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IEEE 1547-2018 Open Source Distributed Energy Resource (OpenDER) Model

Version 2.2

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ABSTRACT

Accurate modeling of distributed energy resources (DERs) in analysis tools is crucial for evaluating their potential impacts on the power grid. As DERs incorporate more advanced grid-support functions, the complexity of their behavioral models increases. EPRI has developed an open-source DER (OpenDER) model (link), which aims to accurately represent solar photovoltaic (PV) and battery energy storage systems (BESS) to comply with IEEE 1547-2018 standard. The model supports steady-state, dynamic, and protection analysis applications. The OpenDER model software is complemented by this model specification report, which documents the model in mathematical format. EPRI continuously improve this model through discussions in a DER Model User's Group (DERMUG). The purpose of this work is to advance the accuracy and capabilities of commercial power system analysis tools and to support increased utilization of smart inverters with grid support capabilities.

This report documents the OpenDER model version 2.2 release in terms of block diagrams and equations. Example model validation results for two IEEE 1547-2018 compliant inverters are also included. EPRI intends to expand the model capabilities in its future releases to include additional DER attributes and functions from other technical standards.

Keywords

Open-source DER model
Distribution analysis
Smart inverter
IEEE 1547-2018
Grid support functions

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1. INTRODUCTION

1.1. Background and Objective

Technical standards have been developed worldwide that define interconnection, functional, and interoperability requirements for distributed energy resources (DERs). These standards are supported in many cases by laws that require the standard functionality in order for a DER to connect to the power grid. Together, these make it possible for utilities to predict and understand DER behavior, to perform analysis to quantify grid impacts, to maximize DER hosting capacity, and to determine how to optimize DER functions and settings.

In 2018, a full revision of the IEEE 1547 standard was approved with significant additions and modifications compared to its original 2003 version and 2014 amendment. This standard provides the basis for DER technical interconnection and interoperability requirements (TIIR) on the distribution systems throughout the US and many countries around the world. The new additions in IEEE 1547-2018 include multiple grid support functions such as voltage and reactive power (volt-var) control, and requirements such as low voltage ride through, that the DER must be able to provide or comply with.

With the release of the revised standard, DER manufacturers, integrators, and certification laboratories are designing, developing, and testing new products following the standard requirements. To prepare for these products, developers of distribution system planning and operational software are also updating their products with internal DER models intended to match the new revisions, and accurately represent IEEE 1547-2018[1] certified DERs. For utilities and researchers, a DER model within simulation software that accurately represents DERs in the field, is crucial for system planning and impact studies.

To advance the understanding of DER behavior among all stakeholders, EPRI released the IEEE 1547-2018 open-source DER (OpenDER) model set forth in this document, representing the standard in detail. The primary objectives of this work are:

- Harmonize accurate interpretations of the IEEE Std 1547-2018 DER interconnection standard among all the stakeholders, including utilities, distribution analysis tool developers, and original equipment manufacturers (OEMs).
- Build consensus through an open-to-all DER Model User's Group (DERMUG), which will utilize EPRI developed model specifications and codes and provide feedback for continuous improvement of the OpenDER model.
- Help the industry properly model the DERs that are (or to be) grid interconnected and evaluate the associated impacts on distribution circuits accurately.

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[1] https://sagroups.ieee.org/scc21/standards/1547rev/.

To develop this DER model, and to maintain and extend it going forward, detailed analysis of the relevant standards will be performed as the basis. For DER behaviors that are not clearly defined in the standards, lab testing of DER are conducted, and test results are used to improve the model. In addition, an open-to-all DER model user group (DERMUG) is established and meet periodically for the industry to critique the model and provide feedback.

This OpenDER model are maintained in two formats:

1. In this document, the model specification is presented in terms of equations and block/flow diagrams. This free, publicly available document can be used by any stakeholder who wants to develop their own model, such as simulation software vendors, R&D organizations, consultants, and academia. Being developed and documented in a modular fashion, this model may be used by developers as a whole, or in part depending on their needs. This document can also be used as a reference to understand the detailed requirements of IEEE 1547-2018, and the associated interpretations.
2. The OpenDER model in software format is released separately in GitHub[2]. The released program code can be used by various stakeholders for their own DER model development. It can also be used to benchmark and validate DER models in commercial simulation tools, by comparing results obtained in the commercial tools with the results generated by the OpenDER Model. In addition, the developed model will be embedded into EPRI's DER Simulator[3] to support studies and co-simulations with other distribution analysis tools using pre-programmed interfaces.

1.2. Development Roadmap

As discussed in the previous section, the maintenance of this DER model will be an ongoing activity. As shown in Figure 1, the development activities started in 2021, and will continue beyond 2025. Notably:

- In version 2.0 released in 2022, the OpenDER model can represent both PV and battery energy storage system (BESS) DERs. The OpenDER includes all IEEE 1547-2018 standard required grid support functions, enter service, trip, and ride-through performances. It supports steady-state, dynamic, and short circuit protection analyses.
- In this document, Version 2.2 is released, including minor model updates and bug fixes identified through the software code development. Example model validation results against two IEEE 1547-2018 compliant inverters are also provided.
- Further update plans include improvements based on model validations, updates on the next revision of IEEE P1547, and more grid support functions from standards worldwide.

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[2] https://github.com/epri-dev/OpenDER.

[3] *Overview of EPRI's DER Simulation Tool for Emulating Smart Solar Inverters and Energy Storage Systems on Communication Networks: An Overview of EPRI's Distributed Energy Resource Simulator*. EPRI, Palo Alto, CA: 2018. 3002013622.

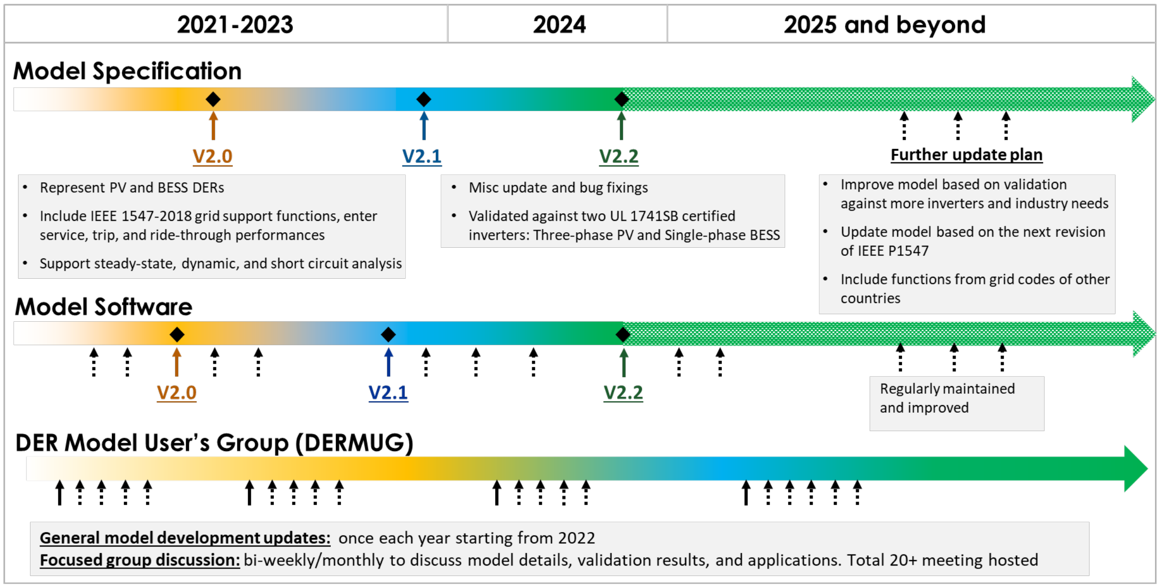

Figure 1. Development roadmap for IEEE 1547-2018 OpenDER Model

EPRI intends to maintain, improve, and expand the model going forward, and plans to include DER control functions that are required by other standards or provided by DER manufacturers, after the major planned releases. In addition, the ambiguities and gaps in the IEEE 1547-2018 identified during the model development process will be documented and provided as input to the upcoming revision of the standard.

1.3. DER Model User's Group (DERMUG)

A DER model user's group (DERMUG) that is open to all interested parties, including utilities, inverter manufacturers, power system analysis tool developers, and consultants is established. The DERMUG is tasked for the industry to assess together, critique, find consensus, prioritize improvements, and refine the DER model. Errors and gaps identified in the DERMUG meetings are addressed accordingly as model revisions updated at or between the major releases. The discussion slides and recordings can be found on the OpenDER homepage[4]

1.4. Major Changes Included in Version 2.2 Release

The detailed changelog can be found in the OpenDER software Github repository[5]. The following additions and updates are made in Version 2.2 release compared to Version 2.1:

- Fixed miscellaneous bugs in various modules including watt-var function, momentary cessation performance, voltage source output, single-phase DER voltage measurement.

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[4] https://www.epri.com/opender.

[5] https://github.com/epri-dev/OpenDER/blob/main/CHANGELOG.rst.

- Added example model validation results against an IEEE 1547-2018 certified three-phase PV inverter
- Added a setting to enable and disable momentary cessation (*MC_ENABLE*)
- Added settings to configure the momentary cessation voltage threshold (*MC_LVRT_V1, MC_HVRT_V1*)
- Added settings to configure the volt-var automatic V_{ref} adjustment mode, maximum and minimum limits V_{ref} (*QV_VREF_MIN, QV_VREF_MAX*)

2. OVERVIEW OF IEEE 1547-2018 OPENDER MODEL

2.1. Scope of IEEE 1547-2018 OpenDER Model

The term Distributed Energy Resource (DER) may indicate a wide range of technologies such as solar photovoltaic (PV) generation, battery energy storage system (BESS), rotating generators, etc. The IEEE 1547-2018 OpenDER Model plans to represent all types of DERs. In this Version 2.1 release, both PV and BESS DERs are modeled according to the functional definition and performance requirements defined in IEEE 1547-2018.

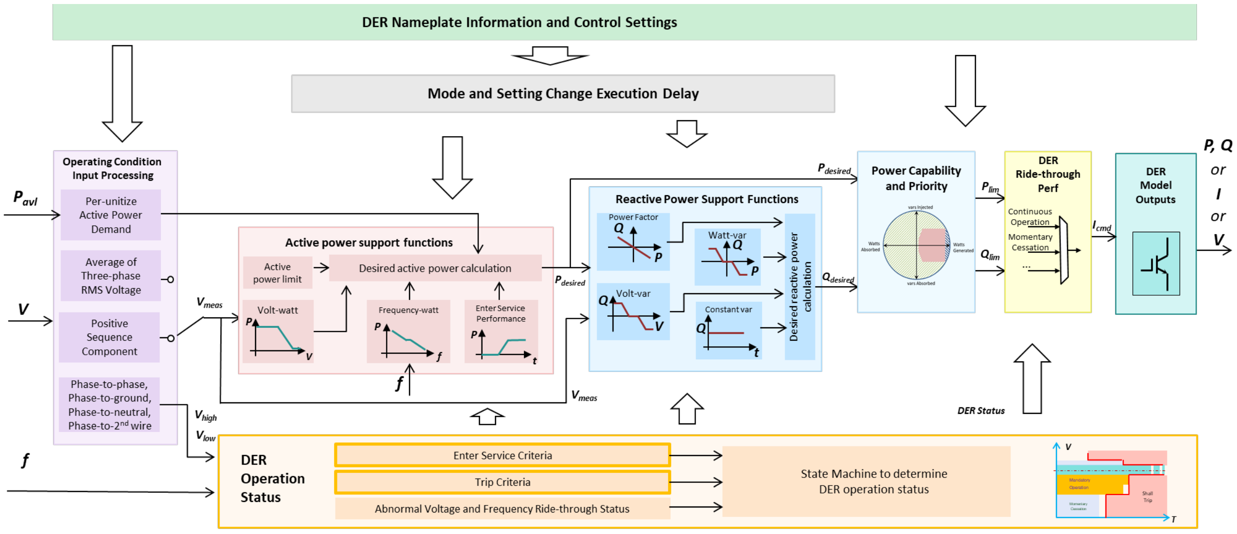
According to IEEE 1547-2018, Reference Point of Applicability (RPA) is the location where a DER measures its voltage and frequency and regulates its active and reactive power based on the measurements. The RPA is generally at the point of common coupling (PCC) for system sizes greater than 500 kW, typically the DER system's primary side. For smaller systems, the RPA can be at the point of DER connection (PoC). To comply with IEEE 1547-2018, the DER model described in this report requires the voltage and frequency at the RPA as the input and produces output values at the RPA. For the use of this model to support power system analysis, these inputs and outputs may be exchanged, for example, with a distribution system simulator.

This model is only applicable for distribution connected DERs at this moment, since IEEE 1547-2018 is not intended for generation resources connected to transmission or networked sub-transmission system, as indicated in Clause 1.4. There is no limit to the modeled DER power and voltage ratings, and both single-phase and three-phase DERs are covered.

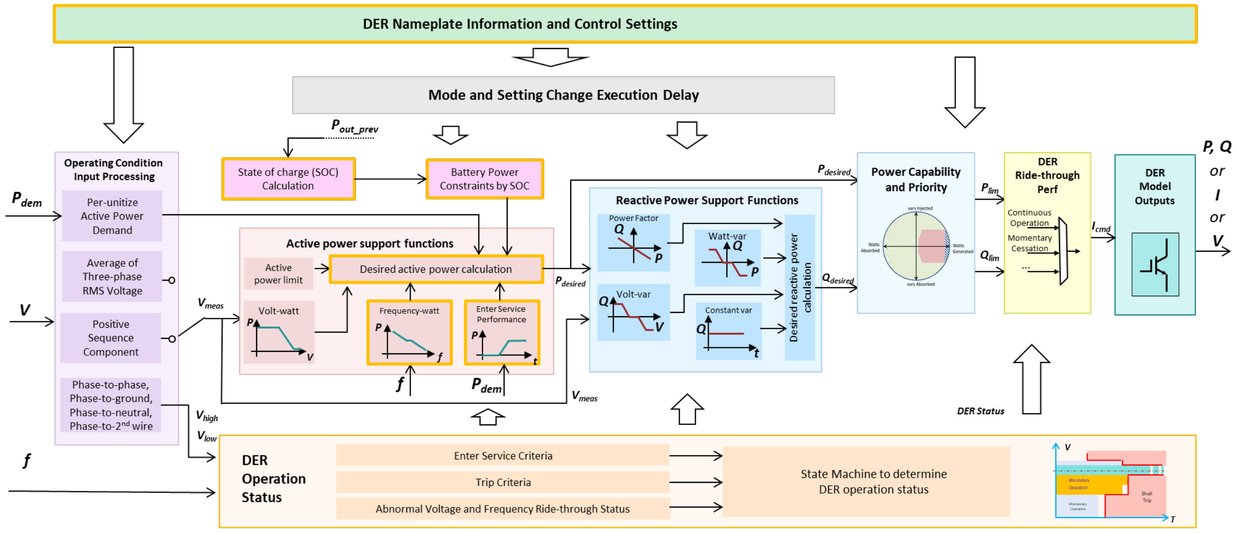
The DER model is developed in time-domain, and can be applicable for various system analyses, including steady state power flow, quasi-static time series (QSTS), and dynamic (RMS). Currently in Version 2 release, grid support functions, enter service and trip performance, DER output capability and priority of responses, as well as DER ride-through performance are included. The OpenDER model in this version can be applied to various system studies such as steady-state voltage and/or hosting capacity analysis, voltage fluctuation, DER control, interactions with distribution voltage regulation devices, fault current contribution, and temporary overvoltage etc.

2.2. Structure of IEEE 1547-2018 OpenDER Model

The structure of the OpenDER model is slightly different for PV and BESS DERs, shown in Figure 2. The model blocks with orange boarder have additional or modified components that are specific to PV or BESS. It is developed with a modular modeling approach. Each individual module of the model represents a specific DER control function or behavior requirement according to the standard definition, requirement, and common DER implementation by the manufacturers. The standard requirements to be captured in terms of each module in the DER model are listed in Table 1.



(a) PV DER model



(b) BESS DER model

Figure 2. IEEE 1547-2018 OpenDER model structure

Table 1. IEEE 1547-2018 requirements to be captured in OpenDER model

OpenDER Model Module	Related IEEE 1547-2018 Clause and Requirement
Operating condition input processing	4.3 Applicable voltages
Mode and setting change execution delay	4.6.3 Execution of mode or parameter changes
Enter service criteria	4.6.1 Capability to disable permit service 4.10.2 Enter service criteria
Trip criteria	4.6.1 Capability to disable permit service 6.4.1 Mandatory voltage tripping requirements 6.5.1 Mandatory frequency tripping requirements
Abnormal voltage and frequency ride-through criteria	6.4.2 Voltage disturbance ride-through requirements 6.5.2 Frequency disturbance ride-through requirements
Active power limit function	4.6.2 Capability to limit active power
Volt-watt function	5.4.2 Voltage-active power mode
Frequency-droop function	6.5.2.7.2 Frequency-droop (frequency-active power) operation
Desired active power calculation	4.7 Prioritization of DER responses
Enter service performance	4.10.3 Performance during entering service
Constant power factor function	5.3.2 Constant power factor mode
Volt-var function	5.3.3 Voltage-reactive power mode
Watt-var function	5.3.4 Active power-reactive power mode
Constant var function	5.3.5 Constant reactive power mode
Desired reactive power calculation	4.7 Prioritization of DER responses 4.6.3 Execution of mode or parameter changes
DER nameplate output capability and priority of responses	5.2 Reactive power capability of the DER
Abnormal voltage and frequency ride-through performance	6.4.2.3.3 Low-voltage ride-through performance 6.4.2.6 Dynamic voltage support 6.4.2.7 Restore output with voltage ride-through …

Each module is explained in detail in Chapter 3. The structure shown in Figure 2 illustrates the flow of the signals and interactions of different modules. With the defined structure and the modular modeling approach, it is expected that each module can be independently updated and maintained with minimal needs to adjust other modules. To represent different DER behaviors, each individual module can be replaced with different implementations. Such variations will be provided in a model library format in a later model revision, such that the users may be able to choose between different options.

2.3. Inputs of IEEE 1547-2018 OpenDER Model

The basic inputs of IEEE 1547-2018 OpenDER Model include nameplate information, function settings variables, and operating conditions variables. Table 2 through Table 6 show the inputs for each group of variables. To the extent possible, the model input variable names and labels are consistent with those in IEEE 1547.1-2020[6] and the common file format developed by EPRI.[7] Additional variables are included in this model to better represent the DER behavior that are not clearly defined in the standard, following a similar naming convention, shown in Table 3.

For some variables, default values are provided and will be used in case a user does not specify the values. When the default value for a variable is empty, it requires input from the user. For example, default values for DER specific variables, such as nameplate information, are not provided. Most of the default control settings are the default values defined in IEEE 1547-2018. These values should be populated once DER normal or abnormal operating performance category is specified as per Section 5 and Section 6 in the IEEE 1547-2018, respectively. Others are for the purpose of model implementation, which should be populated at the creation of the model.

The nameplate information listed in Table 2 indicates the rating of the DER unit or plant at its RPA. The operating condition inputs listed in Table 6 indicate the voltage and frequency at RPA. If the DER is single-phase, the model only requires one array with a single value. But if the DER is three-phase, voltage magnitude and phase angle of each phase must be provided. Unless specified otherwise, for balanced system studies, the voltage phase angles at RPA [*theta_a, theta_b, theta_c*] are set to be [0, -2.0944, 2.0944] by default.[8]

If the DER model is used in a time domain dynamic simulation, it also requires the simulation time step *t_s* as an input. The unit of simulation time step *t_s* is second. This variable is mainly used to model DER time dependent behaviors, such as ramping, time delay, open loop response time, etc. The selection of the DER model time step is briefly discussed in Chapter 5.

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[6] https://standards.ieee.org/standard/1547_1-2020.html.

[7] *Common File Format for DER Settings Exchange and Storage: Version 2.0*. EPRI, Palo Alto, CA: 2022. 3002025445.

[8] The values [0, -2.0944, 2.0944] is calculated from [0, $-\frac{2}{3}\pi, \frac{2}{3}\pi$], assuming the system is balanced.

Table 2. Nameplate variables

Variable Name	Variable Label	Unit
Active power rating at unity power factor	*NP_P_MAX*	W
Active power rating at specified over-excited power factor	*NP_P_MAX_OVER_PF*[9]	W
Specified over-excited power factor	*NP_OVER_PF*[9]	n/a
Active power rating at specified under-excited power factor	*NP_P_MAX_UNDER_PF*[9]	W
Specified under-excited power factor	*NP_UNDER_PF*[9]	n/a
Apparent power maximum rating	*NP_VA_MAX*	VA
Active power charge maximum rating	*NP_P_MAX_CHARGE*	W
Apparent power charge maximum rating	*NP_APPARENT_POWER_CHARGE_MAX*	VA
Normal operating performance category	*NP_NORMAL_OP_CAT*	n/a (CAT_A/CAT_B)
Abnormal operating performance category	*NP_ABNORMAL_OP_CAT*	n/a (CAT_I /CAT_II/CAT III)
Reactive power injected maximum rating	*NP_Q_MAX_INJ*	var
Reactive power absorbed maximum rating	*NP_Q_MAX_ABS*	var
AC voltage nominal rating	*NP_AC_V_NOM*[10]	Volt (RMS)
Reactive susceptance that remains connected to the Area EPS in the cease to energize and trip state	*NP_REACTIVE_SUSCEPTANCE*[9]	siemens

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[9] In this version of OpenDER, it is assumed that the reactive susceptance is connected during Cease to Energize state, but not in Trip state.

[10] The variable *NP_AC_V_NOM* in this model represents the nominal voltage rating at the RPA. For a DER plant with RPA at PCC, the variable should be a medium voltage value. For single-phase DER, it represents the RMS value of the single-phase voltage, whereas for three-phase DER, it represents the RMS value of the line-to-line voltage.

Table 3. Variables defined to describe DER model behavior

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit	Description
DER system efficiency	$NP\_EFFICIENCY$	1	n/a	DER system efficiency may include inverter loss, transformer loss, DC and AC collector loss, etc., depending on the location of RPA. For BESS, indicate round trip efficiency
DER nominal DC voltage	NP_V_DC	1.5 × $NP\_AC\_V\_NOM$	V	DER inverter DC link voltage. If RPA of DER is on medium voltage side, also scale this parameter to medium voltage. This parameter is used to determine the maximum voltage output in section 3.11.3.
Reactive power capability curve	$NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ $(P\_Q\_INJ\_PU)$	[0, 0.04999, 0.05, 0.2, 1]	Array of pu based on DER nominal active power rating	These four variable arrays indicate the DER reactive power capability range, in terms of DER active power generation. If not specified by user, these arrays should be generated to have the same shape as the minimum capability defined in IEEE 1547-2018, Clause 5.2. Detailed model specification is in section 3.9.
	$NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ $(P\_Q\_ABS\_PU)$	[0, 0.04999, 0.05, 0.2, 1]		
	$NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ $(Q\_MAX\_INJ\_PU)$	[0, 0, 0.25, 1, 1]$\times NP\_Q\_MAX\_INJ / NP\_VA\_MAX$	Array of pu based on DER nominal apparent power	
	$NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ $(Q\_MAX\_ABS\_PU)$	[0, 0, 0.25, 1, 1]$\times NP\_Q\_MAX\_ABS / NP\_VA\_MAX$		

Table 3 (continued). Variables defined to describe DER model behavior

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit	Description
Priority outside minimum requirements of reactive power capability	*NP_PRIO_OUTSIDE_MIN_Q_REQ*	REACTIVE	n/a (ACTIVE/ REACTIVE)	This variable indicates the DER output priority for active or reactive power outside of the minimum reactive power capability requirements defined in IEEE 1547-2018. Detailed model specification is in section 3.9.
Unbalanced voltage response for volt-var and volt-watt	*NP_V_MEAS_UNBALANCE*	AVG	n/a (AVG/POS)	This variable indicates the DER response to average of three-phase rms voltage (AVG) or positive sequence voltage (POS) for volt-var and volt-watt function. Detailed model specification is in section 3.3.
Single- or three-phase DER	*NP_PHASE*		n/a (SINGLE /THREE)	This variable indicates whether the modeled DER is single-phase or three-phase. Detailed model specification is in section 3.3.
DER minimum active power output	*NP_P_MIN_PU*	0 for PV DER, -1 of BESS DER	pu based on DER nominal active power rating	This variable indicates the DER minimum active power output due to its prime mover constraint.
Specified value for enter service randomized delay for simulation purpose	*ES_RANDOMIZED_DELAY_ACTUAL*	0	s	If enter service randomized delay is used for a DER, this variable defines a specified value. If the value of this parameter is greater than 0, it will be used as enter service randomized delay for simulation purpose. Detailed model specification is in section 3.5.1.1.

Table 3 (continued). Variables defined to describe DER model behavior

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit	Description
Active Power Limit Response Time	AP_RT	15	s	IEEE 1547-2018 has a non-configurable time requirement of 30s for the DER to limit its active power to not greater than the active power limit setpoint. The variable AP_RT is defined to model this time dependent behavior. The default value may be updated according to field or lab test results.
Constant Power Factor Mode Response Time	$CONST\_PF\_RT$	5	s	In IEEE 1547-2018, the maximum DER response time to maintain constant power factor is defined to be 10 seconds. The variable $CONST\_PF\_RT$ may not be configurable for actual DERs but is defined to model the DER response time. The default value may be updated according to field or lab test results.
Constant Reactive Power Mode Response Time	$CONST\_Q\_RT$	5	s	In IEEE 1547-2018, the maximum DER response time to maintain constant reactive power is defined to be 10 seconds. The variable $CONST\_Q\_RT$ may not be configurable for actual DERs but is defined to model the DER response time. The default value may be updated according to field or lab test results.

Table 3 (continued). Variables defined to describe DER model behavior

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit	Description
Active Power Reactive Power Mode Response Time	QP_RT	5	s	In IEEE 1547-2018, the maximum DER response time to maintain watt-var setting is defined to be 10 seconds. The variable QP_RT may not be configurable for actual DERs but is defined to model the DER response time. The default value may be updated according to field or lab test results.
Frequency-Active power mode enable	PF_MODE_ENABLE	ENABLED	n/a (DISABLED/ ENABLED)	IEEE 1547-2018 frequency-droop function as mandatory, except for Cat_I DER under low-frequency conditions. Frequency-droop function should be always enabled. This enable variable is provided for modeling purpose.
Mode and setting change execution delay time	$NP\_SET\_EXE\_TIME$	0	s	In IEEE 1547-2018, the maximum DER response time after a control parameter setting change is defined to be 30s. The default value may be updated according to field or lab test results.
Time for DER to smoothly transition between control functional modes	$NP\_MODE\_TRANSITION\_TIME$	15	s	In IEEE 1547-2018, if control functional mode changes, it is required for DER to transition its output smoothly over a time period between 5s and 300s. The default value may be updated according to field or lab test results.
Initial condition of DER on/off status	$STATUS\_INIT$	ON	ON/OFF	This variable defines the initial value of DER operation status *der_status* at the start up of the simulation. Detailed model specification is in section 3.5.1.4.

Table 3 (continued). Variables defined to describe DER model behavior

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit	Description
DER grid support function reaction time	NP_REACT_TIME	0	s	This variable defines the reaction time of grid-support functions[11].
DER voltage measurement delay	$NP\_V\_MEAS\_DELAY$	0	s	This variable defines the filter time constant for voltage measurement, which is equivalent to the 2.3 times of WECC Renewable Energy Electrical Control (REEC_*) models' parameter T_{rv}.
DER source resistance for voltage output	$NP\_RESISTANCE$	0.01	pu	This variable defines the resistance of the DER output impedance, which is equivalent to the WECC Renewable Energy Generator/Converter (REGC_B and REGC_C) models' Source resistance (*re*). Detailed model specification is in section 3.11.3
DER source reactance for voltage output	$NP\_REACTANCE$	0.2	pu	This variable defines the reactance of the DER output impedance, which is equivalent to the WECC Renewable Energy Generator/Converter (REGC_B and REGC_C) models' Source reactance (*Xe*). Detailed model specification is in section 3.11.3

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[11] Reaction time is defined in IEEE 2800-2022 as: The duration from a step change in a system quantity measured at a defined location until the output of the system at the same defined location measurably changes in the direction of the control effort.

Table 3 (continued). Variables defined to describe DER model behavior

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit	Description
DER inverter equivalent open loop delay for closed-loop current control	NP_INV_DELAY	0	s	This variable indicates the duration from a step change in the current reference input until the output changes by 90% of its final change. It is equivalent to 2.3 times of the parameter *Tg* (Emulated delay in converter controls [s]) in WECC Renewable Energy Generator/Converter (REGC_A and REGC_B) models. Detailed model specification is in section 3.10.
DER nameplate max current	$NP\_CURRENT\_PU$		pu	This variable defines the maximum current that the DER can output in per unit, which is equivalent to WECC Renewable Energy Electrical Control and Generator/Converter (REEC_* and REGC_*) models' *Imax* parameter.
Recovery time from ride-through	$NP\_RT\_RAMP\_UP\_TIME$	0	s	This variable defines the duration of the active current restore from 0 to 100% of rated current after recovery from momentary cessation to Mandatory Operation or Continuous Operation. It is equivalent to the reciprocal of the parameter *rrpwr* (Rate at which active current (power) recovers after a fault [pu/s]) in WECC Renewable Energy Generator/Converter (REGC_B and REGC_C) models.
Momentary cessation response time	MC_RESP_T	0	s	This variable defines the DER response time to enter momentary cessation. IEEE 1547-2018 has defined the maximum response time as 0.083 s

Table 3 (continued). Variables defined to describe DER model behavior

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit	Description
Cease to Energize response time	$NP\_CTE\_RESP\_T$	0	s	This variable defines the DER response time to Cease to Energize. IEEE 1547-2018 has defined the maximum response time as 0.16 s
Time to start to restore output from momentary cessation	MC_RETURN_T	0	s	This variable defines the time delay before DER start to restore output from goes into momentary cessation state, after voltage recovers to normal range. IEEE 1547-2018 has required the DER to restore 80% of active power within 0.4 s
Momentary cessation enable	MC_ENABLE	ENABLED	n/a (DISABLED/ ENABLED)	IEEE 1547-2018 defines momentary cessation as a mandatory performance for Category III DERs. This parameter is provided for modeling purpose.
Momentary cessation high voltage threshold	MC_HVRT_V1	1.1	pu	IEEE 1547-2018 has defined non-configurable value for momentary cessation voltage threshold, but also allows to change it under mutual agreement when the RPA is at PCC. This parameter is provided for modeling purpose.
Momentary cessation low voltage threshold	MC_LVRT_V1	0.5	pu	IEEE 1547-2018 has defined non-configurable value for momentary cessation voltage threshold, but also allows to change it under mutual agreement when the RPA is at PCC. This parameter is provided for modeling purpose.

Table 3 (continued). Variables defined to describe DER model behavior

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit	Description
Dynamic Voltage Support enable	DVS_MODE_ENABLE	DISABLED	n/a (DISABLED/ ENABLED)	IEEE 1547-2018 allows the DER to support the applicable voltage by supplying current during ride-through operation. This variable indicates the enable signal of this dynamic voltage support function
Dynamic Voltage Support K factor	DVS_K	0	pu	This parameter defines the per unit current increase in respond to a per unit voltage change for both positive and negative sequence in dynamic voltage support mode
Volt-var Auto Vref Adjustment mode Maximum Vref	QV_VREF_MAX	1.05	pu	IEEE P1547 revision proposed to make this as a configurable parameter.
Volt-var Auto Vref Adjustment mode Minimum Vref	QV_VREF_MIN	0.95	pu	IEEE P1547 revision proposed to make this as a configurable parameter.

Table 4. Energy storage specific settings

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit
Total Energy Capacity	*NP_BESS_CAPACITY*		Wh
Maximum Operational State of Charge	*NP_BESS_MAX_SOC*	1	n/a (state of charge)
Minimum Operational State of Charge	*NP_BESS_MIN_SOC*	0	n/a (state of charge)
Self-Discharge Rate (Constant)	*NP_BESS_SELF_DISCHARGE*	0	pu (of *NP_BESS_CAPACITY*) /hr
Self-Discharge Rate (SOC-dependent)	*NP_BESS_SELF_DISCHARGE_SOC*	0	pu (of *NP_BESS_CAPACITY*) / 1 (unit of SOC) / hr
BESS active power ramp rate constraint	*NP_BESS_P_RAMP_TIME*[12]	0	s
Maximum active power limitation by SOC	*NP_BESS_P_MAX_BY_SOC (P_DISCHARGE_MAX_PU)*	[1, 1]	Array of pu based on DER nominal active power rating
	NP_BESS_P_MAX_BY_SOC (SOC_P_ DISCHARGE_MAX)	[*NP_BESS_MIN_SOC, NP_BESS_MAX_SOC*]	Array of unitless SoC values
	NP_BESS_P_MAX_BY_SOC (P_CHARGE_MAX_PU)	[1, 1]	Array of pu based on DER nominal active power rating
	NP_BESS_P_MAX_BY_SOC (SOC_P_CHARGE_MAX)	[*NP_BESS_MIN_SOC, NP_BESS_MAX_SOC*]	Array of unitless SoC values

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[12] Some BESS may have different ramp rate for charging and discharging, as indicated by IEEE 1547.9-2022. In this version of OpenDER, one parameter is defined. This may be updated in later versions based on lab and field test results.

Table 5. Function setting variables

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit
Active Power Limit Enable	AP_LIMIT_ENABLE	DISABLED	n/a (DISABLED/ENABLED)
Active Power Limit	AP_LIMIT	1	If positive, pu based on DER nominal active power rating (NP_P_MAX); If negative, pu based on DER nominal active power charge rating ($NP\_P\_MAX\_CHARGE$)
Permit service activated by request from the area EPS operator	$ES\_PERMIT\_SERVICE$	ENABLED	n/a (DISABLED/ENABLED)
Minimum applicable voltage for enter service criteria	ES_V_LOW	0.917[13]	pu based on DER nominal AC voltage
Maximum applicable voltage for enter service criteria	ES_V_HIGH	1.05[13]	pu based on DER nominal AC voltage
Minimum frequency for enter service criteria	ES_F_LOW	59.5[13]	Hz
Maximum frequency for enter service criteria	ES_F_HIGH	60.1[13]	Hz
Maximum time for enter service randomized delay	$ES\_RANDOMIZED\_DELAY$	300[13]	s
Minimum intentional delay before initiating softstart	ES_DELAY	300[13]	s
Enter service soft-start duration. Time from 0 to 100% of P_{rated}	ES_RAMP_RATE	300[13]	s
Constant Power Factor Mode Enable	$CONST\_PF\_MODE\_ENABLE$	DISABLED	n/a (DISABLED/ENABLED)
Constant Power Factor Setting	$CONST\_PF$	1	n/a

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[13] Values are set as default in IEEE 1547-2018.

Table 5 (continued). Function setting variables

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit
Constant Power Factor Excitation	*CONST_PF_EXCITATION*	ABS	n/a (INJ/ABS)
Voltage-Reactive Power Mode Enable	*QV_MODE_ENABLE*	DISABLED	n/a (DISABLED/ENABLED)
Volt-var mode Autonomous V_{ref} Adjustment Enable	*QV_VREF_AUTO_MODE*	DISABLED	n/a (DISABLED/ENABLED)
Volt-var mode V_{ref} adjustment time Constant	*QV_VREF_TIME*[14]	300[13]	s
Volt-var Curve V_{Ref} Setting	*QV_VREF*	1[13]	pu based on DER nominal AC voltage
Volt-var Curve Point V1 Setting	*QV_CURVE_V1*	0.9 for CAT_A 0.92 for CAT _B[13]	pu based on DER nominal AC voltage
Volt-var Curve Point Q1 Setting	*QV_CURVE_Q1*	0.25 for CAT _A 0.44 for CAT _B[13]	pu based on DER nominal apparent power rating[15]
Volt-var Curve Point V2 Setting	*QV_CURVE_V2*	1 for CAT _A 0.98 for CAT_B[13]	pu based on DER nominal AC voltage
Volt-var Curve Point Q2 Setting	*QV_CURVE_Q2*	0[13]	pu based on DER nominal apparent power rating[15]
Volt-var Curve Point V3 Setting	*QV_CURVE_V3*	1 for CAT_A 1.02 for CAT_B[13]	pu based on DER nominal AC voltage
Volt-var Curve Point Q3 Setting	*QV_CURVE_Q3*	0[13]	pu based on DER nominal apparent power rating[15]
Volt-var Curve Point V4 Setting	*QV_CURVE_V4*	1.1 for CAT_A 1.08 for CAT_B[13]	pu based on DER nominal AC voltage
Volt-var Curve Point Q4 Setting	*QV_CURVE_Q4*	-0.25 for CAT_A -0.44 for CAT_B[13]	pu based on DER nominal apparent power rating[15]

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[14] In the latest version common file format under development, the variable label for Vref adjustment time constant is updated to *QV_VREF_TIME.*

[15] All reactive power per-unit values are based on the maximum apparent power ratings of the DER (*NP_VA_MAX*). Positive value indicates reactive power injection, and negative value indicates reactive power absorption.

Table 5 (continued). Function setting variables

Variable Name	**Variable Label**	**Default value in DER Model if not specified otherwise**	**Unit**
Volt-var open loop response time	QV_OLRT	10 for CAT_A 5 for CAT_B [13]	s
Constant Reactive Power Mode Enable	$CONST\_Q\_MODE\_ENABLE$	DISABLED	n/a (DISABLED/ENABLED)
Constant Reactive Power setting	$CONST\_Q$[15]	0	pu based on DER nominal apparent power rating[15]
Active Power Reactive Power Mode Enable	QP_MODE_ENABLE	DISABLED[16]	n/a (DISABLED/ENABLED)
Active Power Reactive Power Curve Point P1 Setting	$QP\_CURVE\_P1\_GEN$	Greater of 0.2 or $NP\_P\_MIN\_PU$[13]	pu based on DER nominal active power rating
Active Power Reactive Power Curve Point Q1 Setting	$QP\_CURVE\_Q1\_GEN$	0[13]	pu based on DER nominal apparent power rating[15]
Active Power Reactive Power Curve Point P2 Setting	$QP\_CURVE\_P2\_GEN$	0.5[13]	pu based on DER nominal active power rating
Active Power Reactive Power Curve Point Q2 Setting	$QP\_CURVE\_Q2\_GEN$	0[13]	pu based on DER nominal apparent power rating[15]
Active Power Reactive Power Curve Point P3 Setting	$QP\_CURVE\_P3\_GEN$	1[13]	pu based on DER nominal active power rating
Active Power Reactive Power Curve Point Q3 Setting	$QP\_CURVE\_Q3\_GEN$	-0.25 for CAT_A -0.44 for CAT_B[13]	pu based on DER nominal apparent power rating[15]
Active Power Reactive Power Curve Point P’1 Setting	$QP\_CURVE\_P1\_LOAD$	0.2[17]	pu based on DER nominal active power charge rating ($NP\_P\_MAX\_CHARGE$)
Active Power Reactive Power Curve Point Q’1 Setting	$QP\_CURVE\_Q1\_LOAD$	0[13]	pu based on DER nominal apparent power rating[15]

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[16] Watt-var and volt-watt functions are not required for CAT_A DER.

[17] IEEE 1547-2018 specifies the default value for P’1 is the lesser of 0.2×P’rated or minimum active power that DER can absorb. For most types of energy storage DERs, there is no minimum charging power constraint. The parameter that indicates minimum charging power is currently not included in the DER model. It may be added in future revisions due to the user needs.

Table 5 (continued). Function setting variables

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit
Active Power Reactive Power Curve Point P’2 Setting	*QP_CURVE_P2_LOAD*	0.5 [13]	pu based on DER nominal active power charge rating (*NP_P_MAX_CHARGE*)
Active Power Reactive Power Curve Point Q’2 Setting	*QP_CURVE_Q2_LOAD*	0 [13]	pu based on DER nominal apparent power rating[15]
Active Power Reactive Power Curve Point P’3 Setting	*QP_CURVE_P3_LOAD*	1 [13]	pu based on DER nominal active power charge rating (*NP_P_MAX_CHARGE*)
Active Power Reactive Power Curve Point Q’3 Setting	*QP_CURVE_Q3_LOAD*	-0.25 for CAT_A -0.44 for CAT_B [13]	pu based on DER nominal apparent power rating[15]
Voltage-Active Power Mode Enable	*PV_MODE_ENABLE*	DISABLED [16]	n/a (DISABLED/ENABLED)
Voltage Active Power Mode Curve Point P1 Setting	*PV_CURVE_P1*	1 [13]	pu based on DER nominal active power rating
Voltage Active Power Mode Curve Point V1 Setting	*PV_CURVE_V1*	1.06 [13]	pu based on DER nominal AC voltage
Voltage Active Power Mode Curve Point P2 Setting	*PV_CURVE_P2*	For PV DER: Lesser of 0.2 or *NP_P_MIN_PU* [13] For BESS DER: 0	If positive, pu based on DER nominal active power rating (*NP_P_MAX*); If negative, pu based on DER nominal active power charge rating (*NP_P_MAX_CHARGE*)
Voltage Active Power Mode Curve Point V2 Setting	*PV_CURVE_V2*	1.1 [13]	pu based on DER nominal AC voltage
Voltage Active Power Mode Open Loop Response Time	*PV_OLRT*	10 [13]	s
High voltage must trip curve point OV2 voltage setting.	*OV2_TRIP_V*	1.2 [13]	pu based on DER nominal AC voltage

Table 5 (continued). Function setting variables

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit
High voltage must trip curve point OV2 duration setting	$OV2\_TRIP\_T$	0.16 [13]	s
High voltage must trip curve point OV1 voltage setting.	$OV1\_TRIP\_V$	1.1 [13]	pu based on DER nominal AC voltage
High voltage must trip curve point OV1 duration setting	$OV1\_TRIP\_T$	2 for CAT_I 2 for CAT_II 13 for CAT_III [13]	s
Low voltage must trip curve point UV1 voltage setting.	$UV1\_TRIP\_V$	0.7 for CAT_I 0.7 for CAT_II 0.88 for CAT_III [13]	pu based on DER nominal AC voltage
Low voltage must trip curve point UV1 duration setting	$UV1\_TRIP\_T$	2 for CAT_I 10 for CAT_II 21 for CAT_III [13]	s
Low voltage must trip curve point UV2 voltage setting.	$UV2\_TRIP\_V$	0.45 for CAT_I 0.45 for CAT_II 0.5 for CAT_III [13]	pu based on DER nominal AC voltage
Low voltage must trip curve point UV2 duration setting	$UV2\_TRIP\_T$	0.16 for CAT_I 0.16 for CAT_II 2 for CAT_III [13]	s
High frequency must trip curve point OF2 voltage setting.	$OF2\_TRIP\_F$	62 [13]	Hz
High frequency must trip curve point OF2 duration setting	$OF2\_TRIP\_T$	0.16 [13]	s
High frequency must trip curve point OF1 voltage setting.	$OF1\_TRIP\_F$	61.2 [13]	Hz
High frequency must trip curve point OF1 duration setting	$OF1\_TRIP\_T$	300 [13]	s
Low frequency must trip curve point UF1 voltage setting.	$UF1\_TRIP\_F$	58.5 [13]	Hz
Low frequency must trip curve point UF1 duration setting	$UF1\_TRIP\_T$	300 [13]	s

Table 5 (continued). Function setting variables

Variable Name	Variable Label	Default value in DER Model if not specified otherwise	Unit
Low frequency must trip curve point UF2 voltage setting.	$UF2\_TRIP\_F$	56.5 [13]	Hz
Low frequency must trip curve point UF2 duration setting	$UF2\_TRIP\_T$	0.16 [13]	s
Over frequency deadband offset from nominal frequency	PF_DBOF	0.036 [13]	Hz
Under frequency deadband offset from nominal frequency	PF_DBUF	0.036 [13]	Hz
Over frequency per unit frequency change corresponding to a 1 per unit power change (frequency-droop)	PF_KOF	0.05 [13]	n/a (power pu based on DER nominal active power rating, and frequency pu based on DER nominal frequency)
Under frequency per unit frequency change corresponding to a 1 per unit power change (frequency-droop)	PF_KUF	0.05 [13]	n/a (power pu based on DER nominal active power rating, and frequency pu based on DER nominal frequency)
Frequency-Active power open-loop response time	PF_OLRT	5 [13]	s

Table 6. Operating condition inputs to the DER model

Variable Name	Variable Label	Unit
Available DC power (for PV DER, from PV panel, DC optimizer, etc.)	p_dc_w	W
Active power demand (for BESS DER)	p_dem_w	W
Single-phase RMS voltage at RPA of DER (if single-phase DER)	v	Volt (RMS)
Voltage phase angle at RPA (if single-phase DER)	$theta$	Radian
Three-phase line-to-ground RMS voltage at RPA (if three-phase DER)	$[v\_a, v\_b, v\_c]$	Volt (RMS)
Three-phase line-to-ground voltage phase angles at RPA (if three-phase DER)	$[theta\_a, theta\_b, theta\_c]$	Radian
Frequency at RPA	$freq\_hz$	Hz

2.4. Outputs of IEEE 1547-2018 OpenDER Model

As discussed in section 2.1, all IEEE 1547-2018 requirements apply at the RPA of the DER. Thus, the output values of the DER model measured at RPA should match with the requirements in IEEE 1547-2018.

Different system analysis requires different levels of details of the simulation software and DER model. For example, steady-state power flow simulation may only require active and reactive power output from the DER model, whereas fault current contribution simulation may require current output from each individual phase from the DER model. With the intention to cover most of the simulation types and use cases, the OpenDER model provides multiple options to generate different types of outputs. In this way, the model developer may choose the right option(s) for their own development considering the simulation and/or analysis needs.

In Version 2.1 release, the options for OpenDER model output include:

- Power source: total active and reactive power from DER, in per unit, Watts/vars, and kW/kvar
- Current source: phasor current magnitudes and phase angles for individual phases
- Voltage source behind a preset impedance that represents the DER inverter filter and potentially DER interconnection transformer: phasor voltage magnitudes and phase angles for individual phases.

The development effort may extend to EMT simulation to provide instantaneous values of the output current or voltage for more detailed studies after major planned model releases.

3. DETAILED DER MODEL SPECIFICATIONS

This chapter provides detailed DER model specifications, with equations and block diagrams. Each section in this chapter describes a module of the OpenDER Model, with clearly defined input, output, internal, and internal state variables[18]. With the modular modeling approach in mind, variations of each module will be provided in future versions of the DER model.

Three subsections are provided for most of the modules:

- Modeling based on IEEE 1547-2018 requirements
- Modeling specifically for PV DER
- Modeling specifically for BESS DER
- If creating a PV DER model, subsection 1 and 2 should be used. If creating a BESS DER model, subsection 1 and 3 should be used.

3.1. Default Model Inputs Generation

As defined in section 2.3, inputs of the DER nameplate values and control settings information are required for model initialization. Default values are provided for some of the model parameters in Table 3, Table 4 and Table 5. If not modified by the user, these default values defined in the tables shall be used.

The DER model should generate the parameters values which were not provided by the user, based on the existing input. For example, if the DER's normal operating performance category ($NP\_NORMAL\_OP\_CAT$) is category A (CAT_A), the volt-var curve V1 (QV_CURVE_V1) should be populated as 0.9, as the default value defined in IEEE 1547-2018 Clause 5.3.3.

3.2. Model Inputs Validity Check

The model should evaluate its inputs to make sure they are valid. Various checks are performed for nameplate values (Table 7), defined variables to describe DER model behavior (Table 8), BESS specific variables (Table 9), control settings (Table 10), and operating conditions (Table 11). The "purpose" column can also be used as the prompt when the DER model detects violations from the validity checks. These checks are designed to:

- Identify input errors that may break the model calculation, yellow highlighted in the tables.
- Inform users that the settings are outside of IEEE 1547-2018 defined/allowed ranges.

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[18] Internal state variables indicate the variables that store the value of certain variable in the previous timestep. These variables need to be initialized with certain predefined values, for DER model to be properly executed.

For the input errors that may break the model (yellow highlighted rows), an Error message should be generated. And the model should not be executed. If the settings are outside of the IEEE 1547-2018 allowed range, a Warning message should be generated. And the model should be allowed to continue to operate.

Parameter type and value of string inputs should also be checked, which are not included in the tables. For example, volt-var mode enable signal (QV_MODE_ENABLE) should only take "ENABLED" or "DISABLED", and volt-var mode voltage curve point 1 (QV_CURVE_V1) should only take floating point values as input. Violation should be treated as input errors.

If the model inputs are provided at the beginning of the simulation, the validity check is only performed once at model initiation. If the model inputs are acquired during the simulation through user interface or communication, the received values should also be checked.

Table 7. Validity checks for nameplate values

Purpose	Checks performed
DER nameplate ratings should be greater than 0,	$NP\_P\_MAX > 0$ $NP\_P\_MAX\_CHARGE \geq 0$ $NP\_VA\_MAX > 0$ $NP\_APPARENT\_POWER\_MAX\_CHARGE \geq 0$ $NP\_Q\_MAX\_ABS > 0$ $NP\_Q\_INJ\_ABS > 0$
DER nameplate active power rating should be less than or equal to DER nameplate apparent power rating.	$NP\_P\_MAX \leq NP\_VA\_MAX$
For category A DER, its nameplate reactive power absorption rating should be equal to or greater than 25%, and less than 100% of nameplate apparent power rating.	If $NP\_NORMAL\_OP\_CAT = CAT\_A$: $0.25 \times NP\_VA\_MAX \leq NP\_Q\_MAX\_ABS \leq NP\_VA\_MAX$
For category B DER, its nameplate reactive power absorption rating should be equal to or greater than 44%, and less than 100% of nameplate apparent power rating.	If $NP\_NORMAL\_OP\_CAT = CAT\_B$: $0.44 \times NP\_VA\_MAX \leq NP\_Q\_MAX\_ABS \leq NP\_VA\_MAX$
Regardless DER's category, its nameplate reactive power injection rating should be equal to or greater than 44%, and less than 100% of nameplate apparent power rating.	$0.44 \times NP\_VA\_MAX \leq NP\_Q\_MAX\_INJ \leq NP\_VA\_MAX$
By definition, power factor cannot be greater than 1 or less than 0.	$0 \leq NP\_OVER\_PF \leq 1$ $0 \leq NP\_UNDER\_PF \leq 1$
DER nameplate voltage should be greater than 0.	$NP\_AC\_V\_NOM > 0$

Table 8. Validity checks for settings that are defined to describe DER model behavior

Purpose	Checks Performed
DER Efficiency should be greater than 0, and less than or equal to 1.[19]	$0 < NP\_EFFICIENCY \leq 1$
For PV DER: DER minimum active power should be greater or equal to 0, and less than 1	For PV DER: $0 \leq NP\_P\_MIN\_PU < 1$
For BESS DER: DER minimum active power should be less than 0	For BESS DER: $NP\_P\_MIN\_PU < 0$
DER reactive capability curve defined by $NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ should be greater than or equal to the range defined in IEEE 1547-2018 Clause 5.2	The capability curve defined by $NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ should be greater than or equal to the curve defined by:[20] if $NP\_NORMAL\_OP\_CAT{=}CAT\_A$: [0 0.0499999, 0.05, 0.2, 1] ($P\_Q\_INJ\_PU$), [0 0 0.11, 0.44, 0.44] ($Q\_MAX\_INJ\_PU$), [0 0.0499999, 0.05, 0.2, 1] ($P\_Q\_ABS\_PU$), [0 0 0.0625, 0.25, 0.25] ($Q\_MAX\_ABS\_PU$). Or if $NP\_NORMAL\_OP\_CAT{=}CAT\_B$ [0 0.0499999, 0.05, 0.2, 1] ($P\_Q\_INJ\_PU$), [0 0 0.11, 0.44, 0.44] ($Q\_MAX\_INJ\_PU$), [0 0.0499999, 0.05, 0.2, 1] ($P\_Q\_ABS\_PU$), [0 0 0.11, 0.44, 0.44] ($Q\_MAX\_ABS\_PU$)
DER reactive capability curve defined by $NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ is greater than the nameplate values $NP\_Q\_MAX\_INJ$ and $NP\_Q\_MAX\_INJ$.	The capability curve defined by $NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ should be smaller than nameplate values $NP\_Q\_MAX\_INJ$ and $NP\_Q\_MAX\_INJ$.
Active power limit function response time should be greater than or equal to 0, and smaller than or equal to 30 seconds, according to IEEE 1547-2018 Clause 4.6.2.	$0 \leq AP\_RT \leq 30$
Constant power factor function response time should be greater than or equal to 0, and smaller than or equal to 10 seconds, according to IEEE 1547-2018 Clause 5.3.2.	$0 \leq CONST\_PF\_RT \leq 10$
Watt-var function response time should be greater than or equal to 0, and smaller than or equal to 10 seconds, according to IEEE 1547-2018 Clause 5.3.4.	$0 \leq QP\_RT \leq 10$

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[19] For actual DER, its efficiency cannot be 100% or 1. For modeling simplicity, efficiency can be set as 1.

[20] This can be examined by sweeping through the possible DER output power and check all the points on the capability curve are greater than or equal to the standard requirements.

Table 8 (continued). Validity checks for settings that are defined to describe DER model behavior

Purpose	Checks Performed
Constant reactive power function response time should be greater than or equal to 0, and smaller than or equal to 10 seconds, according to IEEE 1547-2018 Clause 5.3.5.	$0 \le CONST\_Q\_RT \le 10$
Mode and setting change execution delay time should be greater than or equal to 0, and smaller than or equal to 30 seconds, according to IEEE 1547-2018 Clause 4.6.3.	$0 \le NP\_SET\_EXE\_TIME \le 30$
Time for DER to smoothly transition between reactive power support modes should be greater than or equal to 5 seconds, and smaller than or equal to 300 seconds, according to IEEE 1547-2018 Clause 4.6.3.	$5 \le NP\_MODE\_TRANSITION\_TIME \le 300$
Typical range of DER voltage measurement time constant is between 0.02 and 0.05 s, according to WECC REEC_* models. The $NP\_V\_MEAS\_DELAY$ parameter in OpenDER implementation is defined as 2.3 times of the T_{rv} parameter in the WECC REEC_* model	$0 \le NP\_V\_MEAS\_DELAY \le 0.13$
The DER voltage source resistance is expected to be greater than 0. Typical range of the DER voltage source resistance is between 0 and 0.01, according to WECC REGC_B/C models.	$0 \le NP\_RESISTANCE \le 0.01$
Typical range of the DER voltage source reactance is between 0.0 and 0.2, according to WECC REGC_B/C models	$0.05 \le NP\_REACTANCE \le 0.2$
DER maximum output current must be greater than 1 per unit	$1 \le NP\_CURRENT\_PU$
IEEE 1547-2018 requires the DER to restore its active current to 80% of pre-disturbance active current level within 0.4s. Thus, the ride-through recovery time should be greater than 0.5s per its definition by OpenDER.	$0 \le NP\_RT\_RAMP\_UP\_TIME \le 0.5$
Typical range of DER inverter control delay is between 0.02 and 0.05 s, according to WECC REGC_B model. The NP_INV_DELAY parameter in OpenDER implementation is defined as 2.3 times of the T_g parameter in the WECC REGC_B model	$0 \le NP\_INV\_DELAY \le 0.13$
IEEE 1547-2018 requires the maximum response time of Momentary Cessation for low- and high-voltage ride-through is 0.083s	$0 \le MC\_RESP\_T \le 0.083$
IEEE 1547-2018 requires the DER to restore 80% of its pre-disturbance active current within 0.4 s.	$0 \le MC\_RETURN\_T \le 0.4$
IEEE 1547-2018 requires the maximum response time of Cease to Energize for low- and high-voltage ride-through is 0.16s	$0 \le NP\_CTE\_RESP\_T \le 0.16$
IEEE P1547 Draft 0.4 proposes to add configurable limitations of volt-var automatic volt-var adjustment mode	$0.88 \le QV\_VREF\_MIN \le 0.98$ $1.02 \le QV\_VREF\_MAX \le 1.1$

Table 9. Validity checks for BESS DER specific variables

Purpose	Checks Performed
Maximum Operational State of Charge should be less than or equal to 1	$0 \leq NP\_BESS\_MAX\_SOC \leq 1$
Minimum Operational State of Charge should be less than or equal to 1	$0 \leq NP\_BESS\_MIN\_SOC \leq 1$
BESS normal operation ramp time should be greater than 0	$NP\_BESS\_P\_RAMP\_TIME > 0$

Table 10. Validity checks for control settings

Purpose	Checks Performed
For PV DER, Active power limit function per unit setpoint should be greater than or equal to 0, and smaller than or equal to 1.	$0 \leq AP\_LIMIT \leq 1$
For BESS DER, Active power limit function per unit setpoint should be greater than or equal to 0, and smaller than or equal to 1.	$-1 \leq AP\_LIMIT \leq 1$
Minimum and maximum applicable voltage for enter service criteria should be within the ranges defined in IEEE 1547-2018 Clause 4.10.2	$0.88 \leq ES\_V\_LOW \leq 0.95$ $1.05 \leq ES\_V\_HIGH \leq 1.06$
Minimum and maximum applicable frequency for enter service criteria should be within the ranges defined in IEEE 1547-2018 Clause 4.10.2	$59.0 \leq ES\_F\_LOW \leq 59.9$ $60.1 \leq ES\_F\_HIGH \leq 61.0$
Minimum intentional delay before initiating softstart should be greater than or equal to 0, and smaller than or equal to 600 s, according to IEEE 1547-2018 Clause 4.10.3	$0 \leq ES\_DELAY \leq 600$
If enabled, maximum time for enter service randomized delay should be greater than or equal to 1, and smaller than or equal to 1000 s, according to IEEE 1547-2018 Clause 4.10.3. Randomized delay is only applicable for DERs less than 500kVA	$(1 \leq ES\_RANDOMIZED\_DELAY \leq 1000$ and $NP\_VA\_MAX < 500)$ or $ES\_RANDOMIZED\_DELAY = 0$
Enter service randomized delay and ramp are mutually exclusive. They cannot be enabled together	$ES\_RANDOMIZED\_DELAY = 0$ or $ES\_RAMP\_RATE = 0$
Enter service soft-start duration should be greater than or equal to 1 s, and smaller than or equal to 1000 s, according to IEEE 1547-2018 Clause 4.10.3	$1 \leq ES\_RAMP\_RATE \leq 1000$ or $ES\_RAMP\_RATE = 0$

Table 10 (continued). Validity checks for control settings

Purpose	Checks Performed
Only one of the four reactive power control modes (constant reactive power, constant power factor, volt-var, and watt-var) can be enabled at a time.	If considering ENABLE as 1 and DISABLE as 0: $CONST\_PF\_MODE\_ENABLE + CONSTANT\_Q\_MODE\_ENABLE + QV\_MODE\_ENABLE + QP\_MODE\_ENABLE \leq 1$
Constant power factor function setpoint should be between 0 and 1.	$0 \leq CONST\_PF \leq 1$
V_{ref} adjustment time constant should be greater than or equal to 300, and smaller than or equal to 5000 s, according to IEEE 1547-2018 Clause 5.3.3	$300 \leq QV\_VREF\_TIME \leq 5000$
V/Q Curve V_{Ref} Setting should be greater than or equal to 0.95, and smaller than or equal to 1.05 per unit, according to IEEE 1547-2018 Clause 5.3.3	$0.95 \leq QV\_VREF \leq 1.05$
For the piecewise linear curve setting of volt-var control, the four corner points should have their voltage settings monotonically increasing and within the ranges defined in IEEE 1547-2018 Clause 5.3.3	$1 - 0.18 \leq QV\_CURVE\_V1 \leq QV\_CURVE\_V2 - 0.02$ $1 - 0.03 \leq QV\_CURVE\_V2 \leq 1$ $1 \leq QV\_CURVE\_V3 \leq 1 + 0.03$[21] $QV\_CURVE\_V3 + 0.02 \leq QV\_CURVE\_V4 \leq 1 + 0.18$
Volt-var function reactive power setpoints use DER nameplate apparent power rating as base. The setpoints should be within its nameplate reactive power injection and absorption ratings, and the ranges defined in IEEE 1547-2018 Clause 5.3.3.	$0 \leq QV\_CURVE\_Q1 \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$ $-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QV\_CURVE\_Q2 \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$ $-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QV\_CURVE\_Q3 \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$ $-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QV\_CURVE\_Q4 \leq 0$
Volt-var function open loop response time should be within the range defined in IEEE 1547-2018 Clause 5.3.3	$1 \leq QV\_OLRT \leq 90$

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[21] For Category A DER, *QV_CURVE_V2* and *QV_CURVE_V3* shall be equal to *QV_VREF*. For DER modeling, it is allowed to be different at setting validity check stage.

Table 10 (continued). Validity checks for control settings

Purpose	Checks Performed
For the piecewise linear curve setting of watt-var control, the corner points should have their voltage settings monotonically increasing and within the ranges defined in IEEE 1547-2018 Clause 5.3.4	$-1 \leq QP\_CURVE\_P3\_LOAD \leq QP\_CURVE\_P2\_LOAD - 0.1$ $-0.8 \leq QP\_CURVE\_P2\_LOAD \leq -0.4$ $QP\_CURVE\_P2\_LOAD + 0.1 \leq QP\_CURVE\_P1\_LOAD \leq 0$[22] $NP\_P\_MIN\_PU \leq QP\_CURVE\_P1\_GEN \leq QP\_CURVE\_P2\_GEN - 0.1$ $0.4 \leq QP\_CURVE\_P2\_GEN \leq 0.8$ $QP\_CURVE\_P2\_GEN + 0.1 \leq QP\_CURVE\_P3\_GEN \leq 1$
Watt-var function reactive power setpoints use DER nameplate apparent power rating as base. The setpoints should be within its nameplate reactive power injection and absorption ratings.	$-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QP\_CURVE\_Q1\_LOAD \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$ $-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QP\_CURVE\_Q2\_LOAD \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$ $-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QP\_CURVE\_Q3\_LOAD \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$ $-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QP\_CURVE\_Q1\_GEN \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$ $-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QP\_CURVE\_Q2\_GEN \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$ $-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq QP\_CURVE\_Q3\_GEN \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$

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[22] In IEEE 1547-2018 Table 9, the maximum value for *QP_CURVE_P1_LOAD* is the minimum power that DER can absorb. As most of energy storage DER does not have this limit, it is not defined and checked here. In addition, this check assumes the DER has the same active power rating for charging and discharging.

Table 10 (continued). Validity checks for control settings

Purpose	Checks Performed
Constant reactive power function setpoint uses DER nameplate apparent power rating as base. It should be within its nameplate reactive power injection and absorption ratings.	$-NP\_Q\_MAX\_ABS/NP\_VA\_MAX \leq CONST\_Q \leq NP\_Q\_MAX\_INJ/NP\_VA\_MAX$
For the piecewise linear curve setting of volt-watt control, the two corner points should have their voltage settings monotonically increasing and within the ranges defined in IEEE 1547-2018 Clause 5.4.2	$1.05 \leq PV\_CURVE\_V1 \leq 1.09$ $PV\_CURVE\_V1 + 0.01 \leq PV\_CURVE\_V2 \leq 1.1$
Volt-watt power settings should be within the ranges defined in IEEE 1547-2018 Clause 5.4.2	$PV\_CURVE\_P2 \leq PV\_CURVE\_P1$ [23] If for PV DER: $NP\_P\_MIN\_PU \leq PV\_CURVE\_P2 \leq 1$ If for BESS DER: $-1 \leq PV\_CURVE\_P2 \leq 1$
Volt-watt function open loop response time should be within the range defined in IEEE 1547-2018 Clause 5.4.2	$0.5 \leq PV\_OLRT \leq 60$
Over- and under-voltage must trip curve point time settings should be within the ranges defined in IEEE 1547-2018 Clause 6.4.1	$OV2\_TRIP\_T = 0.16$ $1 \leq OV1\_TRIP\_T \leq 13$ $2 \leq UV1\_TRIP\_T \leq 50$ $0.16 \leq UV2\_TRIP\_T \leq 21$[24]
Over- and under-voltage must trip curve point voltage settings should be within the ranges defined in IEEE 1547-2018 Clause 6.4.1	$OV2\_TRIP\_V = 1.2$ $1.1 \leq OV1\_TRIP\_V \leq 1.2$ $0 \leq UV1\_TRIP\_V \leq 0.88$ $0 \leq UV2\_TRIP\_V \leq 0.5$
Over- and under-frequency must trip curve point time settings should be within the ranges defined in IEEE 1547-2018 Clause 6.5.1	$0.16 \leq OF2\_TRIP\_T \leq 1000$ $180 \leq OF1\_TRIP\_T \leq 1000$ $180 \leq UF1\_TRIP\_T \leq 1000$ $0.16 \leq UF2\_TRIP\_T \leq 1000$

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[23] In IEEE 1547-2018, there is no minimum and maximum range for *PV_CURVE_P1*. A check is added to ensure it is greater than *PV_CURVE_P2* for volt-var control.

[24] For different DER categories, the allowable setting ranges these variables are different. At data validity check stage, the widest range for Category III is used. Note IEEE 1547a-2020 has an amendment to these values.

Table 10 (continued). Validity checks for control settings

Purpose	Checks Performed
Over- and under-frequency must trip curve point frequency settings should be within the ranges defined in IEEE 1547-2018 Clause 6.5.1	$61.8 \leq OF2\_TRIP\_F \leq 66$ $61 \leq OF1\_TRIP\_F \leq 66$ $50 \leq UF1\_TRIP\_F \leq 59$ $50 \leq UF2\_TRIP\_F \leq 57$
Over- and under-frequency deadband offset from nominal frequency settings for frequency-droop function should be within the ranges defined in IEEE 1547-2018 Clause 6.5.2.7.2	$0.017 \leq PF\_DBOF \leq 1$ $0.017 \leq PF\_DBUF \leq 1$
Over- and under-frequency frequency-droop values should be within the ranges defined in IEEE 1547-2018 Clause 6.5.2.7.2	$0.02 \leq PF\_KOF \leq 0.05$ $0.02 \leq PF\_KUF \leq 10$
Frequency-droop function open-loop response time should be within the range defined in IEEE 1547-2018 Clause 6.5.2.7.2	$0.2 \leq PF\_OLRT \leq 10$

Table 11. Validity checks for operating conditions

Purpose	Checks Performed
Available dc power for PV DER should be greater than or equal to 0	$p\_dc\_kw \geq 0$
Voltage magnitude should be greater than or equal to 0	If NP_PHASE=SINGLE: $v \geq 0$
	If NP_PHASE=THREE: $v\_a \geq 0$ $v\_b \geq 0$ $v\_c \geq 0$

3.3. Operating Condition Input Processing

The variable list of DER model operating condition input processing is shown in Table 12. This procedure mainly calculates the applicable voltage to be used by other modules of the DER model, as well as per-unit value of the available DC power for PV or demand active power for BESS.

Table 12. Operating condition input processing calculation variable list

Variable Type	Variable Name	Description
Input	*[v_a, v_b, v_c]*	Three-phase line-to-ground RMS voltage at RPA (if three-phase DER)
	[theta_a, theta_b, theta_c]	Three-phase line-to-ground voltage phase angles at RPA (if three-phase DER)
	v	Single-phase RMS voltage at RPA of DER (if single-phase DER)
	theta	Single-phase voltage phase angle at RPA (if single-phase DER)
	NP_PHASE	Single- or Three-phase DER
	NP_AC_V_NOM	AC voltage base—nominal voltage rating
	p_dc_w	Available DC power (from PV panel, DC optimizer, etc.)
	p_dem_w	Active power demand (for BESS DER)
	NP_P_MAX	Active power rating at unity power factor
	NP_V_MEAS_DELAY	DER voltage measurement delay
Output	*v_meas_pu*	Applicable voltage for volt-var and volt-watt calculation in per unit
	v_pos_pu	Positive sequence voltage phasor as complex number at RPA
	v_neg_pu	Negative sequence voltage phasor as complex number at RPA
	v_zero_pu	Zero sequence voltage phasor as complex number at RPA
	v_angle	Voltage angle at RPA in radian
	v_high_pu	Maximum applicable voltage as enter service, over voltage trip criterion in per unit
	v_low_pu	Minimum applicable voltage as enter service, over voltage trip criterion in per unit
	p_avl_pu	DER available active power in per unit considering efficiency
	p_dem_pu	BESS DER active power demand in per unit

Table 12 (continued). Operating condition input processing calculation variable list

Variable Type	Variable Name	Description
Internal variable	v_a_pu	Phase a to ground voltage magnitude in per unit based on $NP\_AC\_V\_NOM/\sqrt{3}$
	v_b_pu	Phase b to ground voltage magnitude in per unit based on $NP\_AC\_V\_NOM/\sqrt{3}$
	v_c_pu	Phase c to ground voltage magnitude in per unit based on $NP\_AC\_V\_NOM/\sqrt{3}$
	v_ab_pu	Phase a to phase b voltage magnitude in per unit based on $NP\_AC\_V\_NOM$
	v_bc_pu	Phase b to phase c voltage magnitude in per unit based on $NP\_AC\_V\_NOM$
	v_ca_pu	Phase c to phase a voltage magnitude in per unit based on $NP\_AC\_V\_NOM$

3.3.1. Modeling Based on IEEE 1547-2018 Requirements

If the DER is three-phase ($NP\_PHASE = \mathrm{THREE}$), it has two options to calculate applicable voltage v_meas_pu for volt-var and volt-watt functions, as IEEE 1547-2018 Clause 4.6.3 requires:

> "For voltage-reactive power (volt-var) mode requirements in 5.3.3 and voltage-active (real) power mode requirements in 5.4.2 where DER do not respond to individual phase voltages, the applicable voltages are quantified as the average of the three-phase effective (RMS) values or alternatively positive sequence component of voltages over one fundamental frequency period."

To calculate the applicable voltages, internal variables are calculated to obtain the phase to neutral voltages in per unit:

$$\begin{aligned} v\_a\_pu &= \frac{\sqrt{3} \times v\_a}{NP\_AC\_V\_NOM} \\ v\_b\_pu &= \frac{\sqrt{3} \times v\_b}{NP\_AC\_V\_NOM} \\ v\_c\_pu &= \frac{\sqrt{3} \times v\_c}{NP\_AC\_V\_NOM} \end{aligned} \qquad (3.3.1\text{-}1)$$

- Then, the positive sequence, negative sequence, zero sequence voltage at RPA, and angle for the positive sequence voltage are calculated for further calculations:

$$\begin{gathered} v\_pos\_pu = \frac{v\_a\_pu \cdot e^{i(theta\_a)} + +v\_b\_pu \cdot e^{i\left(\frac{2}{3}\pi + theta\_b\right)} + v\_c\_pu \cdot e^{i\left(-\frac{2}{3}\pi + theta\_c\right)}}{3} \\ v\_neg\_pu = \frac{v\_a\_pu \cdot e^{i(theta\_a)} + v\_b\_pu \cdot e^{i\left(-\frac{2}{3}\pi + theta\_b\right)} + v\_c\_pu \cdot e^{i\left(\frac{2}{3}\pi + theta\_c\right)}}{3} \\ v\_zero\_pu = \frac{v\_a\_pu \cdot e^{i(theta\_a)} + v\_b\_pu \cdot e^{i(theta\_b)} + v\_c\_pu \cdot e^{i(theta\_c)}}{3} \\ v\_angle = angle(v\_pos\_pu) \end{gathered} \tag{3.3.1-2}$$

- where *angle(X)* indicates the angle of the complex number *X* in polar form[25].
- If the DER responds to the average of the three-phase RMS value, $(NP\_V\_MEAS\_UNBALANCE = AVG)$:

$$v\_meas\_pu = lpf\left(\frac{v\_a\_pu + v\_b\_pu + v\_c\_pu}{3}, NP\_V\_MEAS\_DELAY\right) \tag{3.3.1-3}$$

- If the DER responds to the positive sequence component of voltages, $(NP\_V\_MEAS\_UNBALANCE = POS)$[26]:

$$v\_meas\_pu = lpf(|v\_pos\_pu|, NP\_V\_MEAS\_DELAY) \tag{3.3.1-4}$$

A first order delay (*lpf*) is applied to the applicable voltage for volt-var and volt-watt function, to account for the measurement delay of the voltage magnitude.[27]

On the other hand, IEEE 1547-2018 Clause 6.4.1 requires

> "When any applicable voltage is less than an undervoltage threshold, or greater than an overvoltage threshold, as defined in this subclause, the DER shall cease to energize the Area EPS and trip within the respective clearing time as indicated."

This indicates that the applicable voltage for trip settings should be the minimum value among all applicable voltages for under voltage trip, and maximum value for over voltage trip. Also indicated in IEEE 1547-2018 Clause 4.10.1, enter service criteria examine the maximum and minimum values of the applicable voltage defined in IEEE 1547-2018 Clause 4.3, including phase-to-phase voltages and phase-to-neutral voltages for three-phase DERs.

Thus, phase-to-phase voltages are also calculated as internal variables.

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[25] It is calculated as *angle(X) = arctan(b/a),* if *X = a + bi,* where *i* is the imaginary unit number.

[26] If voltage angles $[theta\_a, theta\_b, theta\_c]$ is the default values [0, -2.0944, 2.0944], the positive sequence component is the same as the average of the three-phase RMS value.

[27] The parameter *NP_V_MEAS_DELAY* is equivalent to 2.3 times of the parameter T_{rv} (Filter time constant for voltage measurement) in WECC Renewable Energy Electrical Control (REEC_*) models.

$$
\begin{aligned}
v\_ab\_pu &= \left|\frac{v\_a\_pu - v\_b\_pu \cdot e^{i(theta\_b - theta\_a)}}{\sqrt{3}}\right| \\
v\_bc\_pu &= \left|\frac{v\_b\_pu - v\_c\_pu \cdot e^{i(theta\_c - theta\_b)}}{\sqrt{3}}\right| \\
v\_ca\_pu &= \left|\frac{v\_c\_pu - v\_a\_pu \cdot e^{i(theta\_a - theta\_c)}}{\sqrt{3}}\right|
\end{aligned}
\tag{3.3.1-5}
$$

And the maximum and minimum applicable voltage are calculated as:

$$
\begin{aligned}
v\_low\_pu &= \min\,(v\_a\_pu, v\_b\_pu, v\_c\_pu, v\_ab\_pu, v\_bc\_pu, v\_ca\_pu) \\
v\_high\_pu &= \max\,(v\_a\_pu, v\_b\_pu, v\_c\_pu, v\_ab\_pu, v\_bc\_pu, v\_ca\_pu)
\end{aligned}
\tag{3.3.1-6}
$$

Note that the calculation assumes the three-phase DER has its RPA either at PCC and the Area electric power system is a three-phase three-wire grounded system, or at PoC and the low-voltage winding configuration of the interconnection transformer is grounded wye.

For other connections, according to IEEE 1547-2018 Clause 4.3, the applicable voltages can be different from the ones specified in equation (3.3.1-6).[28] This may be updated in the future revision of the DER model.

The overall block diagram to calculate applicable voltage for three-phase DER is shown in Figure 3.

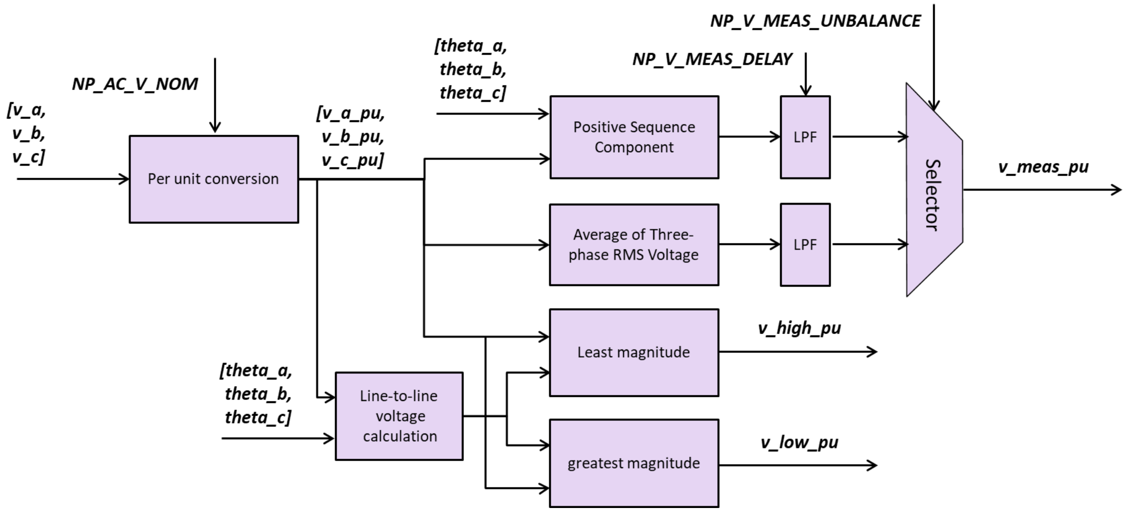

Figure 3. Model structure of to process applicable voltage for three-phase DER

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[28] For example, if the area electric power system at PCC is a three-phase three-wire ungrounded system, phase-to-ground voltages will not be included as applicable voltages.

If the DER is single-phase ($NP\_PHASE = \text{SINGLE}$). The applicable voltages are obtained by:

$$\begin{gathered} v\_meas\_pu = lpf(\frac{v}{NP\_AC\_V\_NOM}, NP\_V\_MEAS\_DELAY) \\ v\_high\_pu = \frac{v}{NP\_AC\_V\_NOM} \\ v\_low\_pu = \frac{v}{NP\_AC\_V\_NOM} \\ v\_pos\_pu = \frac{v}{NP\_AC\_V\_NOM} \cdot e^{i \times theta} \\ v\_neg\_pu = 0 \\ v\_zero\_pu = 0 \\ v\_angle = theta \end{gathered} \tag{3.3.1-7}$$

3.3.2. Modeling for PV DER

For PV DER, this module also calculates available DER power in per unit for other functions to use.

$$p\_avl\_pu = \frac{p\_dc\_w}{NP\_P\_MAX} \times NP\_EFFICIENCY \tag{3.3.2-1}$$

3.3.3. Modeling for BESS DER

Different from PV, BESS DER’s active power output is dependent on the active power demand from system operator or other grid support functions, such as PV smoothing, load following, etc. So instead, a different parameter is used to indicate active power demand in per unit.

$$p\_dem\_pu = \frac{p\_dem\_w}{NP\_P\_MAX} \tag{3.3.3-1}$$

In addition, BESS DER always has active power available when it is in normal operation. So, the DER available power is set to 1.

$$p\_avl\_pu = 1 \tag{3.3.3-2}$$

3.4. Mode and Setting Change Execution Delay

3.4.1. Modeling Based on IEEE 1547-2018 Requirements

IEEE 1547-2018 Clause 4.6.3 requires

> “Transition between modes shall commence in no more than 30 s after the mode setting change is received at the local DER communication interface… For all control and protective function parameter settings, the time following the input to the local DER communication interface and preceding the point in time when the invoked action begins shall be no greater than 30 s.”

This indicates that the DER may not respond to a control mode or setting change immediately and may take a certain duration that is less than 30 s to start to respond. To model this behavior, a mode and setting change execution delay is applied to all the control setting variables defined in Table 5. The variable list of this module is shown in Table 13.

Table 13. Mode and setting change execution delay variable list

Variable type	Variable name	Description
Input variable	AP_LIMIT_ENABLE	Active Power Limit Enable
	AP_LIMIT	Active Power Limit
	$ES\_PERMIT\_SERVICE$	Permit service activated by request from the area EPS operator
	…	All variables in Table 5
Output variable	$ap\_limit\_enable\_exec$	Active Power Limit Enable (AP_LIMIT_ENABLE) after execution delay
	ap_limit_exec	Active Power Limit (AP_LIMIT) after execution delay
	$es\_permit\_service\_exec$	Permit service activated by request from the area EPS operator ($ES\_PERMIT\_SERVICE$) after execution delay
	…	All variables in Table 5, lower cased with *_exec* attached to the end

The output values are determined by the input values, with a time delay of $NP\_SET\_EXE\_TIME$, specified in section 3.12.3. For example:

$$\begin{aligned} ap\_limit\_enable\_exec &= tdelay(AP\_LIMIT\_ENABLE, NP\_SET\_EXE\_TIME) \\ ap\_limit\_exec &= tdelay(AP\_LIMIT, NP\_SET\_EXE\_TIME) \\ es\_permit\_service\_exec &= tdelay(ES\_PERMIT\_SERVICE, NP\_SET\_EXE\_TIME) \end{aligned} \quad (3.4.1\text{-}1)$$

…

All the control variables in Table 5 are processed in this step, the output values have lower case variable names with the term *_exec* attached at the end. The time delay (*tdelay*) auxiliary function is defined in section 3.12.3.

The requirements about mode transitions are addressed and modeled later in section 3.8.1.5.

3.5. DER Operation Status

This module determines the DER operation status *der_status* based on the enter service, trip, and ride-through criteria. The possible DER operation states include: Continuous Operation, Mandatory Operation, Permissive Operation, Momentary Cessation, Cease to Energize, and Trip.

3.5.1. *Modeling Based on IEEE 1547-2018 Requirements*

3.5.1.1. Enter Service Criteria

The variable list of enter service criteria module is shown in Table 14, and the detailed block diagram is provided in Figure 4.

Table 14. Enter service criteria module variable list

Variable Type	Variable Name	Description
Input variable	*v_high_pu*	Maximum applicable voltage as enter service, over voltage trip criterion in per unit
	v_low_pu	Minimum applicable voltage as enter service, over voltage trip criterion in per unit
	freq_hz	Frequency at RPA
	es_v_low_exec	Minimum applicable voltage for enter service criteria (*ES_V_LOW*) signal after execution delay
	es_v_high_exec	Maximum applicable voltage for enter service criteria (*ES_V_HIGH*) signal after execution delay
	es_f_low_exec	Minimum frequency for enter service criteria (*ES_F_LOW*) signal after execution delay
	es_f_high_exec	Maximum frequency for enter service criteria (*ES_F_HIGH*) signal after execution delay
	es_delay_exec	Minimum intentional delay before initiating softstart (*ES_DELAY*) signal after execution delay
	es_permit_service_exec	Permit service activated by request from the area EPS operator (*ES_PERMIT_SERVICE*) after execution delay
	es_randomized_delay_exec	Maximum time for enter service randomized delay (*ES_RANDOMIZED_DELAY*) signal after execution delay
	ES_RANDOMIZED_DELAY_ACTUAL	Specified value for enter service randomized delay for simulation purpose
	es_ramp_rate_exec	Enter service soft-start duration (*ES_RAMP_RATE*) signal after execution delay
	NP_VA_MAX	Apparent power maximum rating

Table 14 (continued). Enter service criteria module variable list

Variable Type	Variable Name	Description
Output variable	*es_crit*	Enter service criteria met
Internal variable	*es_vf_crit*	Enter service voltage and frequency criteria met
	es_vft_crit	Enter service voltage and frequency criteria met for the enter service delay
	es_p_crit	DER output power is greater than the minimum output power
	es_other_crit	Other enter service criteria met
	es_vfto_crit	Enter service voltage and frequency and other enter service criteria met
	es_randomized_delay_time	Enter service randomized delay time (initiated by 0)
Internal state variable	*es_randomized_delay_time_prev*	Value of variable *es_randomized_delay_time* (Enter service randomized delay time) in the previous time step (initiated by 0)

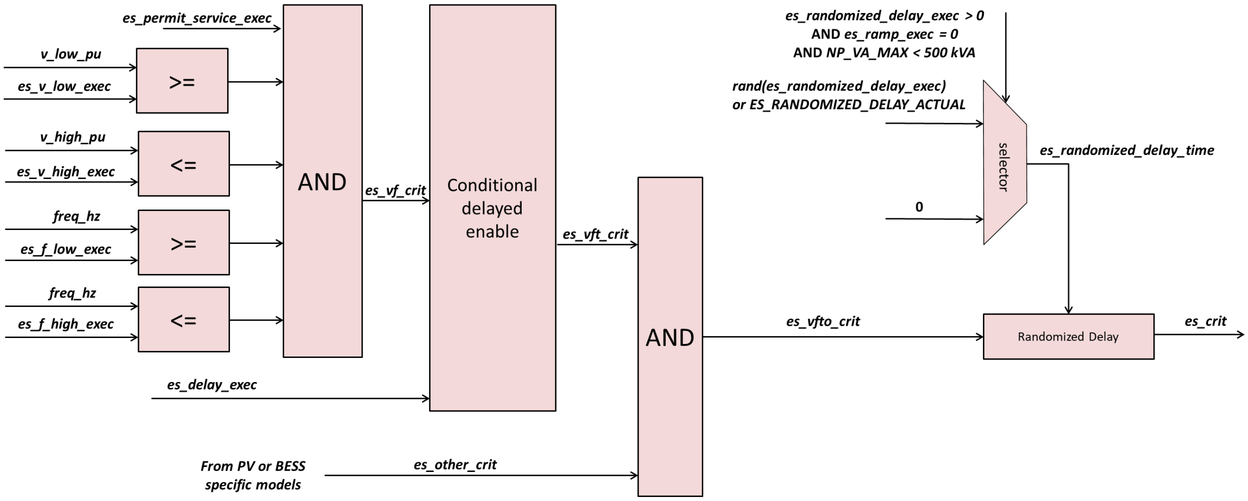

Figure 4. Model structure of enter service criteria

For enter service behavior, an internal variable es_vf_crit is defined to identify whether the DER applicable voltages and frequency are within the permit service range:

$$\begin{gathered} es\_vf\_crit = v\_low\_pu \geq es\_v\_low\_exec \text{ AND } v\_high\_pu \geq es\_v\_high\_exec \\ \text{AND } freq\_hz \geq es\_f\_low\_exec \text{ AND } freq\_hz \geq es\_f\_low\_exec \\ \text{AND } es\_permit\_service\_exec \end{gathered} \quad (3.5.1\text{-}1)$$

If the variable *es_vf_crit* maintains TRUE, i.e., applicable voltage and frequency within range, for the intentional enter service delay time *es_delay_exec*, the defined internal variable *es_vft_crit* can be set to TRUE by conditional delayed enable auxiliary function, specified in section 3.12.4.

$$es\_vft\_crit = con\_del\_enable(es\_vf\_crit, es\_delay\_exec) \qquad (3.5.1\text{-}2)$$

IEEE 1547-2018 does not explicitly require the DER delay the enter service process when the permit service turns to “ENABLED” from “DISABLED”, if the voltage and frequency are already within the range for the intentional delay time. However, in the type test procedure and criteria of IEEE 1547.1-2020 section 5.6, it is mentioned that the DER should not immediately enter service in such a case. Thus, the OpenDER model follows the requirement, and considers $ES\_PERMIT\_SERVICE$ signal as part of the conditional delayed enable block.

The DER shall be allowed to enter service, when the applicable voltage and frequency are within the allowed range, the permit service setting is set to “ENABLED”, and other enter service criteria that is specifically for PV and BESS, discussed in section 3.5.2 and 3.5.3:

$$e\_vfto\_crit = es\_vft\_crit \text{ AND } es\_other\_crit \qquad (3.5.1\text{-}3)$$

IEEE 1547-2018 Clause 4.10.3 specifies an exception to the DER enter service ramp:

> “For Local EPS that have an aggregate DER rating of less than 500 kVA, individual DER units may increase output of active power with no limitation of the rate-of-change, following an additional randomized time delay with a default maximum time random interval of 300 s, and with an adjustable range for the maximum time random interval of 1 s to 1000 s.”.

This indicates that for DER sized smaller than 500kW, the standard allows it to have a randomized delay, in addition to the intentional delay specified by variable ES_DELAY.

Thus, if the DER is smaller than 500 kVA ($NP\_VA\_MAX < 500$), randomized delay is enabled ($es\_randomized\_delay\_exec > 0$), and enter service ramp is disabled ($es\_ramp\_rate\_exec = 0$), a randomized time delay is directly applied to the resultant signal es_crit which indicates the enter service criteria are met. Since the randomized delay time $es\_randomized\_delay\_time$ should be different every time DER enters service, it is recalculated once every time the DER is OFF and keep the value until the DER is turned ON. A random value generator is used in the model implementation, noted as random(0, 1), which should yield a *random* number between 0 and 1.

Only for simulation purpose, a specified value for the randomized delay $ES\_RANDOMIZED\_DELAY\_ACTUAL$ is also provided in the model. If a specified value is provided by the user, the model will use the given value as the randomized delay, such that every time the DER model takes a definitive amount of time to enter service, in order to analyze the worst-case scenarios. This variable is set to FALSE after the DER enters service. This is to avoid the time delay component creating conflict commands with DER trip decision.

If the DER is greater than 500kVA, or the randomized delay is not available, the delay time is set to 0, indicating there is no additional delay for entering service.

$$es\_randomized\_delay\_time = \begin{cases} 0 & \text{if } der\_status \neq \text{"Trip"} \\ ES\_RANDOMIZED\_DELAY\_ACTUAL & \text{If } es\_vfto\_crit \ = \text{TRUE} \\ & \text{AND } ES\_RANDOMIZED\_DELAY\_ACTUAL > 0 \\ & \text{AND } der\_status = \text{"Trip"} \\ random(0,1) \times es\_randomized\_delay\_exec & \text{if } es\_randomized\_delay\_exec > 0 \\ & \text{AND } es_{ramp_{rate_{exec}}} = 0 \text{ AND } NP_{VA_{MAX}} < 500 \\ & \text{AND } es\_randomized\_delay\_time\_prev = 0 \\ & \text{AND } der\_status = \text{"Trip} \\ es\_randomized\_delay\_time\_prev & \text{if } es\_randomized\_delay\_exec > 0 \\ & \text{AND } es\_ramp\_rate\_exec = 0 \text{ AND } NP\_VA\_MAX < 500 \\ & \text{AND } es\_randomized\_delay\_time\_prev \neq 0 \\ & \text{AND } der\_status = \text{"Trip"} \\ 0 & \text{otherwise} \end{cases} \tag{3.5.1-4}$$

$$es\_crit = \ tdelay(es\_vfto\_crit, es\_randomized\_delay\_time) \tag{3.5.1-5}$$

The standard does not have clear guidance on whether in this randomized delay period, the enter service voltage and frequency range criteria shall or shall not take effect. So, in this version of DER model, a randomized delay is applied as a time delay at the end of enter service criteria decision point. If the DER also performs enter service voltage and frequency checks during the randomized delay period, the DER model can be modified by adding the same delay logic to the enter service delay time es_delay_exec. The modeling may be updated in future versions according to lab test results.

Also, if there are multiple DER units within a DER plant, each DER unit will have its own randomized enter service delay, which will not be the same across all the DER units within the plant. For such a DER plant, multiple instances of the DER model shall be used connected in parallel to the RPA of the DER plant in simulation.

3.5.1.2. Trip Criteria

The variable list of trip criteria module is shown in Table 15, and the detailed block diagram is provided in Figure 5.

Table 15. Trip criteria module variable list

Variable Type	Variable Name	Description
Input variable	*v_high_pu*	Maximum applicable voltage as enter service, over voltage trip criterion in per unit
	v_low_pu	Minimum applicable voltage as enter service, over voltage trip criterion in per unit
	freq_hz	Frequency at RPA
	es_permit_service_exec	Permit service activated by request from the area EPS operator (*ES_PERMIT_SERVICE*) after execution delay
	ov2_trip_v_exec	High voltage must trip curve point OV2 voltage setting (*OV2_TRIP_V*) signal after execution delay
	ov2_trip_t_exec	High voltage must trip curve point OV2 duration setting (*OV2_TRIP_T*) signal after execution delay
	ov1_trip_v_exec	High voltage must trip curve point OV1 voltage setting (*OV1_TRIP_V*) signal after execution delay
	ov1_trip_t_exec	High voltage must trip curve point OV1 duration setting (*OV1_TRIP_T*) signal after execution delay
	uv1_trip_v_exec	Low voltage must trip curve point UV1 voltage setting (*UV1_TRIP_V*) signal after execution delay
	uv1_trip_t_exec	Low voltage must trip curve point UV1 duration setting (*UV1_TRIP_T*) signal after execution delay
	uv2_trip_v_exec	Low voltage must trip curve point UV2 voltage setting (*UV2_TRIP_V*) signal after execution delay
	uv2_trip_t_exec	Low voltage must trip curve point UV2 duration setting (*UV2_TRIP_T*) signal after execution delay
	of2_trip_f_exec	High frequency must trip curve point OF2 voltage setting (*OF2_TRIP_V*) signal after execution delay
	of2_trip_t_exec	High frequency must trip curve point OF2 duration setting (*OF2_TRIP_T*) signal after execution delay

Table 15 (continued). Trip criteria module variable list

Variable Type	Variable Name	Description
Input variable	*of1_trip_f_exec*	High frequency must trip curve point OF1 voltage setting (*OF1_TRIP_V*) signal after execution delay
	of1_trip_t_exec	High frequency must trip curve point OF1 duration setting (*OF1_TRIP_T*) signal after execution delay
	uf1_trip_f_exec	Low frequency must trip curve point UF1 voltage setting (*UF1_TRIP_V*) signal after execution delay
	uf1_trip_t_exec	Low frequency must trip curve point UF1 duration setting (*UF1_TRIP_T*) signal after execution delay
	uf2_trip_f_exec	Low frequency must trip curve point UF2 voltage setting (*UF2_TRIP_V*) signal after execution delay
	uf2_trip_t_exec	Low frequency must trip curve point UF2 duration setting (*UF2_TRIP_T*) signal after execution delay
	NP_P_MIN_PU	DER minimum active power output
	p_avl_pu	DER available active power in per unit considering efficiency
Output variable	*trip_crit*	Trip criteria met
Internal variable	*uv1_trip*	DER trip criteria met due to under voltage must trip setting 1 (UV1)
	uv2_trip	DER trip criteria met due to under voltage must trip setting 2 (UV2)
	ov1_trip	DER trip criteria met due to over voltage must trip setting 1 (OV1)
	ov2_trip	DER trip criteria met due to over voltage must trip setting 2 (OV2)
	uf1_trip	DER trip criteria met due to under frequency must trip setting 1 (UF1)
	uf2_trip	DER trip criteria met due to under frequency must trip setting 2 (UF2)
	of1_trip	DER trip criteria met due to over frequency must trip setting 1 (OF1)
	of2_trip	DER trip criteria met due to over frequency must trip setg 2 (OF2)
	p_min_trip	DER trip criteria met due to non-sufficient available power
	other_trip	Other trip criteria in addition to voltage and frequency trips

There are multiple sections in IEEE 1547-2018 that requires the DER to trip, as shown in Table 16. In the V2.1 edition of OpenDER, grey shaded requirements are modeled. Others will be considered in later releases.

Table 16. Trip requirements specified in IEEE 1547-2018

IEEE 1547-2018 Section #	Trip Condition	Trip Time Requirements
4.6.1 Capability to disable permit service	If permit service setting is disabled	No more than 2 s
6.2.1 Area EPS faults	If short-circuit faults on the Area EPS circuit section to which the DER is connected	N/A
6.2.2 Open phase conditions	If any open phase condition occurring directly at the reference point of applicability (RPA)	No more than 2 s
6.4.1 Mandatory voltage tripping requirements	If any of the applicable voltages at RPA exceeds the mandatory trip setting defined in IEEE 1547-2018 Table 11-13[29]	Minimum trip time: 0.16 s for OV2 (1.2 Vpu). Can be adjusted according to IEEE 1547-2018 Table 11-13[29]
6.5.1 Mandatory frequency tripping requirements	If the frequency at RPA exceeds the mandatory trip setting defined in IEEE 1547-2018 Table 18	Minimum trip time: 0.16 s for OF2 and UF2. Can be adjusted according to IEEE 1547-2018 Table 18
7.4.1 Limitation of overvoltage over one fundamental frequency period[30]	The DER shall not contribute to fundamental frequency overvoltages exceed 138%	No more than a duration exceeding one fundamental frequency period.
7.4.2 Limitation of cumulative instantaneous overvoltage[30]	The DER shall not cause the instantaneous voltage on any portion of the Area EPS to exceed the magnitudes and cumulative durations shown in IEEE 1547-2018 Figure 3.	166 ms for 1.3 Vpu … 1.6 ms for 2 Vpu
8.1 Unintentional islanding	If an unintentional island in which the DER energizes a portion of the Area EPS through the PCC	No more than 2 s, can be extended to as much as 5 s upon mutual agreement

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[29] IEEE 1547 amendment in 2020 has changed allowed range for trip time for Table 13.

[30] The standard does not specifically require inverter to trip for these conditions. Inverter may trip to meet the requirements.

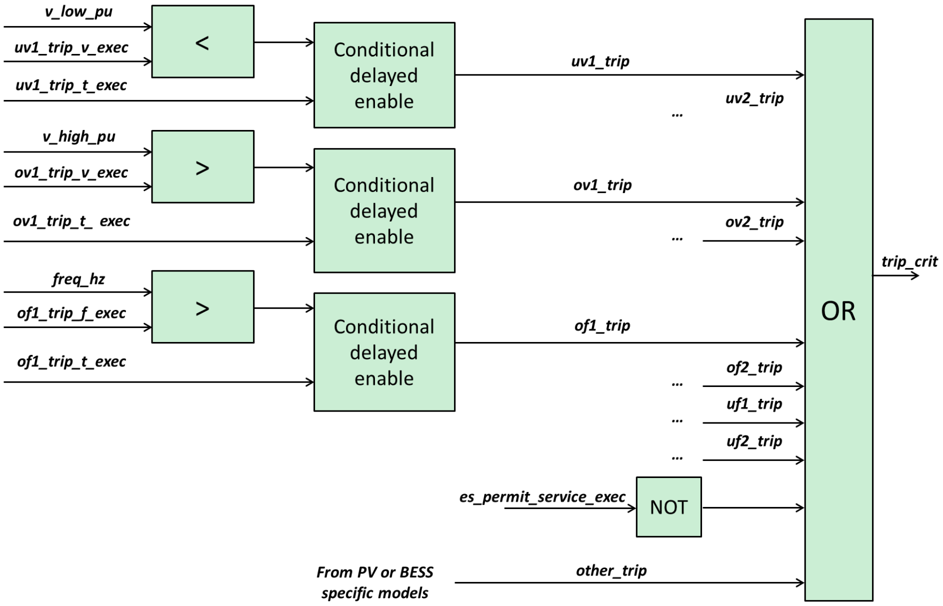

Figure 5. Model structure of trip criteria

For DER abnormal voltage and frequency trip criteria, multiple internal variables are defined to indicate the criterion. For over-voltage, under-voltage, over-frequency, and under-frequency behaviors, conditional delayed enable auxiliary function is used:

$$\begin{aligned}
uv1\_trip &= con\_del\_enable(v\_low\_pu < uv1\_trip\_v\_exec, uv1\_trip\_t\_exec)\\
uv2\_trip &= con\_del\_enable(v\_low\_pu < uv2\_trip\_v\_exec, uv2\_trip\_t\_exec)\\
ov1\_trip &= con\_del\_enable(v\_high\_pu > ov1\_trip\_v\_exec, uv1\_trip\_t\_exec)\\
ov2\_trip &= con\_del\_enable(v\_high\_pu > ov2\_trip\_v\_exec, uv2\_trip\_t\_exec)\\
uf1\_trip &= con\_del\_enable(freq\_hz < uf1\_trip\_f\_exec, uf1\_trip\_t\_exec)\\
uf2\_trip &= con\_del\_enable(freq\_hz < uf2\_trip\_f\_exec, uf2\_trip\_t\_exec)\\
of1\_trip &= con\_del\_enable(freq\_hz > of1\_trip\_f\_exec, uf1\_trip\_t\_exec)\\
of2\_trip &= con\_del\_enable(freq\_hz > of2\_trip\_f\_exec, uf2\_trip\_t\_exec)
\end{aligned} \tag{3.5.1-6}$$

The OpenDER models trip criteria to be: when there is abnormal voltage or frequency, permit service setting is disabled, or other trip criteria that are specifically for PV or BESS DER, discussed in section 3.5.2 and 3.5.3.

$$\begin{aligned}
trip\_crit = {} & uv1\_trip \text{ OR } uv2\_trip \text{ OR } ov1\_trip \text{ OR } ov2\_trip\\
& OR\ uf1\_trip \text{ OR } uf2\_trip \text{ OR } of1\_trip \text{ OR } of2\_trip\\
& \text{OR } other\_trip \text{ OR } (\text{NOT } es\_permit\_service\_exec)
\end{aligned} \tag{3.5.1-7}$$

Note that for actual DERs, there are more trip mechanisms than the ones specified above. For example, IEEE 1547-2018 Clause 6.4.2.5 allows the DER to trip under consecutive voltage disturbances that are within the ride-through settings. These behaviors are not modeled in this version yet and may be included in future revisions.

3.5.1.3. Abnormal Voltage and Frequency Ride-Through Criteria

IEEE 1547-2018 Clause 6.4.2 requires

> "DER shall be designed to provide the voltage disturbance ride-through capability specified in this clause without exceeding DER capabilities."

In addition, IEEE 1547-2018 Clause 6.5.2 requires

> "DER shall be designed to provide the frequency disturbance ride-through capability specified in this clause without exceeding DER capabilities."

Depending on its abnormal operating performance category, the standard has different voltage and frequency ride-through performance requirements. This module determines the DER to operate in the different operating modes/responses defined for voltage and frequency ride-through, including Continuous Operation, Mandatory Operation, Permissive Operation, Momentary Cessation, and Cease to Energize. The parameter list is shown in Table 17.

Table 17. Determining ride-through criteria variable list

Variable type	Variable name	Description
Input variable	v_high_pu	Maximum applicable voltage as enter service, over voltage trip criterion in per unit
	v_low_pu	Minimum applicable voltage as enter service, over voltage trip criterion in per unit
	$freq\_hz$	Frequency at RPA
	$NP\_ABNORMAL\_OP\_CAT$	DER Abnormal operating performance category
	MC_ENABLE	Momentary cessation enable
	MC_HVRT_V1	Momentary cessation high voltage threshold
	MC_LVRT_V1	Momentary cessation low voltage threshold
Output variable	rt_mode_v	DER voltage ride-through performance mode.
	rt_mode_f	DER frequency ride-through performance mode.
	$rt\_pass\_time\_req$	Flag indicating the minimum ride-through time has passed, and the DER is in the "may ride-through and may trip" region
Internal variable	rt_time_lv	Low voltage ride through timer
	rt_time_hv	High voltage ride through timer
	rt_time_lf	Low frequency ride through timer
	rt_time_hf	High frequency ride through timer

IEEE 1547-2018 has defined the performance operating region as:

> "A region bounded by point pairs consisting of magnitude (voltage or frequency) and cumulative time duration which are used to define the operational performance requirements of the DER."

In addition, IEEE 1547-2018 footnote 81 indicates:

> "Overvoltage and undervoltage events usually occur independently from each other, but may also be initiated by the same event (e.g., after clearing a fault, there may be an overvoltage event due to electromagnetic transients or system dynamic response). Thus, the high-voltage ride-through and the low-voltage ride-through requirements are based on cumulative durations and have to be interpreted independently from each other."

The standard indicates there should be independent timers for high-voltage and low-voltage ride-throughs. But it does not clearly provide guidance on whether each ride-through block should have an independent timer[31]. In this version of OpenDER, it is interpreted that there are two separated timers, one for high-voltage, and one for low-voltage ride-through, and there are two timers for frequency ride-throughs, one for high-frequency, one for low-frequency. The model may be updated based on lab or field testing, or DERMUG discussions.

In addition, the standard has indicated the minimum ride-through time. Once the RPA voltage is at the ride-through range longer than the minimum ride-through time, the DER is allowed to trip. This is shown as the "White area" (may ride-through or may trip) in IEEE 1547-2018 Figure H.7-9. In this version of OpenDER, the DER is assumed to continue to operate in the previous state after passing the minimum ride-through time, until the DER shuts down by the trip decision modeled in section 3.5.1.2. However, a variable, $rt\_pass\_time\_req$, is defined to indicate that the standard defined minimum ride-through time has passed, and the actual DER may trip due to its self-protection mechanisms.

First, the voltage ride-through performance mode rt_mode_v is identified. IEEE 1547-2018 Section 6.4.2 requires:

> "During temporary voltage disturbances, for which the applicable voltage on the phase having the greatest/least voltage magnitude is within the permissive operating region, the DER…"

Thus, the maximum and minimum applicable voltage obtained in Section 3.3 is used to determine the DER voltage ride-through performance mode.

Before each time step, clear the current ride-through mode status. Then, sequentially the program will check for each ride-through conditions. If there is no voltage and frequency

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[31] E.g., it could be interpreted that there is one timer for the whole low-voltage ride-through, or there are three timers for the three blocks ($0.70 \le V < 0.88$, $0.50 \le V < 0.70$, and $V < 0.5$) defined for Category III DER

exceeding the ride-through threshold identified, the DER would be in Continuous Operation mode.

$$rt\_mode\_v = \text{None} \tag{3.5.1-8}$$

- For Category I DER ($NP\_ABNORMAL\_OP\_CAT = CAT\_I$):
  - If maximum RPA voltage is greater than 1.1 pu ($v\_high\_pu > 1.1$):
    The high-voltage ride-through timer starts to count:

    $$rt\_time\_hv \; = rt\_time\_hv + t\_s \tag{3.5.1-9}$$

    - If maximum RPA voltage is smaller than or equal to 1.2 ($v\_high\_pu \le 1.2$), voltage ride-through performance mode is Permissive Operation:

      $$rt\_mode\_v = \text{"Permissive Operation"} \tag{3.5.1-10}$$

      - Otherwise, voltage ride-through performance mode is Cease to Energize:

        $$rt\_mode\_v = \text{"Cease to Energize"} \tag{3.5.1-11}$$

    - Then, the high-voltage ride-through timer is compared against the standard defined minimum ride-through time, to indicate that actual DER is allowed to trip if the time greater than the requirement (if ($rt\_time\_hv \le 1$ and $1.1 < v\_high\_pu \le 1.15$) or ($rt\_time\_hv \le 0.5$ and $1.15 < v\_high\_pu \le 1.175$) or ($rt\_time\_hv \le 0.2$ and $1.175 < v\_high\_pu \le 1.2$)

      $$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-12}$$

  - If minimum RPA voltage is smaller than 0.88 pu ($v\_low\_pu < 0.88$):
    The low-voltage ride-through timer starts to count:

    $$rt\_time\_lv \; = rt\_time\_lv + t\_s \tag{3.5.1-13}$$

    - If minimum RPA voltage is between 0.7 and 0.88 pu ($0.7 \le v\_low\_pu < 0.88$), voltage ride-through performance mode is Mandatory Operation:

      $$rt\_mode\_v = \text{"Mandatory Operation"} \tag{3.5.1-14}$$

      - Then, the low-voltage ride-through timer is compared against the standard (if $rt\_time\_lv > 0.7 + 4 \times (v\_low\_pu - 0.7)$):

        $$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-15}$$

    - If minimum RPA voltage is between 0.5 and 0.7 pu ($0.5 \le v\_low\_pu < 0.7$), voltage ride-through performance mode is Permissive Operation:

      $$rt\_mode\_v = \text{"Permissive Operation"} \tag{3.5.1-16}$$

      - Then, the low-voltage ride-through timer is compared against the standard (if $rt\_time\_lv > 0.16$):

        $$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-17}$$

    - If minimum RPA voltage is less than 0.5 pu ($v\_low\_pu < 0.5$), voltage ride-through performance mode is Cease to Energize:

$$rt\_mode\_v = \text{"Cease to Energize"} \tag{3.5.1-18}$$

  - If maximum RPA voltage is greater than momentary cessation threshold ($v\_high\_pu \geq MC\_HVRT\_V1$), and momentary cessation is enabled (MC_ENABLE = True), voltage ride-through performance mode is momentary cessation:

$$rt\_mode\_v = \text{"Momentary Cessation"} \tag{3.5.1-19}$$

  - If minimum RPA voltage is less than momentary cessation threshold ($v\_low\_pu \leq MC\_LVRT\_V1$), and momentary cessation is enabled (MC_ENABLE = True), voltage ride-through performance mode is momentary cessation:

$$rt\_mode\_v = \text{"Momentary Cessation"} \tag{3.5.1-20}$$

- For Category II DER ($NP\_ABNORMAL\_OP\_CAT = CAT\_II$):
  - If maximum RPA voltage is greater than 1.1 pu ($v\_high\_pu > 1.1$):
    The high-voltage ride-through timer starts to count:

$$rt\_time\_hv = rt\_time\_hv + t\_s \tag{3.5.1-21}$$

    - If maximum RPA voltage is smaller than or equal to 1.2 ($v\_high\_pu \leq 1.2$), voltage ride-through performance mode is Permissive Operation:

$$rt\_mode\_v = \text{"Permissive Operation"} \tag{3.5.1-22}$$

      - Otherwise, voltage ride-through performance mode is Cease to Energize:

$$rt\_mode\_v = \text{"Cease to Energize"} \tag{3.5.1-23}$$

    - Then, the high-voltage ride-through timer is compared against the standard defined minimum ride-through time, to indicate that actual DER is allowed to trip if the time greater than the requirement (if ($rt\_time\_hv \leq 1$ and $1.1 < v\_high\_pu \leq 1.15$) or ($rt\_time\_hv \leq 0.5$ and $1.15 < v\_high\_pu \leq 1.175$) or ($rt\_time\_hv \leq 0.2$ and $1.175 < v\_high\_pu \leq 1.2$)

$$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-24}$$

  - If minimum RPA voltage is smaller than 0.88 pu ($v\_low\_pu < 0.88$):
    The low-voltage ride-through timer starts to count:

$$rt\_time\_lv = rt\_time\_lv + t\_s \tag{3.5.1-25}$$

    - If minimum RPA voltage is between 0.65 and 0.88 pu ($0.65 \leq v\_low\_pu < 0.88$), voltage ride-through performance mode is Mandatory Operation:

$$rt\_mode\_v = \text{"Mandatory Operation"} \tag{3.5.1-26}$$

      - Then, the low-voltage ride-through timer is compared against the standard (if $rt\_time\_lv > 3 + 8.7 \times (v\_low\_pu - 0.65)$):

$$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-27}$$

    - If minimum RPA voltage is between 0.45 and 0.65 pu ($0.45 \leq v\_low\_pu < 0.65$), voltage ride-through performance mode is Permissive Operation:

$$rt\_mode\_v = \text{"Permissive Operation"} \tag{3.5.1-28}$$

      - Then, the low-voltage ride-through timer is compared against the standard (if $rt\_time\_lv > 0.32$):

$$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-29}$$

    - If minimum RPA voltage is between 0.3 and 0.45 pu ($0.3 \leq v\_low\_pu < 0.45$), voltage ride-through performance mode is Permissive Operation:

$$rt\_mode\_v = \text{"Permissive Operation"} \tag{3.5.1-30}$$

      - Then, the low-voltage ride-through timer is compared against the standard (if $rt\_time\_lv > 0.16$):

$$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-31}$$

    - If minimum RPA voltage is less than 0.3 pu ($v\_low\_pu < 0.3$), voltage ride-through performance mode is Cease to Energize:

$$rt\_mode\_v = \text{"Cease to Energize"} \tag{3.5.1-32}$$

  - If maximum RPA voltage is greater than momentary cessation threshold ($v\_high\_pu \geq MC\_HVRT\_V1$), and momentary cessation is enabled (MC_ENABLE = True), voltage ride-through performance mode is momentary cessation:

$$rt\_mode\_v = \text{"Momentary Cessation"} \tag{3.5.1-33}$$

  - If minimum RPA voltage is less than momentary cessation threshold ($v\_low\_pu \leq MC\_LVRT\_V1$), and momentary cessation is enabled (MC_ENABLE = True), voltage ride-through performance mode is momentary cessation:

$$rt\_mode\_v = \text{"Momentary Cessation"} \tag{3.5.1-34}$$

- For Category III DER ($NP\_ABNORMAL\_OP\_CAT = CAT\_III$):
  - If maximum RPA voltage is greater than 1.1 pu ($v\_high\_pu > 1.1$):
    The high-voltage ride-through timer starts to count:

$$rt\_time\_hv = rt\_time\_hv + t\_s \tag{3.5.1-35}$$

    - If maximum RPA voltage is greater than momentary cessation threshold ($v\_high\_pu \geq MC\_HVRT\_V1$), and momentary cessation is enabled (MC_ENABLE = True), voltage ride-through performance mode is momentary cessation:

$$rt\_mode\_v = \text{"Momentary Cessation"} \tag{3.5.1-36}$$

      - Otherwise, the DER should operate in Mandatory Operation mode

$$rt\_mode\_v = \text{"Mandatory Operation"} \tag{3.5.1-37}$$

    - Then, the high-voltage ride-through timer is compared against the standard defined minimum ride-through time, to indicate that actual DER is allowed to trip if the time greater than the requirement (if $rt\_time\_hv \leq 12$)

$$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-38}$$

- If minimum RPA voltage is smaller than 0.88 pu ($v\_low\_pu < 0.88$):
  The low-voltage ride-through timer starts to count:

  $$rt\_time\_lv = rt\_time\_lv + t\_s \tag{3.5.1-39}$$

  - If minimum RPA voltage is between 0.7 and 0.88 pu ($0.7 \leq v\_low\_pu < 0.88$), voltage ride-through performance mode is Mandatory Operation:

    $$rt\_mode\_v = \text{"Mandatory Operation"} \tag{3.5.1-40}$$

    - Then, the low-voltage ride-through timer is compared against the standard (if $rt\_time\_lv > 20$):

      $$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-41}$$

  - If minimum RPA voltage is less than 0.7 pu ($v\_low\_pu < 0.7$), voltage ride-through performance mode is Mandatory Operation:

    $$rt\_mode\_v = \text{"Mandatory Operation"} \tag{3.5.1-42}$$

    - Then, the low-voltage ride-through timer is compared against the standard (if $rt\_time\_lv > 10$):

      $$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-43}$$

  - If minimum RPA voltage is less than momentary cessation threshold (v_low_pu ≤ MC_LVRT_V1), and momentary cessation is enabled (MC_ENABLE = True), voltage ride-through performance mode is Momentary Cessation:

    $$rt\_mode\_v = \text{"Momentary Cessation"} \tag{3.5.1-44}$$

    - Otherwise, the DER should operate in Mandatory Operation mode

      $$rt\_mode\_v = \text{"Mandatory Operation"} \tag{3.5.1-45}$$

    - Then, the low-voltage ride-through timer is compared against the standard (if $rt\_time\_lv > 1$):

      $$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-46}$$

Then, for all DER categories, if the applicable voltage is within 0.88 – 1.1pu, ($v\_low\_pu \geq 0.88$, $v\_high\_pu \leq 1.1$), voltage ride-through performance is in Continuous Condition mode. And the ride-through timers are reset.

$$\begin{gathered} rt\_mode\_v = \text{"Continuous Operation"} \\ rt\_time\_lv = 0 \\ rt\_time\_hv = 0 \end{gathered} \tag{3.5.1-47}$$

Next, frequency ride-through performance mode rt_ $mode$ _f is identified based on the frequency at RPA.

- If frequency is between 58.5 – 61.2 Hz ($58.5 \le freq\_hz \le 61.2$), frequency ride-through performance mode is Continuous Operation, and the ride-through timers are reset:

$$\begin{gathered} rt\_mode\_f = \text{"Continuous Operation"} \\ rt\_time\_hf = 0 \\ rt\_time\_lf = 0 \end{gathered} \tag{3.5.1-48}$$

- If frequency is greater than 61.2 Hz ($freq\_hz > 61.2$), the high-frequency ride-through timer starts to count:

$$rt\_time\_hf = rt\_time\_hf + t\_s \tag{3.5.1-49}$$

  - If frequency is smaller than or equal to 61.8 Hz ($freq\_hz \le 61.8$), frequency ride-through performance mode is Mandatory Operation:

$$rt\_mode\_f = \text{"Mandatory Operation"} \tag{3.5.1-50}$$

    - Otherwise, frequency ride-through performance mode is not defined[32]:

$$rt\_mode\_f = \text{"Not Defined"} \tag{3.5.1-51}$$

  - Then, the high-frequency ride-through timer is compared against the standard (if $rt\_time\_hf > 299$):

$$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-52}$$

- If frequency is smaller than 58.8 Hz ($freq\_hz < 58.8$), the low-frequency ride-through timer starts to count:

$$rt\_time\_lf = rt\_time\_lf + t\_s \tag{3.5.1-53}$$

  - If frequency is greater than or equal to 57.0 Hz ($freq\_hz \ge 57.0$), frequency ride-through performance mode is Mandatory Operation:

$$rt\_mode\_f = \text{"Mandatory Operation"} \tag{3.5.1-54}$$

      - Otherwise, frequency ride-through performance mode is not defined:

$$rt\_mode\_f = \text{"Not Defined"} \tag{3.5.1-55}$$

  - Then, the low-frequency ride-through timer is compared against the standard (if $rt\_time\_lf > 299$):

$$rt\_pass\_time\_req = \text{TRUE} \tag{3.5.1-56}$$

---

[32] In IEEE 1547-2018 Table 19, the “Not Defined” frequency range is > 62.0 Hz, which leaves the frequency range of 61.8 – 62.0 unspecified. In this version of OpenDER, it is assumed that 61.8 is the dividing threshold between Mandatory Operation and No ride-through requirement.

3.5.1.4. Determining DER operation status

This module acts as a finite state machine to determine the DER overall operation status, based on the enter service criterion, trip criterion, and ride-through criteria. The variable list is shown in Table 18.

Table 18. Determining DER operation status variable list

Variable type	Variable name	Description
Input variable	rt_mode_v	DER voltage ride-through performance mode.
	rt_mode_f	DER frequency ride-through performance mode.
	es_crit	Enter service criteria met
	$trip\_crit$	Trip criteria met
	t_s	Simulation time step
	$es\_ramp\_rate\_exec$	Enter service ramp time duration (ES_RAMP_RATE) after execution delay
	$es\_completed\_prev$	Enter service ramp completed in the previous time step
Output variable	der_status	DER operation status
	$rt\_pass\_time\_req$	Flag indicating the minimum ride-through time has passed, and the DER is in the "may ride-through and may trip" region
Internal state variable	der_status_prev	Value of variable der_status (Status of DER) in the previous time step (initialized by $STATUS\_INIT$[33])

---

[33] If *STATUS_INIT* is ON (True, 1), *der_status_prev* is initiated as "Continuous Operation", if *STATUS_INIT* is OFF (False, 0), *der_status_prev* is initiated as "Trip".

The illustration of the DER operation status (der_status) finite state machine is shown in Figure 6.

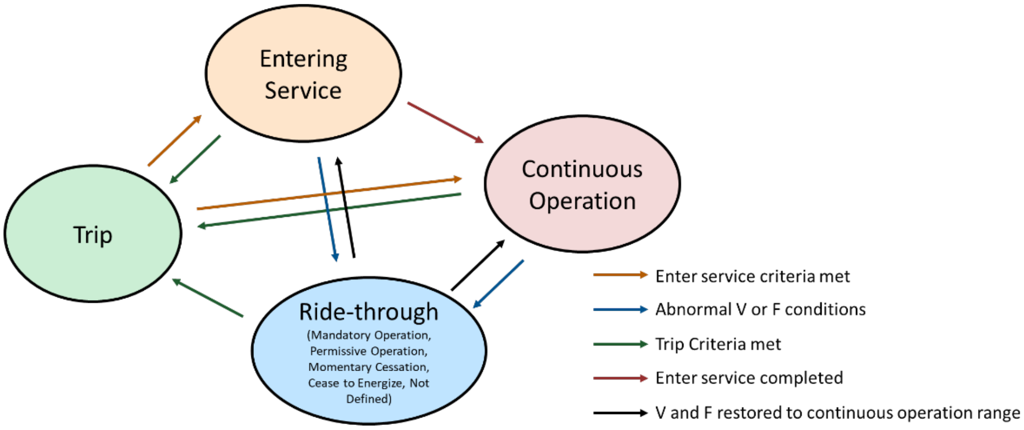

Figure 6. DER operation status (der_status) finite state machine

If DER is not in service in the previous time step (der_status_prev = “Trip”):

- If enter service criteria is met, the DER should start the enter service process.
  - If the simulation time step is shorter than the enter service ramp time ($t\_s < es\_ramp\_rate\_exec$) the DER should start the enter service process

$$der\_status = ”Entering\ Service” \tag{3.5.1-57}$$

  - If the simulation time step is longer than or equal to the enter service ramp time ($t\_s \geq es\_ramp\_rate\_exec$), the DER should be directly operating in the Continuous Operation mode:

$$der\_status = ”Continuous\ Operation” \tag{3.5.1-58}$$

If the DER is in service in the previous time step ($der\_status\_prev \neq$ “Trip”), the DER operation status is determined by the identified voltage and frequency ride-through performance mode, unless the trip criteria is met:

- If the frequency is outside of the required ride-through range, that the frequency ride-through mode is Not Defined, the DER overall ride-through mode is Not Defined.

$$der\_status = ”\mathrm{Not\ Defined}” \tag{3.5.1-59}$$

- Else, and if the voltage ride-through mode is any of Permissive Operation, Momentary Cessation, or Cease to Energize, the DER overall ride-through mode should be determined by the voltage ride-through mode:

$$der\_status = rt\_mode\_v \tag{3.5.1-60}$$

- Else, and if voltage or frequency ride-through mode is Mandatory Operation, the DER overall ride-through mode should be Mandatory Operation

$$der\_status = ”\mathrm{Mandatory\ Operation}” \tag{3.5.1-61}$$

- Otherwise, the DER should be in Continuous Operation or still Entering Service, and the flag to identify ride-through time has passed the standard required time should be cleared.

$$rt\_pass\_time\_req = FALSE \tag{3.5.1-62}$$

  - If the enter service ramp is completed in the previous time step ($es\_completed\_prev$ = TRUE), the DER should be in Continuous Operation.

$$der\_status = \text{"Continuous Operation"} \tag{3.5.1-63}$$

  - Otherwise, the DER should be entering service.

$$der\_status = \text{"Entering Service"} \tag{3.5.1-64}$$

In all conditions, if any of DER trip criteria is met ($trip\_crit$ = TRUE):

$$der\_status = \text{"Trip"} \tag{3.5.1-65}$$

Note that currently the operation status of the OpenDER model considers the modes defined in IEEE 1547-2018. For actual DER, there could be other modes that are not identified. For example, PV inverters may have a specific operating mode to provide reactive power at night without DC power required at its input terminals.

3.5.2. Modeling for PV DER

For PV DER, another criterion is included to allow DER to enter service when the available power is greater than a minimum power output threshold. For this version release, the minimum active power output parameter is used for this purpose. This parameter is also used in frequency-droop function and volt-watt function. Actual DERs may use a different threshold or a different mechanism, such as DC voltage. This DER behavior may be updated based on future lab tests.

$$es\_other\_crit = es\_p\_crit = (p\_avl\_pu \geq NP\_P\_MIN\_PU) \tag{3.5.2-1}$$

On the other hand, if the power output is below the minimum AC output that the DER allows, the DER should trip. Note that actual DERs may use a different threshold or a different mechanism, such as DC voltage. This DER behavior may be updated based on future lab tests:

$$other\_trip = p\_min\_trip = (p\_avl\_pu < NP\_P\_MIN\_PU) \tag{3.5.2-2}$$

Actual PV DERs may have different thresholds for enter service and trip, such as a hysteresis behavior. This behavior may be updated in future version releases as according to lab and field experiences.

3.5.3. Modeling for BESS DER

Different from PV, BESS DER does not have a cut-in or cut-out mechanism, described in equations (3.5.2-1) and (3.5.2-2). There is no additional enter service or trip criteria modeled in this version. Thus, the enter service criteria is always TRUE, and trip criteria is always FALSE.

Additional enter service and/or trip criteria may updated in a future version based on future lab tests.

$$\begin{gathered} es\_other\_crit = \text{TRUE} \\ other\_trip = \text{FALSE} \end{gathered} \tag{3.5.3-1}$$

3.6. BESS Specific Calculations

This section describes the modules that are only for BESS DER. Currently, V2.1 release includes state of charge (SOC) calculation, active power limitation by SOC, and charge/discharge ramp rate limits.

For BESS DER, the output active power is determined by the active power demand p_dem_w (p_dem_pu). It is issued by the system operator or other higher level grid support functions, such as PV smoothing, load shifting, etc. These higher level functions are not included in this version and may be added in a future version.

3.6.1. State of Charge Calculation

This module should only be calculated for time-series or dynamic simulations.

The state of charge (SOC) is calculated for BESS DER, considering its round-trip efficiency, energy capacity, and self-discharge characteristics. The variable list is shown in Table 19.

Table 19. State of Charge Calculation variable list

Variable type	Variable name	Description
Input variable	$NP\_EFFICIENCY$	DER system round-trip efficiency
	$NP\_BESS\_CAPACITY$	BESS Total Energy Capacity in Wh
	$NP\_BESS\_SELF\_DISCHARGE$	Self-Discharge Rate (Constant)
	$NP\_BESS\_SELF\_DISCHARGE\_SOC$	Self-Discharge Rate (SOC-dependent)
	t_s	Simulation time step in seconds
Output variable	$bess\_soc$	BESS state of charge (SOC) in per unit
Internal Variable	p_charge_w	DER charge power in W
	$p\_discharge\_w$	DER discharge power in W
Internal state Variable	$bess\_soc\_prev$	Value of variable $bess\_soc$ (BESS SOC) in the previous time step (initialized by SOC_INIT)
	$p\_out\_w\_prev$	Value of variable p_out_w (DER model output active power) in the previous time step (initialized by 0)

As the first step, the discharge power and charge power are calculated using the DER model output active power in the previous time step.

If DER is in idle condition or in the first simulation time step:

$$\begin{gathered} p\_discharge\_w = 0 \\ p\_charge\_w = 0 \end{gathered} \tag{3.6.1-1}$$

If DER is discharging ($p\_out\_w\_prev > 0$):

$$\begin{gathered} p\_discharge\_w = p\_out\_w\_prev \\ p\_charge\_w = 0 \end{gathered} \tag{3.6.1-2}$$

If DER is charging ($p\_out\_w\_prev < 0$):

$$\begin{gathered} p\_discharge\_w = 0 \\ p\_charge\_w = -p\_out\_w\_prev \end{gathered} \tag{3.6.1-3}$$

Then, the SOC can be calculated considering its self-discharge rate:

$$\begin{aligned} bess\_soc \ = bess\_soc\_prev \ + [&\frac{(NP\_EFFICIENCY * p\_charge\_w - p\_discharge\_w)}{NP\_BESS\_CAPACITY} \\ &-NP\_BESS\_SELF\_DISCHARGE\_SOC \ \times bess\_soc\_prev \\ &-NP\_BESS\_SELF\_DISCHARGE\ ] \times \frac{t\_s}{3600} \end{aligned} \tag{3.6.1-4}$$

Due to the self-discharge mechanism modeled, the SOC may drop below 0, which does not make physical sense. Thus, a safeguard mechanism is added

If $bess\_soc < 0$

$$bess\_soc \ = 0 \tag{3.6.1-5}$$

3.6.2. *Active Power Limitation by SoC*

This module should only be calculated for time-series or dynamic simulations.

Some BESS DERs may have reduced discharging capability at low SOC, or reduced charging capability at high SOC. In addition, for time-series or dynamic simulation, DER output active power should be limited, such that the SOC would not exceed the maximum and minimum operational boundaries. The variable list for this calculation is shown in Table 20.

Table 20. Active Power Limitation by SoC variable list

Variable type	Variable name	Description
Input variable	$NP\_EFFICIENCY$	DER system efficiency for DC/AC power conversion
	$NP\_BESS\_CAPACITY$	BESS Total Energy Capacity in Wh
	$NP\_BESS\_MAX\_SOC$	Maximum Operational State of Charge
	$NP\_BESS\_MIN\_SOC$	Minimum Operational State of Charge
	$NP\_BESS\_SELF\_DISCHARGE$	Self-Discharge Rate (Constant)
	$NP\_BESS\_SELF\_DISCHARGE\_SOC$	Self-Discharge Rate (SOC-dependent)
	$NP\_BESS\_P\_MAX\_BY\_SOC$ $(P\_DISCHARGE\_MAX\_PU,$ $SOC\_P\_DISCHARGE\_MAX,$ $P\_CHARGE\_MAX\_PU,$ $SOC\_P\_CHARGE\_MAX)$	Maximum active power limitation by SOC
Output variable	$p\_max\_charge\_pu$	Maximum charge power in per unit
	$p\_max\_discharge\_pu$	Maximum discharge power in per unit
Internal Variable	$p\_max\_charge\_pu\_ts$	Maximum charge power for the current timestep
	$p\_max\_discharge\_pu\_ts$	Maximum discharge power for the current timestep
	$p\_max\_charge\_pu\_soc$	Maximum charge power for the current SOC, defined by the capability curve $NP\_BESS\_P\_MAX\_BY\_SOC$
	$p\_max\_discharge\_pu\_soc$	Maximum discharge power for the current SOC
Internal state Variable	$bess\_soc\_prev$	Value of variable $bess\_soc$ (BESS SOC) in the previous time step (initialized by SOC_INIT)
	$p\_out\_w\_prev$	Value of variable p_out_w (DER model output active power) in the previous time step (initialized by 0)

The maximum discharge and charge active power at the current SOC, defined by the capability curve $NP\_BESS\_P\_MAX\_BY\_SOC$, are calculated:

$$\begin{gathered} p\_\max\ \_discharge\_pu\_soc \\ = interp(bess\_soc, SOC\_P\_MAX\_DISCHARGE, P\_DISCHARGE\_MAX\_PU) \\ p\_max\_charge\_pu\_soc = interp(bess\_soc, SOC\_P\_MAX\_CHARGE, P\_CHARGE\_MAX\_PU) \end{gathered} \quad (3.6.2\text{-}1)$$

where $interp(x, x\_array, y\_array)$ is a linear interpolation function, which is defined to generate linear interpolant of x, using the piece-wise curve defined by x_array and y_array. Figure 7 shows an example of using the capability curve.

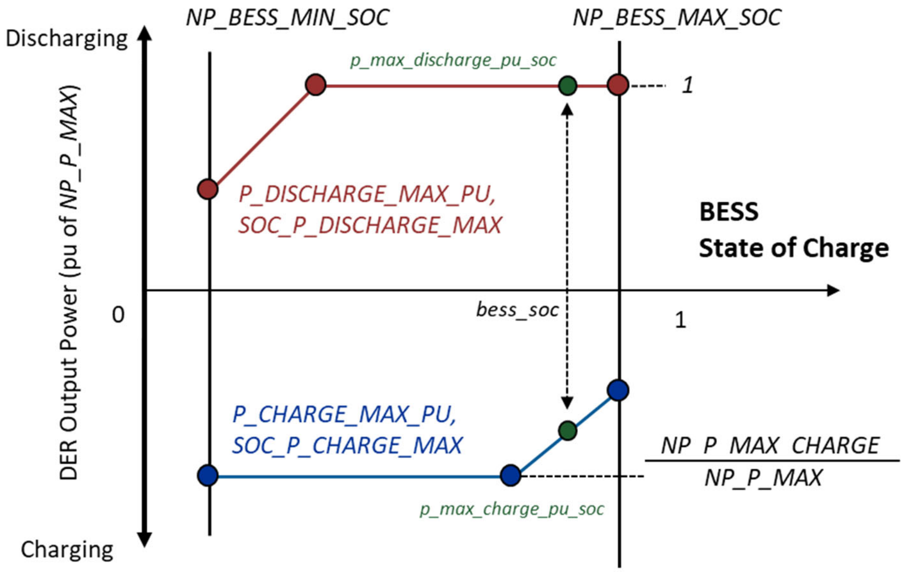

Figure 7. Example of active power limits depending on BESS SOC

Some DER also supports temporary operating capability that exceeds the continuous/normal operating ratings. This capability currently not modeled in this version and may be updated based on the user needs identified in the DERMUG meetings.

Then, to make sure that the BESS is not over-discharged or over-charged in the next time step, the active power is limited:

$$\begin{aligned} & p\_max\_charge\_pu\_ts \\ &\quad = min\Big(\Big(\frac{NP\_BESS\_SOC\_MAX - bess\_soc}{t\_s \times 3600} \\ &\quad + NP\_BESS\_SELF\_DISCHARGE\_SOC \times bess\_soc \\ &\quad + NP\_BESS\_SELF\_DISCHARGE\Big) \\ &\quad \times \frac{NP\_BESS\_CAPACITY}{NP\_EFFICIENCY \times NP\_P\_MAX\_CHARGE}, 1\Big) \end{aligned} \tag{3.6.2-2}$$

$$\begin{aligned} & p\_max\_discharge\_pu\_ts \\ &\quad = max\Big(0, \min\Big(\Big(\frac{bess\_soc - NP\_BESS\_SOC\_MIN}{t\_s \times 3600} \\ &\quad - NP\_BESS\_SELF\_DISCHARGE\_SOC \times bess\_soc \\ &\quad - NP\_BESS\_SELF\_DISCHARGE\Big) \\ &\quad \times \frac{NP\_BESS\_CAPACITY}{NP\_EFFICIENCY \times NP\_P\_MAX\_CHARGE}, 1\Big)\Big) \end{aligned} \tag{3.6.2-3}$$

Finally, the maximum discharge/charge power is the lessor of the two calculated limits.

$$\begin{aligned} p\_max\_discharge\_pu &= min(p\_max\_discharge\_pu\_ts, p\_max\_discharge\_pu\_soc) \\ p\_max\_charge\_pu &= min(p\_max\_charge\_pu\_ts, p\_max\_charge\_pu\_soc) \end{aligned} \tag{3.6.2-4}$$

For snapshot analysis, the operational active power limits in per-unit should be set to 1, so that they do not impact the other modules.

$$\begin{gathered} p\_max\_discharge\_pu = 1 \\ p\_max\_charge\_pu = 1 \end{gathered} \qquad (3.6.2\text{-}5)$$

3.6.3. *Ramp Rate Limits*

As indicated in IEEE 1547.9-2022 table 2, BESS may have charge and discharge ramp rate limits. This module models the ramp rate constraints. Note that:

- IEEE 1547-2018 does not require any ramp rate limits during normal operation, other than during enter service period.
- This module is also different from the Normal Ramp-up Rate limit required in CA Rule 21 section Hh.2.k. As this module applies to both ramp-up and ramp-down.
- Currently one parameter $NP\_BESS\_P\_RAMP\_TIME$ is used for both charging and discharging, whereas the BESS DER may have different ramp rate limits.

The variable list for this calculation is shown in Table 21.

Table 21. BESS ramp rate limit variable list

Variable type	Variable name	Description
Input variable	$NP\_BESS\_P\_RAMP\_TIME$	BESS active power ramp rate constraint
	p_dem_pu	BESS DER active power demand in pu
	der_status	DER operation status
Output variable	$p\_dem\_ramp\_pu$	BESS active power demand considering ramp rate limits

The ramp rate limit is only applied when the inverter is not in Trip condition ($der\_status \neq$ “Trip”).

$$p\_dem\_ramp\_pu = ramp(p\_dem\_pu, NP\_BESS\_P\_RAMP\_TIME, NP\_BESS\_P\_RAMP\_TIME) \qquad (3.6.3\text{-}1)$$

When the inverter is tripped, the ramp function should reset to 0.

$$p\_dem\_ramp\_pu = ramp(0,0,0) \qquad (3.6.3\text{-}2)$$

3.7. Active Power Support Functions Calculation

The logic flow of the reference active power calculation module is illustrated in Figure 8. This includes the volt-watt function, active power limit function, frequency-droop function, and a final calculation to determine the desired active power.

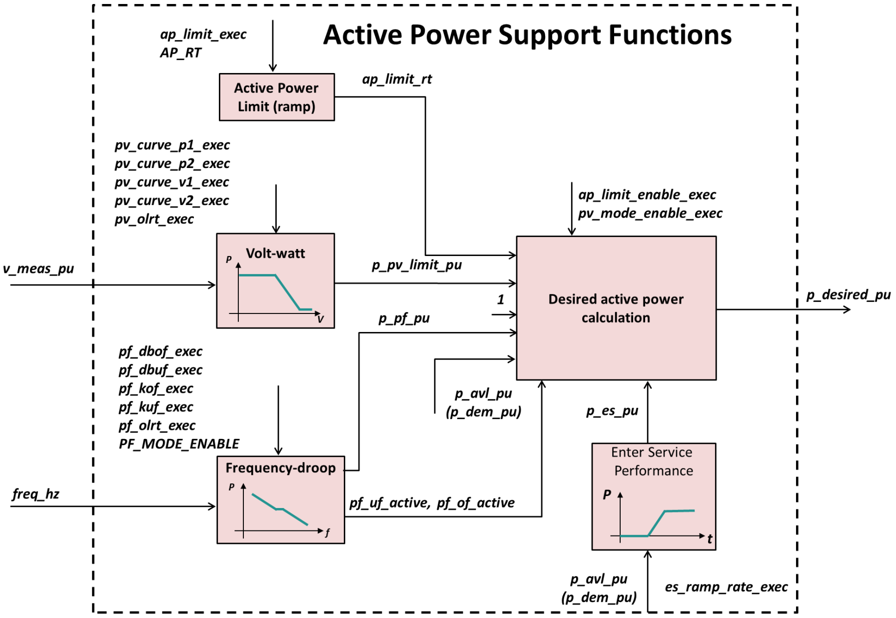

Figure 8. Model structure of active power related functions

3.7.1. Modeling Based on IEEE 1547-2018 Requirements

3.7.1.1. Voltage – Active Power (Volt-watt) Function

IEEE 1547-2018 Clause 5.4.2 requires

> “When in this mode, the DER shall actively limit the DER maximum active power as a function of the voltage following a voltage-active power piecewise linear characteristic.”

The variable list of volt-watt function is shown in Table 22, and the block diagram is shown in Figure 9.

Table 22. Volt-watt function variable list

Variable type	Variable name	Description
Input variable	*v_meas_pu*	Applicable voltage for volt-var and volt-watt calculation
	NP_P_MAX	Active power rating at unity power factor
	NP_P_MAX_CHARGE	Maximum active power charge rating
	pv_curve_p1_exec	Volt-watt Curve Point P1 Setting (*PV_CURVE_P1*) signal after execution delay
	pv_curve_v1_exec	Volt-watt Curve Point V1 Setting (*PV_CURVE_V1*) signal after execution delay
	pv_curve_p2_exec	Volt-watt Curve Point P2 Setting (*PV_CURVE_P2*) signal after execution delay
	pv_curve_v2_exec	Volt-watt Curve Point V2 Setting (*PV_CURVE_V2*) signal after execution delay
	pv_olrt_exec	Volt-watt open loop response time setting (*PV_OLRT*) signal after execution delay
	pv_mode_enable_exec	Volt-watt enable (*PV_MODE_ENABLE*) signal after execution delay
	NP_REACT_TIME	DER grid support function reaction time
Output variable	*p_pv_limit_pu*	Volt-watt power limit in per unit based on *NP_P_MAX*
Internal variable	*p_pv_limit_ref_pu*	Volt-watt power limit reference in per unit before low pass filter
	p_pv_limit_ref_w	Volt-watt power limit reference in W before low pass filter
	p_pv_limit_lpf_pu	Volt-watt power limit reference in per unit after low pass filter, before reaction time
	pv_curve_p1_w	Volt-watt Curve Point P1 Setting in W
	pv_curve_p2_w	Volt-watt Curve Point P2 Setting in W

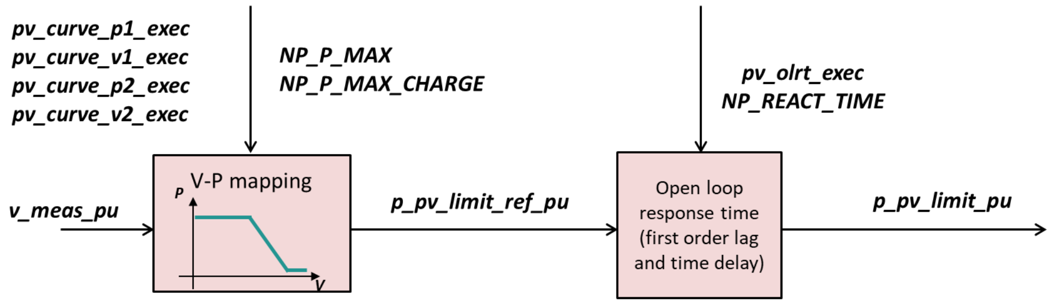

Figure 9. Model structure of volt-watt function

IEEE 1547-2018 has defined volt-watt function for DERs that can generate and absorb active power, i.e., energy storage DERs. It allows to set the volt-watt limit to the negative real power half plane, i.e., charging mode. If active, the DER should not charge less or discharge, according to the volt-watt curve as long as available energy storage capacity permits. As mentioned in Table 21, the volt-watt power setpoint 2 is a per-unit value. Its base is active power discharge rating (NP_P_MAX) if it is positive, and active power charge rating ($NP\_P\_MAX\_CHARGE$) if it is negative. An illustration for a BESS DER with $NP\_P\_MAX\ of\ 100kW$, and $NP\_P\_MAX\_CHARGE$ of 75kW is shown in Figure 10.

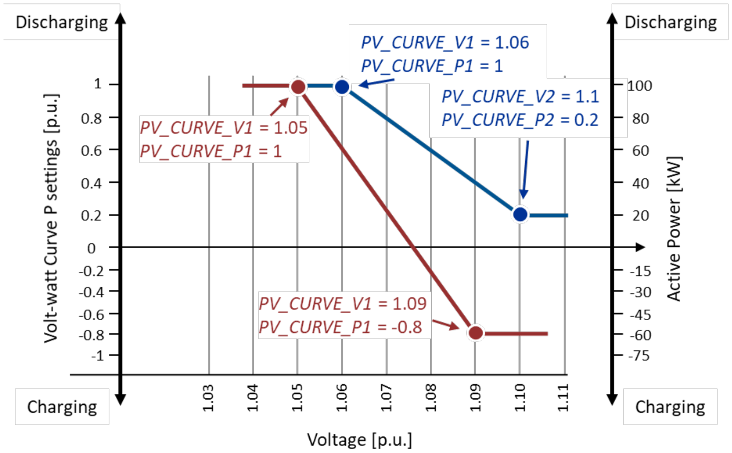

Figure 10. Example of volt-watt setting for a BESS DER that has *NP_P_MAX* of 100kW, and *NP_P_MAX_CHARGE* of 75kW

Thus, in order to have a linear relationship between the two volt-watt setpoints, the volt-watt power limitation reference is calculated in Watts:

$$pv\_curve\_p1\_w = pv\_curve\_p1\_exec \times NP\_P\_MAX$$

$$pv\_curve\_p2\_w = \begin{cases} pv\_curve\_p2\_exec \times NP\_P\_MAX & \text{if } pv\_curve\_p2\_exec \geq 0 \\ pv\_curve\_p2\_exec \times NP\_P\_MAX\_CHARGE & \text{if } pv\_curve\_p2\_exec < 0 \end{cases} \tag{3.7.1-1}$$

$$p\_pv\_limit\_ref\_w = \begin{cases} pv\_curve\_p1\_w \\ \qquad \text{if } v\_meas\_pu \leq pv\_curve\_v1\_exec \\ pv\_curve\_p1\_w - \dfrac{v\_meas\_pu - pv\_curve\_v1\_exec}{pv\_curve\_v2\_exec - pv\_curve\_v1\_exec} \\ \times (pv\_curve\_p1\_w - pv\_curve\_p2\_w) \\ \qquad \text{if } pv\_curve\_v1\_exec < v\_meas\_pu < pv\_curve\_v2\_exec \\ pv\_curve\_p2\_w \\ \qquad \text{if } v\_meas\_pu \geq pv\_curve\_v2\_exec \end{cases} \tag{3.7.1-2}$$

Then, the power limitation reference is converted to per unit with the base of DER nameplate discharge rating (NP_P_MAX).

$$p\_pv\_limit\_ref\_pu = p\_pv\_limit\_ref\_w/NP\_P\_MAX \tag{3.7.1-3}$$

IEEE 1547-2018 has an open loop response time (OLRT) requirement for volt-watt function. In dynamic simulation, the final power limitation is subjected to the OLRT. It does not reach the active power limit reference value immediately, but has a time-dependent characteristic:

$$\begin{gathered} p\_pv\_limit\_lpf\_pu = lpf(p\_pv\_limit\_ref\_pu, pv\_olrt\_exec - NP\_REACT\_TIME) \\ p\_pv\_limit\_pu = tdelay(p\_pv\_limit\_lpf\_pu, NP\_REACT\_TIME) \end{gathered} \tag{3.7.1-4}$$

In this report, a first order lag (lpf) function followed by a time delay ($tdelay$) is used to model the open loop response time behavior, which is defined in section 3.12.1 and 3.12.3. Note that there can be other ways to implement the OLRT behavior in an actual DER. The model may be updated in a future version, according to the lab test results.

When the inverter is tripped or volt-watt function is disabled, the first order lag and time delay functions outputs are reset to 1.

$$\begin{aligned} p\_pv\_limit\_lpf\_pu &= lpf(1{,}0) \\ p\_pv\_limit\_pu &= tdelay(1{,}0) \end{aligned} \tag{3.7.1-5}$$

3.7.1.2. Active Power Limit

IEEE 1547-2018 Clause 4.6.2 requires

> "The DER shall be capable of limiting active power as a percentage of the nameplate active power rating. The DER shall limit its active power output to not greater than the active power limit set point in no more than 30 s or in the time it takes for the primary energy source to reduce its active power output to achieve the requirements of the active power limit set point, whichever is greater."

The variable list of active power limit function is shown in Table 23.

Table 23. Active power limit function variable list

Variable type	Variable name	Description
Input variable	ap_limit_exec	Active power limit (AP_LIMIT) signal after execution delay
	$ap\_limit\_enable\_exec$	Active power limit enable (AP_LIMIT_ENABLE) signal after execution delay
	AP_RT	Active power limit response time
	NP_REACT_TIME	DER grid support function reaction time
Output variable	ap_limit_rt	Active power limit after its time response behavior
Internal variable	ap_limit_pu	Active power limit based on DER nameplate discharge active power rating (NP_P_MAX)
	ap_limit_ramp	Active power limit function after ramp behavior before reaction time

Similar to volt-watt function, the AP_LIMIT signal is a per-unit value. Its base is active power discharge rating (NP_P_MAX) if it is positive, and active power charge rating ($NP\_P\_MAX\_CHARGE$) if it is negative. To allow easier calculation, the value is converted to a per-unit value based on NP_P_MAX rating.

$$ap\_limit\_pu = \begin{cases} ap\_limit\_exec & \text{if } ap\_limit\_exec \geq 0 \\ ap\_limit\_exec \times \dfrac{NP\_P\_MAX\_CHARGE}{NP\_P\_MAX} & \text{if } ap\_limit\_exec < 0 \end{cases} \tag{3.7.1-6}$$

The final power limitation is subjected to the response time[34]:

$$\begin{aligned} & ap\_limit\_ramp \\ & = \begin{cases} ramp(ap\_limit\_pu, AP\_RT - NP\_REACT\_TIME, AP\_RT - NP\_REACT\_TIME) & \text{if } ap\_limit\_ex \\ ramp(1, 0,0) & \text{if } ap\_limit\_ex \end{cases} \end{aligned}$$

$$ap\_limit\_rt = tdelay(ap\_limit\_ramp, NP\_REACT\_TIME) \tag{3.7.1-7}$$

In this version release, a ramp rate limit ($ramp$) followed by a time delay ($tdelay$) is applied for the active power limit function, defined in section 3.12.2 and 3.12.3. Note that there can be multiple different ways to implement this behavior in an actual DER. The model may be updated in a future version, according to the lab test results.

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[34] IEEE 1547-2018 footnote 45 indicates that "*Linear ramping and step-wise ramping with small step sizes may be desirable.*"

When the active power limit function is not enabled (ap_limit_exec = FALSE) or the inverter is tripped, the actual active power limit value returns to 1.

$$\begin{aligned} ap\_limit\_ramp &= ramp(1,0,0) \\ ap\_limit\_rt &= tdelay(1,0) \end{aligned} \tag{3.7.1-8}$$

3.7.1.3. Enter Service Performance

The variable list of enter service performance module is shown in Table 24.

Table 24. Enter service performance variable list

Variable type	Variable name	Description
Input variable	der_status	DER operation status
	$es\_ramp\_rate\_exec$	Enter service soft-start duration (ES_RAMP_RATE) signal after execution delay
Output variable	p_es_pu	DER enter service ramp reference

IEEE 1547-2018 Clause 5.3.1 requires

> "DER shall increase output of active power, or exchange of active power for energy-storage-DER, during enter service as specified. Active power shall increase linearly, or in a stepwise linear ramp, with an average rate-of-change not exceeding the DER nameplate active power rating divided by the enter service period. The duration of the enter service period shall be adjustable over a range of 1 s to 1000 s with a default time of 300 s"

To model this, a ramp rate limited signal to indicate the maximum power output during enter service period is defined, as p_es_pu.

If the DER is tripped (der_status = "Trip"), the value should be reset to 0.

$$p\_es\_pu = ramp(0, 0, 0) \tag{3.7.1-9}$$

When the DER is not tripped, the value linearly ramps to a value greater than 1, for the purpose of identifying the completion of the enter service ramp process.:

$$p\_es\_pu = ramp(1.1, es\_ramp\_rate\_exec, 0) \tag{3.7.1-10}$$

where ramp rate limit auxiliary function is defined in section 3.12.2.

The completion of the enter service process is identified after all active power support functions are considered, specified in section 3.7.1.5.

For energy storage DER, the standard indicates the exchange of active power should be ramp rate limited. So, for the case when demand is to absorb active power, the active power absorption should also increase limited. More discussion and model specification for energy storage DER is in 3.7.3.2.

If the DER uses randomized delay as an exception of enter service ramp, as specified in IEEE 1547-2018 Clause 4.10.3, *ES_RAMP_RATE* and thus *es_ramp_rate_exec* should be set as 0. The ramp rate limited value *p_es_ramp_pu* should be the same as its input *p_act_supp_pu*.

IEEE 1547-2018 also indicates that stepwise linear ramp is allowed, if each single step is less than or equal to 20% of the DER nameplate active power rating, and the rate of change over the period between any two consecutive steps does not exceed the average rate-of-change over the full enter service period. This behavior is not yet modeled in this version release, and may be included in a future version, according to the lab or field test results.

3.7.1.4. Frequency-Droop Function

IEEE 1547-2018 Clause 6.5.2.7.2 requires

> "During temporary frequency disturbances, for which the system frequency is outside the adjustable deadband db_{OF} and db_{UF} as specified in Table 24, but still between the trip settings in Table 18, the DER shall adjust its active power output from the pre-disturbance levels, according to the formulas in Table 23. The active power output shall be as defined by the relevant formula in Table 23, plus any inertial response to the rate of change of frequency, until frequency returns to within the deadband." [35]

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[35] IEEE 1547-2018 has an errata on frequency-droop section to correct equations and description in Table 23. https://standards.ieee.org/content/dam/ieee-standards/standards/web/documents/erratas/1547-2018_errata.pdf.

The variable list of frequency-droop function is shown in Table 25, and the block diagram is shown in Figure 11.

Table 25. Frequency-droop function variable list

Variable type	Variable name	Description
Input variable	$freq\_hz$	DER frequency measurement in Hertz, from model input
	PF_MODE_ENABLE	Frequency-Active power mode enable
	pf_dbof_exec	Over frequency deadband offset from nominal frequency signal (PF_DBOF) after execution delay
	pf_dbuf_exec	Under frequency deadband offset from nominal frequency signal (PF_DBUF) after execution delay
	pf_kof_exec	Over frequency slope signal (PF_KOF) after execution delay
	pf_kuf_exec	Under frequency slope signal (PF_KUF) after execution delay
	pf_olrt_exec	Frequency-Active power open-loop response time signal (PF_OLRT) after execution delay
	p_avl_pu	DER available active power in pu considering efficiency
	p_dem_pu	BESS DER active power demand in pu
	ap_limit_rt	Active power limit signal after time response
	$p\_pv\_limit\_pu$	Volt-watt power limit
	$NP\_EFFICIENCY$	DER system efficiency for DC/AC power conversion
	$NP\_P\_MIN\_PU$	DER minimum active power output
	NP_P_MAX	DER active power rating at unity power factor
	NP_REACT_TIME	DER grid support function reaction time
Output variable	p_pf_pu	Output active power from frequency-droop function
	pf_of_active	Frequency-droop over-frequency active
	pf_uf_active	Frequency-droop under-frequency active

Table 25 (continued). Frequency-droop function variable list

Variable type	Variable name	Description
Internal variable	pf_of	Over-frequency detected
	pf_uf	Under-frequency detected
	pf_olrt_appl	Applied open-loop response time for frequency-droop function
	$p\_pf\_of\_pu$	Frequency droop active power reference for over-frequency condition
	$p\_pf\_uf\_pu$	Frequency droop active power reference for under-frequency condition
	$p\_pf\_normal\_pu$	Active power if no grid-support functions ($freq\text{-}droop$, volt-watt and active power limit) are enabled
	$p\_pf\_ref\_pu$	Frequency droop active power reference in per unit
	$p\_pf\_lpf\_pu$	Frequency droop active power after low pass filter, before reaction time
	$p\_pf\_pre\_pu$	Pre-disturbance active power output, defined by the active power output at the point of time the frequency exceeds the deadband.
Internal state variable	$p\_pf\_pre\_pu\_prev$	Value of variable $p\_pf\_pre\_pu$ (pre-disturbance active power output) in the previous time step (initialized by the minimum value of the first value of p_avl_pu, ap_limit_rt, and $p\_pv\_limit\_pu$)
	$p\_out\_w\_prev$	Value of variable p_out_w (DER model output active power) in the previous time step (initialized by the minimum value of the first value of $p\_avl\_pu \times NP\_P\_MAX$ and $ap\_limit\_rt \times NP\_P\_MAX$, and $p\_pv\_limit\_pu \times NP\_P\_MAX$)
	pf_of_prev	Value of variable pf_of (Over-frequency detected) in the previous time step (initialized by the first value of pf_of)
	pf_uf_prev	Value of variable pf_uf (Under-frequency detected) in the previous time step (initialized by the first value of pf_uf)

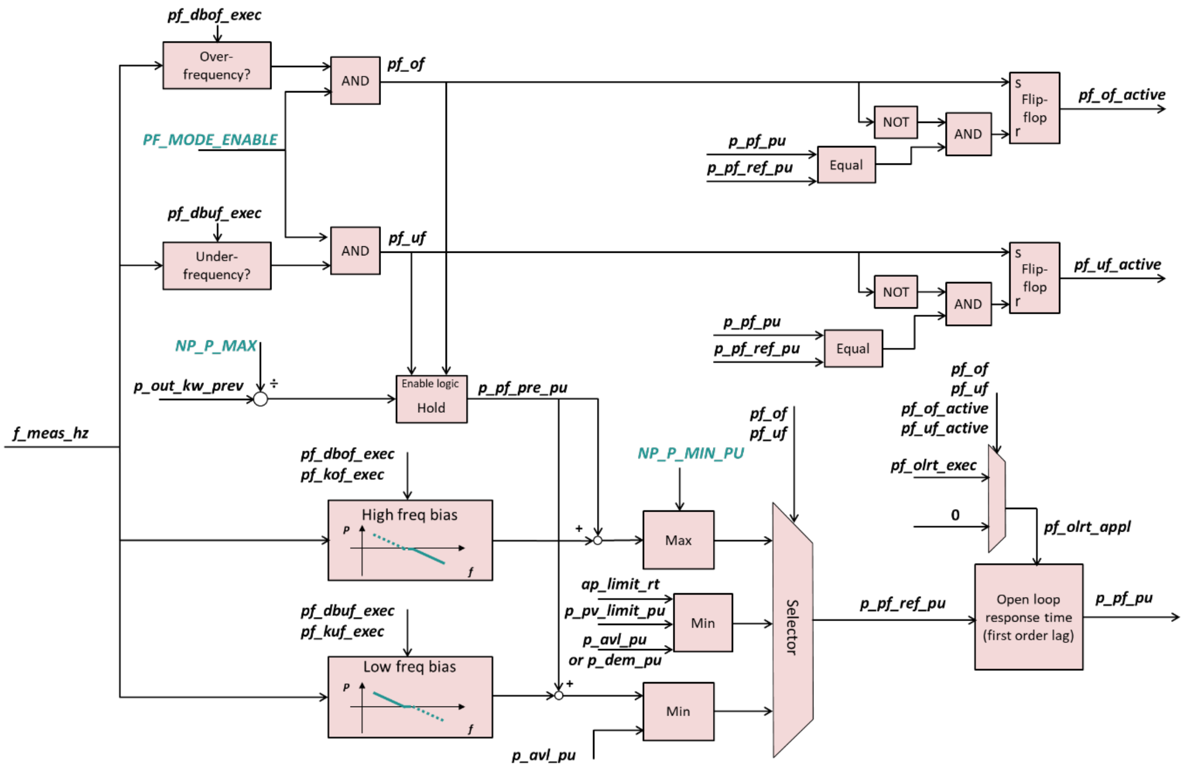

Figure 11. Model structure of frequency-droop function

Under- or over-frequency is detected by:

$$
\begin{aligned}
pf\_uf &= \begin{cases} 1 & \text{if } f\_meas\_hz < 60 - pf\_dbuf\_exec \text{ AND } PF\_MODE\_ENABLE \\ 0 & \text{otherwise} \end{cases} \\
pf\_of &= \begin{cases} 1 & \text{if } f\_meas\_hz > 60 + pf\_dbof\_exec \text{ AND } PF\_MODE\_ENABLE \\ 0 & \text{otherwise} \end{cases}
\end{aligned}
\qquad (3.7.1\text{-}11)
$$

By the definition of IEEE 1547-2018 clause 6.5.2.7.2, the pre-disturbance active power output is the active power output at the point of time the frequency exceeds the deadband. However, it is possible for the measured frequency to have a step change between the over- and under-frequency range without returning to the deadband. Under this rare circumstance, IEEE 1547-2018 does not provide a clear guidance on the pre-disturbance active power output.

Figure 12 presents an example case, when DER has its active power limited a P_0 when the frequency is at 60Hz. After an over-frequency event, the DER output power is reduced to P_1 to support the system frequency regulation. In this case, P_0 is the pre-disturbance active power output. Then, the frequency has a step change to the under-frequency region. Assuming the inverter's measurement sample does not capture the frequency return to the deadband, there can be different implementations to select the pre-disturbance active power output. P_0 may be used, if the under- and over-frequency conditions are considered as a single event. Or if the DER consider the under-frequency and over-frequency as separated events, P_1 would be used as the pre-disturbance active power output. The second interpretation is used in this version of the DER. Lab tests will be conducted in future to confirm or update the modeled DER behavior. This implementation may be updated in future revisions accordingly.

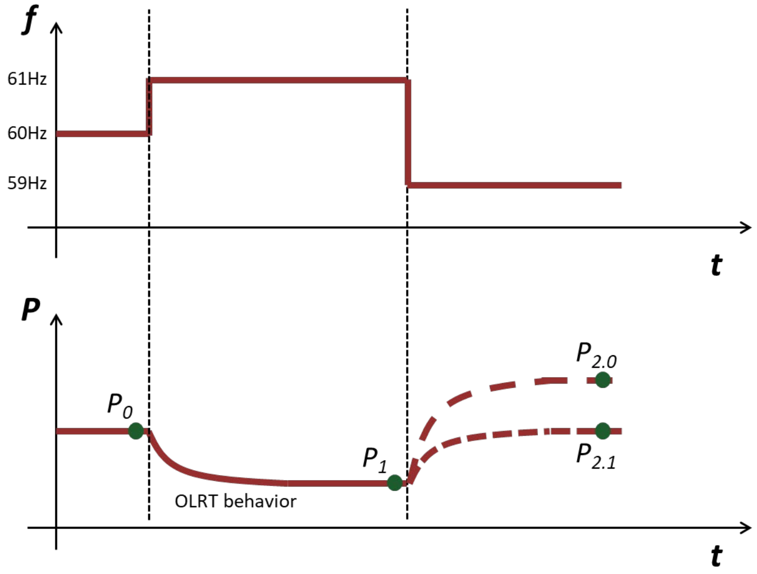

Figure 12. Illustration of pre-disturbance active power output for frequency-droop function

In the DER model, the pre-disturbance active power is determined by a sample and hold logic. During under- or over-frequency event, the pre-disturbance value is hold at the value in the previous time-step. The hold is released when the applicable frequency is within the deadband or exit the under- or over-frequency range.

$$p\_pf\_pre\_pu = \begin{cases} p\_pf\_pre\_pu\_prev & \text{if } pf\_uf = 1 \text{ and } pf\_uf\_prev = 1 \\ p\_pf\_pre\_pu\_prev & \text{if } pf\_of = 1 \text{ and } pf\_of\_prev = 1 \\ p\_out\_w\_prev/NP\_P\_MAX & \text{otherwise} \end{cases} \quad (3.7.1\text{-}12)$$

Then, active power output reference for frequency-droop follows the equations defined in IEEE 1547-2018, Table 23[35].

$$p\_pf\_of\_pu = \max\left(p\_pf\_pre\_pu - \frac{f\_meas\_hz - (60 + pf\_dbof\_exec)}{60 \times pf\_kof\_exec}, NP\_P\_MIN\_PU\right) \quad (3.7.1\text{-}13)$$

$$p\_pf\_uf\_pu = \min\left(p\_pf\_pre\_pu + \frac{(60 - pf\_dbuf\_exec) - f\_meas\_hz}{60 \times pf\_kuf\_exec}, p\_avl\_pu\right) \quad (3.7.1\text{-}14)$$

Next, the active power reference for the frequency-droop function is determined by the over- and under-frequency status. If the frequency is within the deadband, the reference value is determined by all the other active power support functions. Specifically, the enter service ramp behavior is considered. If the DER is entering service, the DER output active power in the previous time step should be used, and otherwise, the available power should be used.

$$p\_pf\_normal\_pu = \begin{cases} p\_out\_w\_prev/NP\_P\_MAX & \text{if } der\_status = \text{"Entering Service"} \\ p\_avl\_pu & \text{Otherwise} \end{cases} \quad (3.7.1\text{-}15)$$

$$p\_pf\_ref\_pu = \begin{cases} p\_pf\_of\_pu & \text{if } pf\_of = 1 \\ p\_pf\_uf\_pu & \text{if } pf\_uf = 1 \\ \min\,(p\_pf\_normal\_pu, ap\_limit\_pu, p\_pv\_limit\_pu) & \text{otherwise} \end{cases} \tag{3.7.1-16}$$

The final value is subject to OLRT for small signal performance when the active power change is less than 5%. Since the standard does not specify clearly whether OLRT is applicable for large signal performance, in this version of DER model, a first order lag (lpf) followed by a time delay ($tdelay$) is applied to all responses to generate the final frequency-droop power output. If lab and field test results show a different response, the model will be updated in a future model revision.

$$\begin{gathered} pf\_olrt\_appl = \begin{cases} pf\_olrt\_exec & \text{if } pf\_uf \text{ OR } pf\_of \\ pf\_olrt\_exec & \text{if } pf\_uf\_active \text{ OR } pf\_of\_active \\ 0 & \text{Otherwise} \end{cases} \\ p\_pf\_lpf\_pu = lpf(p\_pf\_ref\_pu, pf\_olrt\_appl - NP\_REACT\_TIME) \\ p\_pf\_pu = tdelay(p\_pf\_lpf\_pu, NP\_REACT\_TIME) \end{gathered} \tag{3.7.1-17}$$

In addition, IEEE 1547-2018 indicates that the DER shall not be required to change its output power at a rate greater than 20% of nameplate value per minute, if the frequency deviation results in an active power change of equal to or greater than 5% of rated value, and this only applies to the DERs whose primary energy source is physically unable to provide a greater response rate. Since most modern DERs do not have such constraints, this behavior is not included in this version of the DER model and may be updated in a future model revision.

To allow the calculation of the overall desired active power from all active power grid support functions, the activation status of frequency-droop function can be provided as:

$$\begin{gathered} pf\_uf\_active = flipflop((pf\_uf \text{ AND } PF\_MODE\_ENABLE), \\ \text{NOT}(pf\_uf \text{ AND } PF\_MODE\_ENABLE) \text{ AND } (p\_pf\_pu = p\_pf\_ref\_pu), 0) \\ pf\_of\_active = flipflop((pf\_of \text{ AND } PF\_MODE\_ENABLE), \\ \text{NOT}(pf\_of \text{ AND } PF\_MODE\_ENABLE) \text{ AND } (p\_pf\_pu = p\_pf\_ref\_pu), 0) \end{gathered} \tag{3.7.1-18}$$

where flipflop auxiliary function is defined in section 3.12.5. The reset logic of the flipflop is added to maintain the open loop response time behavior when entering the frequency-droop function deadband. In actual implementation, a small margin can be added for the equality decision condition of p_pf_pu and its value in the previous time step.

Similar to other functions, if the DER is tripped, the outputs should be reset to 0

$$\begin{gathered} p\_pf\_lpf\_pu = lpf(0,0) \\ p\_pf\_pu = tdelay(0,0) \end{gathered} \tag{3.7.1-19}$$

3.7.1.5. Active Power Support Functions Calculation

DER active power output is determined by the active power limit, frequency-droop, and volt-watt function, depending on the function enable commands and its active status. The variable list is shown in Table 26.

Table 26. Active power support functions variable list

Variable type	Variable name	Description
Input variable	ap_limit_rt	Active power limit after time response
	$p\_pv\_limit\_pu$	Volt-watt power limit
	p_pf_pu	Frequency-droop power command
	$ap\_limit\_enable\_exec$	Active power limit enable (AP_LIMIT_ENABLE) signal after execution delay
	$pv\_mode\_enable\_exec$	Volt-watt enable (PV_MODE_ENABLE) signal after execution delay
	p_es_pu	DER enter service ramp reference
	p_avl_pu	DER available power in pu considering efficiency
	pf_of_active	Frequency-droop over-frequency active
	pf_uf_active	Frequency-droop under-frequency active
Output variable	$p\_desired\_pu$	Desired output active power from active power support functions in per unit
	$es\_completed$	Enter service completed

IEEE 1547-2018 Clause 4.7 subclause d) requires

> "If both voltage-active power and frequency-droop modes are active, the lesser of the power value shall take precedence."

So, if both volt-watt and frequency-droop functions are active, (i.e., both functions are enabled, applicable voltage is greater than volt-watt curve point V1 setting (PV_CURVE_V1), and applicable frequency is outside of the frequency-droop deadband), the lesser of the power value should be used.

IEEE 1547-2018 Clause 4.8 subclause e) also requires

> "The response to active power limit signal specified in 4.6.2 shall take precedence over all other requirements within Clause 5 and Clause 6, with the exception of tripping and ride-through requirements listed in item b) and item c) above, and voltage-active power mode requirements and frequency-droop response requirements listed in item d)."

This means frequency-droop and volt-watt responses take precedence over active power limit signal:[36]

- Both volt-watt and active power limit functions active: Since both functions impose maximum DER active power output limits, the lesser of the power value should be used.
- Both frequency-droop and active power limit functions active: Frequency-droop function takes precedence over active power limit function.
- All three functions are active: Active power limit function value will be overwritten by the lesser of the power value between volt-watt and frequency-droop.
- As IEEE 1547-2018 does not provide any guidance on the priority of the enter service ramp as specified in its section 4.6.3, this version of OpenDER assumes the enter service ramp has the lowest priority, i.e., if active power limit, volt-watt, or frequency-droop becomes active, their value may overwrite the enter service ramp process.

---

[36] It may be desirable to include active power limit function into consideration if frequency-droop function is active. For example, during an over-frequency event, the system operator may issue an active power limit command that is even lower than the frequency-droop output power to further help with frequency regulation. For Version 2.0 release, the OpenDER Model follows the requirement of the standard.

The desired active power $p\_act\_supp\_pu$ in per-unit system can be obtained:

- If DER is in service ($der\_status \neq$ “Trip”):

$$p\_desired\_pu = \begin{cases} \min(p\_avl\_pu, p\_es\_pu, 1) & \text{if } ap\_limit\_enable\_exec = 0 \text{ and } pv\_mode\_enable\_exec = 0 \\ & \text{and } pf\_uf\_active = 0 \text{ and } pf\_of\_active = 0 \\ \min(p\_avl\_pu, ap\_limit\_rt, p\_es\_pu, 1) & \text{if } ap\_limit\_enable\_exec = 1 \text{ and } pv\_mode\_enable\_exec = 0 \\ & \text{and } pf\_uf\_active = 0 \text{ and } pf\_of\_active = 0 \\ \min(p\_avl\_pu, p\_pv\_limit\_pu, p\_es\_pu, 1) & \text{if } ap\_limit\_enable\_exec = 0 \text{ and } pv\_mode\_enable\_exec = 1 \\ & \text{and } pf\_uf\_active = 0 \text{ and } pf\_of\_active = 0 \\ \min(p\_avl\_pu, ap\_limit\_rt, p\_pv\_limit\_pu, p\_es\_pu, 1) & \text{if } ap\_limit\_enable\_exec = 1 \text{ and } pv\_mode\_enable\_exec = 1 \\ & \text{and } pf\_uf\_active = 0 \text{ and } pf\_of\_active = 0 \\ \min(p\_avl\_pu, p\_pf\_pu, 1) & \text{if } pv\_mode\_enable\_exec = 0 \text{ and } pf\_of\_active = 1 \\ \min(p\_avl\_pu, p\_pv\_limit\_pu, p\_pf\_pu, 1) & \text{if } pv\_mode\_enable\_exec = 1 \text{ and } pf\_of\_active = 1 \\ \min(p\_avl\_pu, p\_pf\_pu, 1) & \text{if } pv\_mode\_enable\_exec = 0 \text{ and } pf\_uf\_active = 1 \\ \min(p\_avl\_pu, p\_pv\_limit\_pu, p\_pf\_pu, 1) & \text{if } pv\_mode\_enable\_exec = 1 \text{ and } pf\_uf\_active = 1 \end{cases} \quad (3.7.1\text{-}20)$$

In addition, if the enter service ramp reference is greater than 1 ($p\_es\_pu > 1$), it is considered that the DER enter service is completed.

$$es\_completed = \text{TRUE} \quad (3.7.1\text{-}21)$$

If DER is not in service ($der\_status =$ “Trip”), the desired active power should be 0, and it is not considered that enter service process is completed. In addition, the active power support functions should also be reset, by using equations (3.7.1-5), (3.7.1-8), (3.7.1-9), and (3.7.1-19).

$$\begin{aligned} p\_desired\_pu &= 0 \\ es\_completed &= \text{FALSE} \end{aligned} \quad (3.7.1\text{-}22)$$

3.7.2. Modeling for PV DER

The active power output of PV DER should always be positive, i.e., injecting active power to the grid. Thus, some model equations may be simplified. For example, volt-watt function may be calculated in per-unit system, rather than converting to Watts, described in equations (3.7.1-1) to (3.7.1-3).

To keep the simplicity, reduced model specification that is only for modeling PV is not presented in this document.

3.7.3. Modeling for BESS DER

For BESS DERs, there is no additional considerations for volt-watt and active power limit functions. The only consideration is that the output active power is determined by the active power demand from the system operator or higher level grid support functions, instead of the available DC power. This affects enter service ramp, frequency-droop function and final desired active power calculation function. In addition, if in time-series simulation, the output active power is also limited by the operational constraints by the SOC, as calculated in section 3.6.2

3.7.3.1. Frequency-droop function

For BESS DER, the DC power is always available. The output power is determined by the active power demand. Thus, the initial value of two internal state variables should be changed, as shown in Table 27.

Table 27. Initial value of frequency droop parameters

Variable Name and Description	Variable Initial value of PV DER	Variable Initial value of BESS DER
$p\_pf\_pre\_pu\_prev$ Value of variable $p\_pf\_pre\_pu$ (pre-disturbance active power output) in the previous time step	Initialized by the minimum value of the first value of $\boldsymbol{p\_avl\_pu}$, ap_limit_rt, and $p\_pv\_limit\_pu$)	Initialized by the minimum value of the first value of $\boldsymbol{p\_dem\_pu}$, ap_limit_rt, and $p\_pv\_limit\_pu$)
$p\_out\_w\_prev$ Value of variable p_out_w (DER model output active power) in the previous time step	Initialized by the minimum value of the first value of $\boldsymbol{p\_avl\_pu}\times NP\_P\_MAX$ and $ap\_limit\_rt\times NP\_P\_MAX$, and $p\_pv\_limit\_pu\times NP\_P\_MAX$)	Initialized by the minimum value of the first value of $\boldsymbol{p\_dem\_pu}\times NP\_P\_MAX$ and $ap\_limit\_rt\times NP\_P\_MAX$, and $p\_pv\_limit\_pu\times NP\_P\_MAX$)

In addition, the frequency-droop active power reference value should also be updated for the case when the frequency-droop function is not active. The equation (3.7.3-1) should replace (3.7.1-15) for BESS DER.

$$p\_pf\_normal\_pu = \begin{cases} p\_out\_pu\_prev & \text{if } der\_status = \text{”Entering Service”} \\ p\_dem\_pu & \text{Otherwise} \end{cases} \tag{3.7.3-1}$$

3.7.3.2. Desired Active Power Calculation

Similarly, the final desired active power calculation should also be updated with BESS active power demand. The parameter list is shown in Table 28.

Table 28. Desired active power calculation for BESS DER variable list

Variable type	Variable name	Description
Input variable	ap_limit_rt	Active power limit after time response
	$p\_pv\_limit\_pu$	Volt-watt power limit
	p_pf_pu	Frequency-droop power command
	$ap\_limit\_enable\_exec$	Active power limit enable (AP_LIMIT_ENABLE) signal after execution delay
	$pv\_mode\_enable\_exec$	Volt-watt enable (PV_MODE_ENABLE) signal after execution delay
	p_es_pu	DER enter service ramp reference
	p_dem_pu	BESS DER active power demand in pu
	$NP\_P\_MAX\_CHARGE$	DER active power charge rating
	NP_P_MAX	Active power rating at unity power factor
	pf_of_active	Frequency-droop over-frequency active
	pf_uf_active	Frequency-droop under-frequency active
Output variable	$p\_desired\_pu$	Desired output active power from active power support functions in per unit
Internal variable	$p\_act\_supp\_bess\_pu$	Desired output active power from active power support functions in per unit without considering the BESS related constraints
	$p\_es\_dem\_pu$	Active power demand considering enter service ramp

The equations (3.7.3-2) through (3.7.3-4) should replace (3.7.1-20) for BESS DER. First, the power demand considering enter service ramp is calculated. As discussed in section 3.7.1.3, the enter service ramp should also be applied when the BESS DER is absorbing power. The ramp rate limit should only be applied when increasing of magnitude, and not be applied when decreasing of magnitude.

$$p\_es\_dem\_pu = \max\left(\min\left(p\_dem\_ramp\_pu, p\_es\_pu\right), -p\_es\_pu\right) \qquad (3.7.3\text{-}2)$$

Then, the desired active power from the grid support functions are calculated:

$$
p\_act\_supp\_bess\_pu = \begin{cases}
\min(p\_dem\_pu, 1) & \text{if } ap\_limit\_enable\_exec = 0 \text{ and } pv\_mode\_enable\_exec = 0 \\
& \text{and } pf\_uf\_active = 0 \text{ and } pf\_of\_active = 0 \\
\min(p\_dem\_pu, ap\_limit\_rt, 1) & \text{if } ap\_limit\_enable\_exec = 1 \text{ and } pv\_mode\_enable\_exec = 0 \\
& \text{and } pf\_uf\_active = 0 \text{ and } pf\_of\_active = 0 \\
\min(p\_dem\_pu, p\_pv\_limit\_pu, 1) & \text{if } ap\_limit\_enable\_exec = 0 \text{ and } pv\_mode\_enable\_exec = 1 \\
& \text{and } pf\_uf\_active = 0 \text{ and } pf\_of\_active = 0 \\
\min(p\_dem\_pu, ap\_limit\_rt, p\_pv\_limit\_pu, 1) & \text{if } ap\_limit\_enable\_exec = 1 \text{ and } pv\_mode\_enable\_exec = 1 \\
& \text{and } pf\_uf\_active = \\
0 \text{ and } pf\_of\_active = 0 & \\
\min(p\_pf\_pu, 1) & \text{if } pv\_mode\_enable\_exec = 0 \text{ and } pf\_of\_active = 1 \\
\min(p\_pv\_limit\_pu, p\_pf\_pu, 1) & \text{if } pv\_mode\_enable\_exec = 1 \text{ and } pf\_of\_active = 1 \\
\min(p\_pf\_pu, 1) & \text{if } pv\_mode\_enable\_exec = 0 \text{ and } pf\_uf\_active = 1 \\
\min(p\_pv\_limit\_pu, p\_pf\_pu, 1) & \text{if } pv\_mode\_enable\_exec = 1 \text{ and } pf\_uf\_active = 1
\end{cases} \tag{3.7.3-3}
$$

Finally, the output value should be constraint considering the nameplate rating and limitations by BESS SOC:

$$
p\_desired\_pu = \max\left(-p\_max\_charge\_pu, -NP\_P\_MAX\_CHARGE/NP\_P\_MAX, \min\left(p\_act\_supp\_pu, \quad p\_max\_discharge\_pu\right)\right) \tag{3.7.3-4}
$$

3.8. Reactive Power Support Functions Calculation

3.8.1. Modeling Based on IEEE 1547-2018 Requirements

IEEE 1547-2018 Clause 5.3.1 requires

> “The DER shall, as specified in Table 6, provide the capabilities of the following mutually exclusive modes of reactive power control functions:
>
> - Constant power factor mode
> - Voltage-reactive power mode
> - Active power-reactive power mode
> - Constant reactive power mode.
>
> The DER shall be capable of activating each of these modes one at a time.”

The logic flow of the reference reactive power calculation module is illustrated in Figure 13. This includes the volt-var, constant power factor, watt-var, and constant var functions. Finally, a mode selection module is used to decide the final output determined by the function mode enable settings.

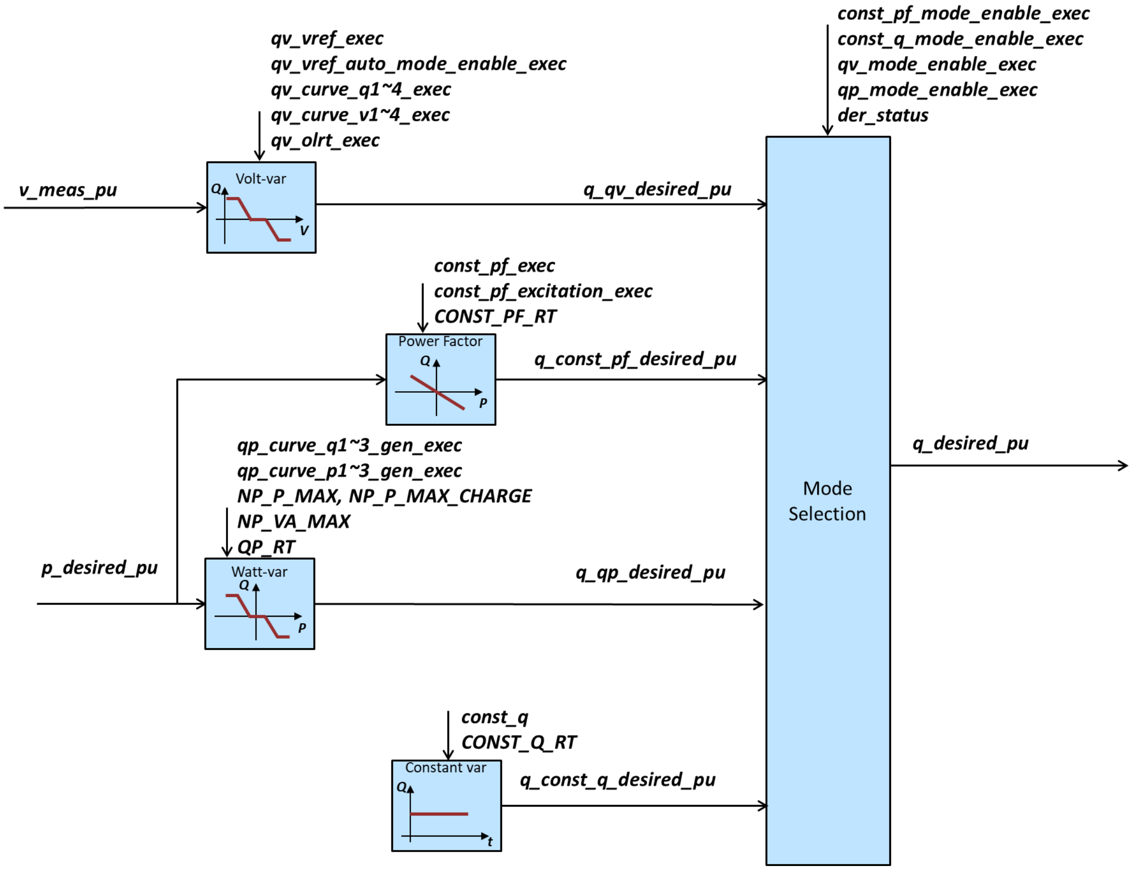

Figure 13. Model structure of reactive power support functions

3.8.1.1. Constant Power Factor Function

IEEE 1547-2018 Clause 5.3.2 requires

> "When in this mode, the DER shall operate at a constant power factor."

The variable list of constant power factor function is shown in Table 29.

Table 29. Constant power factor function variable list

Variable Type	Variable Name	Description
Input variable	$const\_pf\_exec$	Constant Power Factor Setting ($CONST\_PF$) after execution delay
	$const\_pf\_excitation\_exec$	Constant Power Factor Excitation ($CONST\_PF\_EXCITATION$) after execution delay
	$CONST\_PF\_RT$	Constant Power Factor Mode Response Time
	NP_REACT_TIME	DER grid support function reaction time
	NP_P_MAX	Active power rating at unity power factor
	NP_VA_MAX	Apparent power maximum rating
	$p\_desired\_pu$	Desired output active power considering DER enter service performance
Output variable	$q\_const\_pf\_desired\_pu$	Output reactive power from constant power factor function
Internal variable	$q\_const\_pf\_desired\_ref\_pu$	Constant power factor reactive power reference before response time
	$q\_const\_pf\_lpf\_pu$	Constant power factor reactive power reference after first order lag

The constant power factor setpoint is determined by a single variable $const\_pf\_exec$, and whether the DER is injecting or absorbing reactive power is determined by the variable $const\_pf\_excitation\_exec$. Thus, reactive power reference for constant power factor function $q\_const\_pf\_desired\_ref\_pu$ is calculated by:

$$q\_const\_pf\_desired\_ref\_pu = \begin{cases} p\_desired\_pu \times \dfrac{\sqrt{1 - const\_pf\_exec^2}}{const\_pf\_exec} \times \dfrac{NP\_P\_MAX}{NP\_VA\_MAX} & \text{if } const\_pf\_excitation\_exec = \mathrm{INJ} \\ -p\_desired\_pu \times \dfrac{\sqrt{1 - const\_pf\_exec^2}}{const\_pf\_exec} \times \dfrac{NP\_P\_MAX}{NP\_VA\_MAX} & \text{if } const\_pf\_excitation\_exec = \mathrm{ABS} \end{cases} \quad (3.8.1\text{-}1)$$

IEEE 1547-2018 requires the maximum time for a DER to maintain the constant power factor setpoint is 10 seconds. Thus, the DER output reactive power may not change immediately after a setting change received or active power change. In this report, a first order lag (lpf) followed by a time delay ($tdelay$) is used to model this time-dependent behavior, which is defined in section 3.12.1.

$$q\_const\_pf\_lpf\_pu = lpf(q\_const\_pf\_desired\_ref\_pu, CONST\_PF\_RT - NP\_REACT\_TIME)$$
$$q\_const\_pf\_desired\_pu = tdelay(q\_const\_pf\_lpf\_pu, NP\_REACT\_TIME) \quad (3.8.1\text{-}2)$$

Note that there can be multiple different ways to implement this behavior in an actual DER. The model may be updated in a future version, according to the lab test results.

When the inverter is tripped, the first order lag and time delay functions outputs are reset to 1.

$$q\_const\_pf\_lpf\_pu = lpf(0,0)$$
$$q\_const\_pf\_desired\_pu = tdelay(0,0) \quad (3.8.1\text{-}3)$$

3.8.1.2. Voltage – Reactive Power (Volt-var) Function

IEEE 1547-2018 Clause 5.3.3 requires

> “When in this mode, the DER shall actively control its reactive power output as a function of voltage following a voltage-reactive power piecewise linear characteristic.”

The variable list of volt-var function is shown in Table 30, and the block diagram is shown in Figure 14.

Table 30. Volt-var function variable list

Variable Type	Variable Name	Description
Input variable	qv_vref_exec	V/Q Curve V_{Ref} Setting (QV_VREF) after execution delay
	$qv\_vref\_auto\_mode\_exec$	Autonomous V_{ref} Adjustment Enable ($QV\_VREF\_AUTO\_MODE$) after execution delay
	$qv\_vref\_time\_exec$	V_{ref} adjustment time Constant (QV_VREF_TIME) after execution delay
	$qv\_curve\_v1\_exec$	V/Q Curve Point V1 Setting (QV_CURVE_V1) after execution delay
	$qv\_curve\_q1\_exec$	V/Q Curve Point Q1 Setting (QV_CURVE_Q1) after execution delay
	$qv\_curve\_v2\_exec$	V/Q Curve Point V2 Setting (QV_CURVE_V2) after execution delay
	$qv\_curve\_q2\_exec$	V/Q Curve Point Q2 Setting (QV_CURVE_Q2) after execution delay
	$qv\_curve\_v3\_exec$	V/Q Curve Point V3 Setting (QV_CURVE_V3) after execution delay
	$qv\_curve\_q3\_exec$	V/Q Curve Point Q3 Setting (QV_CURVE_Q3) after execution delay
	$qv\_curve\_v4\_exec$	V/Q Curve Point V4 Setting (QV_CURVE_V4) after execution delay

Table 30 (continued). Volt-var function variable list

Variable Type	Variable Name	Description
Input variable	$qv\_curve\_q4\_exec$	V/Q Curve Point Q4 Setting (QV_CURVE_Q4) after execution delay
	qv_olrt_exec	Volt-var open loop response time after execution delay
	v_meas_pu	Applicable voltage for volt-var and volt-watt calculation
	NP_REACT_TIME	DER grid support function reaction time
	$qv\_vref\_max\_exec$	Volt-var automatic Vref adjustment mode maximum Vref setting after execution delay
	$qv\_vref\_min\_exec$	Volt-var automatic Vref adjustment mode minimum Vref setting after execution delay
Output variable	$q\_qv\_desired\_pu$	Output reactive power from volt-var function
Internal variable	$q\_qv\_desired\_ref\_pu$	Volt-var function reactive power reference before response time
	$q\_qv\_lpf\_pu$	Volt-var function reactive power reference after first order lag
	qv_vref_eff	Effective V_{Ref} setting to determine the applied voltage settings
	$qv\_curve\_v1\_eff$	Effective V1 setting with volt-var curve shifting when V_{Ref} changes
	$qv\_ curve\_v2\_eff$	Effective V2 setting with volt-var curve shifting when V_{Ref} changes
	$qv\_ curve\_v3\_eff$	Effective V3 setting with volt-var curve shifting when V_{Ref} changes
	$qv\_ curve\_v4\_eff$	Effective V4 setting with volt-var curve shifting when V_{Ref} changes
	qv_vref_lpf	Low pass filtered measurement voltage for volt-var V_{Ref} tracking mode

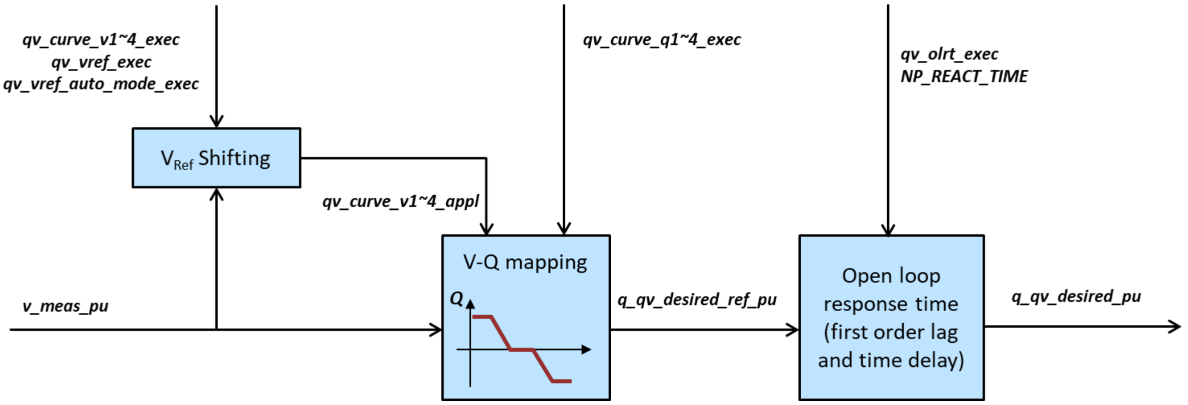

Figure 14. Model structure of volt-var function

IEEE 1547-2018 Clause 5.3.3 requires:

> “The DER shall be capable of autonomously adjusting reference voltage (V_{ref}) with V_{ref} being equal to the low pass filtered measured voltage… The voltage-reactive power Volt-Var curve characteristic shall be adjusted autonomously as V_{Ref} changes.”

Thus, the effective V_{Ref} is determined by either the V_{Ref} control setpoint or low pass filtered applicable voltage, depending on the enable signal:

$$\begin{aligned} qv\_vref\_lpf \; &= \max(qv\_vref\_min\_\mathrm{exec}, \\ &\qquad \min(lpf(v\_meas\_pu, qv\_vref\_time\_exec \times 2.3), \\ &\qquad\quad qv\_vref\_max\_exec)) \\ qv\_vref\_eff &= \begin{cases} qv\_vref\_exec & \text{if } qv\_vref\_auto\_mode\_exec \; = \; \mathrm{DISABLED} \\ qv\_vref\_lpf & \text{if } qv\_vref\_auto\_mode\_exec \; = \; \mathrm{ENABLED} \end{cases} \end{aligned} \tag{3.8.1-4}$$

For the autonomous adjusting reference voltage volt-var, the standard requires for the Time Constant of the low pass filter, instead of open loop response time. Hence, there is a 2.3 times factor equation 3.8.1-4 to convert the setting for low pass filter calculations.

The effective volt-var curve voltage settings should shift according to the changes of V_{Ref}.

$$\begin{cases} qv\_curve\_v1\_eff = qv\_curve\_v1\_exec + qv\_vref\_eff \; - 1 \\ qv\_curve\_v2\_eff = qv\_curve\_v2\_exec + qv\_vref\_eff \; - 1 \\ qv\_curve\_v3\_eff = qv\_curve\_v3\_exec + qv\_vref\_eff \; - 1 \\ qv\_curve\_v4\_eff = qv\_curve\_v4\_exec + qv\_vref\_eff \; - 1 \end{cases} \tag{3.8.1-5}$$

After the effective voltage setpoints are determined, the reactive power reference from volt-var function piecewise linear characteristic mapping $q\_qv\_desired\_ref\_pu$ in per unit is calculated by:

$$q\_qv\_desired\_ref\_pu = \begin{cases} qv\_curve\_q1\_exec \\ \qquad\qquad \text{if } v\_meas\_pu < qv\_curve\_v1\_eff \\ qv\_curve\_q1\_exec - \dfrac{v\_meas\_pu - qv\_curve\_v1\_eff}{qv\_curve\_v2\_eff - qv\_curve\_v1\_eff} \\ \times (qv\_curve\_q1\_exec - qv\_curve\_q2\_exec) \\ \qquad\qquad \text{if } qv\_curve\_v1\_eff \leq v\_meas\_pu \leq qv\_curve\_v2\_eff \\ qv\_curve\_q2\_exec - \dfrac{v\_meas\_pu - qv\_curve\_v2\_eff}{qv\_curve\_v3\_eff - qv\_curve\_v2\_eff} \\ \qquad \times (qv\_curve\_q2\_exec - qv\_curve\_q3\_exec) \\ \qquad\qquad \text{if } qv\_curve\_v2\_eff < v\_meas\_pu < qv\_curve\_v3\_eff \\ qv\_curve\_q3\_exec - \dfrac{v\_meas\_pu - qv\_curve\_v3\_eff}{qv\_curve\_v4\_eff - qv\_curve\_v3\_eff} \\ \times (qv\_curve\_q3\_exec - qv\_curve\_q4\_exec) \\ \qquad\qquad \text{if } qv\_curve\_v3\_eff \leq v\_meas\_pu \leq qv\_curve\_v4\_eff \\ qv\_curve\_q4\_exec \\ \qquad\qquad \text{if } v\_meas\_pu > qv\_curve\_v4\_eff \end{cases} \tag{3.8.1-6}$$

IEEE 1547-2018 has an OLRT requirement for volt-var function. In dynamic simulation, the DER output is subjected to the open loop response time, which does not reach the reactive power reference value immediately, but has a time-dependent characteristic:

$$\begin{aligned} q\_qv\_lpf\_pu &= lpf(q\_qv\_desired\_ref\_pu, qv\_olrt\_exec - NP\_REACT\_TIME) \\ q\_qv\_desired\_pu &= tdelay(q\_qv\_lpf\_pu, NP\_REACT\_TIME) \end{aligned} \tag{3.8.1-7}$$

In this report, a first order lag (lpf) followed by a time delay ($tdelay$) is used to model the open loop response time behavior, which is defined in section 3.12.1 and 3.12.3. Note that there can be multiple different ways to implement this behavior in an actual DER. The model may be updated in a future version, according to the lab test results.

When the inverter is tripped, the first order lag and time delay functions outputs are reset to 1.

$$\begin{aligned} q\_qv\_lpf\_pu &= lpf(0{,}0) \\ q\_qv\_desired\_pu &= tdelay(0{,}0) \end{aligned} \tag{3.8.1-8}$$

3.8.1.3. Active Power – Reactive Power (Watt-var) Function

IEEE 1547-2018 Clause 5.3.4 requires

> "When in this mode, the DER shall actively control the reactive power output as a function of the active power output following a target piecewise linear active power-reactive power characteristic, without intentional time delay."

The variable list of watt-var function is shown in Table 31.

Table 31. Watt-var function variable list

Variable Type	Variable Name	Description
Input variable	$qp\_curve\_p1\_gen\_exec$	P-Q Curve Point P1 Setting ($QP\_CURVE\_P1\_GEN$) after execution delay
	$qp\_curve\_q1\_gen\_exec$	P-Q Curve Point Q1 Setting ($QP\_CURVE\_Q1\_GEN$) after execution delay
	$qp\_curve\_p2\_gen\_exec$	P-Q Curve Point P2 Setting ($QP\_CURVE\_P2\_GEN$) after execution delay
	$qp\_curve\_q2\_gen\_exec$	P-Q Curve Point Q2 Setting ($QP\_CURVE\_Q2\_GEN$) after execution delay
	$qp\_curve\_p3\_gen\_exec$	P-Q Curve Point P3 Setting ($QP\_CURVE\_P3\_GEN$) after execution delay
	$qp\_curve\_q3\_gen\_exec$	P-Q Curve Point Q3 Setting ($QP\_CURVE\_Q3\_GEN$) after execution delay
	$qp\_curve\_p1\_load\_exec$	P-Q Curve Point P'1 Setting ($QP\_CURVE\_P1\_LOAD$) after execution delay
	$qp\_curve\_q1\_load\_exec$	P-Q Curve Point Q'1 Setting ($QP\_CURVE\_Q1\_LOAD$) after execution delay
	$qp\_curve\_p2\_load\_exec$	P-Q Curve Point P'2 Setting ($QP\_CURVE\_P2\_LOAD$) after execution delay
	$qp\_curve\_q2\_load\_exec$	P-Q Curve Point Q'2 Setting ($QP\_CURVE\_Q2\_LOAD$) after execution delay
	$qp\_curve\_p3\_load\_exec$	P-Q Curve Point P'3 Setting ($QP\_CURVE\_P3\_LOAD$) after execution delay
	$qp\_curve\_q3\_load\_exec$	P-Q Curve Point Q'3 Setting ($QP\_CURVE\_Q3\_LOAD$) after execution delay
	QP_RT	Active Power Reactive Power Mode Response Time
	$p\_desired\_pu$	Desired output active power considering DER enter service performance
	NP_P_MAX	Active power rating at unity power factor
	$NP\_P\_MAX\_CHARGE$	DER active power charge rating
	NP_VA_MAX	Apparent power maximum rating
	NP_REACT_TIME	DER grid support function reaction time

Table 31 (continued). Watt-var function variable list

Variable Type	Variable Name	Description
Output variable	$q\_qp\_desired\_pu$	Output reactive power from watt-var function
Internal variable	$q\_qp\_desired\_ref\_pu$	Watt-var function reactive power reference value before response time
	$q\_qp\_lpf\_pu$	Watt-var function reactive power reference value after first order lag
	$p\_desired\_qp\_pu$	Desired output active power in per unit for BESS considering the different nameplate ratings for charging and discharging

The watt-var curve points are defined in per unit system. So, the first step is to calculate the desired active power in per-unit.

$$p\_desired\_qp\_pu = \begin{cases} p\_desired\_pu & \text{if } p\_desired\_pu \geq 0 \\ \dfrac{p\_desired\_kw \times NP\_P\_MAX}{NP\_P\_MAX\_CHARGE} & \text{if } p\_desired\_pu < 0 \end{cases} \tag{3.8.1-9}$$

Then, the reactive power reference for watt-var function piecewise linear characteristic mapping $q\_qp\_desired\_ref\_pu$ is calculated by:

$$
\mathit{q\_qp\_desired\_ref\_pu} =
\begin{cases}
\mathit{qp\_curve\_q3\_load\_exec} & \text{if } \mathit{p\_desired\_qp\_pu} \leq \mathit{qp\_curve\_q3\_load\_exec} \\
\mathit{qp\_curve\_q3\_gen\_exec} - \dfrac{\mathit{p\_desired\_qp\_pu} - \mathit{qp\_curve\_p3\_gen\_exec}}{\mathit{qp\_curve\_p2\_gen\_exec} - \mathit{qp\_curve\_p3\_gen\_exec}} \times (\mathit{qp\_curve\_q3\_gen\_exec} - \mathit{qp\_curve\_q2\_gen\_exec}) & \text{if } \mathit{qp\_curve\_p3\_gen\_exec} < \mathit{p\_desired\_qp\_pu} \leq \mathit{qp\_curve\_p2\_gen\_exec} \\
\mathit{qp\_curve\_q2\_gen\_exec} - \dfrac{\mathit{p\_desired\_qp\_pu} - \mathit{qp\_curve\_p2\_gen\_exec}}{\mathit{qp\_curve\_p1\_gen\_exec} - \mathit{qp\_curve\_p2\_gen\_exec}} \times (\mathit{qp\_curve\_q2\_gen\_exec} - \mathit{qp\_curve\_q1\_gen\_exec}) & \text{if } \mathit{qp\_curve\_p2\_gen\_exec} < \mathit{p\_desired\_qp\_pu} \leq \mathit{qp\_curve\_p1\_gen\_exec} \\
\mathit{qp\_curve\_q1\_gen\_exec} - \dfrac{\mathit{p\_desired\_qp\_pu} - \mathit{qp\_curve\_p1\_gen\_exec}}{\mathit{qp\_curve\_p1\_load\_exec} - \mathit{qp\_curve\_p1\_gen\_exec}} \times (\mathit{qp\_curve\_q1\_gen\_exec} - \mathit{qp\_curve\_q1\_load\_exec}) & \text{if } \mathit{qp\_curve\_p1\_load\_exec} < \mathit{p\_desired\_qp\_pu} \leq \mathit{qp\_curve\_p1\_gen\_exec} \\
\mathit{qp\_curve\_q1\_gen\_exec} - \dfrac{\mathit{p\_desired\_qp\_pu} - \mathit{qp\_curve\_p1\_gen\_exec}}{\mathit{qp\_curve\_p2\_gen\_exec} - \mathit{qp\_curve\_p1\_gen\_exec}} \times (\mathit{qp\_curve\_q1\_gen\_exec} - \mathit{qp\_curve\_q2\_gen\_exec}) & \text{if } \mathit{qp\_curve\_p1\_gen\_exec} < \mathit{p\_desired\_qp\_pu} \leq \mathit{qp\_curve\_p2\_gen\_exec} \\
\mathit{qp\_curve\_q2\_gen\_exec} - \dfrac{\mathit{p\_desired\_qp\_pu} - \mathit{qp\_curve\_p2\_gen\_exec}}{\mathit{qp\_curve\_p3\_gen\_exec} - \mathit{qp\_curve\_p2\_gen\_exec}} \times (\mathit{qp\_curve\_q2\_gen\_exec} - \mathit{qp\_curve\_q3\_gen\_exec}) & \text{if } \mathit{qp\_curve\_p2\_gen\_exec} < \mathit{p\_desired\_qp\_pu} \leq \mathit{qp\_curve\_p3\_gen\_exec} \\
\mathit{qp\_curve\_q3\_gen\_exec} & \text{if } \dfrac{\mathit{p\_desired\_kw}}{\mathit{NP\_P\_MAX}} > \mathit{qp\_curve\_p3\_gen\_exec}
\end{cases}
\tag{3.8.1-10}
$$

IEEE 1547-2018 requires the response time of watt-var function to be 10 seconds. Thus, the DER output reactive power may not change immediately after a setting change received or active power change. In this report, a first order lag (lpf) followed by a time delay ($tdelay$) is used to model this time-dependent behavior, which is defined in section 3.12.1 and 3.12.3.

$$q\_qp\_lpf\_pu = lpf(q\_qp\_desired\_ref\_pu, QP\_RT - NP\_REACT\_TIME)$$
$$q\_qp\_desired\_pu = tdelay(q\_qp\_lpf\_pu, NP\_REACT\_TIME) \tag{3.8.1-11}$$

Note that there can be multiple different ways to implement this behavior in actual DER. The model may be updated in a future version, according to the lab test results.

When the inverter is tripped, the first order lag and time delay functions outputs are reset to 1.

$$q\_qp\_lpf\_pu = lpf(0,0)$$
$$q\_qp\_desired\_pu = tdelay(0,0) \tag{3.8.1-12}$$

3.8.1.4. Constant Reactive Power (var) Function

IEEE 1547-2018 Clause 5.3.5 requires

> "When in this mode, the DER shall maintain a constant reactive power. The target reactive power level and mode (injection or absorption) shall be specified by the Area EPS operator and shall be within the range specified in 5.2."

The variable list of constant var function is shown in Table 32.

Table 32. Constant reactive power function variable list

Variable type	Variable name	Description
Input variable	$const\_q\_exec$	Constant Reactive Power Setting ($CONST\_Q$) after execution delay
	$CONST\_Q\_RT$	Constant Reactive Power Mode Response Time
	NP_VA_MAX	Apparent power maximum rating
	NP_REACT_TIME	DER grid support function reaction time
Output variable	$q\_const\_q\_desired\_pu$	Output reactive power from constant reactive power function
Internal variable	$q\_const\_q\_lpf\_pu$	Constant Reactive Power function reactive power reference after first order lag

IEEE 1547-2018 requires the maximum time for a DER to maintain the constant var setpoint is 10 seconds. Thus, the DER output reactive power may not change immediately after a setting change received. In this report, a first order lag (lpf) function is used to model this time-dependent behavior, which is defined in section 3.12.1 and 3.12.3.

$$q\_const\_q\_lpf\_pu = lpf(const\_q\_exec, CONST\_Q\_RT - NP\_REACT\_TIME)$$
$$q\_const\_q\_desired\_pu = tdelay(q\_const\_q\_lpf\_pu, NP\_REACT\_TIME) \tag{3.8.1-13}$$

Note that there can be multiple different ways to implement this behavior in actual DER. The model may be updated in a future version, according to the lab test results.

When the inverter is tripped, the first order lag and time delay functions outputs are reset to 1.

$$q\_const\_q\_lpf\_pu = lpf(0,0)$$
$$q\_const\_q\_desired\_pu = tdelay(0,0) \tag{3.8.1-14}$$

3.8.1.5. Desired Reactive Power Calculation

The variable list of desired reactive power calculation is shown in Table 33, and the block diagram is shown in Table 26.

Table 33. Desired reactive power calculation variable list

Variable Type	Variable Name	Description
Input variable	$const\_pf\_mode\_enable\_exec$	Constant Power Factor Mode Enable ($CONST\_PF\_MODE\_ENABLE$) after execution delay
	$q\_const\_pf\_desired\_pu$	Output reactive power from constant power factor function
	$qv\_mode\_enable\_exec$	Voltage-Reactive Power Mode Enable (QV_MODE_ENABLE) after execution delay
	$q\_qv\_desired\_pu$	Output reactive power from volt-var function
	$qp\_mode\_enable\_exec$	Active Power Reactive Power Mode Enable (QP_MODE_ENABLE) after execution delay
	$q\_qp\_desired\_pu$	Output reactive power from watt-var function
	$const\_q\_mode\_enable\_exec$	Constant Reactive Power Mode Enable ($CONST\_Q\_MODE\_ENABLE$) after execution delay
	$q\_const\_q\_desired\_pu$	Output reactive power from constant reactive power function
	der_status	DER operation status
	NP_VA_MAX	Apparent power maximum rating
	$NP\_MODE\_TRANSITION\_TIME$	Time for DER to smoothly transition between reactive power support modes
Output variable	$q\_desired\_pu$	Desired output reactive power from reactive power support functions

Table 33 (continued). Desired reactive power calculation variable list

Variable Type	Variable Name	Description
Internal variable	*q_desired_ref_pu*	Desired output reactive power reference from reactive power support functions before ramp rate limit for mode transitions
	q_desired_ref_pu	Desired output reactive power reference from reactive power support functions after ramp rate limit for mode transitions
	q_mode_ramp_flag	Flag to determine pass through ramp rate limited reactive power during mode transition or not ramp rate limited value
	q_mode_ramp_flag_set	Set value to create flipflop logic of variable *q_mode_ramp_flag*
	q_mode_ramp_flag_reset	Reset value to create flipflop logic of variable *q_mode_ramp_flag*
Internal state variable	*const_pf_mode_enable_exec_prev*	Value of variable *const_pf_mode_enable_exec* in the previous time step (initialized by the first value of *CONST_PF_MODE_ENABLE*)
	qv_mode_enable_exec_prev	Value of variable *qv_mode_enable_exec* in the previous time step (initialized by the first value of *QV_MODE_ENABLE*)
	qp_mode_enable_exec_prev	Value of variable *qp_mode_enable_exec* in the previous time step (initialized by the first value of *QP_MODE_ENABLE*)
	const_q_mode_enable_exec_prev	Value of variable *const_q_mode_enable_exec* in the previous time step (initialized by the first value of *CONST_Q_MODE_ENABLE*)

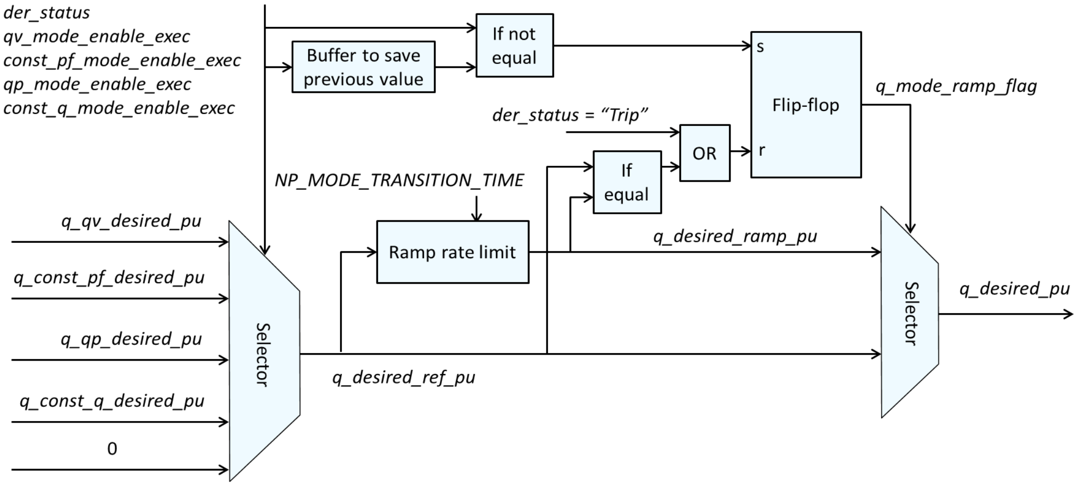

Figure 15. Model structure of desired reactive power calculation

If DER is not tripped, ($der\_status \neq$ "Trip"), the desired reactive power reference $q\_desired\_ref\_pu$ in per unit is determined by the enable commands, where only one of them can be enabled at a time. IEEE 1547-2018 Section 5.1 mentions that:

> "The requirements of this subclause apply to the continuous operation region when the voltage is between 0.88 and 1.1 times the nominal voltage (VN). Continued operation of functions defined in Clause 5 outside of the continuous operation region may be acceptable to support functions covered in 6.4. During abnormal voltage conditions, this reactive power range shall be provided subject to the limitations of the DER."

In this version of OpenDER, it is assumed that the reactive power support functions continue to operate outside of the Continuous Operation region. And this behavior may be updated according to lab and field test results.

IEEE 1547-2018 Section 5.3.1 also mentions that:

> "Constant power factor mode with unity power factor setting shall be the default mode of the installed DER unless otherwise specified by the Area EPS operator."

For modeling purpose, if no function is enabled, the desired reactive power value should be 0.

$$q\_desired\_ref\_pu = \begin{cases} q\_const\_pf\_desired\_pu & \text{if } const\_pf\_mode\_enable\_exec = \text{ENABLED} \\ q\_qv\_desired\_pu & \text{if } qv\_mode\_enable\_exec = \text{ENABLED} \\ q\_qp\_desired\_pu & \text{if } qp\_mode\_enable\_exec = \text{ENABLED} \\ q\_const\_q\_desired\_pu & \text{if } const\_q\_mode\_enable\_exec = \text{ENABLED} \\ 0 & \text{otherwise} \end{cases} \tag{3.8.1-15}$$

If there are no mode changes on reactive power support functions, the reference value $q\_desired\_ref\_kvar$ should be output as the desired reactive power output $q\_desired\_kvar$.

However, IEEE 1547-2018 Clause 4.6.3 requires

> "Changes of control functional modes shall be executed such that the DER output is transitioned smoothly over a time period between 5 s and 300 s."

This indicates that when mode transitions, there should be a smoothing mechanism to change the output reactive power gradually.

Since this smoothing mechanism should be only activated during the mode transitions, a flipflop logic is used to identify whether the DER is in the middle of mode transitions. The flipflop logic is set to enabled, when any of the reactive power control mode enable signals are different from their respective value in the previous time step:

$$q\_mode\_ramp\_flag\_set = \begin{cases} 1 & \text{if } const\_pf\_mode\_enable\_exec \neq const\_pf\_mode\_enable\_exec\_prev \\ 1 & \text{if } qv\_mode\_enable\_exec \neq qv\_mode\_enable\_exec\_prev \\ 1 & \text{if } qp\_mode\_enable\_exec \neq qp\_mode\_enable\_exec\_prev \\ 1 & \text{if } const\_q\_mode\_enable\_exec \neq const\_q\_mode\_enable\_exec\_prev \\ 0 & \text{otherwise} \end{cases} \tag{3.8.1-16}$$

If the DER is mode transition, i.e., when $q\_mode\_ramp\_flag\_set$ is 1 or $q\_mode\_ramp\_flag$ is 1, a smoothing effect should take place. There can be many ways to implement this feature in a real product. In this model, a ramp rate limit is applied. And it will be updated according to the lab test results. The ramp rate limited value $q\_desired\_ramp\_pu$ is calculated as:

$$q\_desired\_ramp\_pu = ramp(q\_desired\_ref\_pu, NP\_MODE\_TRANSITION\_TIME, NP\_MODE\_TRANSITION\_TIME) \tag{3.8.1-17}$$

where ramp rate limit auxiliary function is defined in section 3.12.2.

If the DER is not in mode transition, the ramp rate limited value $q\_desired\_ramp\_pu$ should catch up with the DER reactive power output quickly. A ramp time of 0 is provided to the ramp rate limit for this purpose.

$$q\_desired\_ramp\_pu = ramp(q\_desired\_ref\_pu, 0, 0) \tag{3.8.1-18}$$

When the ramp rate limited value has reached to the same value as its input or the DER is shutdown, the flipflop logic it is reset to disabled:

$$q\_mode\_ramp\_flag\_reset = \begin{cases} 1 & \text{if } q\_desired\_ref\_kvar = q\_desired\_ramp\_kvar \\ 0 & \text{otherwise} \end{cases} \tag{3.8.1-19}$$

Thus, the flipflop logic output $q\_mode\_ramp\_flag$ is calculated as:

$$q\_mode\_ramp\_flag = flipflop(q\_mode\_ramp\_flag\_set, q\_mode\_ramp\_flag\_reset, 0) \tag{3.8.1-20}$$

where flipflop auxiliary function is defined in section 3.12.5. The initial state of the flipflop is set at 0, indicating the mode is not transitioning at the start of the simulation.

And the DER desired output reactive power is determined as:

$$q\_desired\_pu = \begin{cases} q\_desired\_ramp\_pu & \text{if } q\_mode\_ramp\_flag = 1 \\ q\_desired\_ref\_pu & \text{if } q\_mode\_ramp\_flag = 0 \end{cases} \tag{3.8.1-21}$$

If DER is tripped (der_status = “Trip”), the desired reactive power should be 0. The reactive power support functions should also be reset, by using equations (3.8.1-3), (3.8.1-8), (3.8.1-12) , (3.8.1-14). In addition, the mode transition flipflop and ramp functions should also be reset.

$$\begin{gathered} p\_desired\_pu = 0 \\ q\_desired\_ramp\_pu = ramp(0, 0, 0) \\ q\_mode\_ramp\_flag = flipflop(0,0,0) \end{gathered} \tag{3.8.1-22}$$

3.8.2. Modeling for PV DER

There are no specific considerations for PV DER. However, if needed, the watt-var function can be simplified for model calculation efficiency considerations.

3.8.3. Modeling for BESS DER

In IEEE 1547-2018 Section 10.6.2, the parameters of constant power factor include constant power factor setting, which is a value between 0-1, and the constant power factor excitation setting, which can be over-excited and under-excited.

The definition is clear for PV DERs which only inject power to the grid. But it may be ambiguous for energy storage DERs, as it may be interpreted to require energy storage DERs keeping the same reactive power direction for both charging and discharging mode. IEEE 1547.9-2022 (Guide for Using IEEE Std 1547™ for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems), Section 5.3.2 has suggested that:

> “The power factor line should continue as a straight line into the opposite quadrant to avoid a discontinuity in EPS system voltage stability.”

Thus, for modeling constant power factor performance of energy storage DER under charging condition, it is assumed that the DER injects reactive power in charging mode, and absorb reactive power in discharging mode, when specified as under-excited. There are no changes needed for model specification to reflect this.

3.9. DER Nameplate Output Capability and Priority of Responses

3.9.1. Modeling Based on IEEE 1547-2018 Requirements

As discussed in section 3.7, DER desired active power output $p\_desired\_kw$ is within the nameplate capability of the modeled DER. This module is to ensure that the DER output reactive power and overall apparent power are also within its nameplate capability range. There are two aspects to be considered:

- DER nameplate apparent power charge and discharge rating (NP_VA_MAX and $NP\_APPARENT\_POWER\_CHARGE\_MAX$)

- DER reactive power capability. In DER common file format, this information is defined as DER nameplate reactive power injected and absorbed maximum rating ($NP\_Q\_MAX\_INJ$ and $NP\_Q\_MAX\_ABS$). On the other hand, the DER output reactive power may not only be limited by a simple maximum rating. IEEE 1547-2018 does not require a DER to have reactive power capability when its active power output is less than 5% of the nameplate rating. It has a reduced capability requirement when its active power is less than 20%. The DER manufacturer may offer the capability to output reactive power greater than the minimum requirement specified in IEEE 1547-2018. To capture different reactive power capability curves offered by different DER system at lower power, a set of capability curve is defined in the DER model, noted as $NP\_Q\_CAPABILITY\_BY\_P\_CURVE$. If left unspecified, the capability curve will be automatically generated using the DER reactive power nameplate ratings, assuming the reactive capability is maintained regardless of active power output.

The variable list of DER nameplate output capability and priority of responses calculation is shown in Table 34.

Table 34. DER Nameplate output capability and priority of responses calculation variable list

Variable type	Variable name	Description
Input variable	$p\_desired\_pu$	Desired output active power from DER active power support functions in per unit
	NP_P_MAX	Active power rating at unity power factor
	$q\_desired\_pu$	Desired output reactive power from reactive power support functions in per unit
	$NP\_Q\_MAX\_INJ$	Reactive power injected maximum rating
	$NP\_Q\_MAX\_ABS$	Reactive power absorbed maximum rating
	$NP\_Q\_CAPABILITY\_BY\_P\_CURVE$ $(P\_Q\_INJ\_PU, Q\_MAX\_INJ\_PU, P\_Q\_ABS\_PU, Q\_MAX\_ABS\_PU)$	DER reactive power capability curves
	NP_VA_MAX	Apparent power maximum rating
	$const\_pf\_mode\_enable\_exec$	Constant Power Factor Mode Enable ($CONST\_PF\_MODE\_ENABLE$) after execution delay
	$qv\_mode\_enable\_exec$	Voltage-Reactive Power Mode Enable (QV_MODE_ENABLE) after execution delay
Input variable (continued)	$qp\_mode\_enable\_exec$	Active Power Reactive Power Mode Enable (QP_MODE_ENABLE) after execution delay
	$const\_q\_mode\_enable\_exec$	Constant Reactive Power Mode Enable ($CONST\_Q\_MODE\_ENABLE$) after execution delay
	$NP\_PRIO\_OUTSIDE\_MIN\_Q\_REQ$	Priority outside minimum requirements
	$NP\_NORMAL\_OP\_CAT$	Normal operating performance category

Table 34 (continued). DER Nameplate output capability and priority of responses calculation variable list

Variable type	Variable name	Description
Output variable	$p\_limited\_w$	DER output active power after considering DER apparent power limits
	$q\_limited\_var$	DER output reactive power after considering DER apparent power limits
Internal variable	$p\_desired\_pu$	Desired output active power from DER active power support functions in per unit
	$q\_desired\_pu$	Desired output reactive power from DER reactive power support functions in per unit
	$np\_va\_max\_appl$	Applicable nameplate apparent power rating depending on inject or absorb active power
	q_max_inj	Maximum reactive power injection at the desired active power output, defined by the capability curve $NP\_Q\_CAPABILITY\_BY\_P\_CURVE$
	q_max_abs	Maximum reactive power absorption at the desired active power output, defined by the capability curve $NP\_Q\_CAPABILITY\_BY\_P\_CURVE$
	p_itcp_w	Intercept point active power of DER apparent power capability circle and a piecewise curve
	q_itcp_var	Intercept point active power of DER apparent power capability circle and a piecewise curve
	$q\_requirement\_inj$	Reactive power injection capability required by IEEE 1547-2018
	$q\_requirement\_abs$	Reactive power absorption capability required by IEEE 1547-2018
	$q\_limited\_by\_p\_var$	Desired output reactive power after considering DER reactive power capability curve in volt-var or constant reactive power mode.
	$Q\_limited\_pf\_var$	Desired output reactive power after considering DER apparent power capability circle in constant power factor mode
	$q\_limited\_qp\_var$	Desired output reactive power after considering DER apparent power capability circle in watt-var mode
	$p\_limited\_pf\_w$	Desired output active power after considering DER apparent power capability circle in constant power factor mode

As a first step, the per unit values are transformed to actual values in Watts and vars to compare with the nameplate maximum ratings.

$$\begin{aligned} p\_desired\_w &= p\_desired\_pu \times NP\_P\_MAX \\ q\_desired\_var &= q\_desired\_pu \times NP\_VA\_MAX \end{aligned} \tag{3.9.1-1}$$

IEEE 1547-2018 Clause 5.3.1 requires

> "Operation at any active power output above 20% of rated active power shall not constrain the delivery of reactive power injection or absorption, up to the capability specified in Table 7, as required by the active control function at the time, as defined in 5.3. Curtailment of active power to meet apparent power constraints is permissible."

This indicates that the standard requires the DER to prioritize reactive power production over active power, if q_desire_kvar is within the minimum requirements specified in IEEE 1547-2018. The final DER output can be modeled depending on what reactive power support function is enabled.

Depending on the DER normal operating performance category, the reactive power capability requirements are different. Thus, intermediate variables are defined for later easier calculation:

$$\begin{aligned} q\_requirement\_inj &= 0.44 \times NP\_VA\_MAX \\ q\_requirement\_abs &= \begin{cases} 0.25 \times NP\_VA\_MAX & \text{if } NP\_NORMAL\_OP\_CAT = CAT\_A \\ 0.44 \times NP\_VA\_MAX & \text{if } NP\_NORMAL\_OP\_CAT = CAT\_B \end{cases} \end{aligned} \tag{3.9.1-2}$$

In addition, since the nameplate apparent power may be different for charging and discharging for BESS DERs, as indicated in IEEE 1547-2018 Table 28. A variable to indicate the applicable apparent power rating is defined:

$$np\_va\_max\_appl = \begin{cases} NP\_VA\_MAX & \text{if } p\_desired\_w \geq 0 \\ NP\_APPARENT\_POWER\_CHARGE\_MAX & \text{if } p\_desired\_w < 0 \end{cases} \tag{3.9.1-3}$$

<u>If volt-var or constant reactive power function is enabled</u>
($qv\_mode\_enable\_exec$ = ENABLED, or $const\_q\_mode\_enable\_exec$ = ENABLED):

As the first step, the maximum reactive power injection and absorption at the desired active power output, defined by the capability curve $NP\_Q\_CAPABILITY\_BY\_P\_CURVE$, are calculated:

$$\begin{aligned} q\_max\_inj &= interp(p\_desired\_pu, P\_Q\_INJ\_PU, Q\_MAX\_INJ\_PU) \times NP\_VA\_MAX \\ q\_max\_abs &= interp(p\_desired\_pu, P\_Q\_ABS\_PU, Q\_MAX\_ABS\_PU) \times NP\_VA\_MAX \end{aligned} \tag{3.9.1-4}$$

where $interp(x, x\_array, y\_array)$ is a linear interpolation function, which is defined to generate linear interpolant of x, using the piece-wise curve defined by x_array and y_array. Figure 16 shows an example of using the capability curve for PV DER.

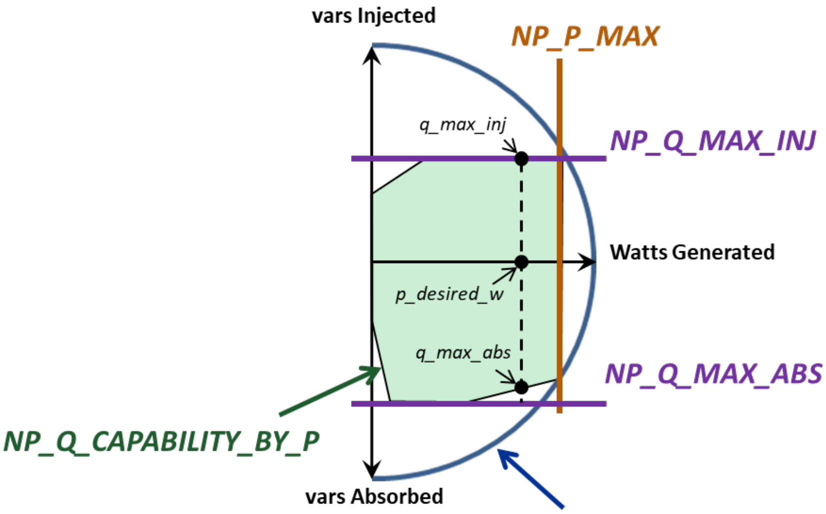

Figure 16. Example of reactive power capability for PV DER

Then, the DER output reactive power, limited by the capability curve, can be generated by:

$$q\_limited\_by\_p\_var = \min\left(q\_max\_inj\,, \max\left(-q\_max\_abs, q\_desired\_var\right)\right) \tag{3.9.1-5}$$

Next step is to consider the DER nameplate apparent power rating.

- If desired output apparent power is within the nameplate rating ($\sqrt{p\_desired\_w^2 + q\_limited\_low\_p\_var^2} \leq np\_va\_max\_appl$), the outputs are kept as same as the inputs

$$\begin{cases} p\_limited\_w = p\_desired\_w \\ q\_limited\_var = q\_limited\_low\_p\_var \end{cases} \tag{3.9.1-6}$$

- If desired output apparent power is outside the nameplate rating ($\sqrt{p\_desired\_w^2 + q\_limited\_low\_p\_var^2} > np\_va\_max\_appl$), the outputs should be reduced based on the following discussion of DER prioritization strategy:
  - If desired reactive power output is within the minimum requirement of IEEE 1547-2018, the active power should be curtailed to fulfill reactive power production, as required in IEEE 1547-2018 Clause 5.2.
  - A DER may have a greater capability than the minimum reactive power requirements specified in the IEEE 1547-2018. The standard does not provide guidance on its behavior outside of its minimum reactive power capability. It is up to the DER manufacturer to decide the response in this case. In this version of DER model, a variable $NP\_PRIO\_OUTSIDE\_MIN\_Q\_REQ$ is defined to represent two possible behaviors outside of IEEE 1547-2018's minimum requirements.
    - DER may prioritize active power generation beyond IEEE 1547-2018's minimum reactive power requirement ($NP\_PRIO\_OUTSIDE\_MIN\_Q\_REQ$ = ACTIVE). In this case, the final output for DER model should at least output reactive power to the

minimum requirement specified by IEEE 1547-2018 and maximize its active power generation.

$$
\begin{aligned}
q\_limited\_var &= \min(q\_requiremet\_inj, \\
&\max(q\_limited\_by\_p\_var, -q\_requirement\_abs)) \\
p\_limited\_w &= \sqrt{np\_va\_max\_appl^2 - q\_limited\_var^2} \\
&\times sign(p\_desired\_w)
\end{aligned}
\tag{3.9.1-7}
$$

where $sign(x)$ function yields +1 or -1 depending on the sign of its input x.

- DER may prioritize to fulfill reactive power support, even beyond IEEE 1547-2018's minimum reactive power requirement. ($NP\_PRIO\_OUTSIDE\_MIN\_Q\_REQ =$ REACTIVE)

$$
\begin{aligned}
q\_limited\_var &= q\_limited\_by\_p\_var \\
p\_limited\_w &= \sqrt{np\_va\_max\_appl^2 - q\_limited\_var^2} \\
&\times sign(p\_desired\_w)
\end{aligned}
\tag{3.9.1-8}
$$

Note this implementation also covers the case when desired reactive power is within the minimum capability requirement of IEEE 1547-2018.

The illustrative PV DER responses in volt-var or constant reactive power modes are shown in Figure 17. Hollow circles indicate DER desired active and reactive power output, and solid circles indicate DER active and reactive power output limited by the constraints.

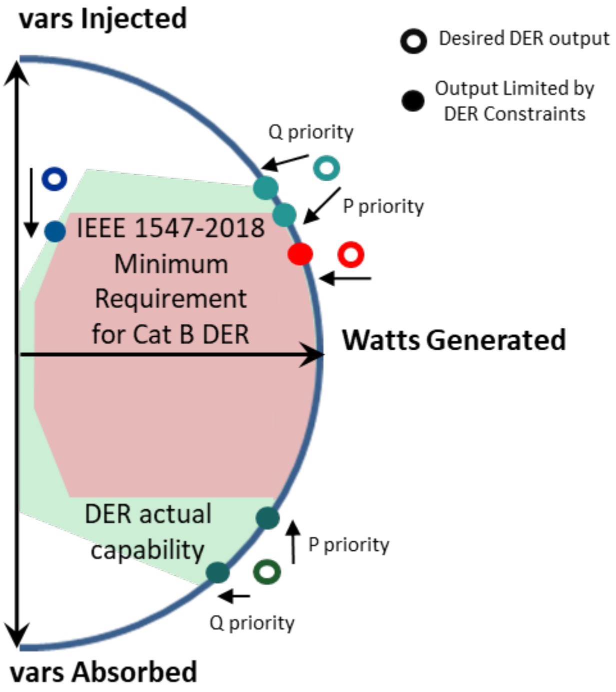

Figure 17. Illustrative responses of DER output active and reactive power in volt-var or constant reactive power mode.

If constant power factor function is enabled ($const\_pf\_mode\_enable\_exec = \text{ENABLED}$):

In this mode, as required by the standard, DER output active and reactive power should keep the constant power factor setting. Thus,

- If desired output apparent power is within the nameplate rating ($\sqrt{p\_desired\_w^2 + q\_desired\_var^2} \leq np\_va\_max\_appl$),

$$\begin{cases} p\_limited\_pf\_w = p\_desired\_w \\ q\_limited\_pf\_var = q\_desired\_var \end{cases} \tag{3.9.1-9}$$

- If desired output apparent power is outside of the nameplate rating ($\sqrt{p\_desired\_w^2 + q\_desired\_var^2} > np\_va\_max\_appl$),

$$\begin{cases} p\_limited\_pf\_w = \dfrac{np\_va\_max\_appl}{\sqrt{p\_desired\_w^2 + q\_desired\_var^2}} \times p\_desired\_w \\ q\_limited\_pf\_var = \dfrac{np\_va\_max\_appl}{\sqrt{p\_desired\_w^2 + q\_desired\_var^2}} \times q\_desired\_var \end{cases} \tag{3.9.1-10}$$

On the other hand, some DER manufacturers may offer to operate the DER with a smaller power factor than 0.9 when operating at lower active power generation condition. IEEE 1547-2018 does not provide guidance in this case. For the model implementation, the output reactive power magnitude is reduced to its capability range.

The calculation requires finding the intercept point between the DER reactive power capability curve and DER apparent power capability circle, indicated as p_itcp_kw and q_itcp_kvar.

$$p\_limited\_w = \begin{cases} \min(abs(p\_itcp\_w), \text{abs}(p\_limited\_pf\_w)) \times sign(p\_desired\_w) \\ \text{ if abs}(q\_limited\_pf\_var) > q\_itcp\_var \\ p\_limited\_pf\_w \\ \\ \text{Otherwise} \end{cases}$$

$$\begin{aligned} q\_max\_inj \ &= interp(\frac{p\_limited\_w}{NP\_P\_MAX}, P\_Q\_INJ\_PU, Q\_MAX\_INJ\_PU) \times NP\_VA\_MAX \\ q\_max\_abs \ &= interp(\frac{p\_limited\_w}{NP\_P\_MAX}, P\_Q\_ABS\_PU, Q\_MAX\_ABS\_PU) \times NP\_VA\_MAX \\ q\_limited\_var &= \min\,(q\_max\_inj\,, \max\,(-q\_max\_abs, q\_limited\_pf\_var)) \end{aligned} \tag{3.9.1-11}$$

The illustrative PV DER responses in constant power factor mode are shown in Figure 18. Hollow circles indicate DER desired active and reactive power output, and solid circles indicate DER active and reactive power output limited by the constraints. **Note that this behavior may be updated in future releases based on lab test results.**

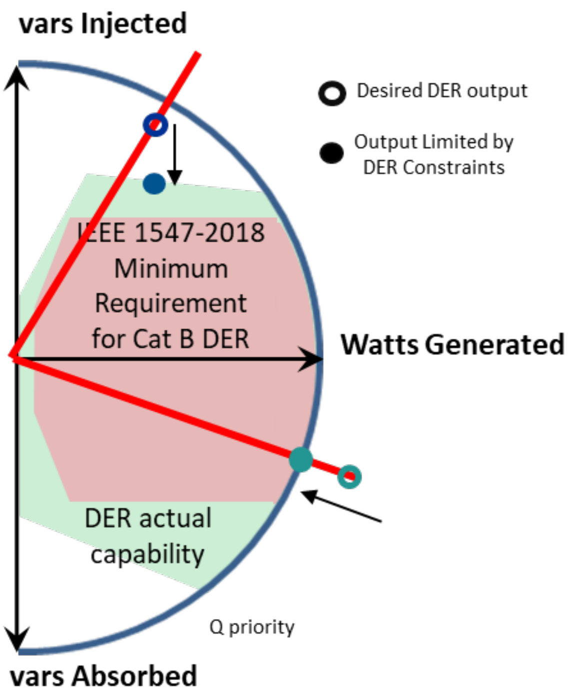

Figure 18. Illustrative responses of DER output active and reactive power in constant power factor mode.

If watt-var function is enabled ($qp\_mode\_enable\_exec = \text{ENABLED}$):

In this mode, DER output active and reactive power should keep the watt-var setting.

- If desired output apparent power is within the nameplate rating ($\sqrt{p\_desired\_w^2 + q\_desired\_var^2} \leq np\_va\_max\_appl$),

$$\begin{cases} p\_limited\_w = p\_desired\_w \\ q\_limited\_qp\_var = q\_desired\_var \end{cases} \tag{3.9.1-12}$$

- If desired output apparent power is outside of the nameplate rating ($\sqrt{p\_desired\_w^2 + q\_desired\_var^2} > np\_va\_max\_appl$), the DER should reduce its output to the intersection point of the watt-var setting curve and the DER apparent power capability curve, indicated as $p\_limited\_w$ and $q\_limited\_qp\_var$. They can be obtained by numerically sweeping through the settings.

Similar to the discussion in constant power factor mode, the final output reactive power is reduced to its capability range:

$$\begin{aligned} q\_max\_inj &= interp(\frac{p\_limited\_w}{NP\_P\_MAX}, P\_Q\_INJ\_PU, Q\_MAX\_INJ\_PU) \times NP\_VA\_MAX \\ q\_max\_abs &= interp(\frac{p\_limited\_w}{NP\_P\_MAX}, P\_Q\_ABS\_PU, Q\_MAX\_ABS\_PU) \times NP\_VA\_MAX \\ q\_limited\_var &= \min\,(q\_max\_\text{inj}\,, \max\,(-q\_max\_abs, q\_limited\_qp\_var)) \end{aligned} \tag{3.9.1-13}$$

Note that this module only provides the possible responses that may be offered by the DER manufacturers. There can be other responses available, especially with different grid support functions. This model may also be updated according to future lab test results.

3.9.2. Modeling for PV and BESS DER

Although the modeling considerations are mostly for PV DER in the previous section 3.9.1, the equation can be applied also for BESS DER. There are no additions in this version of model release.

3.10. Abnormal Voltage and Frequency Ride-through Performance

This module is the final step before generating the output values of the DER model. It is intended to model the DER responses as according to the voltage and frequency ride-through requirements as defined in IEEE 1547-2018. The structure is presented in Figure 19.

As discussed in section 2.4, The OpenDER model offers different options as the output of the DER model, according to the simulation needs. The developers or users can select the appropriate one for their application. In Version 2.1 release, 3 options are provided, such that the model can output as a power source, current source, or a voltage source behind an impedance. Other options may be added in future releases.

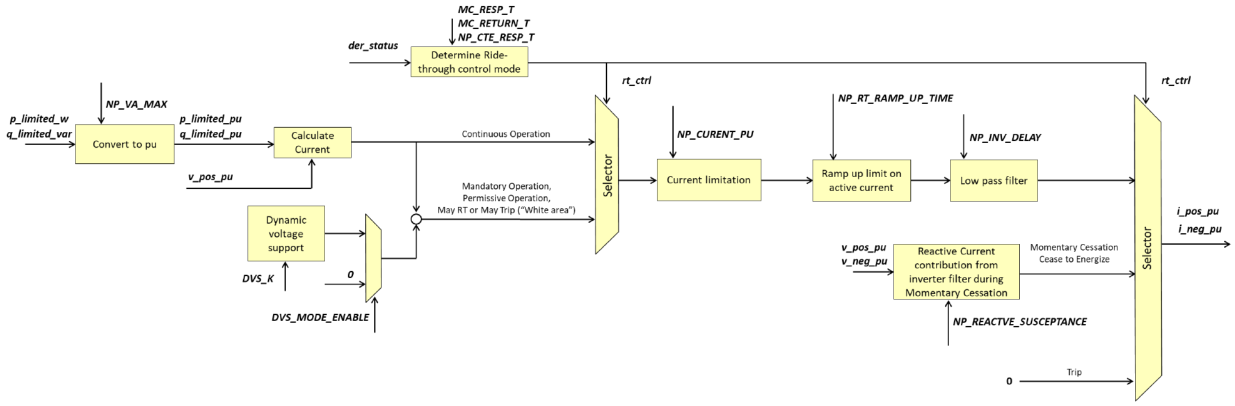

Figure 19. Model structure of remaining DER control and circuit equivalents

3.10.1. Modeling Based on IEEE 1547-2018 Requirements

This module calculates the DER output current at RPA depending on the DER ride-through performance required by IEEE 1547-2018, which will in turn be used to calculate the final DER model output. The parameter list is shown in Table 35.

Table 35. DER ride-through performance variable list

Variable type	Variable name	Description
Input variable	*p_limited_w*	DER output active power after considering DER apparent power limits
	q_limited_var	DER output reactive power after considering DER apparent power limits
	v_pos_pu	Positive sequence voltage phasor as complex number at RPA
	v_neg_pu	Negative sequence voltage phasor as complex number at RPA
	v_angle	Voltage angle at RPA in radian
	der_status	DER operation status
	NP_VA_MAX	DER nameplate apparent power rating
	DVS_MODE_ENABLE	Dynamic Voltage Support during ride-through enable
	DVS_K	Dynamic Voltage Support K factor (Per unit current increase in respond to per unit voltage change during ride-through)
	NP_CURRENT_PU	DER nameplate max current in per unit
	NP_RT_RAMP_UP_TIME	Recovery time from ride-through
	NP_INV_DELAY	DER inverter equivalent open loop delay for closed-loop current control
	MC_RESP_T	Momentary cessation response time
	MC_RETURN_T	Time to start to restore output from momentary cessation
	NP_CTE_RESP_T	Cease to Energize response time
Output variable	*i_pos_pu*	DER output positive sequence current phasor as complex number in per unit
	i_neg_pu	DER output negative sequence current phasor as complex number in per unit

Table 35 (continued). DER ride-through performance variable list

Variable type	Variable name	Description
Internal variable	rt_ctrl	DER ride-through control mode
	$p\_limited\_pu$	DER output active power in per unit after considering DER apparent power limits (per unit based on NP_VA_MAX)
	$q\_limited\_pu$	DER output reactive power in per unit after considering DER apparent power limits (per unit based on NP_VA_MAX)
	$i\_pos\_d\_ref\_pu$	Active current magnitude in positive sequence
	$i\_pos\_q\_ref\_pu$	Reactive current magnitude in positive sequence
	$i\_neg\_ref\_pu$	Current phasor as complex number in negative sequence
	$i\_pos\_d\_limited\_ref\_pu$	Active current magnitude in positive sequence after limitation
	$i\_pos\_q\_limited\_ref\_pu$	Reactive current magnitude in positive sequence after limitation
	$i\_pos\_limited\_ref\_pu$	Positive sequence current phasor as complex number after limitation and active current ramp up limit
	$i\_neg\_limited\_ref\_pu$	Negative sequence current phasor as complex number after limitation
	$i\_pos\_d\_rrl\_ref\_pu$	Active current magnitude in positive sequence after ramp rate limit
	i_max_pu	Maximum of phase current before limitation

First, the DER ride-through status is determined by the based on the performance requirements of the ride-through modes. The summary of the performance requirements is shown in Table 36.

Table 36. IEEE 1547-2018 requirements on ride-through performance

Operating mode	Selected Performance Requirements
Continuous Operation	IEEE 1547-2018 Section 5 (Reactive power capability and voltage/power control requirements) applies. IEEE 1547-2018 Section 6.4.2.2 requires: “Voltage disturbances of any duration, for which the applicable voltage as specified in 4.3 remains within Range B as defined by ANSI C84.1, shall not cause the DER to cease to energize and trip from the Area EPS. The DER shall remain in operation during any such disturbance, and shall continue to deliver available active power of magnitude at least as great as its pre-disturbance level of active power, prorated by the per-unit voltage level of the least phase voltage if that voltage is less than the nominal voltage. Temporary deviations of active power having durations not exceeding 0.5 s shall be allowed.”
Mandatory Operation	IEEE 1547-2018 Section 6.4.2.3.3 for voltage ride-through requires: • “Shall maintain synchronism with the Area EPS. • Shall continue to exchange current with the Area EPS. • Shall neither cease to energize nor trip. DER of Category II and Category III shall, by default, not reduce its total apparent current during the disturbance period in mandatory operation mode below 80% of the pre-disturbance value or of the corresponding active current level subject to the available active power, whichever is less, subject to the following: ……” IEEE 1547-2018 Section 6.5.2.3.2 and 6.5.2.5.2 for frequency ride-through has similar requirements, and additionally requires the frequency-droop behavior. It also requires the DER to continue to exchange the pre-disturbance active power output during the ride-through period for Category II and III DERs.
Permissive operation	IEEE 1547-2018 Section 6.4.2.3.3 and 6.4.2.4.3 requires: • “Shall maintain synchronism with the Area EPS or shall not trip. • May continue to exchange current with the Area EPS or may cease to energize. • If DER ceases to energize, shall restore output as specified in 6.4.2.7.”
Momentary Cessation	IEEE 1547-2018 Section 6.4.2.3.3 and 6.4.2.4.3 requires: • “Shall not trip. • Shall cease to energize. • Shall restore output as specified in 6.4.2.7.”

Table 36 (continued). IEEE 1547-2018 requirements on ride-through performance

Operating mode	Selected Performance Requirements
Cease to Energize	IEEE 1547-2018 Section 3 defines Cease to Energize as: "cease to energize: Cessation of active power delivery under steady-state and transient conditions and limitation of reactive power exchange. NOTE 1—This may lead to momentary cessation or trip. NOTE 2—This does not necessarily imply, nor exclude disconnection, isolation, or a trip. NOTE 3—Limited reactive power exchange may continue as specified, e.g., through filter banks. NOTE 4—Energy storage systems are allowed to continue charging but are allowed to cease from actively charging when the maximum state of charge (maximum stored energy) has been achieved.[37] NOTE 5—Refer to 4.5 for additional details."
Dynamic Voltage Support	IEEE 1547-2018 Section 6.4.2.6 mentions: "The dynamic voltage support capability may be utilized during mandatory operation or permissive operation under a mutual agreement with the Area EPS operator considering both the capability and the DER-specific implementation of the dynamic voltage support function. The DER shall maintain synchronism with the Area EPS and may provide dynamic voltage support to the Area EPS during and following temporary voltage disturbances, for which the applicable voltage on any phase is as follows:……"

The standard allows different implementations from DER manufacturers and developers in the ride-through modes. Assumptions are made in the current version of OpenDER, which will be further updated based on lab and field test results, and DERMUG meetings.

- In Continuous Operation mode, the DER is controlled in "Normal Operation", with all grid support functions active.
- In Mandatory Operation mode, the DER is assumed to be controlled the same way as Continuous Operation, referred as "Normal Operation". In addition, if Dynamic Voltage Support is utilized, the DER operates in "Dynamic Voltage Support" status. Note that other behaviors may also be possible.
- In Permissive Operation mode, the DER is assumed to be controlled the same way as Continuous Operation, referred as "Normal Operation". In addition, if Dynamic Voltage Support is utilized, the DER operates in "Dynamic Voltage Support" status. Note that other behaviors may also be possible.[38]

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[37] In IEEE 1547.9-2022 Section 4.5, it is clarified that Energy Storage DER is allowed to charge only for continuation of supply to housekeeping and auxiliary loads.

[38] For example, IEEE 1547.1-2020 Table 3-4 has indicated that if the DER is entering the Permissive Operation mode from Cease to Energize mode, the DER may continue to cease to energize.

- In Momentary Cessation mode, the DER is controlled to stop exchanging the active and reactive power, referred as “Cease to Energize”. The standard allows a maximum of 0.083 s response time. A parameter MC_RESP_T is defined to model a non-zero response time.
- In Cease to Energize mode, the DER is controlled to stop exchanging the active and reactive power, referred as “Cease to Energize”. The standard allows a maximum of 0.16 s response time. A parameter $NP\_CTE\_RESP\_T$ is defined to model a non-zero response time.
- If DER returns from “Momentary Cessation” or “Cease to Energize” to normal operation, the DER may have a delay to start to exchange current. A parameter MC_RETURN_T is defined to model a non-zero response time.
- In Not Defined mode (when frequency is outside of the ride-through range), the DER is assumed to be controlled the same way as Continuous Operation, referred as “Normal Operation”.

Based on the interpretations above, the DER ride-through control condition, rt_ctrl, is determined:

- If der_status = “Trip”

  $$rt\_ctrl = \text{"Trip"}$$
- If $con_del_enable($$der_status$ = “Momentary Cessation” or der_status = “Cease to Energize”, $MC\_RETURN\_T)$
  - If der_status = “Continuous Operation”

    $$rt\_ctrl = \text{"Normal Operation"}$$
  - If der_status = “Not Defined”

    $$rt\_ctrl = \text{"Normal Operation"}$$
  - If der_status = “Entering Service”

    $$rt\_ctrl = \text{"Normal Operation"}$$
  - If (der_status = “Mandatory Operation” or der_status = “Permissive Operation”) and ($DVS\_MODE\_ENABLE = \text{DISABLED}$)

    $$rt\_ctrl = \text{"Normal Operation"}$$
  - If (der_status = “Mandatory Operation” or der_status = “Permissive Operation”) and ($DVS\_MODE\_ENABLE = \text{ENABLED}$)

    $$rt\_ctrl = \text{"Dynamic Voltage Support"}$$
- If $con_del_enable($$der_status$ = “Momentary Cessation”, MC_RESP_T)

  $$rt\_ctrl = \text{"Cease to Energize"}$$
- If $con_del_enable($$der_status$ = “Cease to Energize”, NP_CTE_RESP_T)

  $$rt\_ctrl = \text{"Cease to Energize"}$$

(3.10.1-1)

The next step is to calculate the DER output current based on the identified DER ride-through control condition. The per-unit active and reactive power is first calculated, using the nameplate apparent power as base.

$$\begin{gathered} p\_limited\_pu = p\_limited\_w / NP\_VA\_MAX \\ q\_limited\_pu = q\_limited\_var / NP\_VA\_MAX \end{gathered} \tag{3.10.1-2}$$

- If the DER is tripped (rt_ctrl = “Trip”), the DER output current should be 0.:

  $$\begin{gathered} i\_pos\_pu = 0 \\ i\_neg\_pu = 0 \end{gathered} \tag{3.10.1-3}$$

  In addition, the state variables for the ramp rate limit and low pass filter in equations (3.10.1-10) and (3.10.1-11) should be reset.

- If the DER is controlled to cease to energize or in momentary cessation, (rt_ctrl = “Cease to Energize”), the DER output current is determined by the passive devices, including supplemental capacitor banks, inverter filter, underground cable capacitance, etc. IEEE 1547-2018 requires the DER operator to provide the reactive susceptance upon request. The parameter $NP\_REACTIVE\_SUSCEPTANCE$ is identified as a nameplate information in common file format, and is used in the calculation.

  $$\begin{gathered} i\_pos\_d\_ref\_pu = 0 \\ i\_pos\_q\_ref\_pu = -NP\_REACTIVE\_SUSCEPTANCE \times abs(v\_pos\_pu) \\ i\_pos\_ref\_pu = (i\_pos\_d\_ref\_pu + i \times i\_pos\_q\_ref\_pu) \times e^{i \times v\_angle} \\ i\_neg\_ref\_pu = i \times NP\_REACTIVE\_SUSCEPTANCE \times v\_neg\_pu \end{gathered} \tag{3.10.1-4}$$

  In addition, the state variables for the ramp rate limit and low pass filter in equations (3.10.1-10) and (3.10.1-11) should be reset.

- Otherwise, the DER actively exchanges current with the grid:
  - If the DER is controlled in normal operation (rt_ctrl = “Normal Operation”), the active and reactive current on positive sequence is calculated, and negative sequence current is 0.

    $$\begin{gathered} i\_pos\_d\_ref\_pu = p\_limited\_pu / abs(v\_pos\_pu) \\ i\_pos\_q\_ref\_pu = -q\_limited\_pu / abs(v\_pos\_pu) \\ i\_neg\_ref\_pu = 0 \end{gathered} \tag{3.10.1-5}$$

  - If the DER is controlled to provide dynamic voltage support in abnormal voltage ride-through condition, (rt_ctrl = “Dynamic Voltage Support”), IEEE 1547-2018 does not provide explicit guidance on the DER’s performance. Thus, the requirement of VDE standard is used to model the potential DER behavior, that reactive current on positive sequence and negative sequence current are proportional to the voltage deviation by a factor of DVS_K.

$$\begin{aligned} i\_pos\_d\_ref\_pu &= p\_limited\_pu/abs(v\_pos\_pu)\\ i\_pos\_q\_ref\_pu &= -q\_limited\_pu/abs(v\_pos\_pu)\\ &\quad +(abs(v\_pos\_pu)-1)\times DVS\_K\\ i\_neg\_ref\_pu &= v\_neg\_pu \times DVS\_K \times i \end{aligned} \tag{3.10.1-6}$$

Then, a current limitation mechanism is applied, such that the DER output current on any phase does not exceed the limit. In this version of OpenDER model, it is done by calculating the maximum of the three-phase current, i_max_pu.

$$\begin{aligned} i\_max\_pu = max(abs(convert\_symm\_to\_abc((i\_pos\_d\_ref\_pu\\ + i \times i\_pos\_q\_ref\_pu) \times e^{i \times v\_angle}, i\_neg\_pu, 0)))) \end{aligned} \tag{3.10.1-7}$$

- If i_max_pu is smaller than the DER current capability $NP\_CURRENT\_PU$, the DER inverter is able to carry out the current reference:

$$\begin{aligned} i\_pos\_d\_limited\_ref\_pu &= i\_pos\_d\_ref\_pu\\ i\_pos\_q\_limited\_ref\_pu &= i\_pos\_q\_ref\_pu\\ i\_neg\_limited\_ref\_pu &= i\_neg\_ref\_pu \end{aligned} \tag{3.10.1-8}$$

- If i_max_pu is greater than the DER current capability $NP\_CURRENT\_PU$, the DER inverter has to reduce its output current. Currently, OpenDER assumes the reactive current priority[39].
  - First, perform equation (3.10.1-7) again assuming $i\_pos\_d\_ref\_pu$ is 0. If i_max_pu is still greater than the DER current capability $NP\_CURRENT\_PU$. The DER inverter is not able to inject any active current.

$$\begin{aligned} i\_pos\_d\_limited\_ref\_pu &= 0\\ i\_pos\_q\_limited\_ref\_pu &= i\_pos\_q\_ref\_pu \times \frac{NP\_CURRENT\_PU}{i\_max\_pu}\\ i\_neg\_limited\_ref\_pu &= i\_neg\_ref\_pu \times \frac{NP\_CURRENT\_PU}{i\_max\_pu} \end{aligned} \tag{3.10.1-9}$$

  - If assuming $i\_pos\_d\_ref\_pu$ is 0. If i_max_pu is smaller than the DER current capability $NP\_CURRENT\_PU$. The DER inverter keeps the reactive power reference, and find out the active power component by sweeping through the possible values.

Next, the ride-through recovery performance, as a ramp rate limit, is modeled to represent the requirement in IEEE 1547-2018 Section 6.4.2.7 is modeled. The ramp rate limit is only applied to the active current component. The parameter $NP\_RT\_RAMP\_UP\_TIME$ is defined as the time required for the active current restore from 0 to 100% of rated current. This ramp rate limit is only applied for ramp up[40].

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[39] This is not required by IEEE 1547-2018, but required by IEEE 2800-2022 and VDE grid codes.

[40] The parameter *NP_RT_RAMP_UP_TIME* is equivalent to the reciprocal of the parameter *rrpwr* (Rate at which active current (power) recovers after a fault [pu/s]) in WECC Renewable Energy Generator/Converter (REGC_B and REGC_C) models.

If $i\_pos\_d\_limited\_ref\_pu > 0$

$$i\_pos\_d\_rrl\_pu = ramp(i\_pos\_d\_limited\_ref\_pu, NP\_RT\_RAMP\_UP\_TIME, 0)$$

If $i\_pos\_d\_limited\_ref\_pu \leq 0$ (3.10.1-10)

$$i\_pos\_d\_rrl\_pu = ramp(i\_pos\_d\_limited\_ref\_pu, 0, NP\_RT\_RAMP\_UP\_TIME)$$

$$i\_pos\_limited\_ref\_pu = (i\_pos\_d\_rrl\_pu + i \times i\_pos\_q\_limited\_ref\_pu) \times e^{i \times v\_angle}$$

Finally, first order lag low pass filters are applied to the DER output current references, emulating the closed-loop DER inverter control delay. The parameter NP_INV_DELAY indicates the duration from a step change in the current reference input until the output changes by 90% of its final change[41].

$$\begin{gathered} i\_pos\_pu = lpf(i\_pos\_limited\_ref\_pu, NP\_INV\_DELAY) \\ i\_neg\_pu = lpf(i\_neg\_limited\_ref\_pu, NP\_INV\_DELAY) \end{gathered} \quad (3.10.1\text{-}11)$$

3.10.2. Modeling for PV and BESS DER

There are no special considerations for modeling DER ride-through performance for PV and BESS in this version of model release.

3.11. DER Model Outputs

Based on the calculated DER output currents from the DER ride-through performance, this module calculates the DER model outputs as a power source, a current source, or a voltage source behind impedance. Different options may be suitable or not suitable to be used for different system level analysis, as discussed in Table 37. The listed analysis types are just for example and not exhaustive.

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[41] The parameter *NP_INV_DELAY* is equivalent to 2.3 times of the parameter *Tg* (Emulated delay in converter controls [s]) in WECC Renewable Energy Generator/Converter (REGC_A and REGC_B) models.

Table 37. Analysis applications of DER model output options

Analysis Type	Power Source	Current Source	Voltage Source behind Impedance
Voltage fluctuation	Suitable	Suitable	Suitable
Rapid voltage change	Suitable	Suitable	Suitable
Fault current contribution	Not suitable	Suitable	Suitable
Temporary Overvoltage[42]	Not suitable	Not suitable	Somewhat Suitable
Open phase detection[43]	Not suitable	Somewhat suitable	Somewhat suitable
Stability (grid support functions related)	Suitable	Suitable	Suitable
Stability (inverter control related)[44]	Not suitable	Somewhat suitable	Somewhat suitable
Flicker[45]	Suitable	Suitable	Suitable

3.11.1. Power Source

As a power source, the DER model exchanges its output active and reactive power with the circuit simulation. For the ease of integration with circuit simulation tool, the output active and reactive powers are provided with different options of units. For three-phase DER, a single value of the DER total output on all three-phases is provided. Calculation for individual phases may be updated in the future releases depending on the needs, that will be identified through DERMUG meetings.

This option can be used in steady state, QSTS, or dynamic (RMS) simulation for system studies such as hosting capacity analysis, voltage fluctuation, DER control, and line voltage regulator interaction analysis, etc. However, this method may not be accurate enough if the RPA voltage is unbalanced, or in islanded or open phase condition. The parameter list is shown in Table 38.

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[42] Including load rejection overvoltage (LROV) and ground fault overvoltage (GFOV). EMT analysis is recommended for more accurate result.

[43] This version of OpenDER model does not include active open phase detection method, which may be added in later version release. EMT analysis is recommended for more accurate result.

[44] This version of OpenDER model only includes open loop representations of DER inverter's closed-loop control. EMT analysis is recommended for more accurate result.

[45] DER inverter's fast control or harmonic contribution may contribute to the flicker in rare circumstances, which may not be represented currently in OpenDER model.

Table 38. DER model output as power source variable list

Variable type	Variable name	Description
Input variable	i_pos_pu	DER output positive sequence current in per unit
	v_pos_pu	Positive sequence voltage at RPA
	NP_VA_MAX	DER nameplate apparent power rating
Output variable	p_out_pu	DER output active power in per unit based on the DER nameplate apparent power rating
	q_out_pu	DER output reactive power in per unit based on the DER nameplate apparent power rating
	p_out_w	DER output active power in Watts
	q_out_var	DER output reactive power in vars
	p_out_kw	DER output active power in kilowatts
	q_out_kvar	DER output reactive power in kilovars

The DER output active and reactive power in per unit, based on the DER nameplate apparent power rating is calculated by multiplying the positive sequence voltage and the current at RPA. To capture the unbalanced (negative sequence) behavior, the options of current source or voltage source behind impedance are recommended.

$$\begin{aligned} p\_out\_pu &= Re(i\_pos\_pu \times Conjugate\ (v\_pos\_pu)) \\ q\_out\_pu &= Im(i\_pos\_pu \times Conjugate(v\_pos\_pu)) \end{aligned} \tag{3.11.1-1}$$

where $Re(X)$ indicates the real part of the complex number X, $Im(X)$ indicates the imaginary part of the complex number X, and $Conjugate(X)$ indicates the conjugate of complex number.

Then, the DER outputs in watts/vars and kW/kvar are calculated.

$$\begin{aligned} p\_out\_w &= p\_out\_pu \times NP\_VA\_MAX \\ q\_out\_var &= q\_out\_pu \times NP\_VA\_MAX \end{aligned} \tag{3.11.1-2}$$

$$\begin{aligned} p\_out\_kw &= p\_out\_w \times 0.001 \\ q\_out\_kvar &= q\_out\_var \times 0.001 \end{aligned} \tag{3.11.1-3}$$

3.11.2. Current Source

As a current source, the DER model exchanges its output currents with the circuit simulation. Similar to power source option, the output currents are also provided with different options of units. For three-phase DER, three values of the DER output currents on individual phases are provided. This option can be used most distribution analyses except for temporary overvoltage. The parameter list is shown in Table 39.

Table 39. DER model output as current source variable list

Variable type	Variable name	Description
Input variable	i_pos_pu	DER output positive sequence current in per unit
	i_neg_pu	DER output negative sequence current in per unit
	v_angle	Voltage angle at RPA in radian
	NP_VA_MAX	DER nameplate apparent power rating
	$NP\_AC\_V\_NOM$	AC voltage base—nominal voltage rating
	NP_PHASE	Single- or Three-phase DER
Output variable	i_mag_pu (if three-phase DER: array of $[i\_a\_mag\_pu, i\_b\_mag\_pu, i\_c\_mag\_pu])$	For single-phase DER: an array of a single floating number of DER output current magnitude in per unit
		For three-phase DER: an array of three floating numbers of DER three-phase output current magnitude in per unit
	i_mag_amp (if three-phase DER: array of [$i\_a\_mag\_amp, i\_b\_mag\_amp, i\_c\_mag\_amp$])	For single-phase DER: an array of a single floating number of DER output current magnitude in Ampere
		For three-phase DER: an array of three floating numbers of DER three-phase output current magnitude in Ampere
	i_theta (if three-phase DER: array of [$i\_a\_theta, i\_b\_theta, i\_c\_theta$])	For single-phase DER: an array of a single floating number of DER output current angle
		For three-phase DER: an array of three floating numbers of DER three-phase output current angle

If three-phase DER ($NP\_PHASE = \mathrm{THREE}$), the current magnitudes in the three-phases are calculated based on the positive and negative sequence current per unit values.

$$i\_a\_mag\_pu, i\_b\_mag\_pu, i\_c\_mag\_pu = abs(convert\_symm\_to\_abc(i\_pos\_pu, i\_neg\_pu, 0) \qquad (3.11.2\text{-}1)$$

Additionally, the currents in the units of Ampere is also calculated.

$$\begin{aligned} i\_a\_mag\_amp &= i\_a\_pu \times \frac{NP\_VA\_MAX}{\sqrt{3} \times NP\_AC\_V\_NOM} \\ i\_b\_mag\_amp &= i\_b\_pu \times \frac{NP\_VA\_MAX}{\sqrt{3} \times NP\_AC\_V\_NOM} \\ i\_c\_mag\_amp &= i\_c\_pu \times \frac{NP\_VA\_MAX}{\sqrt{3} \times NP\_AC\_V\_NOM} \end{aligned} \qquad (3.11.2\text{-}2)$$

Finally, the phase angles of the currents are calculated.

$$i\_a\_theta, i\_b\_theta, i\_c\_theta = angle(convert\_symm\_to\_abc(i\_pos\_pu, i\_neg\_pu, 0) \tag{3.11.2-3}$$

The current magnitude and phase angle is calculated, if DER is single-phase ($NP\_PHASE =$ SINGLE):

$$\begin{gathered} i\_mag\_pu = |i\_pos\_pu| \\ i\_mag\_amp = i\_mag\_pu \times \frac{NP\_VA\_MAX}{NP\_AC\_V\_NOM} \\ i\_theta\_pu = angle(i\_pos\_pu) \end{gathered} \tag{3.11.2-4}$$

3.11.3. Voltage Source Behind Impedance

As a voltage source behind impedance, the DER model exchanges its internal circuit's voltage with the circuit simulation, separated by an impedance. This impedance may represent the DER inverter filter and potentially interconnection transformer, if the RPA is at PCC[46].

Similar to the other DER outputs, the output voltages are also provided with different options of units. For three-phase DER, three values of the DER output voltages on individual phases are provided. This option can be the more accurate than current source and power source option, but it requires more information of the DER model, including the DER inverter's DC voltage and source impedance. The parameter list is shown in Table 40.

Table 40. DER model output as voltage source behind impedance variable list

Variable type	Variable name	Description
Input variable	i_pos_pu	DER output positive sequence current in per unit
	i_neg_pu	DER output negative sequence current in per unit
	v_angle	Voltage angle at RPA in radian
	v_pos_pu	Positive sequence voltage at RPA
	v_neg_pu	Negative sequence voltage at RPA
	$NP\_AC\_V\_NOM$	AC voltage base—nominal voltage rating
	NP_V_DC	DC voltage scaled to AC voltage base at RPA
	NP_PHASE	Single- or Three-phase DER
	$NP\_RESISTANCE$	DER source resistance for voltage output
	$NP\_REACTANCE$	DER source reactance for voltage output

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[46] In WECC Renewable Energy Generator/Converter (REGC_B and REGC_C) models, the typical range of Source resistance (*re*) is between 0–0.01 pu, and the typical range of Source reactance (*Xe*) is between 0.05–0.2 pu

Table 40 (continued). DER model output as voltage source behind impedance variable list

Variable type	Variable name	Description
Output variable	$v\_out\_mag\_pu$ (if three-phase DER: array of $[v\_a\_out\_mag\_pu, v\_b\_out\_mag\_pu, v\_c\_out\_mag\_pu]$)	For single-phase DER: an array of a single floating number of DER output voltage magnitude in per unit
		For three-phase DER: an array of three floating numbers of DER three-phase output voltage magnitude in per unit
	$v\_out\_mag\_v$ (if three-phase DER: array of $[v\_a\_out\_mag\_v, v\_b\_out\_mag\_v, v\_c\_out\_mag\_v]$)	For single-phase DER: an array of a single floating number of DER output current magnitude in Volt
		For three-phase DER: an array of three floating numbers of DER three-phase output current magnitude in Volt
	v_out_theta (if three-phase DER: array of $[v\_a\_out\_theta, v\_b\_out\_theta, v\_c\_out\_theta]$)	For single-phase DER: an array of a single floating number of DER output current angle
		For three-phase DER: an array of three floating numbers of DER three-phase output current angle
Internal Variables	$v\_pos\_out\_cmd\_pu$	DER output positive sequence voltage magnitude before limitation in per unit
	$v\_neg\_out\_cmd\_pu$	DER output negatve sequence voltage magnitude before limitation in per unit
	$v\_pos\_out\_pu$	DER output positive sequence voltage magnitude in per unit
	$v\_neg\_out\_pu$	DER output negatve sequence voltage magnitude in per unit
	v_max_pu	DER output maximum phase voltage

As the first step, the voltage source's positive and negative sequence voltages are calculated based on the voltage at the grid side, and the current flow through the impedance.

$$\begin{aligned} v\_pos\_out\_cmd\_pu &= v\_pos\_pu + i\_pos\_pu \times (NP\_RESISTANCE + i \times NP\_REACTANCE) \\ v\_neg\_out\_cmd\_pu &= v\_neg\_pu + i\_neg\_pu \times (NP\_RESISTANCE + i \times NP\_REACTANCE) \end{aligned} \tag{3.11.3-1}$$

The voltage magnitude(s) should not be greater than the voltage that can be supplied by the DER inverter. Typically, the maximum voltage that can be produced by an inverter is determined by its DC voltage.

Thus, for three-phase DER ($NP\_PHASE =$ THREE), in this version of OpenDER model, it is done by calculating the maximum of the three-phase voltage, v_max_pu.

$$v\_max\_pu = max(abs(convert\_symm\_to\_abc(v\_pos\_out\_cmd\_pu, v\_neg\_out\_cmd\_pu, 0))) \tag{3.11.3-2}$$

If v_max_pu is greater than the DER voltage output capability, which is assumed to $\frac{NP\_V\_DC}{NP\_AC\_V\_NOM}$, all voltage components are scaled proportionally. This voltage limiting mechanism may be updated in the future based on lab and field test results.

$$\begin{gathered} v\_pos\_out\_pu = v\_pos\_out\_cmd\_pu \times \frac{NP\_V\_DC}{NP\_AC\_V\_NOM} \div v\_max\_pu \\ v\_neg\_out\_pu = v\_neg\_out\_pu \times \frac{NP\_V\_DC}{NP\_AC\_V\_NOM} \div v\_max\_pu \end{gathered} \tag{3.11.3-3}$$

Then, the voltage source's three-phase voltages in per unit and in Volts are calculated,

$$\begin{aligned} & v\_a\_out\_mag\_pu, v\_b\_out\_mag\_pu, v\_c\_out\_mag\_pu \\ & \qquad = abs(convert\_symm\_to\_abc(v\_pos\_out\_pu, v\_neg\_out\_pu, 0)) \end{aligned} \tag{3.11.3-4}$$

$$\begin{gathered} v\_a\_out\_mag\_v = v\_a\_out\_mag\_pu \times \frac{NP\_V\_AC\_NOM}{\sqrt{3}} \\ v\_b\_out\_mag\_v = v\_b\_out\_mag\_pu \times \frac{NP\_V\_AC\_NOM}{\sqrt{3}} \\ v\_c\_out\_mag\_v = v\_c\_out\_mag\_pu \times \frac{NP\_V\_AC\_NOM}{\sqrt{3}} \end{gathered} \tag{3.11.3-5}$$

And the voltage source's three-phase voltage angles are calculated.

$$\begin{aligned} & v\_a\_out\_theta, v\_b\_out\_theta, v\_c\_out\_theta \\ & \qquad = angle(convert\_symm\_to\_abc(v\_pos\_out\_pu, v\_neg\_out\_pu, 0)) \end{aligned} \tag{3.11.3-6}$$

For single-phase DER ($NP\_PHASE = \mathrm{SINGLE}$), in this version of OpenDER model, similar voltage limiting strategy is adopted. If $v\_pos\_out\_cmd\_pu$ is smaller than $\sqrt{2} \times NP\_AC\_V\_NOM$,

$$v\_out\_mag\_pu = |v\_pos\_out\_pu| \tag{3.11.3-7}$$

Otherwise,

$$v\_out\_mag\_pu = \frac{NP\_V\_DC}{\sqrt{2} \times NP\_AC\_V\_NOM} \tag{3.11.3-8}$$

And the voltage magnitude in Volts, as well as voltage angle, are calculated.

$$\begin{gathered} v\_out\_mag\_v = v\_out\_mag\_pu \times NP\_V\_AC\_NOM \\ v\_out\_theta = angle(v\_pos\_out\_pu) \end{gathered} \tag{3.11.3-9}$$

3.12. Commonly Used Auxiliary Functions

This section introduces the commonly used auxiliary functions that are invoked by multiple different functions, which include first order lag (*lpf*), ramp rate limit (*ramp*), time delay (*tdelay*), conditional delayed enable (*con_del_enable*), and flipflop logic (*flipflop*).

All of the defined auxiliary functions require internal state variables to store values in the previous timestep(s). For each instance of such auxiliary function invoked by the DER model, separated internal state variables shall be created, initialized, and stored.

3.12.1. First Order Lag (lpf)

This auxiliary function essentially applies a first order low pass filter to its input value lpf_in and generates its output lpf_out. The variables needed are the Open Loop Response Time (OLRT)[47] t_olrt. The DER model simulation timestep t_s will also be used in the calculation.

In the detailed model specification, this function is invoked by

$$lpf\_out = lpf(lpf\_in, t\_olrt). \tag{3.12.1-1}$$

Since this is a time-dependent function, it requires internal buffer variables to store the value of the function input and output in the previous timestep, using variable lpf_in_prev, and lpf_out_prev respectively. Both of the internal state variables lpf_in_prev and lpf_out_prev should be initialized with the first value of the input lpf_in when the simulation starts.

The output value lpf_out is calculated by:

$$lpf\_out = \begin{cases} lpf\_in & \text{if } t\_olrt < 1.15 \times t\_s \\ \dfrac{t\_s}{t\_s + \dfrac{t\_olrt}{1.15}} \times (lpf\_in + lpf\_in\_prev) + \dfrac{\dfrac{t\_olrt}{1.15} - t\_s}{t\_s + \dfrac{t\_olrt}{1.15}} \times lpf\_out\_prev & \text{if } t\_olrt \geq 1.15 \times t\_s \end{cases} \tag{3.12.1-2}$$

The equation is calculated from the linearization of a first order lag.[48] Figure 20 shows an example simulation result. The red star indicates the time series output values lpf_out, with an input step changes from 0 to 1 at 5 seconds. The blue curve is the actual response of a first order lag system with an equivalent time constant.

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[47] In IEEE 1547-2018, the open loop response time is defined as the duration from a step change in control signal input (reference value or system quantity) until the output changes by 90% of its final change, before any overshoot. It is equal to 2.3 times the time constant of a first-order lag system.

[48] Bilinear (Tustin) transformation is used for this linearization. There are other possible implementations available.

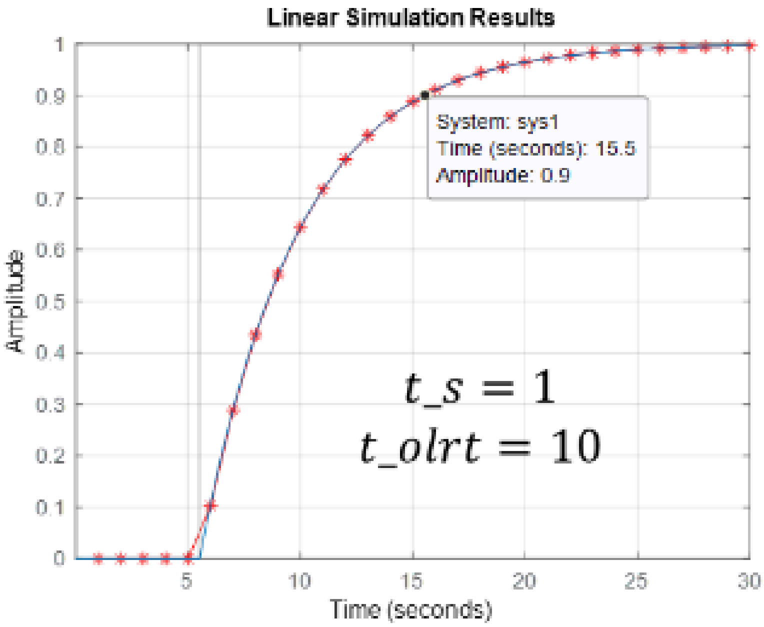


Figure 20. Simulation result of the first order lag function

3.12.2. Ramp Rate Limit (ramp)

This auxiliary function essentially applies a ramp rate limit to its input value $ramp\_in$ and generates its output $ramp\_out$. The variables needed are the ramping time for both directions $ramp\_up\_time$ and $ramp\_down\_time$. The DER model simulation timestep t_s will also be used in the calculation.

In the detailed model specification, this function is invoked by

$$ramp\_out = ramp(ramp\_in, ramp\_up\_time, ramp\_down\_time). \tag{3.12.2-1}$$

Thus, the ramp rate limit for both directions can be calculated as:

$$\begin{aligned} ramp\_up\_limit &= t\_s/ramp\_up\_time \\ ramp\_down\_limit &= t\_s/ramp\_down\_time \end{aligned} \tag{3.12.2-2}$$

If provided ramping time ($ramp\_up\_time$ and $ramp\_down\_time$) is equal to or less than 0, it indicates there is no ramp rate limit need to be applied. The corresponding ramp calculation case structure in equation (3.12.2-3) does not need to be executed.

Since this is a time-dependent function, it requires internal state variables to store the values of the function output in the previous timestep using variable $ramp\_out\_prev$. The internal state variable $ramp\_out\_prev$ should be initialized with the first value of the input $ramp\_in$ when the simulation starts.

The output value $ramp\_out$ is calculated by:

$$ramp\_out = \begin{cases} ramp\_out\_prev - ramp\_down\_limit & \text{if } ramp\_out\_prev - ramp\_down\_limit > ramp\_in \\ ramp\_out\_prev + ramp\_up\_limit & \text{if } ramp\_out\_prev + ramp\_up\_limit < ramp\_in \\ ramp\_in & \text{otherwise} \end{cases} \quad (3.12.2\text{-}3)$$

3.12.3. Time Delay (tdelay)

This auxiliary function essentially applies a time delay to its input value $tdelay\_in$ and generates its output $tdelay\_out$. The variable needed is the delay time $tdelay\_time$. The DER model simulation timestep t_s will also be used in the calculation.

In the detailed model specification, this function is invoked by

$$tdelay\_out = tdelay(tdelay\_in, tdelay\_time). \quad (3.12.3\text{-}1)$$

If delay time $tdelay\_time$ is less than the simulation time step t_s, the auxiliary function output should be the same as input:

$$tdelay\_out = tdelay\_in \quad (3.12.3\text{-}2)$$

If delay time $tdelay\_time$ is a non-zero value and larger than the simulation time step, this auxiliary function is a time-dependent function, and it requires internal state variables to store the input values of the function in the previous timestep using variable $tdelay\_in\_prev$. This variable should be initialized with the first value of the input $tdelay\_in$ when the simulation starts. Another internal state variable $tdelay\_out\_hold$ is defined to keep the output value of the time delay function.

This time delay auxiliary function also requires two internal state variable arrays to record the past inputs and their elapsed time, namely $tdelay\_in\_value\_array$ and $tdelay\_in\_time\_array$. The two arrays should be initialized as empty when simulation starts. The size of the arrays may grow and shrink during the simulation.

Each timestep, every element in the $tdelay\_in\_value\_array$ shall be subtracted by the simulation time step t_s. If there is an element in the time array $tdelay\_in\_time\_array$ is less than 0, it indicates the time delay has passed. And the corresponding input value shall be pass to the internal state variable $tdelay\_out\_hold$, which is exported as the function output $tdelay\_out$.

If the input variable $tdelay\_in$ changes during the simulation ($tdelay\_in \neq tdelay\_in\_prev$) and its value is valid, the input value shall be added to the array $tdelay\_in\_value\_array$ as a new element. Also, the time delay $tdelay\_time$ shall be added to the array $tdelay\_in\_time\_array$ with the same index.

Pseudo code of this function, if the delay time is greater than the DER model simulation timestep, is:

```
1. If the function is first called, initialize empty internal state variable array $tdelay\_in\_value\_array$, empty internal state variable $tdelay\_in\_time\_array$, internal state variables $tdelay\_in\_prev$ and $tdelay\_out\_hold$ using the first input of $tdelay\_in$
2. If $tdelay\_in\_time\_array$ is not empty:
    a. $tdelay\_in\_time\_array = tdelay\_in\_time\_array - t\_s$
    b. For every element in $tdelay\_in\_time\_array$, if $tdelay\_in\_time\_array[i] \leq 0$
        i. $tdelay\_out\_hold = tdelay\_in\_value\_array[i]$
        ii. Remove $tdelay\_in\_time\_array[i]$ in $tdelay\_in\_time\_array$
        iii. Remove $tdelay\_in\_value\_array[i]$ in $tdelay\_in\_value\_array$
3. If $tdelay\_in \neq tdelay\_in\_prev$ and $tdelay\_in \neq$ null:
    a. $tdelay\_in\_value\_array = [tdelay\_in\_value\_array,\ tdelay\_in]$
    b. $tdelay\_in\_time\_array = [tdelay\_in\_time\_array,\ tdelay\_time]$
4. If $tdelay\_in \neq$ null:
    a. $tdelay\_in\_prev = tdelay\_in$
    b. $tdelay\_out = tdelay\_out\_hold$
```

An example of the function input, internal, and output variables are shown in Table 41, assuming the simulation time step t_s is 1 s, and the time delay $tdelay\_time$ is 5 s. The function output $tdelay\_out$ is delayed by 5 seconds from the function input $tdelay\_in$.

Table 41. Time delay auxiliary function example parameter values

Sim. Time	$tdelay\_in$	$tdelay\_in\_pr$	$tdelay\_in\_va$	$tdelay\_in\_ti$	$tdelay\_out\_h$	$tdelay\_out$
0s	5	5	[]	[]	5	5
1s	5	5	[]	[]	5	5
2s	6	5	[6]	[5]	5	5
3s	7	6	[6, 7]	[4, 5]	5	5
4s	8	7	[6, 7, 8]	[3, 4, 5]	5	5
5s	Null	8	[6, 7, 8]	[2, 3, 4]	5	5
6s	Null	8	[6, 7, 8]	[1, 2, 3]	5	5
7s	Null	8	[7, 8]	[1, 2]	6	6
8s	Null	8	[8]	[1]	7	7
9s	Null	8	[]	[]	8	8
10s	Null	8	[]	[]	8	8
11s	Null	8	[]	[]	8	8

Note that there can be various ways to implement the time delay auxiliary function to achieve the same objective.

3.12.4. Conditional Delayed Enable (con_del_enable)

This auxiliary function sets its output *value con_del_enable_out* as TRUE, if its input value *value con_del_enable_in* is TRUE continuously for a defined period *value con_del_enable_time*. But it will set the output value to be FALSE immediately, if its input value is FALSE. The DER model simulation timestep *t_s* will also be used in the model calculation. The block diagram of this function is shown in Figure 21.

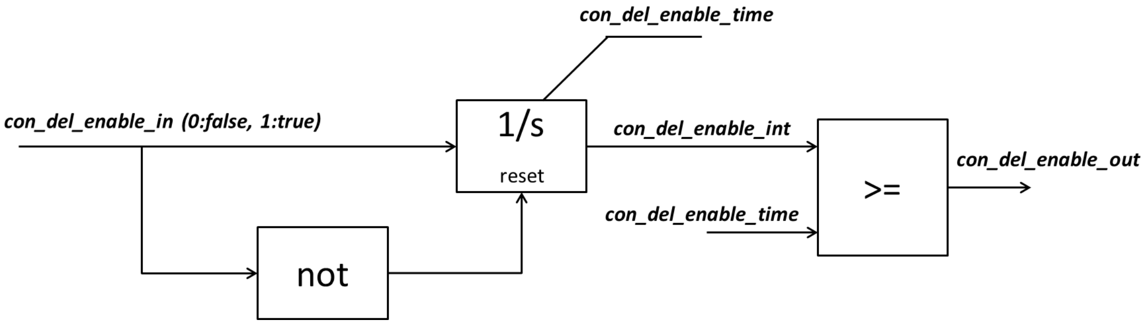


Figure 21. Model structure of conditional delayed enable auxiliary function

In the detailed model specification, this function is invoked by

$$con\_del\_enable\_out = con\_del\_enable(con\_del\_enable\_in, con\_del\_enable\_time). \qquad (3.12.4\text{-}1)$$

Since this is a time-dependent function, it requires an internal state variable to store the elapsed time when the input is TRUE, defined as *con_del_enable_int*, and its value in the previous timestep is *con_del_enable_int_prev*. Both internal state variables *con_del_enable_int* and *con_del_enable_int_prev* are initialized with value of infinity.

If the input is FALSE (*con_del_enable_in* = FALSE), the elapsed time does not increase, and the output is 0 or FALSE:

$$\begin{gathered} con\_del\_enable\_int = 0 \\ con\_del\_enable\_out = 0 \end{gathered} \qquad (3.12.4\text{-}2)$$

If the input is TRUE (*con_del_enable_in* = TRUE), each time step, the elapsed time integrator adds the simulation time step to its value in the previous time step:

$$con\_del\_enable\_int = min(con\_del\_enable\_time, con\_del\_enable\_int\_prev + t\_s) \qquad (3.12.4\text{-}3)$$

And if the elapsed time is greater than the defined period, (*con_del_enable_int* ≥ *con_del_enable_time*), the output is 1 or TRUE:

$$con\_del\_enable\_out = 1 \qquad (3.12.4\text{-}4)$$

3.12.5. Flipflop Logic (flipflop)

This auxiliary function applies a flipflop logic to its input value ff_set and ff_reset, and generates its output ff_out.

In the detailed model specification, this function is invoked by

$$ff\_out = flipflop(ff\_set, ff\_reset, ff\_init). \quad (3.12.5\text{-}1)$$

Since this is a time-dependent function, it requires internal state variables to store the values of the function output in the previous timestep using variable ff_out_prev. The internal state variable ff_out_prev should be initialized with model input ff_init when the simulation starts.

The output value ff_out is calculated by:

$$ff\_out = \begin{cases} ff\_out\_prev & \text{if } ff\_set = 0, \text{and } ff\_reset = 0 \\ 1 & \text{if } ff\_set = 1, \text{and } ff\_reset = 0 \\ 0 & \text{if } ff\_set = 0, \text{and } ff\_reset = 1 \\ 0 & \text{if } ff\_set = 1, \text{and } ff\_reset = 1 \end{cases} \quad (3.12.5\text{-}2)$$

Note that the model prevents the case when both ff_set and ff_reset are 1 in most of the cases. To avoid creating instability, when such a case happens in rare conditions, the logic outputs 0.

3.12.6. Symmetrical Component Composition (convert_symm_to_abc)

This auxiliary function converts symmetrical components in positive and negative sequence to phase values in abc axes.

In the detailed model specification, this function is invoked by

$$a\_pu, b\_pu, c\_pu = convert\_symm\_to\_abc(pos\_pu, neg\_pu, zero\_pu). \quad (3.12.6\text{-}1)$$

A constant $alpha$ is defined as a complex number of $e^{\frac{2}{3}\pi i}$, and square of alpha is defined as alpha2, with the value of $e^{-\frac{2}{3}\pi i}$.

The output values are calculated as:

$$\begin{aligned} a\_pu &= pos\_pu + neg\_pu + zero\_pu \\ b\_pu &= alpha2 \times pos\_pu + alpha \times neg\_pu + zero\_pu \\ c\_pu &= alpha \times pos\_pu + alpha2 \times neg\_pu + zero\_pu \end{aligned} \quad (3.12.6\text{-}2)$$

4. EXAMPLE MODEL VALIDATION RESULTS

To validate the OpenDER model's ability to represent actual commercial DERs in distribution analysis, extensive testing has compared the model's performance against laboratory results from IEEE 1547-2018 / UL 1741SB certified smart inverters. In this version 2.2 release, OpenDER has validated against 2 inverters: a single-phase energy storage inverter and a three-phase PV inverter.

The results are presented for various topics, including DER power capability, constant power factor, volt-var, frequency-droop, fault current contribution, and momentary cessation performance. For each topic, the model validation results for the two inverters are introduced separately. Mismatches in the results are also identified as future opportunities for model improvement.

4.1. Model Validation Methodology

Figure 22 shows the model methodology to validate the OpenDER model. The process begins with lab tests conducted on commercial inverters under various operating conditions and control settings. The voltage at the inverter terminal is measured and used as input for the OpenDER model. Then, the output current or power from the OpenDER model is compared against the actual measurements obtained from the inverter.

By applying the same test conditions (i.e., voltage, available power level/command, and control settings) to both the OpenDER model and the actual inverter, the accuracy of the OpenDER model can be assessed. This comparison validates the modeled behavior when the results match closely, while also identifies gaps or area for improvements when difference are observed.

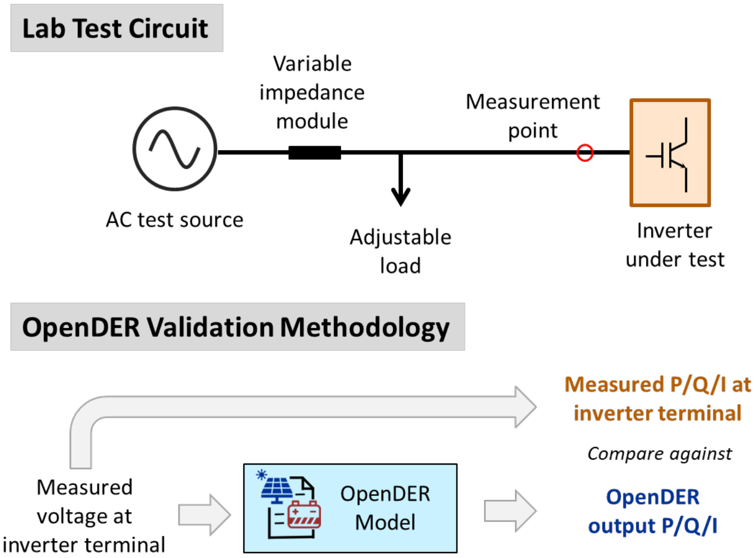
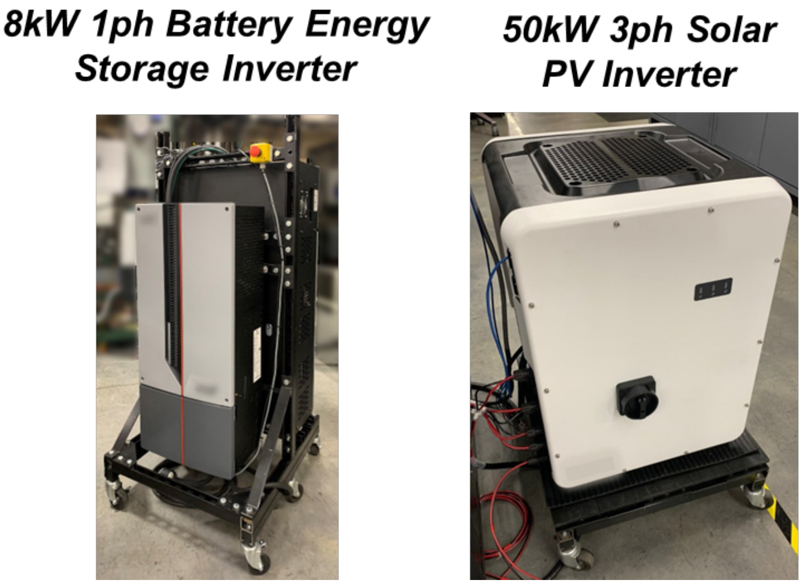


Figure 22. Lab test circuit and model validation methodology

The rest of this section introduces the inverters used for model validation. The pictures are shown in Figure 23.



8kW 1ph Battery Energy Storage Inverter

50kW 3ph Solar PV Inverter

Figure 23. Inverters used for OpenDER model validation.

The relevant DER configuration parameters for the 8kW single-phase energy storage inverter are shown in Table 42. The values are identified through the inverter datasheet as well as lab test results.

Table 42. DER configuration variables for the example 8kW single-phase energy storage DER inverter

Variable Name	Variable Label	Value	Unit
Active power rating at unity power factor	NP_P_MAX	7680	W
Apparent power maximum rating	NP_VA_MAX	7680	VA
Active power charge maximum rating	$NP\_P\_MAX\_CHARGE$	7680	W
Apparent power charge maximum rating	$NP\_APPARENT\_POWER\_CHARGE\_MAX$	7680	VA
Normal operating performance category	$NP\_NORMAL\_OP\_CAT$	CAT_B	n/a (CAT_A/CAT_B)
Abnormal operating performance category	$NP\_ABNORMAL\_OP\_CAT$	CAT_III	n/a (CAT_I /CAT_II/CAT III)
Reactive power injected maximum rating	$NP\_Q\_MAX\_INJ$	7680	var
Reactive power absorbed maximum rating	$NP\_Q\_MAX\_ABS$	7680	var

Table 42 (continued). DER configuration variables for the example 8kW single-phase energy storage DER inverter

Variable Name	Variable Label	Value	Unit
AC voltage nominal rating	*NP_AC_V_NOM*	240	Volt (RMS)
Reactive susceptance that remains connected to the Area EPS in the cease to energize and trip state	*NP_REACTIVE_SUSCEPTANCE*	0.001	siemens
Priority outside minimum requirements of reactive power capability	*NP_PRIO_OUTSIDE_MIN_Q_REQ*	REACTIVE	n/a (ACTIVE/ REACTIVE)
Single- or three-phase DER	*NP_PHASE*	SINGLE	n/a (SINGLE /THREE)
DER minimum active power output	*NP_P_MIN_PU*	-1	pu based on DER nominal active power rating
DER grid support function reaction time	*NP_REACT_TIME*	0	s
DER voltage measurement delay	*NP_V_MEAS_DELAY*	0	s
DER inverter equivalent open loop delay for closed-loop current control	*NP_INV_DELAY*	0.04	s
DER nameplate max current	*NP_CURRENT_PU*	1.07	pu
Recovery time from ride-through	*NP_RT_RAMP_UP _TIME*	0	s
Momentary cessation response time	*MC_RESP_T*	0.02	s
Cease to Energize response time	*NP_CTE_RESP_T*	0	s
Time to start to restore output from momentary cessation	*MC_RETURN_T*	0.2	s
Dynamic Voltage Support enable	*DVS_MODE_ENABLE*	DISABLED	n/a (DISABLED/ ENABLED)
Constant Reactive Power Mode Response Time	*CONST_Q_RT*	0.9	s
BESS active power ramp rate constraint	*NP_BESS_P_RAMP_TIME*	1	s

The relevant DER configuration parameters for the 50kW three-phase PV inverter are shown in Table 43. The values are identified through the inverter datasheet as well as lab test results.

Table 43. DER configuration variables for the example 50kW three-phase PV DER inverter

Variable Name	Variable Label	Value	Unit
Active power rating at unity power factor	NP_P_MAX	50000	W
Apparent power maximum rating	NP_VA_MAX	50000	VA
Normal operating performance category	$NP\_NORMAL\_OP\_CAT$	CAT_B	n/a (CAT_A/CAT_B)
Abnormal operating performance category	$NP\_ABNORMAL\_OP\_CAT$	CAT_III	n/a (CAT_I /CAT_II/CAT III)
Reactive power injected maximum rating	$NP\_Q\_MAX\_INJ$	30000	var
Reactive power absorbed maximum rating	$NP\_Q\_MAX\_ABS$	30000	var
AC voltage nominal rating	$NP\_AC\_V\_NOM$	480	Volt (RMS)
Reactive susceptance that remains connected to the Area EPS in the cease to energize and trip state	$NP\_REACTIVE\_SUSCEPTANCE$	0.007	siemens
Priority outside minimum requirements of reactive power capability	$NP\_PRIO\_OUTSIDE\_MIN\_Q\_REQ$	REACTIVE	n/a (ACTIVE/ REACTIVE)
Single- or three-phase DER	NP_PHASE	THREE	n/a (SINGLE /THREE)
DER minimum active power output	$NP\_P\_MIN\_PU$	0	pu based on DER nominal active power rating
DER grid support function reaction time	NP_REACT_TIME	0	s
DER voltage measurement delay	$NP\_V\_MEAS\_DELAY$	0	s
DER inverter equivalent open loop delay for closed-loop current control	NP_INV_DELAY	0.04	s
DER nameplate max current	$NP\_CURRENT\_PU$	1.07	pu
Recovery time from ride-through	$NP\_RT\_RAMP\_UP\_TIME$	0.07	s

Table 43 (continued). DER configuration variables for the example 50kW three-phase PV DER inverter

Variable Name	Variable Label	Value	Unit
Momentary cessation response time	MC_RESP_T	0.01	s
Cease to Energize response time	$NP\_CTE\_RESP\_T$	0	s
Time to start to restore output from momentary cessation	MC_RETURN_T	0.03	s
Dynamic Voltage Support enable	DVS_MODE_ENABLE	DISABLED	n/a (DISABLED/ ENABLED)
Constant Reactive Power Mode Response Time	$CONST\_Q\_RT$	0.9	s
Active power limit function response time	AP_RT	5	s
Watt-var function response time	QP_RT	5	s
BESS active power ramp rate constraint	$NP\_BESS\_P\_RAMP\_TIME$	1	s

4.2. Model Validation Results

This section presents example results, comparing the OpenDER model output results against the lab test measurements. The results are grouped by various modeling aspects. For each topic, the comparison results for the two inverters are shown.

4.2.1. Power Capabilities

4.2.1.1. Single-phase Energy Storage Inverter

According to the datasheet, the reactive power capability of the single-phase energy storage inverter under test is 100% of the apparent power rating. Thus, all nameplate ratings are set to 7680 watts/vars/kVAs.

When the inverter terminal voltage is at 1pu, the OpenDER results match the inverter output with reasonable accuracy, as shown in Figure 24. However, when the inverter terminal voltage is reduced to 0.89, there are some mismatches, as shown in Figure 25. As highlighted in red, the actual inverter reduces more active power than the OpenDER model outputs. This indicates the inverter may have additional output limitations than the ones currently modeled in OpenDER.

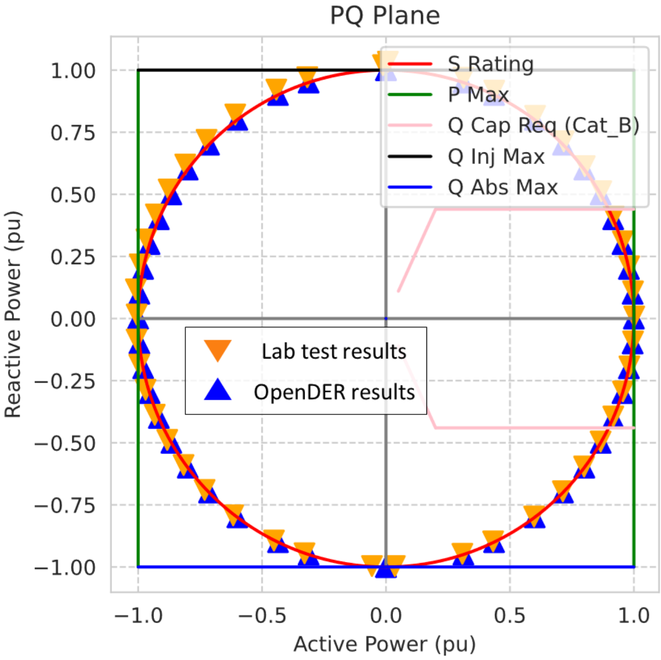


Figure 24. Model validation of active and reactive power capability when voltage is at 1pu

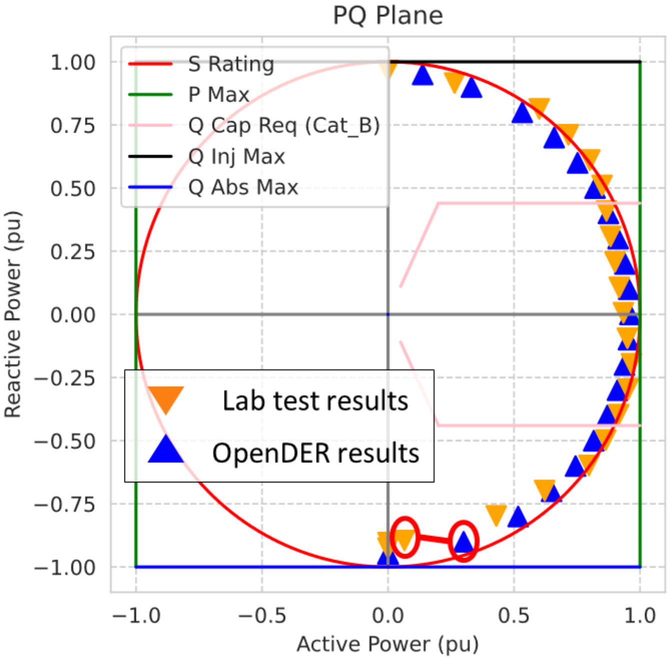


Figure 25. Model validation of P&Q capability for single-phase energy storage inverter when voltage is at 0.89pu

4.2.1.2. Three-phase PV Inverter

The datasheet only specifies the capability of the three-phase PV inverter under test is 50kW. The other ratings are identified through the values reported by the local communication interface, and confirmed by lab testing. It is identified that the inverter under test has 50kVA apparent power rating, and 30kvar reactive power rating for both injection and absorption. Figure 26 and Figure 27 shows the model validation results when the inverter terminal voltage is at 1pu and 0.89pu, respectively. The results confirms that the inverter has reactive power priority even outside of the IEEE 1547-2018 minimum reactive power capability range, and can produce the reactive power to the nameplate rating when the DER output power is less than 20%. OpenDER can be parameterized to represent the inverter performance reasonably well.

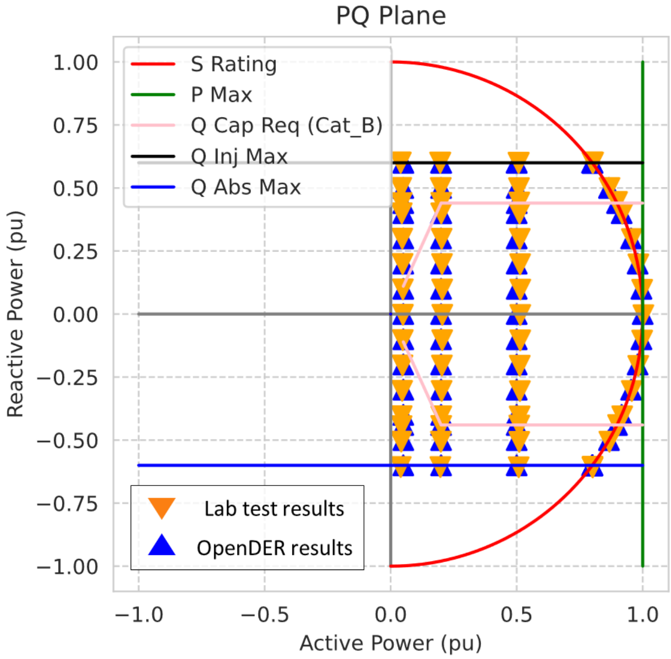


Figure 26. Model validation of P&Q capability for three-phase PV inverter when voltage is at 1pu

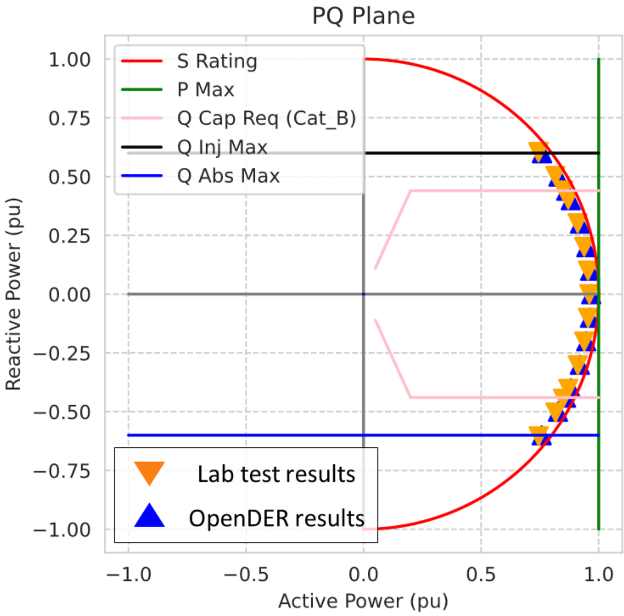


Figure 27. Model validation of P&Q capability for three-phase PV inverter when voltage is at 0.89pu

4.2.2. Constant Power Factor Function

4.2.2.1. Single-phase Energy Storage Inverter

The steady-state validation results are shown in Figure 28. The inverter is set to 0.95 constant power factor absorption. The active power demand is set to -1 to 1 pu, with 0.1pu increments. As can be seen, OpenDER model outputs match with the inverter test results, following the reactive power priority as required by the standard. Also, when charging active power, both the model and the inverter still maintain the reactive power priority, which the standard does not have requirements for. The reactive power output errors between model outputs and lab results are less than 0.016 pu.

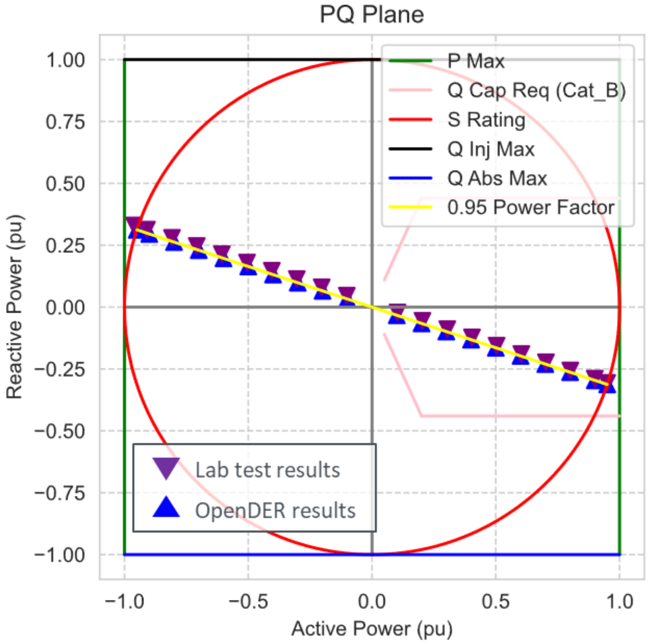


Figure 28. Model validation of single-phase energy storage inverter constant power factor function steady-state performance

The time response of constant power factor function is also examined, as shown in Figure 29. The constant power factor setting is 0.9 absorption. The inverter was provided with various active power commands to observe the dynamic performance. As can be seen, the OpenDER model match with the inverter's performance reasonably well. It can also be noticed that the BESS inverter under test has a slower ramp rate when discharging, compared with discharging. This different ramp rate performance under charging and discharging is not captured in this version of OpenDER model.

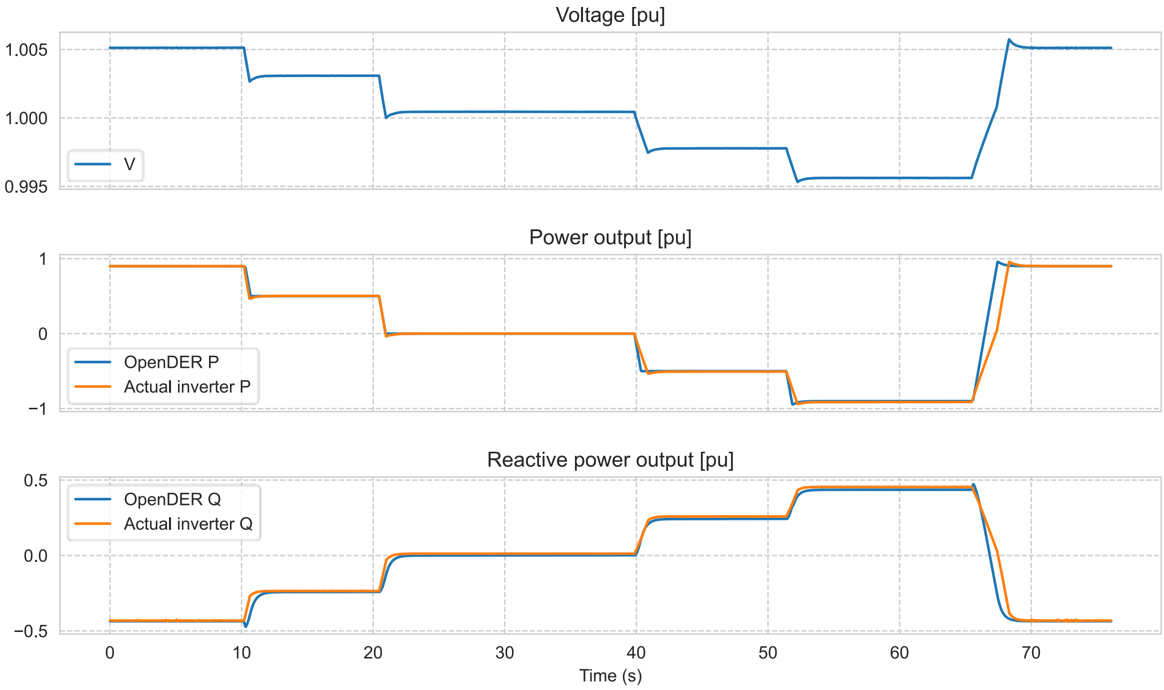


Figure 29. Model validation of constant power factor function dynamic performance

4.2.2.2. Three-phase PV Inverter

The model validation results for the three-phase PV inverter are shown in Figure 30. The figure includes four data series corresponding to the DER being configured to operate at constant power factors of 0.9 and 0.95, both in injection and absorption modes. The OpenDER results match the test results.

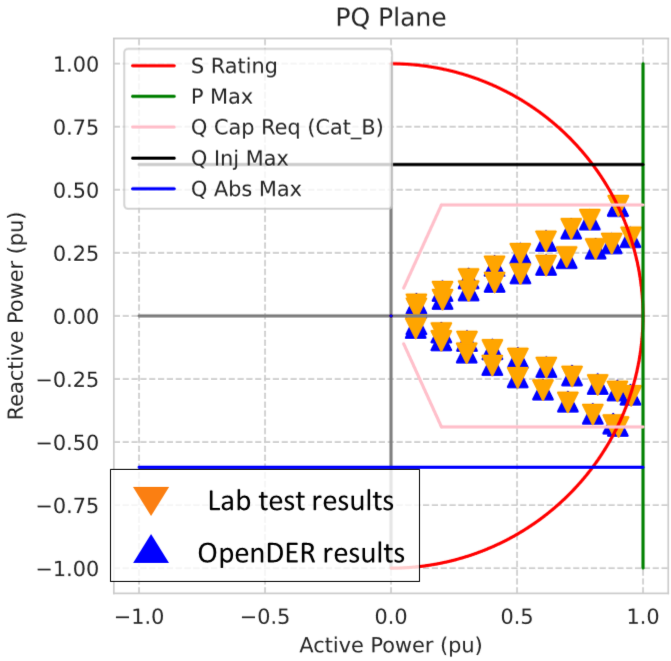


Figure 30. Model validation of three-phase PV inverter constant power factor function steady-state performance

4.2.3. Volt-Var Function

4.2.3.1. Single-phase Energy Storage Inverter

Figure 31 shows the model validation results when the single-phase energy storage inverter is configured with IEEE Std 1547-2018 Category B default volt-var settings. The OpenDER model is exposed to the same voltage profile as the inverter, and the model generated results are shown in the same graph as the measured lab test results. The OpenDER output reactive power matches well with the lab test results, indicating the modeling of OLRT behavior represents the actual inverter. On the other hand, the active power performance of the OpenDER model depends on the nameplate current rating ($NP\_CURRENT\_PU$) parameter, which impacts the inverter's capability to maintain the output apparent power level if the terminal voltage is less than 1 pu. As can be seen, when the nameplate current rating is set to 1.07 pu, the model output matches the test results better than other values.

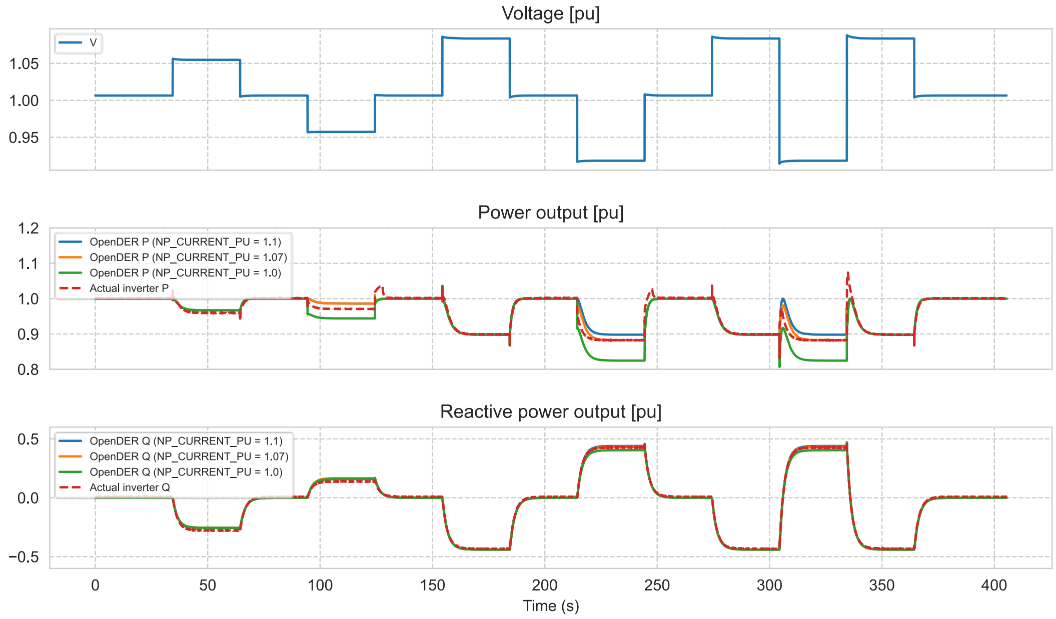


Figure 31. Model validation of single-phase energy storage inverter volt-var function

4.2.3.2. Three-phase PV Inverter

Figure 32 shows the similar model validation results for the three-phase PV inverter. As can be seen, both active and reactive power performance matches well with the lab test results, except the transient excursions when the voltage step changes. This behavior may require more detailed EMT modeling to be captured.

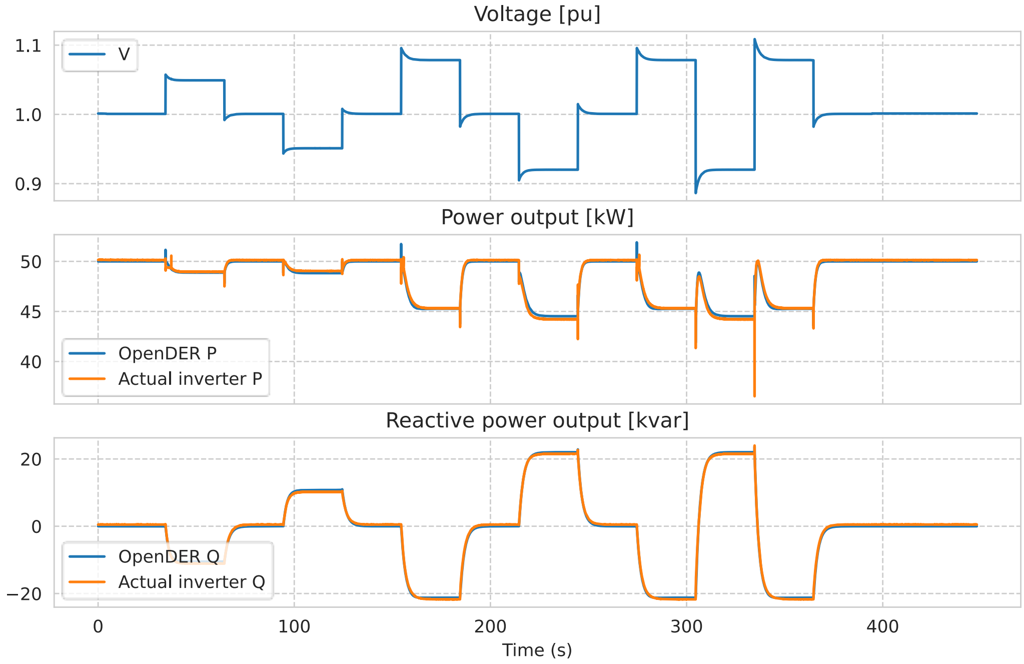


Figure 32. Model validation of three-phase PV inverter volt-var function

4.2.4. *Frequency-Droop Function*

4.2.4.1. Single-phase Energy Storage Inverter

Figure 33 shows the model validation results by comparing the OpenDER model outputs with lab test results. Various frequencies are applied to the inverter and the OpenDER model, with 1.0, 0.8, and 0.5 pu pre-disturbance active power generation. The lab test results and the active power output errors between model and lab results are less than 0.006 pu.

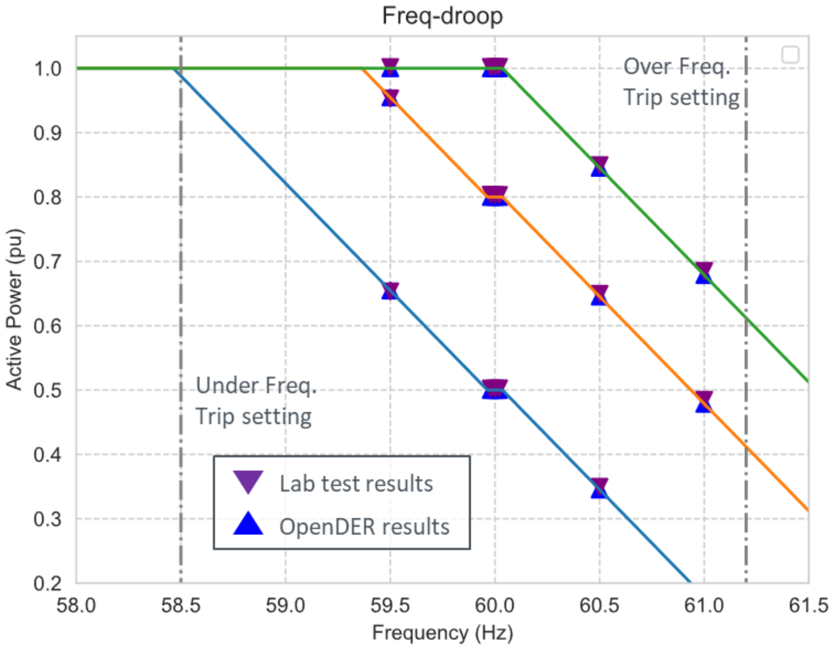


Figure 33. Model validation of single-phase energy storage inverter frequency-droop function

4.2.4.2. Three-phase PV Inverter

Figure 34 shows the results when pre-disturbance active power is determined by the available active power from the PV modules. As shown, at high-frequency conditions, the active power decreases for both the OpenDER model and the actual inverter, with the values match well. However, at low-frequency conditions, the active power output remains unchanged since it cannot exceed the available power.

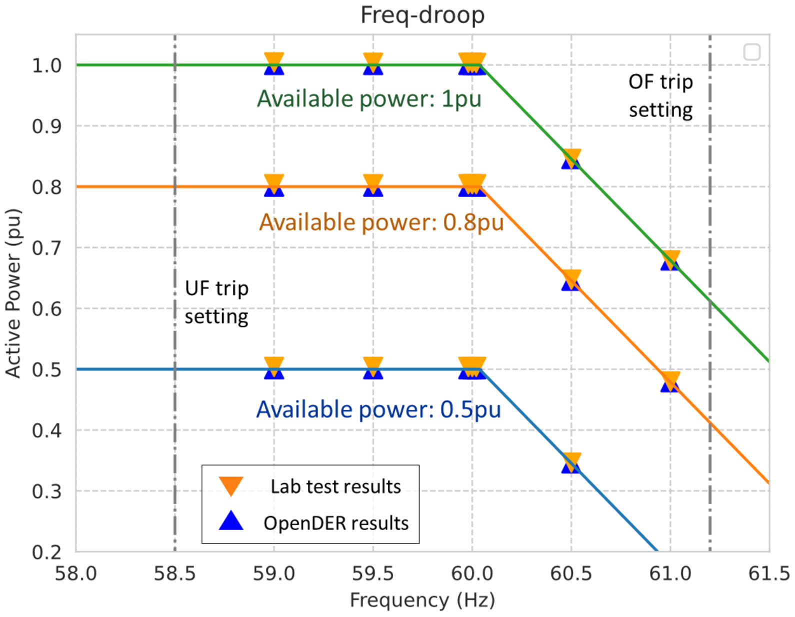


Figure 34. Model validation of three-phase PV inverter frequency-droop function (change available active power)

On the other hand, Figure 35 shows the results when pre-disturbance active power is regulated by the active power limit control, with available active power kept at 1 pu for all cases. In this scenario, the active power can exceed the limit, validating that the priority logic implemented in the OpenDER model accurately reflects the behavior of the actual inverter.

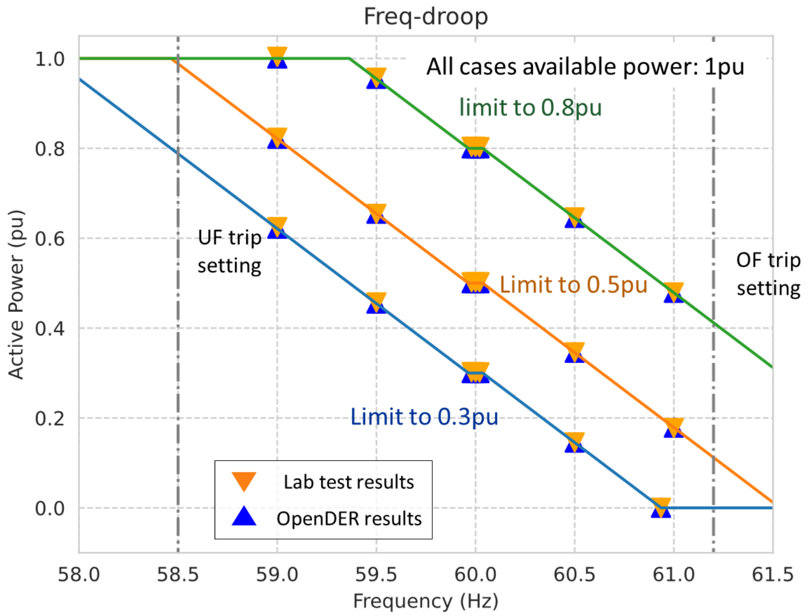


Figure 35. Model validation of three-phase PV inverter frequency-droop function (change active power limit)

Figure 36 shows the dynamic performance of the frequency-droop function. As can be seen, although the steady-state values match, the OpenDER currently does not model the of the frequency-droop reaction delay of the actual inverter. This behavior may be updated in the future version.

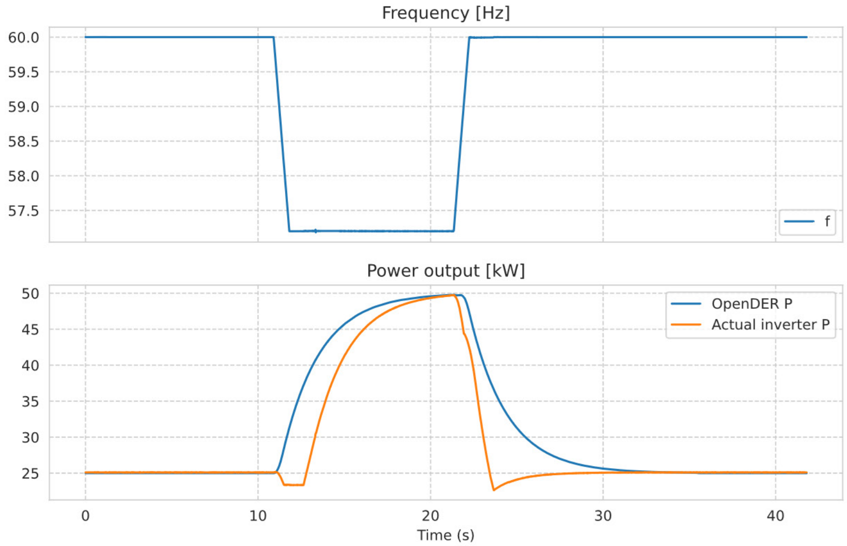


Figure 36. Model validation of three-phase PV inverter frequency-droop function dynamic performance

4.2.5. Fault Current Contribution

4.2.5.1. Single-phase Energy Storage Inverter

Figure 37 shows the model validation results when the voltage reduces to 0.8 pu for 9.8 second. The steady-state current calculated by OpenDER model matches well with the actual inverter's output, for both magnitude and angle. However, there are some mismatches when the fault starts and ends. The actual inverter has a slower response than the OpenDER model. This is likely due to the dynamic performance introduced by inverter current closed-loop control, which is not modeled in detail by OpenDER model. Figure 38 shows another model validation result when volt-var function is enabled when voltage reduces to 0.6. As can be seen, OpenDER calculated fault current matches well with the actual inverter, with minor inaccuracy at the beginning and the end of the fault.

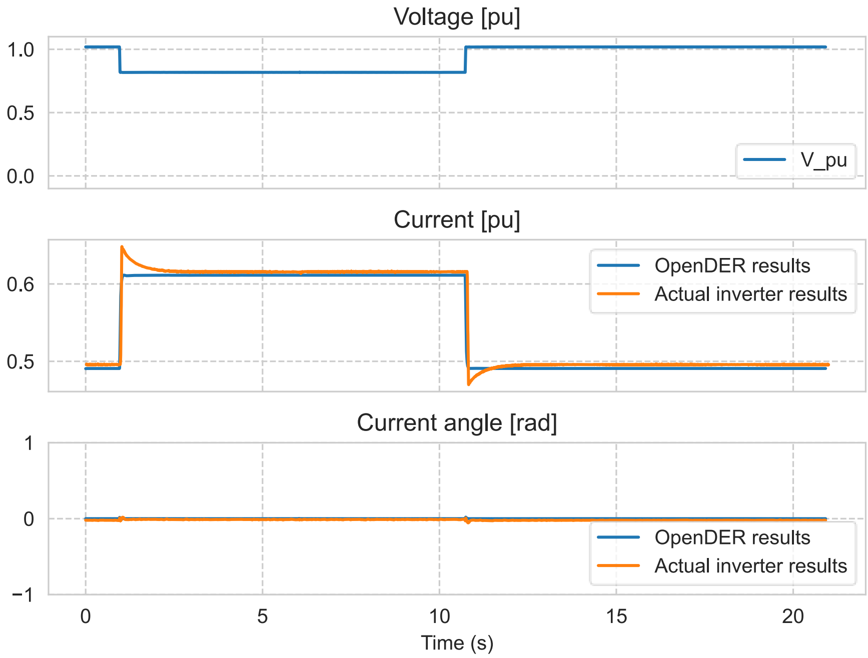


Figure 37. Model validation of single-phase energy storage inverter fault current contribution when voltage drops to 0.8pu.

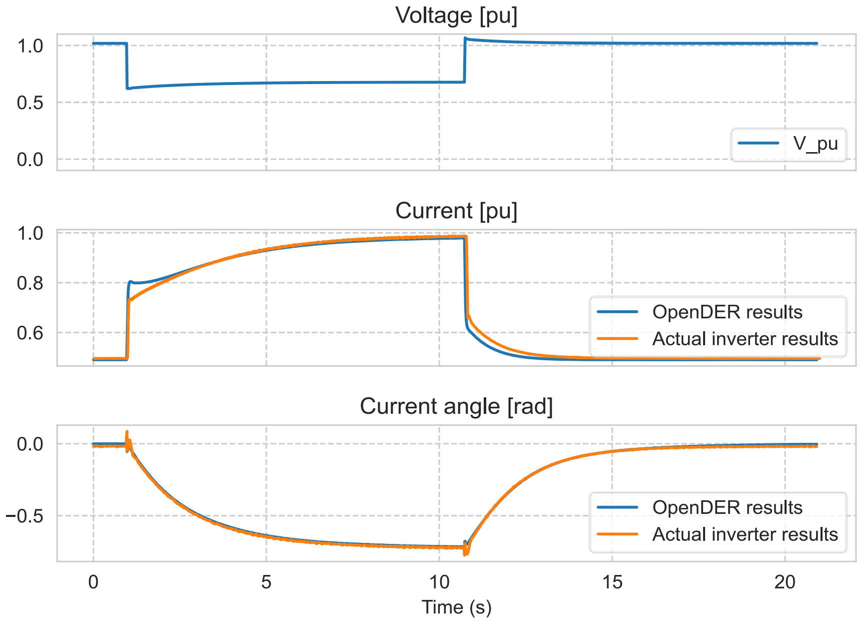


Figure 38. Model validation of single-phase energy storage inverter fault current contribution when voltage drops to 0.6pu, and volt-var function is enabled.

4.2.5.2. Three-phase PV Inverter

Figure 37 shows the model validation results for both cases when volt-var is disabled and enabled, under balanced voltage drops. The currents calculated by OpenDER model match well with the actual inverters, except some minor mismatches during the transients.

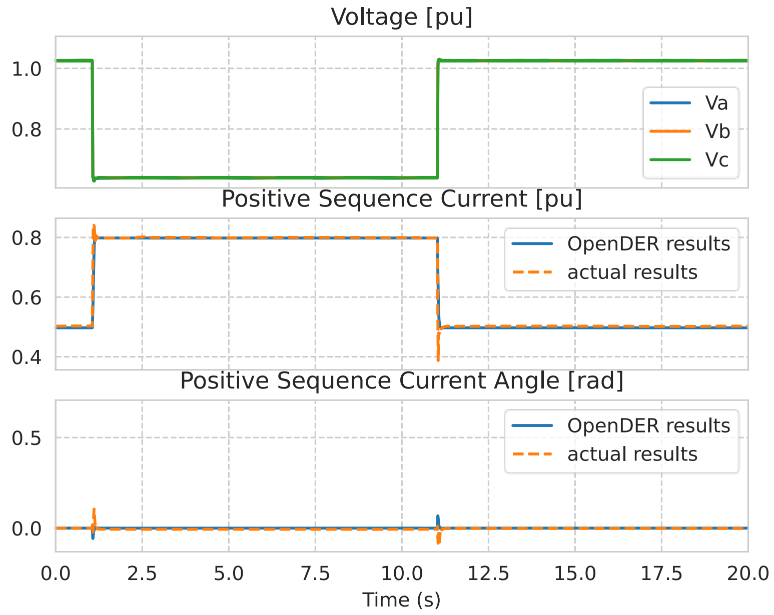


Figure 39. Model validation of three-phase PV inverter fault current contribution when voltage drops to 0.6pu

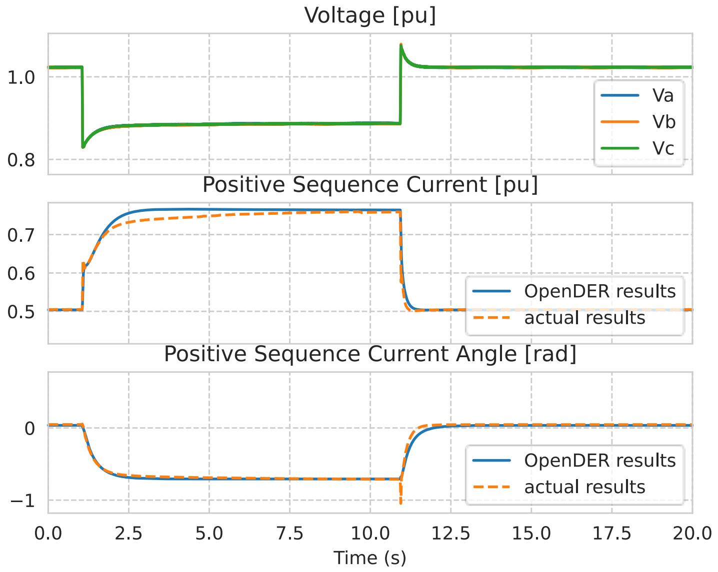


Figure 40. Model validation of three-phase PV inverter fault current contribution when voltage drops to 0.85pu, and volt-var function is enabled.

OpenDER can also represent this example three-phase PV inverter's fault current during unbalanced fault. Figure 41 shows two examples: single line to ground fault with a residual voltage of 0.6pu, and line-to-line fault with a residual voltage of 0.6pu between the faulted lines. As can be seen, the results match well.

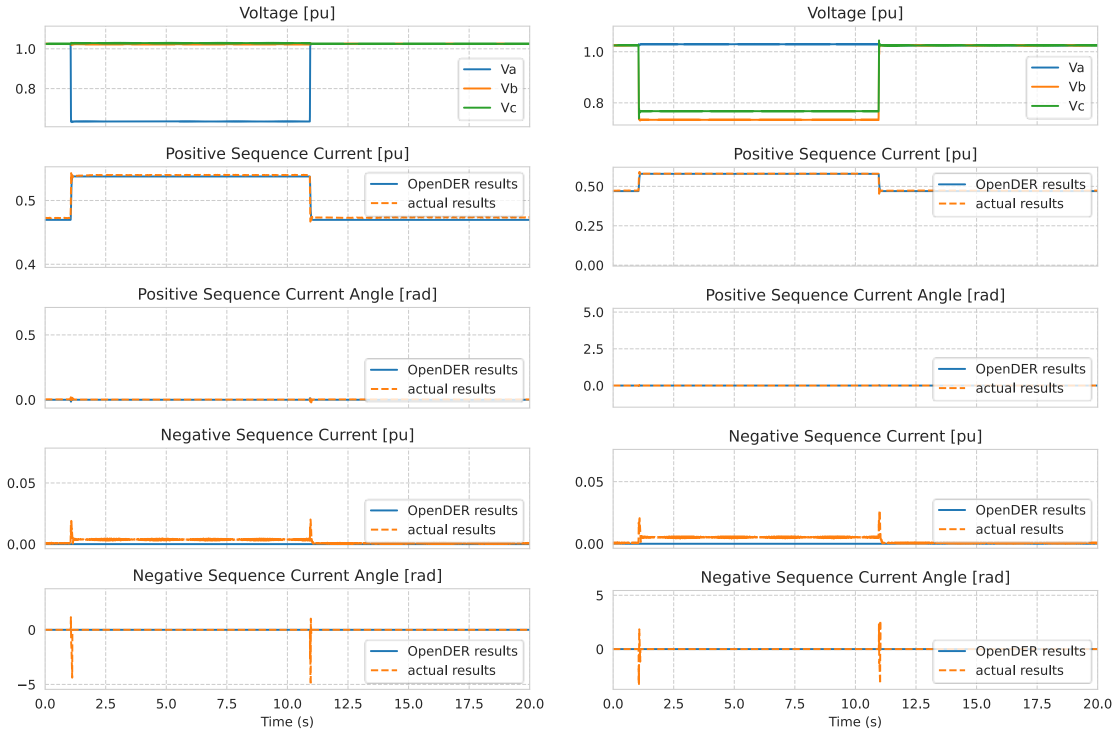


Figure 41. Model validation of three-phase PV inverter fault current contribution under unbalanced faults.

This example three-phase PV inverter also supports dynamic voltage support mode specified in section 3.10.1. Figure 42 shows the model validation results under single-line-to-ground and line-to-line faults, with the dynamic voltage support mode enabled and its gain (*DVS_K*) configured as 2. As can be seen, the negative sequence current contribution results match well, while there are some mismatches on the positive sequence current. The OpenDER may be updated in the future to allow better alignment with the test data, if this is behavior consistent across other inverters.

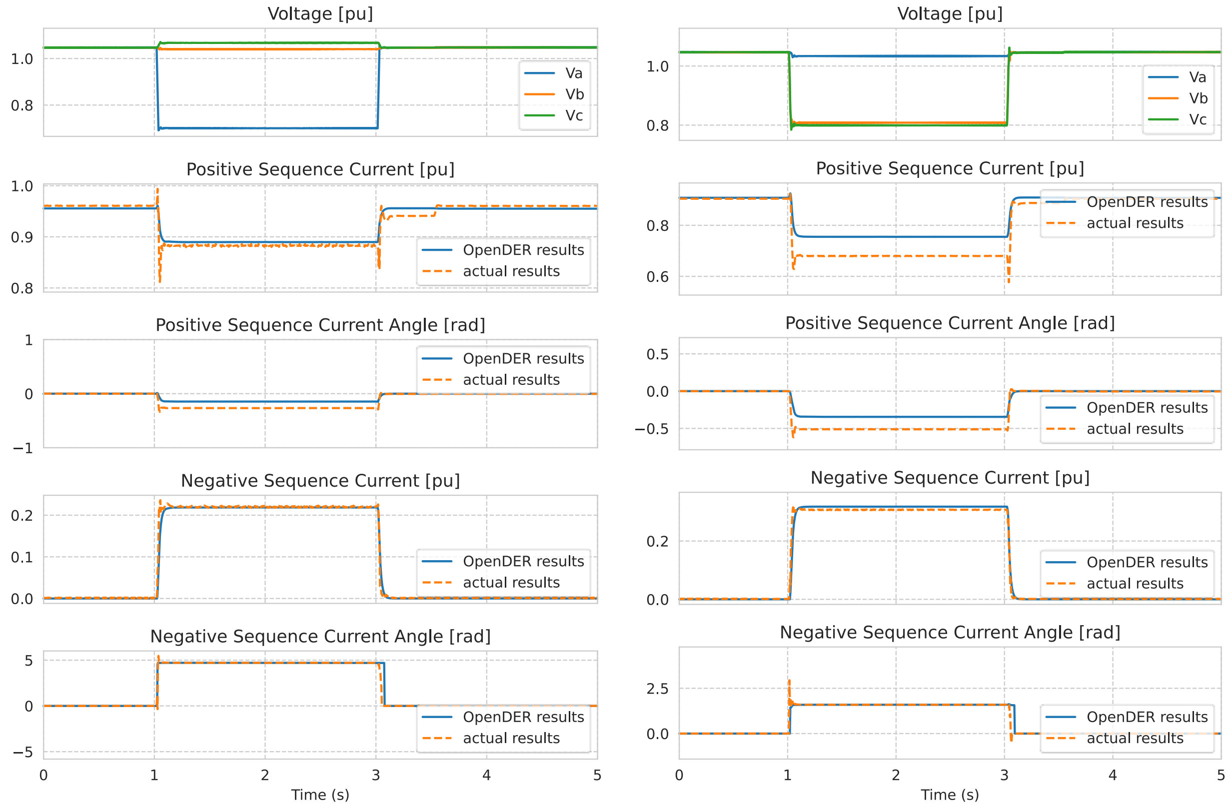


Figure 42. Model validation of three-phase PV inverter fault current contribution under unbalanced faults, when dynamic voltage support mode is enabled.

4.2.6. *Momentary Cessation Performance*

4.2.6.1. Single-phase Energy Storage Inverter

Figure 43 and Figure 44 show the model validation results when the inverter terminal voltage drops to 0 and 0.2pu, respectively. As can be seen, the current magnitude and angle calculated from OpenDER follow the actual inverter model with reasonable accuracy. There are some mismatches on the current overshoot when the fault begins, and some mismatches on the delay time when the inverter starts to restore outputs after the fault recovers.

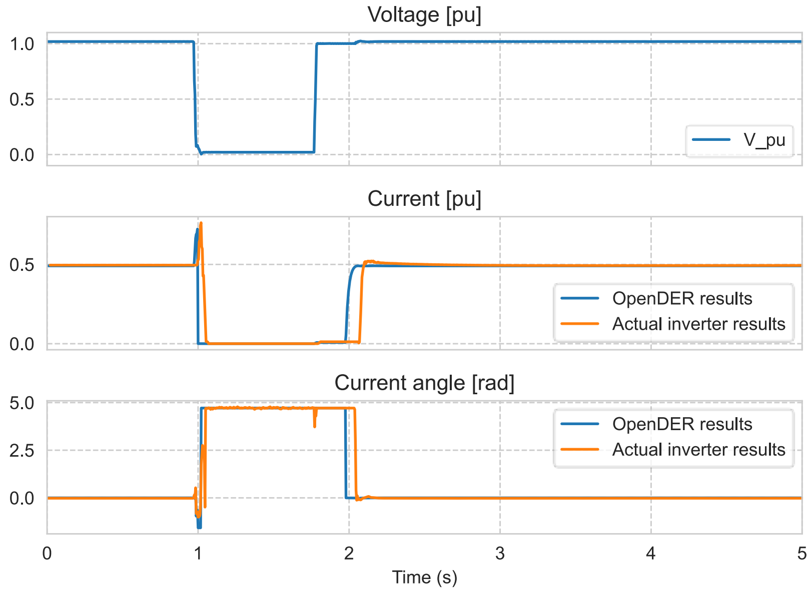


Figure 43. Model validation of single-phase energy storage inverter momentary cessation performance when voltage drops to 0pu.

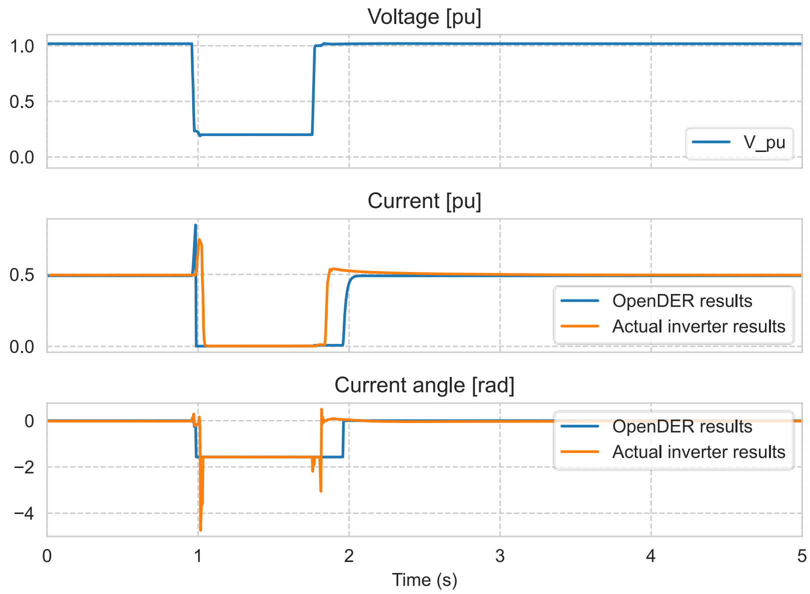


Figure 44. Model validation of single-phase energy storage inverter momentary cessation performance when voltage drops to 0.2pu.

4.2.6.2. Three-phase PV Inverter

Figure 42 shows the model validation for the three-phase inverter under unbalanced faults. The residual voltage for the single-line-to-ground fault is 0.1pu, and the residual voltage for the line-to-line fault is 0.2pu. For both cases, the OpenDER results match the actual inverter output well in steady-state, with the transient performance not captured.

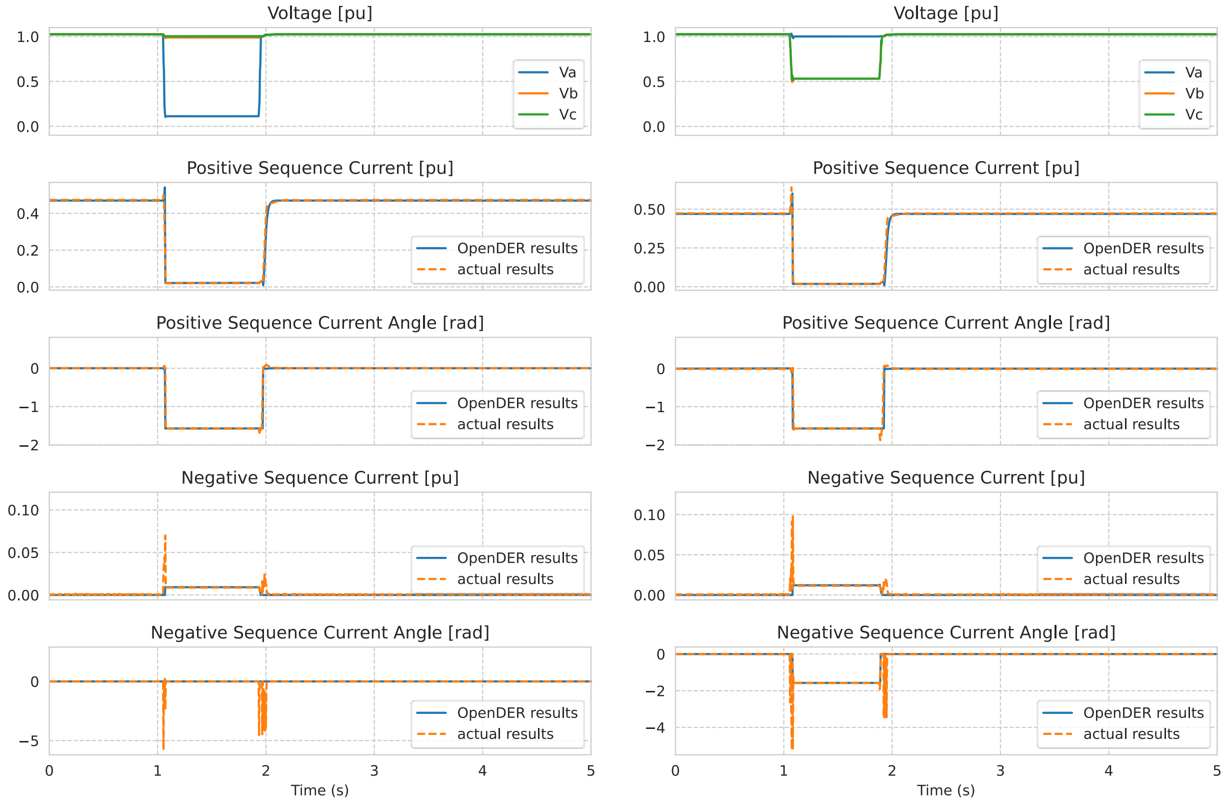


Figure 45. Model validation of three-phase PV inverter momentary cessation performance under unbalanced faults

4.2.7. Enter Service Performance

4.2.7.1. Single-phase Energy Storage Inverter

Figure 46 shows the model validation results of DER enter service performance. The enter service delay (ES_DELAY) was set to 30s and enter service ramp time (ES_RAMP_RATE) was set to 20s. Volt-var was enabled to observe the reactive power performance, with Category B default parameters. The grid voltage is set to 0.93 pu, within the enter service range but outside of the volt-var deadband.

The inverter was tripped by disabling the permit service signal at around 18 second. The permit service signal was enabled again at around 34 seconds. As can be seen, the actual inverter has a slightly slower ramp rate than the OpenDER model. In addition, as there is no ramp rate requirement on reactive power, both actual inverter and OpenDER model start to inject reactive power immediately after entering service, with some mismatch during the transient.

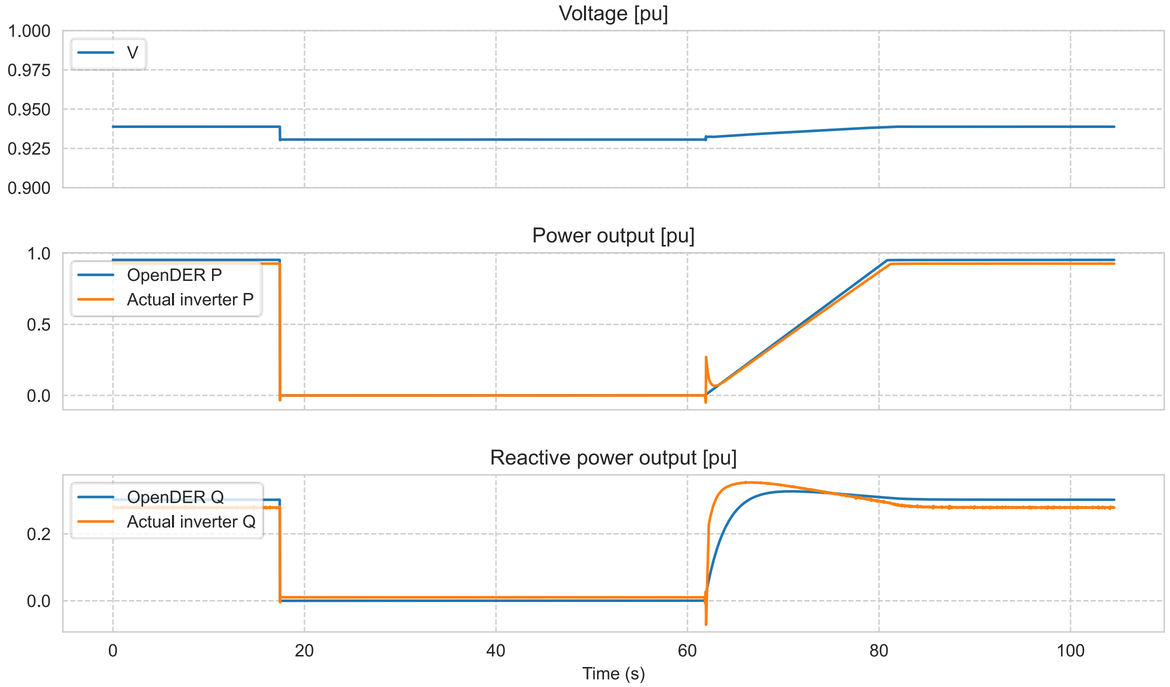


Figure 46. Model validation of enter service performance for the single-phase energy storage inverter.

4.2.7.2. Three-phase PV Inverter

A similar case is also conducted for the three-phase PV inverter, as shown in Figure 47. As can be seen, both OpenDER and the actual inverter can start reactive power function during the enter service ramp period. However, the OpenDER assumes Q support immediately after DER is in service, while the actual inverter starts it when P is about 5%. This behavior may be modeled by the OpenDER model by parameterizing the reactive power capability curve (*NP_Q_CAPABILITY _BY_P_CURVE).*

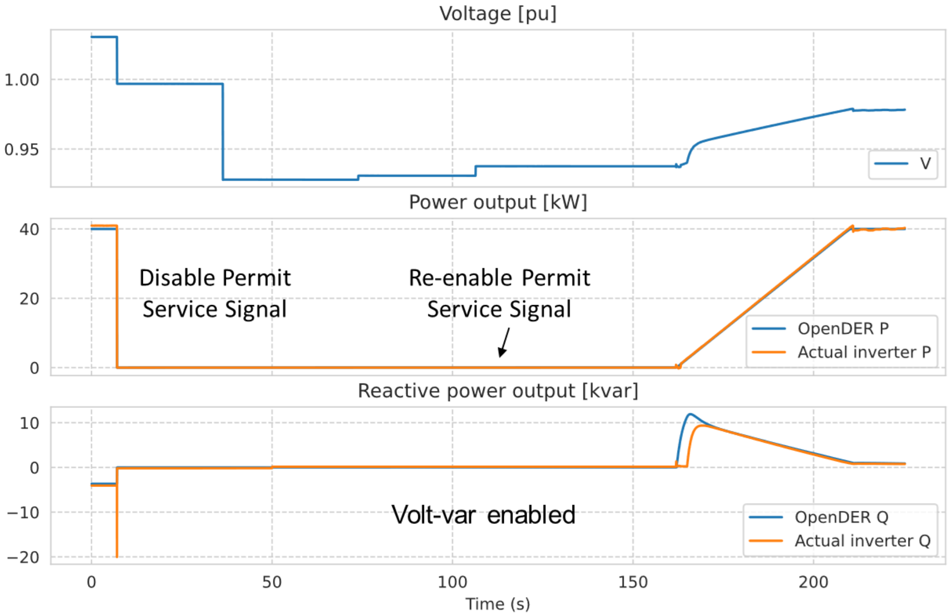


Figure 47. Model validation of enter service performance for the three-phase PV inverter.

4.2.8. *Voltage Ride-Through Performance During Enter Service*

4.2.8.1. Single-phase Energy Storage Inverter

Figure 48 and Figure 49 shows the voltage ride through performance during enter service. The abnormal voltage was triggered when the inverter is in the middle of the enter service ramp. The inverter responded to the abnormal voltage, and returns to continue the ramp once the voltage returns to normal. This performance is updated in OpenDER Version 2.1 according to the test result.

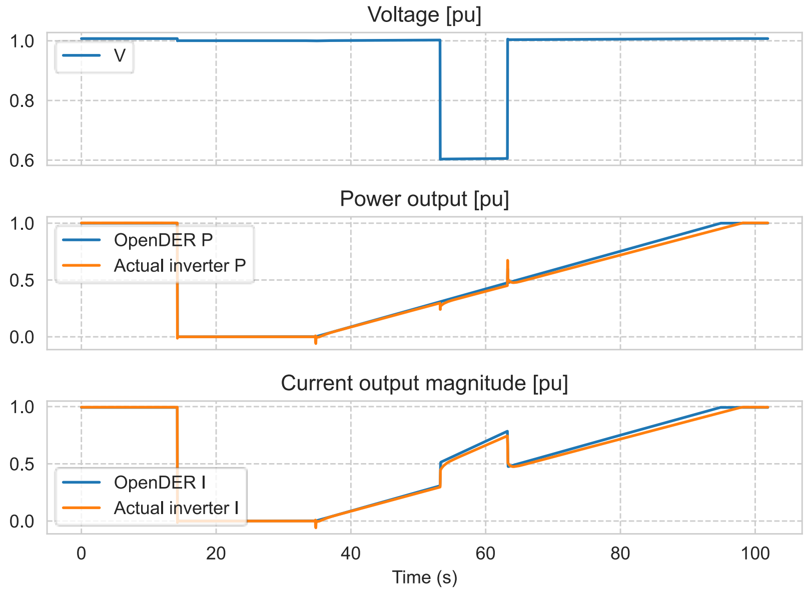


Figure 48. Model validation of voltage ride-through during enter service performance for single-phase energy storage inverter

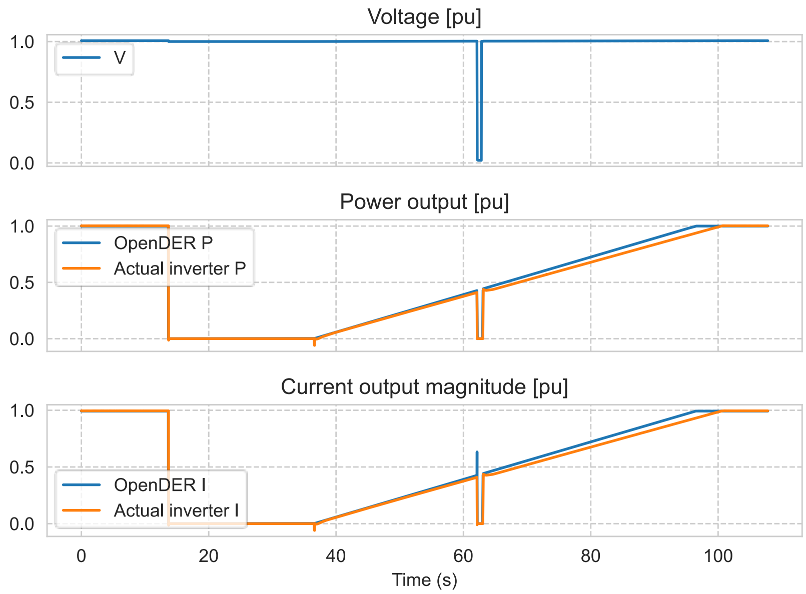


Figure 49. Model validation of momentary cessation during enter service performance for single-phase energy storage inverter

4.2.8.2. Three-phase PV Inverter

Similar tests are performed for the three-phase PV inverter. Figure 50 and Figure 51 shows the model validation results. As can be seen, the OpenDER results match the actual inverter well.

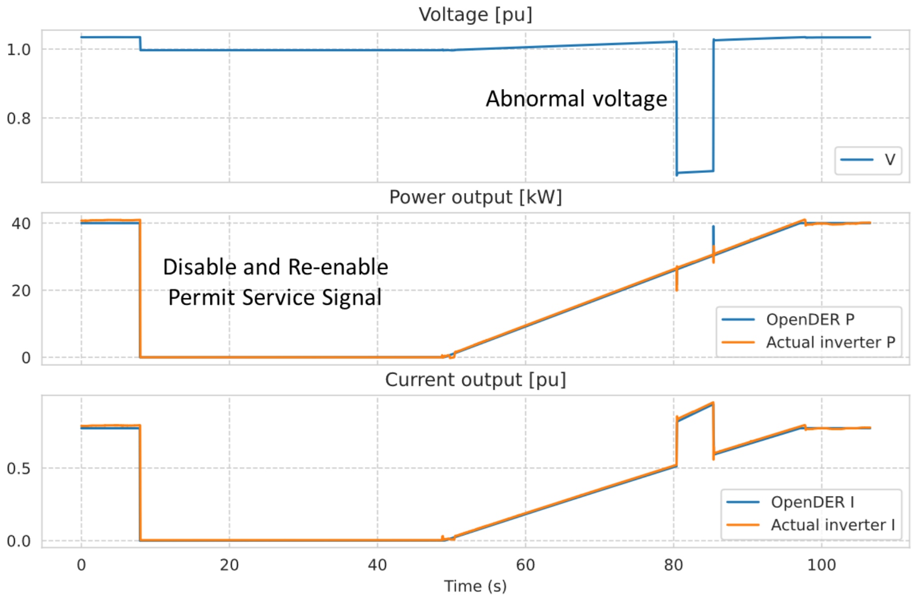


Figure 50. Model validation of voltage ride-through during enter service performance for three-phase PV inverter

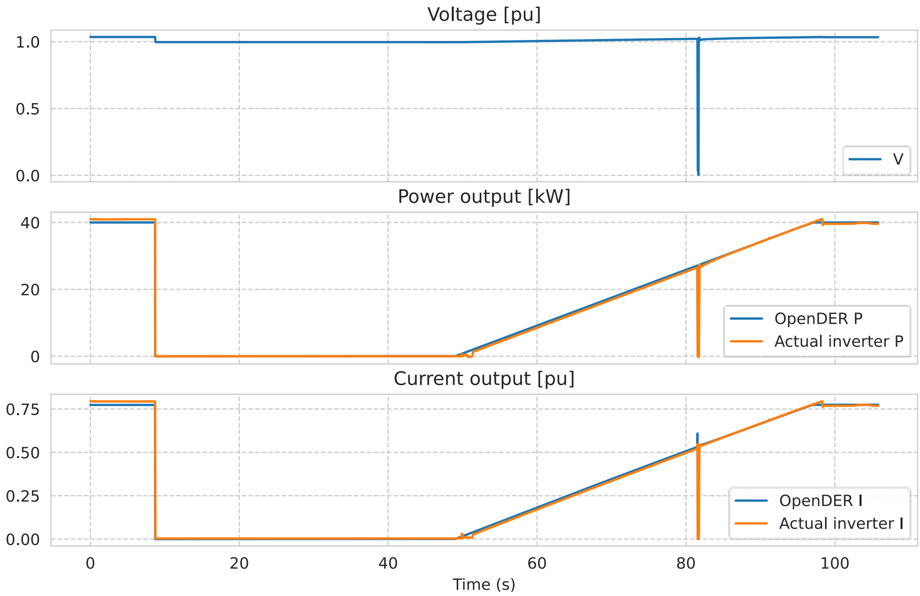


Figure 51. Model validation of momentary cessation during enter service performance for three-phase PV inverter

4.2.9. Frequency-Droop Interactions with Enter Service Performance

4.2.9.1. Single-phase Energy Storage Inverter

Figure 52 and Figure 53 shows the frequency-droop performance during enter service. The permit service signal was disabled at around 15 second. When the inverter is tripped, the grid frequency was adjusted to 59.6 Hz. Then, the permit service signal was enabled. Since the grid frequency is still within the enter service range, the inverter starts to enter service after the intentional delay.

The output active power between the inverter and OpenDER model do not match. It is speculated that the actual inverter uses the active power command or the active power output before trip as the pre-disturbance active power for frequency-droop calculation. On the other hand, the OpenDER model uses 0 as the pre-disturbance active power. It is because when the frequency disturbance happens, the active power output of the inverter is 0.

This behavior may be updated in future model revisions, based on the field or lab test results from other inverters.

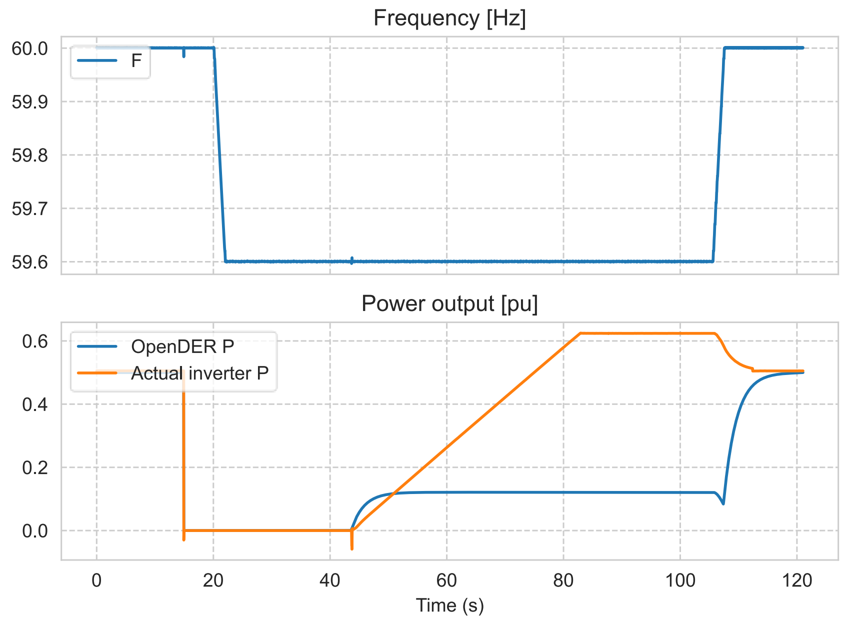


Figure 52. Single-phase energy storage inverter and OpenDER results of frequency-droop performance when frequency disturbance happens before entering service (discharging)

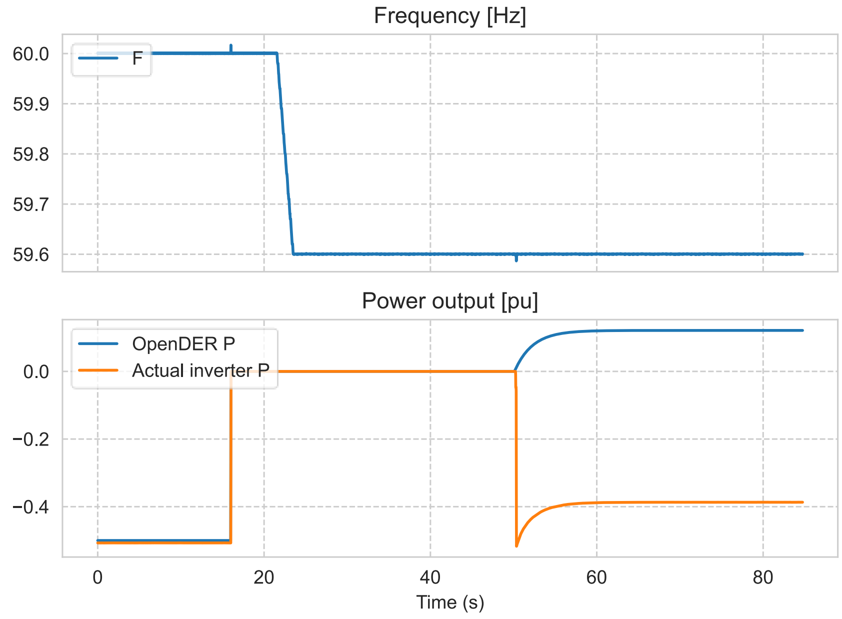


Figure 53. Single-phase energy storage inverter and OpenDER results of frequency-droop performance when frequency disturbance happens before entering service (charging)

On the other hand, Figure 54 shows the frequency-droop performance during enter service ramp. The under-frequency disturbance was triggered when the inverter is in the middle of enter service ramp. The inverter is expected to output more power according to the frequency-droop performance. Both actual inverter and OpenDER settle down at a similar active power level, indicating the pre-disturbance active power selection is the same. But the actual inverter takes another 20 seconds to ramp to the steady-state value, whereas OpenDER takes 5 seconds, following the open loop response time performance of the frequency-droop function. When the frequency goes back to 60Hz, the actual inverter follows the open loop response time requirement to return to the pre-disturbance active power value, and immediately step change to the active power demand level of 1pu, whereas OpenDER model follows the open loop response time requirement to directly go to the active power demand.

This mismatch is likely due to the ambiguity in the IEEE 1547-2018, where the priority between enter service ramp is not specified, as discussed in section 3.7.1.5. In this version, OpenDER assumes that enter service ramp has a lower priority. And this may be updated in future revisions based on field or lab test results from other inverters.

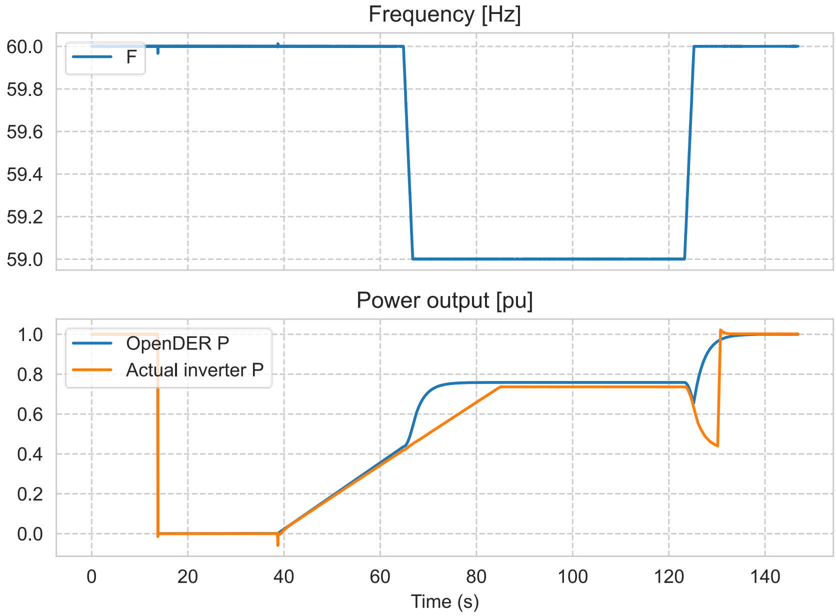


Figure 54. Single-phase energy storage inverter and OpenDER results of frequency-droop performance when under-frequency disturbance happens during enter service ramp.

4.2.9.2. Three-phase PV Inverter

Another case is studied for the example three-phase PV inverter, shown in Figure 55. The DER was tripped due to low frequency at around 8s. After frequency returns within the enter service range, the DER returns to service. However, the frequency is still outside of the frequency droop range. In this scenario, the inverter stabilized at a relatively low active power, as it may consider 0 as the pre-disturbance active power for frequency-droop operation. On the other hand, OpenDER consider the pre-disturbance active power to be the value when frequency exceeds the deadband, which is the value the last time it was in service. OpenDER cannot represent the PV inverter in corner scenario.

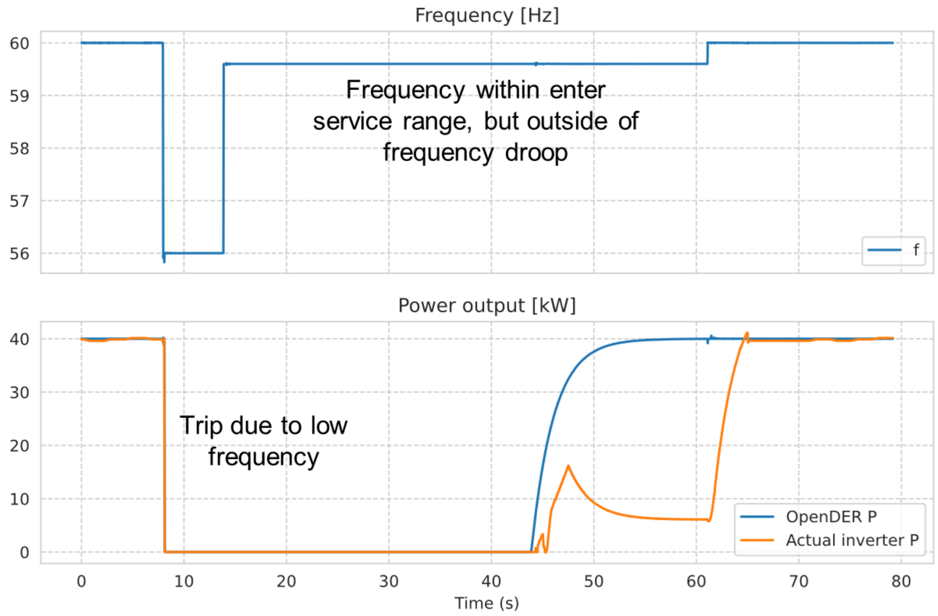


Figure 55. Three-phase PV inverter and OpenDER results of frequency-droop performance when under-frequency disturbance happens before enter service ramp

The discussions are ongoing in the IEEE P1547 revision. And the OpenDER will be updated according to the clarifications agreed by the working group.

4.2.10. Other Model Validation Results Discussion

As discussed in section 3.7.1.5 and footnote 36, IEEE 1547-2018 requires the frequency-droop has a higher priority than the active power limit signal. This indicates that during an over-frequency condition, the DER may not follow the active power limit signal, if the DER is designed to follow the standard strictly. In the testing, the two inverters are found to ignore the active power limit signal under frequency disturbances. This matches OpenDER’s assumption.

As discussed in section 3.5.1.1, the standard does not have clear guidance on whether in the enter service randomized delay period, the enter service voltage and frequency range criteria shall or shall not take effect. In the testing, the single-phase energy storage inverter is found to also perform voltage and frequency checks during the randomized delay period. And the three-phase PV inverter does not support this optional function. The modeling may be updated in future versions according to lab or field test results from other inverters.

5. INTERFACE BETWEEN DER MODEL AND SIMULATION TOOLS

This chapter provides general guidance for analysis where a simulation tool that uses the IEEE 1547-2018 OpenDER Model directly through application programming interfaces (API).

The DER model can be called or invoked by a simulation tool, which conducts circuit level simulation. To connect the DER model with a specific simulation tool, a tool-specific interface will be needed to exchange information. Since the model is intended for multiple types of distribution system analyses, the interface between the DER model and simulation tools may also be different for different simulation types. The interface is not part of the DER model. In addition, it may need to be updated if a new version of the simulation tool and/or DER model is released.

If the DER model is used in a steady-state snapshot power flow simulation without a timestep, the DER model can be re-initialized for each snapshot simulation. In this case, the user only needs to specify the initial value for the status of the DER ($STATUS\_INIT$), such that the DER model will not go through the delay and ramping process to reach steady-state operation for each snapshot simulation. For other internal state variables,[18] it is not the user's responsibility to specify their initial value. The DER model is designed to generate steady-state values for snapshot studies.

For time domain (Time series or RMS) simulation, the DER model assumes a fixed timestep. If used in a simulation with variable timestep, the model equations must be changed and adapted according to the timestep of the simulation.

The DER model shall select sufficiently small time steps such that its own dynamics are properly simulated. A general rule of thumb is to choose a simulation timestep smaller than one-tenth (1/10) of the fastest DER dynamics that of concern, which may include open loop response time, time delay, ramp rate limit, and trip time settings, depending on the analysis needs. This timestep shall be recommended to the external simulation circuit as the maximum timestep to capture the modeled DER dynamics.

The DER model may be used with a smaller timestep than the external circuit simulation. In such a case, the DER model can be executed multiple integer times within one timestep of the external circuit simulation, in order to properly simulate its own dynamics. However, the system simulation will not be able to accurately capture the dynamics close to or faster than its timestep. While OpenDER may support this operation, it is the simulation tool's responsibility to ensure sufficient accuracy of the whole system simulation.

EPRI has also open source released a simulation interface between OpenDER and OpenDSS.[49] This package is designed to be used as an intermediate solution to analyze the circuit level impact of IEEE 1547-2018 compliant DER. The operating principle of the package is as shown in

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[49] https://github.com/epri-dev/OpenDER_interface.

Figure 56. The OpenDER is represented as a generic generator or DER model in the circuit simulation engine. This model interface transfers voltage, active power and reactive power between the circuit simulation tool and the OpenDER model to facilitate the co-simulation. Examples on how to utilize the software packages are included in the repository.

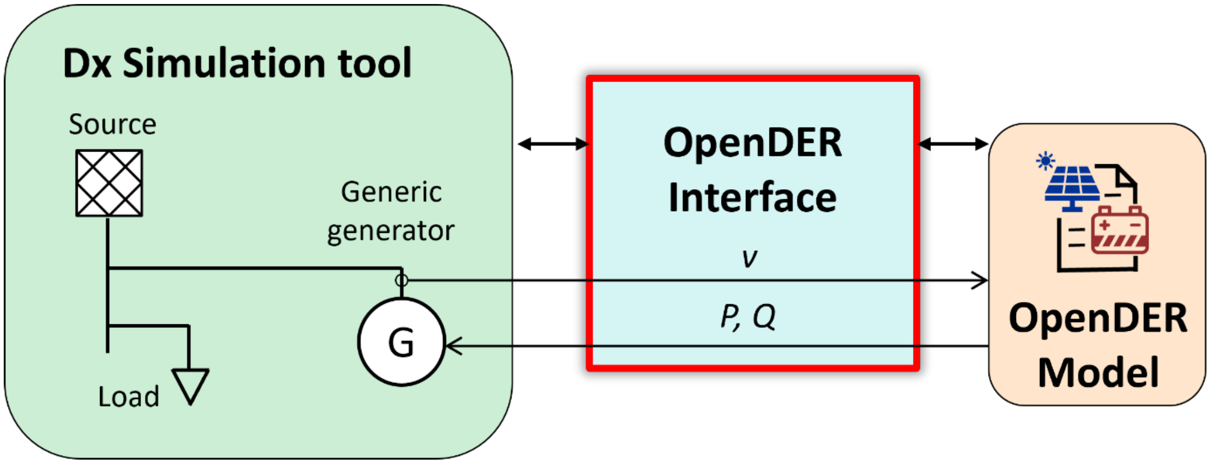

Figure 56. Operating principle of OpenDER interface to distribution analysis tool

6. CONCLUSION AND FUTURE WORK

6.1. Conclusion

EPRI started a multi-year research initiative to develop an Open-source DER (OpenDER) model, which aims to capture all detailed requirements by the IEEE 1547-2018 standard. The intent is to advance the understanding of the standard and DER behavior among all stakeholders, and to accelerate the development of internal DER model in commercial distribution simulation tools for accurate system studies.

This model specification document is developed to supplement the software model, and presented with block diagrams and equations. A modular approach is taken, where each module represents a certain standard requirement or expected behavior from DER. The presented DER model specification as a whole, or each individual module can be used as a reference by stakeholders to develop their own DER model.

Software code of the OpenDER model in Python is open source released separately in GitHub[50].

6.2. Future Plans for OpenDER Model Development

This section describes the aspects that are considered or planned, but not yet covered in the presented OpenDER Model Version 2.2. A summary of the future improvement plan is shown in Table 44.

6.2.1. Model validation against IEEE 1547-2018 certified inverters

In Version 2.2, the OpenDER model is validated against two IEEE 1547-2018 certified inverters, with gaps identified. It is planned to validate the modeled results against more inverters. The model will be updated to reflect the consistent behaviors across different inverters.

6.2.2. Proposed Changes in IEEE P1547 Standard Revision

The next revision of IEEE P1547 standard started in 2023. The updates and clarifications proposed in the next revision will be modeled in OpenDER to analyze their impacts.

6.2.3. Grid Support Functions in Other Standards

There are other grid support functions defined in the standards from other countries. For example, AS/NZS 4777.2:2020 from Australia and New Zealand has defined a “voltage balance mode” to inject unbalanced current for maintain balanced voltage. Selected functions may be implemented in OpenDER in future version releases.

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[50] https://github.com/epri-dev/OpenDER/.

6.2.4. *Islanding Detection*

Inadvertent unintentional island is a common concern for DER. Most of the DER inverters incorporate a certain type or a combination of different types of islanding detection mechanisms. Passive mechanisms may include rate of change of frequency (ROCOF) based protection, and active injections may include perturbing the active and/or reactive power output in observation of voltage and/or frequency changes. Although islanding detection studies are mostly conducted in EMT simulations, some behavior may be modeled in phasor (RMS) domain. In a later version release, islanding detection related DER behaviors may be modeled to the extent possible.

6.2.5. *Efficiency Variation with Operating Conditions*

In the current version release, a fixed efficiency value is used. However in reality, the efficiency may depend on various factors, including power output, temperature, etc. This may be updated in the future, depending on the level of details that the industry needs.

6.2.6. *Plant Controller Model*

For a DER plant with its RPA located at the PCC, a power plant controller may be used to manage the output of individual inverters within the system. However, the current OpenDER model is developed under the assumption that the entire DER plant behaves similarly to a single inverter. This simplification can lead to inaccuracies. For example, it may not accurately model the plant's apparent and reactive power capabilities, especially if there are power losses between the inverter terminals and the RPA. Other potential gaps may also arise. Future updates to OpenDER could address these issues by including more detailed plant controller modeling, depending on the level of precision required by the industry.

Table 44. Future plans for IEEE 1547-2018 OpenDER Model

Aspects to be included future versions of OpenDER Model	Future Plans
Model validation against IEEE 1547-2018 certified inverters	Continued model validation against more inverter test results
Changes in IEEE P1547 revision	Include proposed updates and clarifications in the IEEE P1547 standard revision
Grid support functions in other standards	New control functions will be added in the OpenDER model and feeder level impact will be analyzed.
Islanding Detection	May be included to the extent possible
Inverter efficiency variation for different operating conditions	May be updated, depending on the level of details that the industry needs
Plant controller model	May be updated, depending on the level of details that the industry needs

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