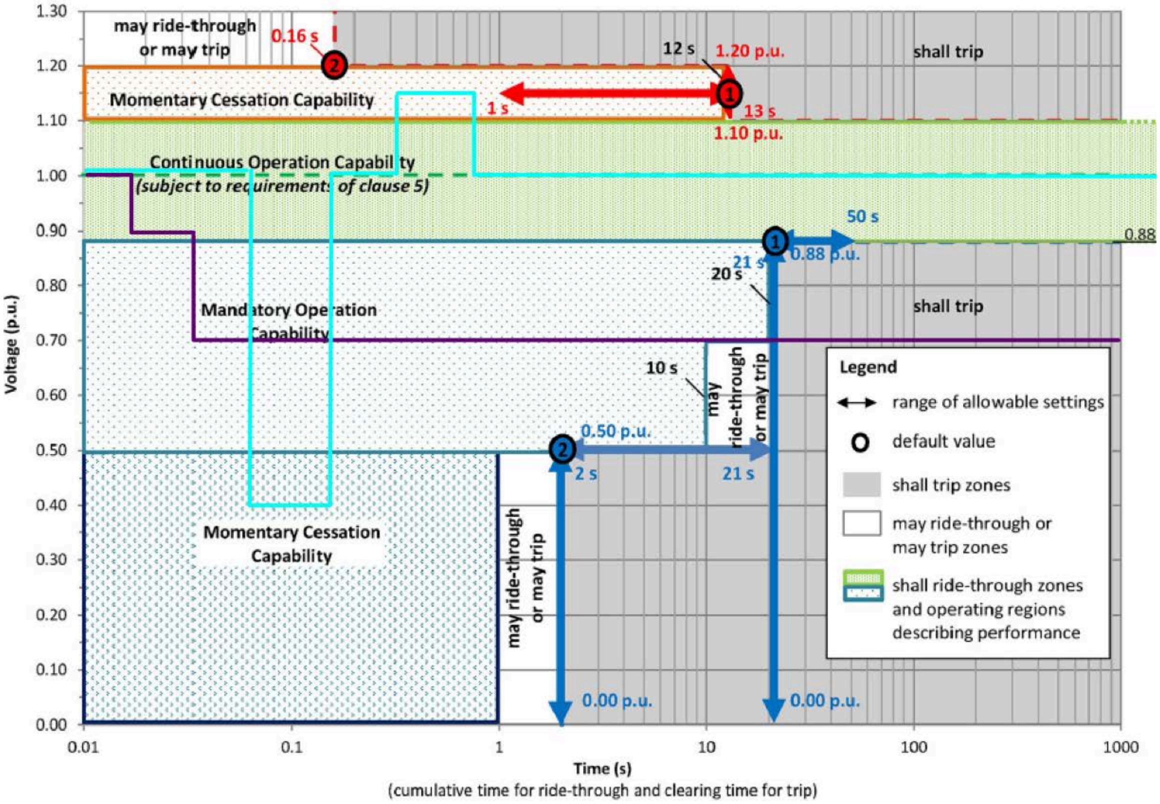

Figure 7. DER response to abnormal voltages and voltage ride-through requirements for a Category III DER. ***Figure from IEEE 1547-2018 (IEEE 2018, Figure H.9)***

There are two lines overlaid to illustrate the voltage fault ride-through test cases. The purple line belongs to Case 1 and the cyan line to Case 2, as presented in Section 4.1.

IEEE 1547-2018 requires a DER to respond to voltage faults with droop control as presented in Figure 8. We adjusted the deadband and droop parameters to reflect the default settings for a Category B DER: $V_3 = 1.02 \times V_{ref}$, $V_4 = 1.08 \times V_{ref}$, $Q_4 = 44\%$, 5-s 10% settling time (V represents voltage, Q represents reactive power, and V_{ref} represents reference voltage. The plot is symmetrical around V_{ref}.

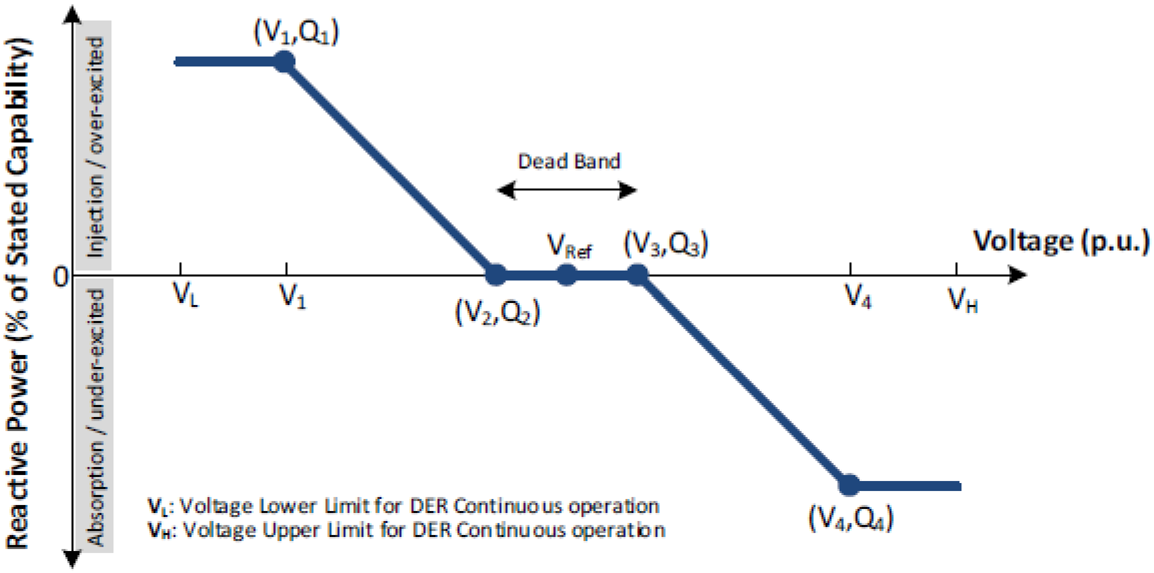

Figure 8. Example voltage–reactive power characteristic. ***Figure from IEEE 1547-2018 (IEEE 2018, Figure H.4)***

3.3.2 Reactive Power Command Tracking

A distributed wind turbine may receive external reactive power commands to help support local voltage. The nature of voltage support is the same whether the wind turbine is in a front-of-the-meter or behind-the-meter deployment. For behind-the-meter configurations, the DER should optimize value to the customer, especially relative to the energy and power transactions that their utility meter reads. Some large commercial and industrial customers with significant induction loads, like electric motors, have a high reactive power draw. If such customers have a wind turbine operating behind the meter, it likely makes economic sense to use the wind turbine to provide both real and reactive power and minimize high reactive power demand charges on their utility bill. A wind turbine operating at a leading power factor (see operation point M2 in Figure 9) can offset local reactive loads and save reactive power charges on a utility bill. Figure 9 displays the real–reactive power limits of the CART. Notice that within the bounds, the same amount of real power can be provided regardless of the reactive power production or absorption. At operating point M1 in Figure 9, with a 0.75 lagging power factor, the CART produces 400 kW of real power and absorbs 300 kW of reactive power. At operating point M2, with a 0.75 leading power factor, the CART produces 400 kW of real power and injects 300 kW of reactive power. Integrated storage may facilitate such reactive power support for a prolonged period as required by industrial loads.

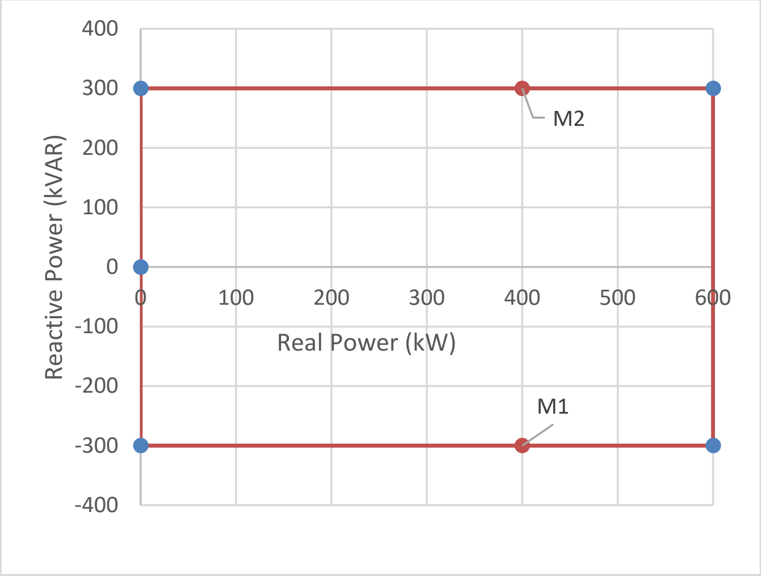

Figure 9. Real–reactive power characteristics of the 600-kW CART.

kVAR = kilovolt-ampere reactive

One study revealed the impact on the distribution voltage of wind turbines connected to rural distribution feeders (Allen 2014). Using Type 3 and Type 4 wind turbines connected to the distribution circuit, the study found that there is a nearly perfect linear relationship between the resistance from the substation to the wind turbine bus and the voltage rise when wind turbine generators are operated at unity power factor. The authors presented a generalized rule for relating the maximum allowable wind power generation at any three-phase bus on the feeder to the resistance to the substation from that bus. The rule has been developed considering only the ANSI voltage criterion.

3.4 Black Start

Black start is an emergency service that supports the restoration of a local power system after an outage. Some generators can 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, distribution lines, and other larger generators, eventually stitching the entire grid together for normal operation. A wind turbine can also provide black start if it has a grid-forming inverter (i.e., voltage source converter) and an integrated battery storage system (Anderson, Poudel, Krishnan, et al. 2022). Wind turbine original equipment manufacturer Siemens Gamesa is also developing black-start capabilities (Siemens-Gamesa n.d.). However, because wind turbines are relatively small compared to other generators in the power system, using them to support black start in grid-connected applications may only be economically viable if multiple wind turbines are aggregated.

3.5 Techno-Economic Valuation of Ancillary Services From Distributed Wind Turbines

Although Type 3 and 4 distributed wind turbines can provide a range of ancillary services when equipped with advanced controls and power electronics (Banshwar et al. 2017), there are economic trade-offs and constraints inherent to the nature of the variable wind resource. To create headroom for an upward ramp of power, a wind turbine must operate at a curtailed state until the need to increase the power output arises. Such curtailed operation, even if it can provide a wider range of grid services, comes at the cost of reduced bulk power production. An integrated battery energy storage system (Poudel et al. 2021) can facilitate the process by providing additional capacity that is available on demand, but it requires some additional control that interfaces with the existing turbine control system. A hybrid control approach using integrated batteries may be limited by the size (energy and power rating) of the battery and the size of the grid-side converter. Whether it makes sense for a wind turbine to be outfitted to provide a certain class of ancillary services depends on the project and underlying market.

Few ancillary services are procured at the distribution level because of the economy of scale and a legacy top-down approach prevailing in the electric power market. This situation might change as DERs become more capable of providing such services and policy intervention, such as the Federal Energy Regulatory Commission Order 2222, gradually opens the wholesale market. Based on recent changes to grid codes and standards, distributed wind turbines and other DERs will be better prepared to respond to future market opportunities. Furthermore, at the local level, there could be instances where grid services from wind energy are essential, particularly in a higher-contribution scenario. In fact, some grid codes, such as CA Rule 21, demand these capabilities explicitly. These grid services do not require much additional investment for Type 3 and Type 4 wind turbines other than the one-time cost to develop advanced control functionalities.

4 Simulation Results

This section uses the grid-connected wind turbine model described in Section 2.2.1. In these simulations, the wind turbine responds to grid voltage and frequency deviations and tracks grid commands that are used to regulate voltage and frequency. The simulation cases presented in Subsections 4.1.2 and 4.2.1 are designed according to wind turbine performance expectations in IEEE 1547-2018. Table 2 presents parameter values used for fault ride-through, unless otherwise stated. The results are presented in terms of real power, reactive power, real current, and reactive current. A single distributed wind turbine or small wind farm can only have significant impact on a smaller electric grid or a localized distribution feeder. However, from a market operator's perspective, if many generators perform the same service, they can provide significant support to a larger, stronger grid, such as the bulk transmission system. The simulations here use an infinite grid to represent the bulk power system, so the single wind turbine will not noticeably affect grid voltage or frequency.

Table 2. Fault Ride-Through Parameters (Close to IEEE 1547-2018 Defaults) for This Study

Parameter	Voltage	Frequency
Deadband	±0.02 pu	±0.036 Hz
Droop	13.6%	5%
Max. Reactive Power Injection/Absorption	0.44 pu	n/a
Continuous Operation Band	0.88–1.1 pu	58.8–61.2 Hz
Mandatory Operation Band(s)	0.5–0.88 pu	57–58.8, 61.2–61.9 Hz
Momentary Cessation Bands	0–0.5, 1.1–1.2 pu	n/a

4.1 Frequency Support

4.1.1 Inertial Response

Figure 10 displays the CART model providing inertial response. When grid frequency drops below a 0.02-Hz deadband, inertial response is initiated by increasing the generator electrical torque command (gain) to decelerate the rotor and extract some of its inertia, following the logic of the torque-limited inertial control (Anderson, Poudel, Reilly, et al. 2022). When frequency dips at 10 s, torque gain ramps up to the 1.3-pu limit, providing 3 s of extra power (0.2 pu, about 120 kW). This decelerates the rotor. Next, the torque and power dip as the rotor accelerates back to normal operating conditions.

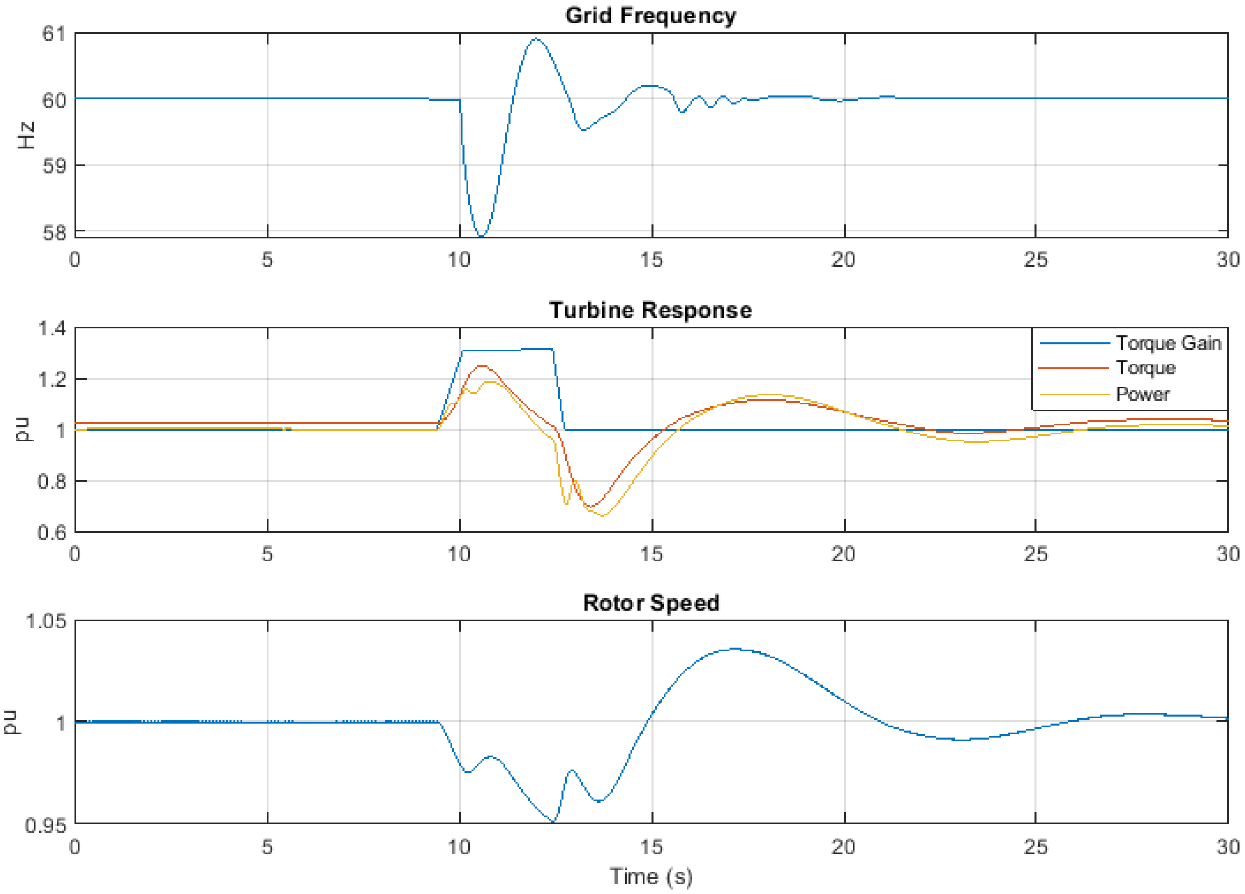

Figure 10. Inertial response to a frequency dip

4.1.2 Primary Frequency Response and Fault Ride-Through

We show that the CART model is capable of frequency fault ride-through and providing PFR, in adherence to IEEE 1547-2018 as a Category III DER. We use a frequency droop of 5% and a deadband of 0.036 Hz, the default value in the IEEE standard. The three cases presented next demonstrate the high-frequency, low-frequency, and frequency ramp events and the corresponding PFR of the CART.

4.1.2.1 Case 1: Primary Frequency Response to Small Frequency Deviation

This case demonstrates the CART reducing its power output in response to a small frequency increase. Per IEEE 1547-2018, a frequency deviation resulting in a power change of less than 5% of the rated real power requires an open-loop response time of 5 s (default value) to settle to the new real power output. The new real power output is given by an equation specified in the standard (IEEE 2018).

Figure 11 presents a test case of the high-frequency condition, beyond the deadband, at 1 s. The wind turbine reduces its power accordingly by 5% and settles to the new real power output in about 4.6 s, exceeding the requirement.

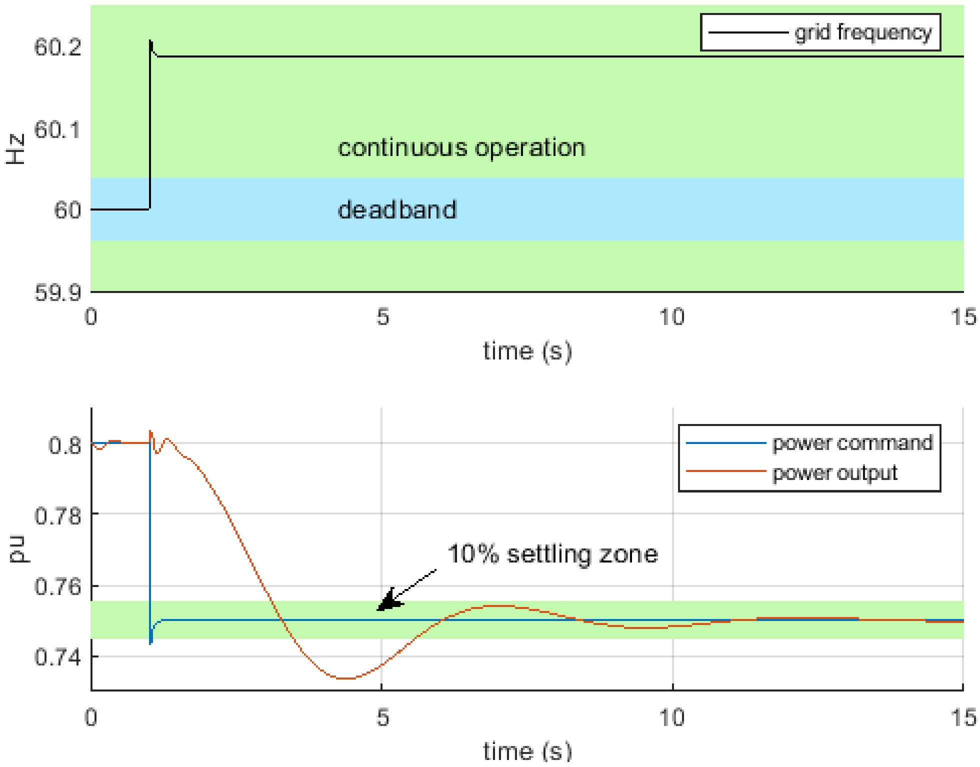

Figure 11. Real power response to a small overfrequency deviation

4.1.2.2 Case 2: Primary Frequency Response to a Large Frequency Deviation

This case demonstrates the CART increasing its power output in response to a large frequency decrease. 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. Figure 12 presents a test case of a low-frequency event at 1 s. The wind turbine increases its available real power accordingly to the maximum value and settles to the new mode of operation within 8 s, exceeding the requirement.

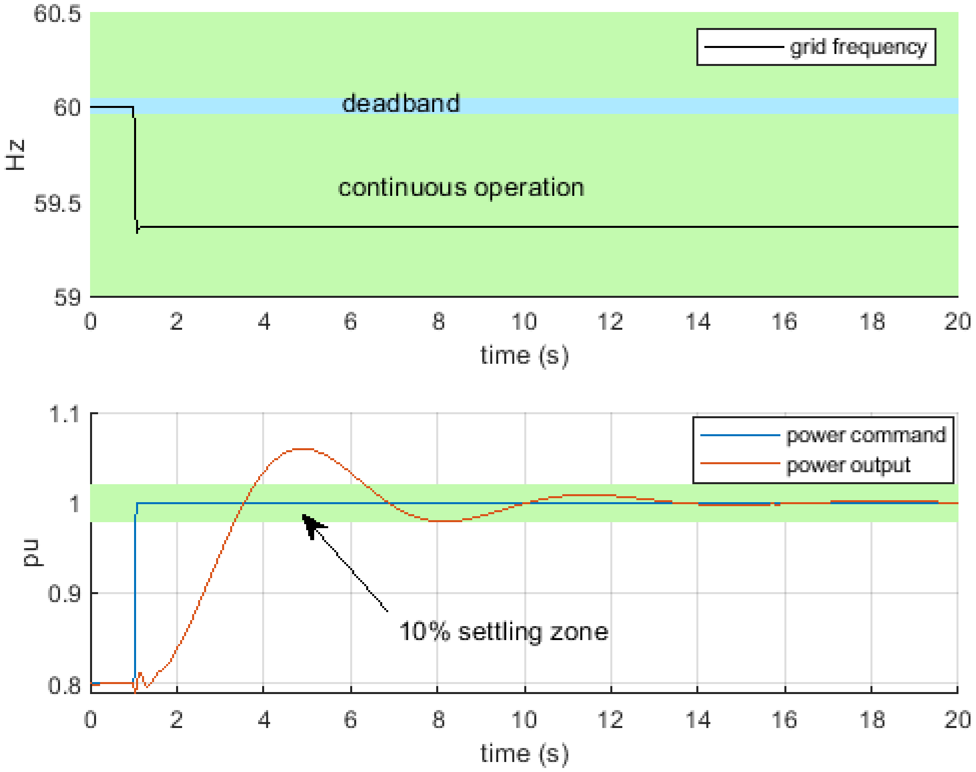

Figure 12. Large underfrequency deviation and real power response of the wind turbine

4.1.2.3 Case 3: Rate of Change of Frequency Ride-Through

Here, we present the CART riding through a frequency ramp into the trip zone. Figure 13 illustrates a linear frequency ramp event. At 0.5 s, the frequency drops below the deadband, and the power command increases to counteract the frequency ramp down. This power command is limited by the CART's rated power. Before the real power output can reach the power command, frequency passes the "may operate or trip" threshold at 1 s. After 0.16 s in the "may operate or trip" zone, the wind turbine trips per IEEE 1547-2018, and the power command and output both drop to zero.

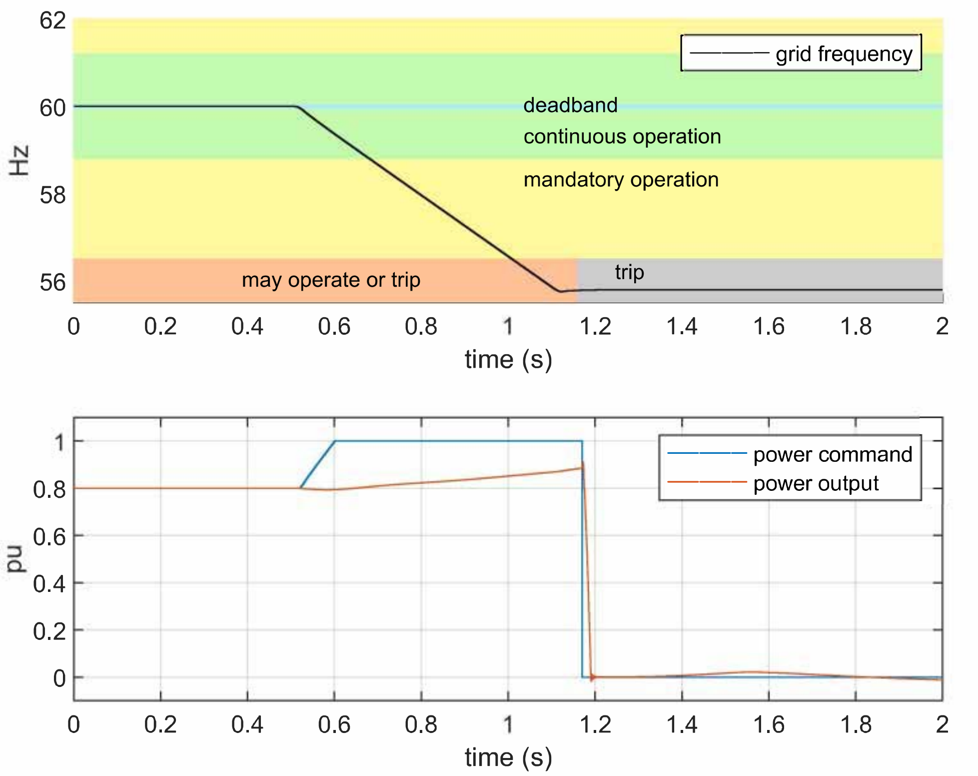

Figure 13. Wind turbine real power response and trip due to an underfrequency ramp

To provide PFR in these cases, the CART starts derated to provide headroom to increase power in the event of a frequency dip. Therefore, this may be a paid service to offset lost power generation revenue.

4.1.3 External Real Power Command Tracking

The grid operator would provide a real power command to a wind turbine that is serving as a reserve unit. In behind-the-meter applications, the wind turbine could similarly respond to such external commands from a local smart metering system that balances local real power needs. Figure 14 portrays a sequence of step-change commands and the response of the CART. The CART responds faster to the step-down commands than to the step-up commands. It returns even slower to rated power, at the limit of the machine's ability. The response speed is limited by the rotor physically pitching to reach a new operating point.

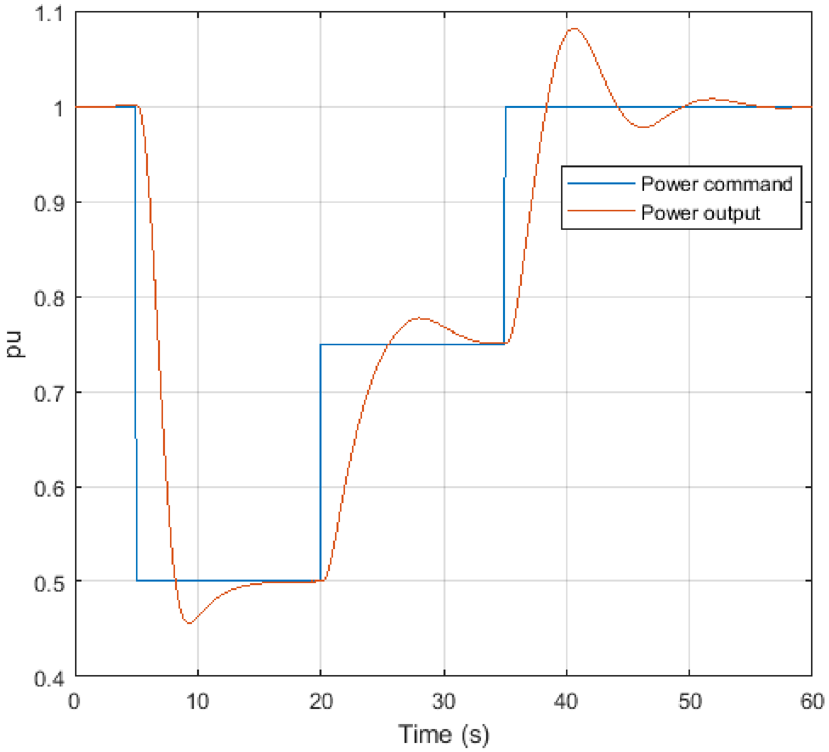

Figure 14. Response to a real power command

4.2 Voltage Support

4.2.1 Voltage Response and Fault Ride-Through

We show that the CART model is capable of riding through the voltage fault sequence specified for a Category B/III DER and providing voltage response. We use a voltage droop of 13.6% and deadband of 0.02 pu, the default value in the IEEE standard.

4.2.1.1 Case 1: Voltage Response via V-Q Droop Control

Figure 15 presents voltage response and trip. Initially, while the grid voltage remains within the deadband, the CART operates at nominal real power and zero reactive power. At 1 s, the voltage dips below the deadband, prompting a reactive power increase. At 6 s, the voltage further dips into the mandatory operation zone, prompting both real and reactive power to return to the nominal values. A voltage response is not required in this zone. After 21 s of operation in the mandatory operation zone, the machine trips, per IEEE 1547-2018.

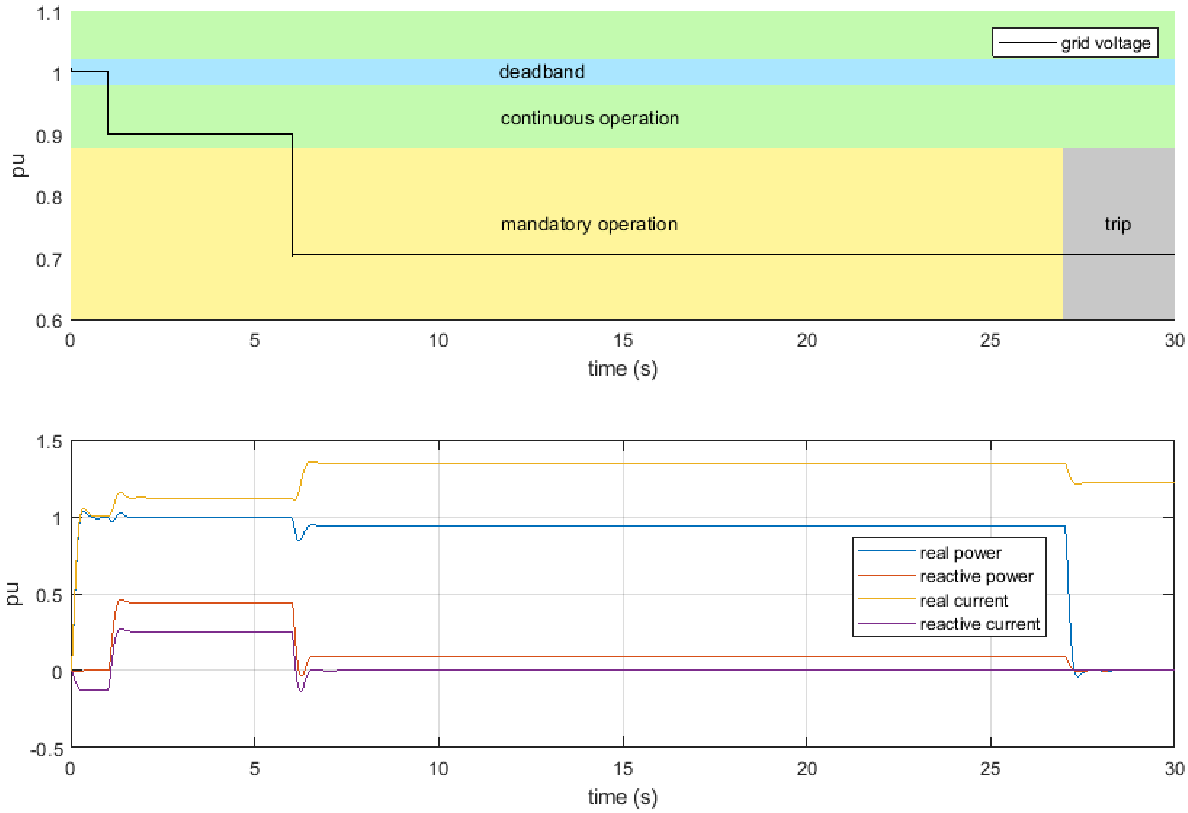

Figure 15. Wind turbine demonstrating voltage response and trip

4.2.1.2 Case 2: Momentary Cessation (A Fault Ride-Through Method)

IEEE 1547-2018 defines momentary cessation as follows: When grid voltage or frequency strays outside of certain thresholds, a DER must temporarily cease energizing the grid, while staying connected, and immediately restore power when voltage or frequency return to within the thresholds.

Figure 16 demonstrates momentary cessation. Initially, the CART operates at nominal real power and zero reactive power while grid voltage remains within the deadband. Voltage dips into the momentary cessation zone at 5 s, and real power drops to zero in about 31 ms. The CART remains connected to the grid 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.

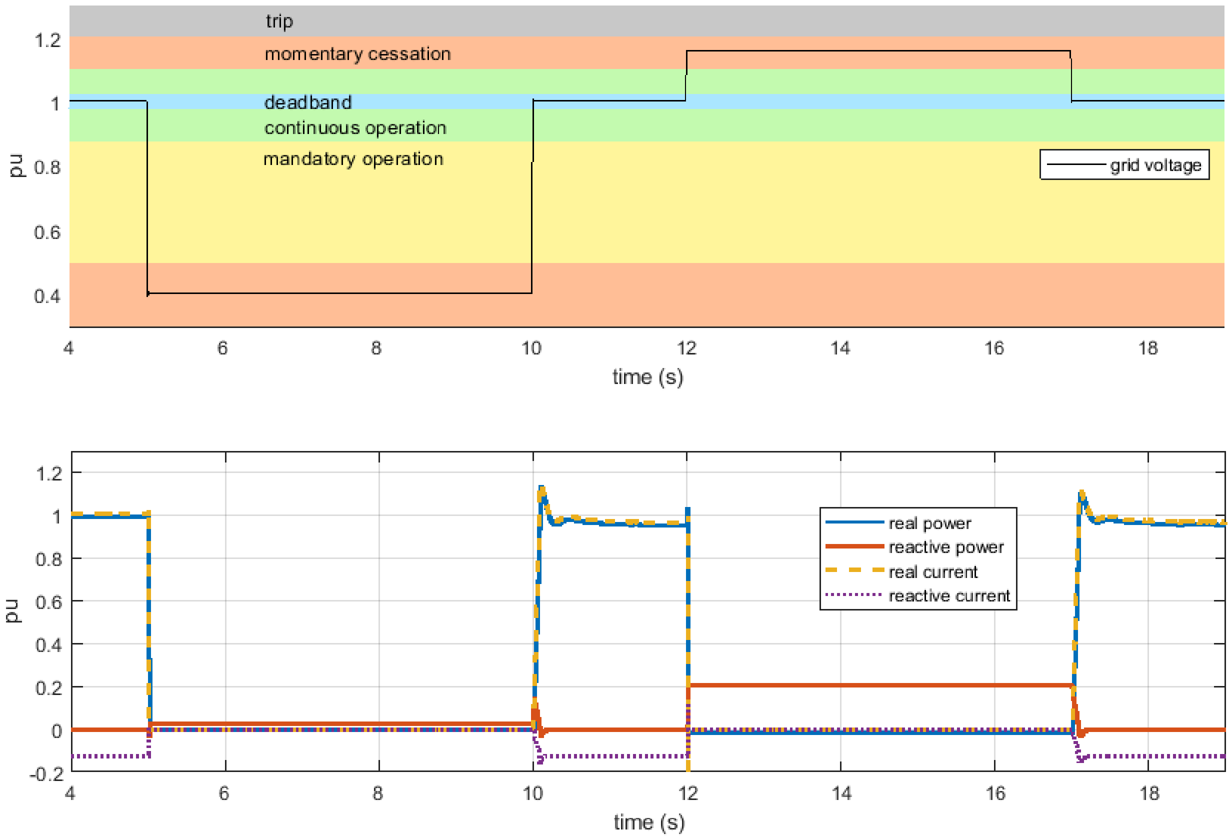

Figure 16. Wind turbine demonstrating momentary cessation

Per IEEE 1547-2018, the real power must drop to zero within a maximum response time of 83 ms. The CART complies with this requirement for both low- and high-frequency momentary cessation zones. This case demonstrates the CART model exceeding the expectation of IEEE 1547-2018 regarding momentary cessation of real power into the grid.

4.2.1.3 Case 3: Category III Voltage Ride-Through

The IEEE 1547-2018 Category III voltage profile is presented in Figure 4. Figure 17 portrays the wind turbine model successfully riding through this profile. The voltage dips enter the mandatory operation zone, requiring the CART to stay connected but not requiring it to provide a voltage response.

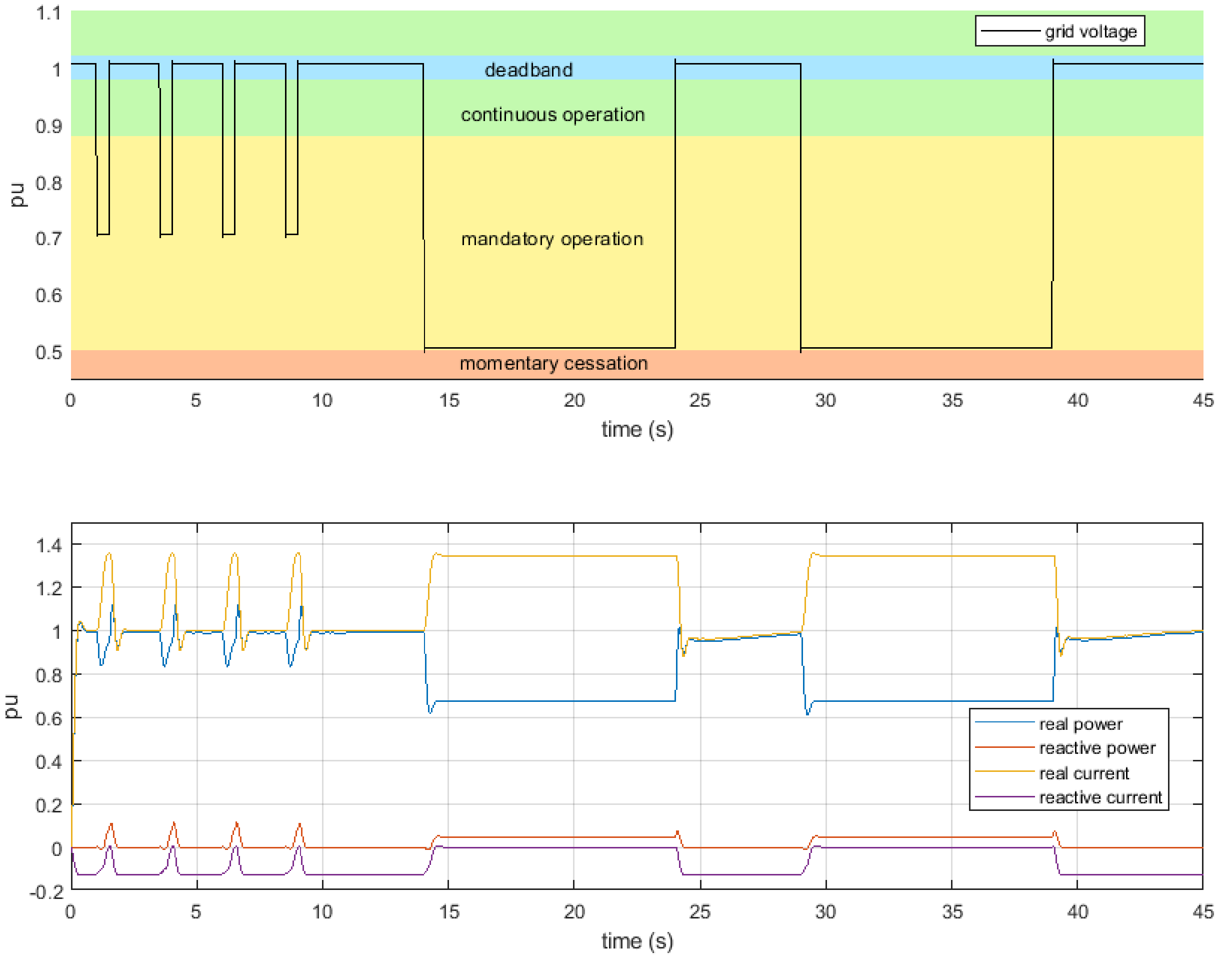

Figure 17. IEEE 1547-2018 Category III consecutive voltage disturbance ride-through

During the voltage dips to about 0.7 pu and to about 0.5 pu in the upper plot, real current reference (and, to a lesser extent, reactive current reference) increase to bolster the machine's power output. Without an increase in the real current (see the lower plot), the machine's real power output would drop to 0.7 pu and 0.5 pu for the small and large dips, respectively. The real power corresponding to these dips, with increased real and reactive current, are about 0.85 pu and 0.7 pu, respectively.

4.2.2 External Reactive Power Command Tracking

The grid operator would provide a reactive power command to a wind turbine that is providing voltage support. In behind-the-meter applications, a wind turbine would similarly respond to such external commands from a local smart metering system that balances local reactive power needs. This case demonstrates the CART tracking an external reactive power command. Figure 18 portrays a sequence of command step changes and the response of the wind turbine. All responses occur within 1 s. These responses are much faster than those to real power commands because they are accomplished by current control in the power electronics, and don't require the mechanical systems to change their operating points.

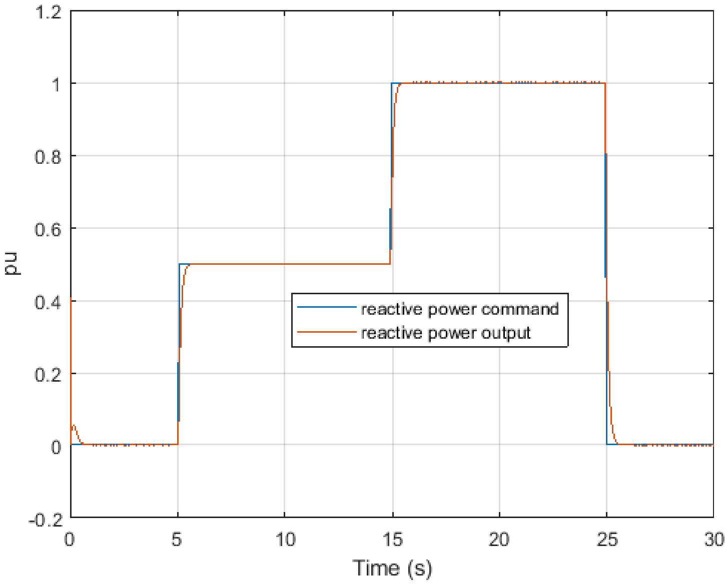

Figure 18. Response to a reactive power command

5 Conclusion

This report presents some of the abilities of distributed wind turbines to provide services in a grid-connected context. We enhance the model of NREL's CART to include voltage and frequency fault ride-through capabilities in addition to ancillary capabilities documented in the isolated grid report (Anderson, Poudel, Krishnan, et al. 2022). The results demonstrate that fault ride-through and grid support capabilities follow the requirements stipulated in IEEE 1547-2018 for the most advanced Category B/III DERs. We demonstrate the wind turbine providing inertial response to frequency deviations and responding to both real and reactive power commands that would come from the grid operator or local smart metering system, depending on the use case. In all cases, the wind turbine responses met or exceeded response settling time requirements. These capabilities are essential to increase the amount of distributed wind turbines on a utility grid, particularly as the renewable fraction increases.

The current model is idealized, with an infinite grid connected to a single wind turbine. In the future, the MIRACL team plans to analyze more applied grid-connected use cases, such as the Iowa Lakes Electric Cooperative, in which a distributed wind turbine is powering an ethanol plant in a front-of-the-meter deployment. In the current models, the modeler sets the faults manually and puts the wind turbine in the correct operating mode to respond to them. In future work, faults will be created randomly, and the wind turbine will dynamically shift between the appropriate operating modes. We are building these advanced control capabilities step by step. Integrating them all into a single wind turbine control and demonstrating it through hardware-in-the-loop experiments will be a final step to validate this effort. At present, we use perfect foresight for control function evaluation. The future version of the control will consider wind and load forecasts and corresponding uncertainty to enable an economic dispatch at the minute time scale. We plan to make these control frameworks and functionalities publicly accessible, so that original equipment manufacturers may use or customize them to reduce the soft costs associated with enabling the grid integration and interoperability of distributed wind turbines.

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