Inverter Modelling

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1 Purpose

This technical note describes the inverter modelling applied to PVSystem and Storage elements, recently implemented in 2019.

2 Why?

OpenDSS inverter modelling has passed through an update, released at the end of 2019. These are mainly related to the new minimum reactive power capability requirements for Distributed Energy Resources (DER) specified in IEEE 1547-2018 [1]. This technical note has been elaborated not only to explain the new features, but also to document how the inverter is modelled in OpenDSS, including all functions available up to date and how the simultaneous operation of several functions are handled. The new features/modifications are:

- Addition of properties $\%PminNoVars$ and $\%PminkvarMax$ to provide a region with active power generation/absorption only and a region with ascending linear limit of reactive power, respectively;
- Addition of property $\%kvarMaxAbs$ to provide the possibility of having different limits for maximum absorption and maximum generation of reactive power;
- Addition of property $PFpriority$ to enable power factor priority for when the requested operation point is outside the inverter capability curve and for operation under either constant power factor or constant reactive power functions;
- Renaming of some properties names to more suitable ones, in accordance with IEEE 1547-2018 [1];

3 General Remarks

Up to this date, there is no standalone element for an inverter in OpenDSS. All inverter-related settings/functions span over PVSystem and Storage Power Conversion Element (PCE) and InvControl Control Element (CE) models. Even though IEEE 1547-2018 is applicable to DER with different power conversion device technologies such as synchronous machines, induction machines and static power inverters/converters, the features described in this document apply only to the aforementioned OpenDSS PCE. Figure 1 shows the relation between these elements and references [2] and [3] provide a detailed explanation about them.

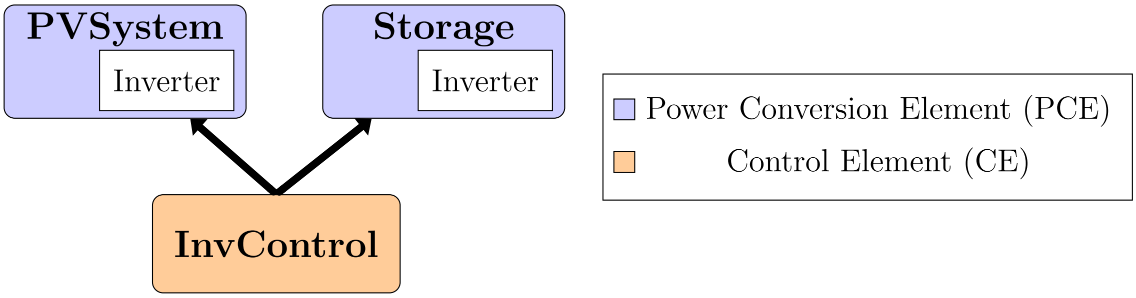


Figure 1: Relation between PVSystem, Storage and InvControl elements

4 Brief Introduction

Settings and limits such as apparent power, cut-in/cut-out power and maximum reactive power are modeled within PVSystem and Storage models. These PCEs are also responsible for carrying the definition of other inverter-related parameters, for instance, losses and a few autonomous functions, named as "direct functions" throughout this document. "Direct functions" include constant power factor, constant reactive power (constant kvar) and limit DER power output (commonly used for generation curtailment when power is being generated) functions.

Other functions currently implemented in OpenDSS such as Volt-Var (VV), Volt-Watt (VW) and Dynamic Reactive Current (DRC), referred to in this document as "voltage-dependent functions" are modeled in a separate element, the InvControl CE. The motivation for this approach is that the operation of any PCE at the interface with the grid depends primarily on a nominal power to be injected or absorbed. Because of that, and due to the nature of the constant power factor, constant kvar and limit DER power output functions, they are implemented within the PCE itself. In other words, these functions have all information they need to set the nominal power at grid the interface before solving a power flow. On the other hand, "voltage-dependent" functions rely on a reference voltage, which means that "voltage-dependent" functions first need a successful power flow solution before assigning new nominal power values to the PCE. Thus, the "voltage-dependent" functions are modeled in InvControl CE. Refer to [4] and [5] for more information about how OpenDSS models control elements and manages the operation of multiple control elements during the simulation.

This document first describes the modelling of the inverter capability curve and its associated parameters by showing the most general shape of the curve, including possible modifications to its shape and how OpenDSS handles cases in which the requested complex power violates it. A quick explanation of how the inverter efficiency curve is modeled is also given. Then, all inverter-related functions currently modeled are briefly presented and segmented by the specific elements in which each of them can be defined in OpenDSS scripting language. Next, the precedence rules of settings and functions is presented along with an explanation about which functions are mutually exclusive and which can operate simultaneously. Finally, a few commented examples are provided.

5 Inverter Capability Curve

5.1 General Description

The most flexible inverter capability curve is presented in Figure 2. All measures are on the AC side of the inverter. Note that %CutIn and %CutOut have been assumed equal. If that's not the case, once the inverter is on, only %CutOut is considered.

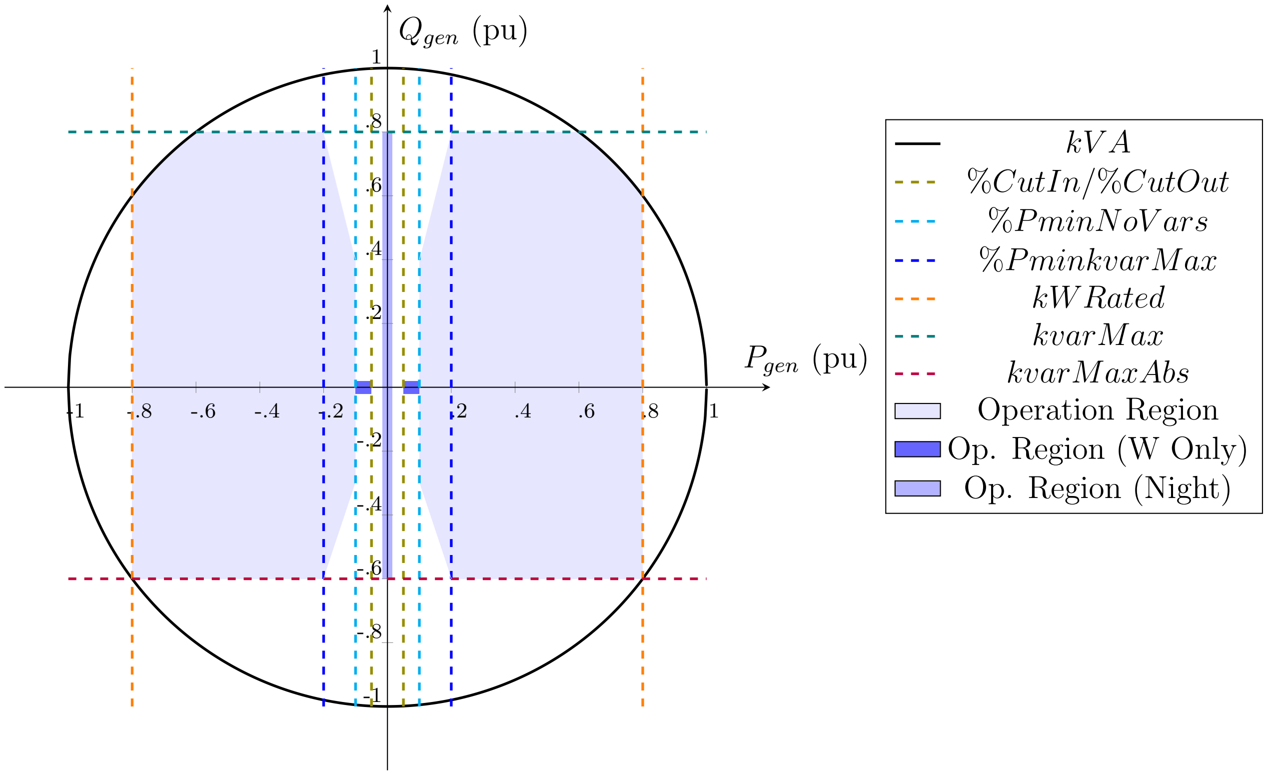


Figure 2: General Inverter Capability Curve

The following properties are utilized to define the inverter capability curve:

- kVA [kVA]: indicates the inverter nameplate capability. For PVSystem, it serves as the default value for $kvarMax$ and $kvarMaxAbs$ properties in case they are not specified. For Storage, this property is automatically set to $kWRated$ whenever kVA has not been specified yet. Defaults to 500 for PVSystem and to $kWRated$ for Storage.
- $kWRated$ [kW]: indicates the maximum active power that the DER can deliver to the grid. It is currently available only for Storage element. Defaults to 25. Meanwhile for PVSystem, the same effect (limit on active power delivered) can be obtained through property $\%Pmpp$ (see subsection 8.1).
- $kvarMax$ [kvar]: Indicates the maximum reactive power generation (un-signed numerical variable in kvar) for the inverter. Defaults to kVA rating of the inverter.
- $kvarMaxAbs$ [kvar]: Indicates the maximum reactive power absorption (un-signed numerical variable in kvar) for the inverter. Defaults to $kvarMax$.
- $\%CutIn$ [unit-less]: cut-in power as a percentage of inverter kVA rating. It is the minimum DC power necessary to turn the inverter ON when it is OFF. Must be greater than or equal to $\%CutOut$. Defaults to 2 for PVSystems and 0 for Storage elements which means that the inverter state will be always ON for this element. $\%CutIn$ in Figure 2 represents the specified $\%CutIn$ adjusted by inverter losses, i.e., the equivalent $\%CutIn$ at the AC side of the inverter.

- $\%CutOut$ [unit-less]: cut-out power as a percentage of inverter kVA rating. It is the minimum DC power necessary to keep the inverter ON. Must be less than or equal to $\%CutIn$. Defaults to 2 for PVSystems and 0 for Storage elements which means that, once ON, the inverter state will be always ON for this element. $\%CutOut$ in Figure 2 represents the specified $\%CutOut$ adjusted by inverter losses, i.e., the equivalent $\%CutOut$ at the AC side of the inverter.

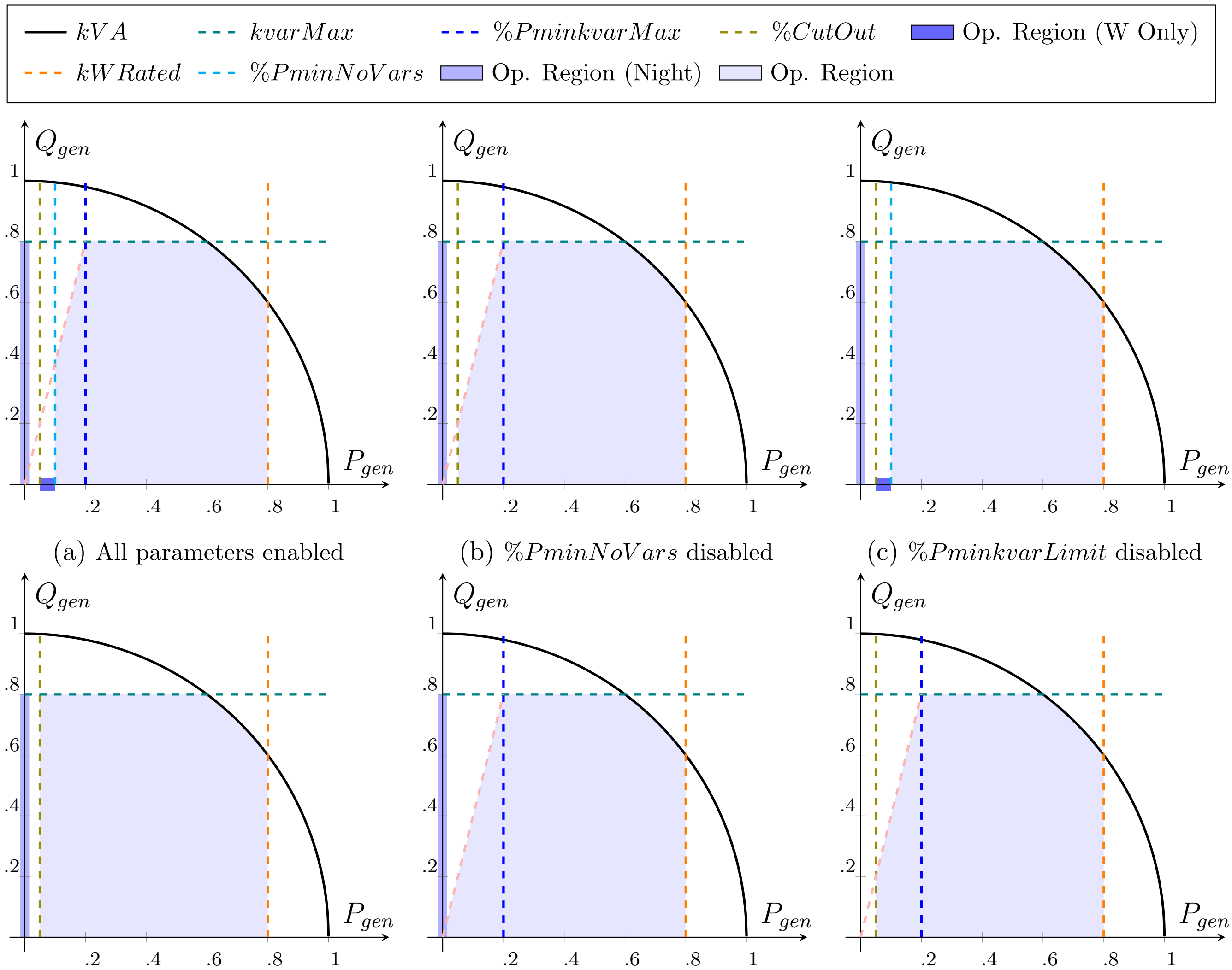
- $\%PminNoVars$ [unit-less]: minimum active power as percentage of $kWrated$ for Storage and as percentage of $Pmpp$ for PVSystem under which there is no reactive power production/absorption. Defaults to 0 (disabled).

- $\%PminkvarMax$ [unit-less]: minimum active power as percentage of $kWrated$ for Storage and as percentage of $Pmpp$ for PVSystem that allows the inverter to produce/absorb reactive power up to its maximum reactive power, which can be either $kvarMax$ or $kvarMaxAbs$, depending on the current operation quadrant. Defaults to 0 (disabled).

- $varFollowInverter$ [True/False]: Defaults to False, which indicates that the reactive power generation/absorption does not respect the inverter status. When set to True, the reactive power generation/absorption will cease when the inverter status is off, due to DC kW dropping below $\%Cutout$. The reactive power generation/absorption will begin again when the DC kW is above $\%Cutin$. When set to False, the storage will generate/absorb reactive power regardless of the status of the inverter.

5.2 Enabling/Disabling a specific parameter

As mentioned earlier, Figure 2 shows the inverter capability curve resulting from the use of all possible properties. In order to generate simpler curves, OpenDSS allows some of the properties to be disabled. Figure 3 describes possible modifications to the capability curve by enabling/disabling the *%PminNoVars*, *%PminkvarLimit* and *varFollowInverter*. For simplicity, the resulting capability curve is shown for operation in first quadrant only (the disabling of any parameter also affect the capability curve in the other quadrants). Note that *%CutOut* and *varFollowInverter* can also be disabled.



(a) All parameters enabled

(b) $\%PminNoVars$ disabled

(c) $\%PminkvarLimit$ disabled

(d) $\%PminNoVars$ and $\%PminkvarLimit$ disabled

(e) $\%PminNoVars$ and $\%CutOut$ disabled

(f) $\%PminNoVars$ disabled and $varFollowInverter$=True

Figure 3: Possible Shapes for Inverter Capability Curve

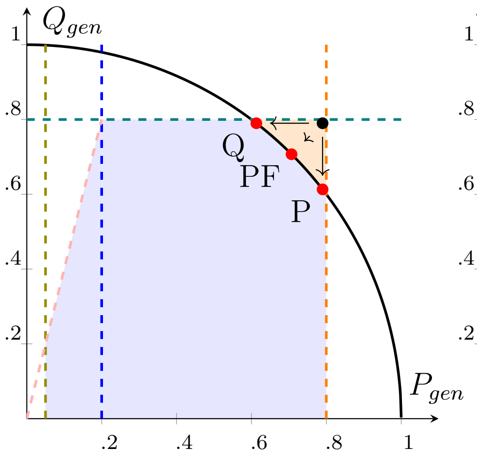
6 Violation of Inverter Capability Curve Limits

Whenever the total complex power determined by the combination of the available (for PVSystem) or the desired (for Storage) active power output and the reactive power resulting from the application of the functions described in this document exceeds the inverter capability curve, OpenDSS ensures that it will return to the allowed operating region. This "returning" can be controlled by the user by assigning different priorities. There are three types of priorities: active power, reactive power and power factor. They can be selected through two parameters of the PCE:

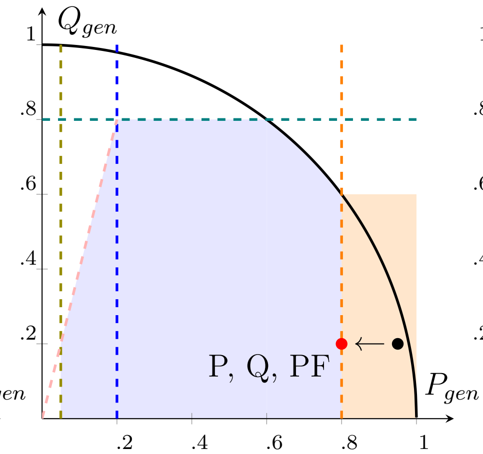
- $WattPriority$ [Yes|No or True|False]: If set to True, priority is given to active power. If set to False, priority is given to reactive power. Defaults to False.
- $PFPriority$ [Yes|No or True|False]: If set to True, priority is given to power factor and $WattPriority$ is neglected. It works only if operating in either constant PF or constant kvar modes. Defaults to False.

Depending on the region where the desired complex power is located, different priorities lead to different final operating points, as follows:

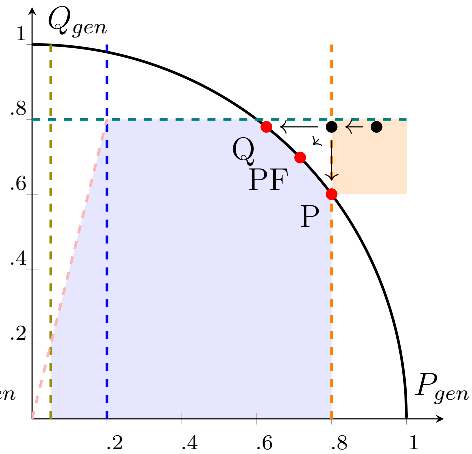
- kVA Violation: The desired active and reactive power are less than their limits, $kvarMax$ and $kWRated$, respectively. In this case, all three priorities are applicable, as shown in Figure 4a.
- $kWRated$ Violation: The final operating point will be on the $kWRated$ axis regardless the priority selected, as shown in Figure 4b. If either VW or Limit DER Power Output functions are also active, the most restricting limit applies.
- $kWRated$ and kVA Violation: In this region, first the active power output is limited by $kWRated$, and then, the same rules applies as for kVA violation case. If $WattPriority$ is set to True, the final operating point will be at the intersection of kVA and $kWRated$, as shown in Figure 4c.
- $kvarMax$ Violation: In this region, only active power and power factor priorities apply. In both cases the final reactive power is limited by $kvarMax$, as shown in Figure 4d.
- Reactive Power Violation on Region of Ascending Linear Limit: The power factor priority is not applicable in the region of ascending linear reactive power limit because the limit crosses the complex plane origin. Thus, only active power priority applies, as shown in Figure 4e.
- $kvarMax$ and kVA Violation: In this region, first the reactive power output is limited by $kvarMax$, and then, the same rules applies as for kVA violation case. With $WattPriority$ set to False, the final operating point will be at the intersection of kVA and $kvarMax$, as shown in Figure 4f.
- $kWRated$, $kvarMax$ and kVA Violation: First, $kWRated$ limit is applied, then $kvarMax$, and finally, kVA. The final operating point will be at the intersection of kVA and $kWRated$ if $WattPriority$ is True, and at the intersection of kVA and $kvarMax$ if $WattPriority$ is False, as shown in Figure 4g.



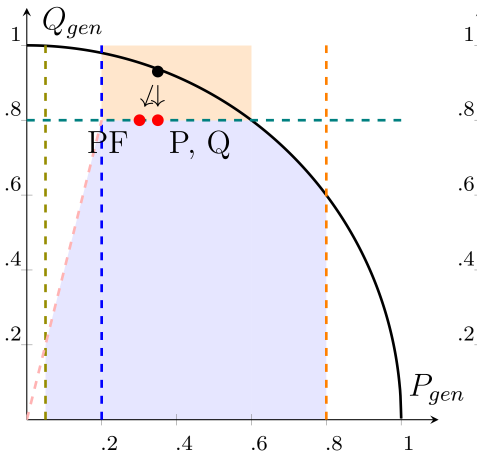
(a) kVA Violation



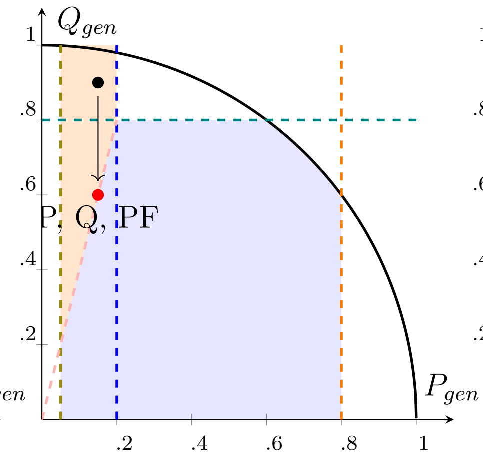
(b) $kWRated$ Violation



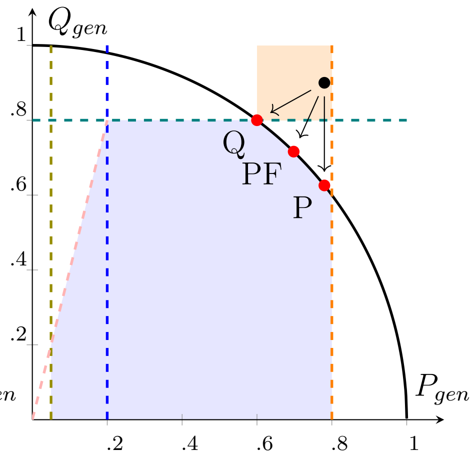
(c) $kWRated$ and kVA Violation



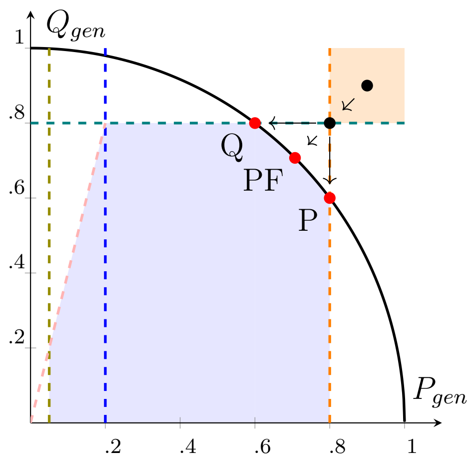
(d) $kvarMax$ Violation



(e) $kvarMax$ Violation on Region of Ascending Linear vars Limit



(f) $kvarMax$ and kVA Violation



(g) $kWRated$, $kvarMax$ and $kVAMax$ Violation

Figure 4: Response for Violations in Different Regions of the Inverter Capability Curve and for Different Priorities

7 Inverter Efficiency Curve

The efficiency curve of an inverter corresponds to a family of curves with varying DC link voltages. In the present version of the model, it is possible to define a single curve only, which is generally selected considering the rated DC link voltage. It can be defined through property $EffCurve$ of each DER, for which a $XYCurve$ object that characterizes the variation of the inverter efficiency as a function of P_{dc}, the DC power in per unit of its kVA rating, must be assigned. For PVSystems, P_{dc} varies with *Pmpp* and ambient conditions, so the calculation of the efficiency is straight forward, whereas for Storage, as active the power is defined first at the interface with the grid, the calculation is backwards, i.e, an efficiency and a DC power that leads to the given AC power are calculated simultaneously. Refer to [2] and [3] for detailed information. An example of how to define a $XYCurve$ object is shown below. If P_{dc} goes beyond the highest or lowest value of *xarray*, OpenDSS calculates the corresponding efficiency by assuming the same slope of the two nearest points defined.

```
New XYCurve.Eff npts=4 xarray=[.1 .2 .4 1.0] yarray=[.86 .9 .93 .97]
```

8 Smart-Inverter Functions

8.1 "Direct Functions"

In the OpenDSS environment, these are the functions specified within the PCE definition. They are the following:

- **Limit DER Power**: this function establish an upper limit on the real power that the DER can produce/discharge and charge at its interface with the grid [6]. For Storage, it is specified by the property *%kWRated*, which currently applies to both charging and discharging states. For PVSystems, it is specified through property *%Pmpp* (as a percentage of *Pmpp*). In both cases, the default value is 100, which means that this function is disabled.
- **Constant Power Factor (PF)**: it can be enabled by defining the property pf of the PCE. The sign convention used in OpenDSS dictates that a positive pf means reactive power in the same direction as active power. On the other hand, a negative pf means reactive power and active power with opposed signs. Note that for Storage elements, it means that, for a given pf , as it charges and discharges the reactive power sign is changed accordingly. For instance, assume that a positive pf has been specified and the selected operation mode dictates that the element should charge at the beginning of the day and discharge in the evening. In this case, there would be vars absorption and generation, respectively. Also, during operation in idling state, the reactive power dispatched by a storage element is calculated based on the specified idling losses, if any.
- **Constant Reactive Power (kvar)**: it can be enabled by defining the property $kvar$ at the DER element. The sign follows the generator convention, i.e., a positive $kvar$ means generated vars whereas a negative $kvar$ means absorbed vars.

8.2 "Voltage-Dependent" Functions

These are the functions which are defined through an InvControl CE. This section intends to provide a quick presentation of how they can be enabled and interact with each other. For a detailed explanation of their implementation, see [2]. The "voltage-dependent functions" currently implemented in InvControl are:

- **Volt-Watt (VW)**: it can be enabled by two different ways. If operating alone, by setting InvControl's *mode* property to VW. If operating with VV, by setting InvControl's *combimode* property to VV_ VW;
- **Volt-Var (VV)**: it can be enabled by three different ways. If operating alone, through InvControl's *mode* property, by setting it to VV. If operating with DRC, by setting InvControl's *combimode* property to VV_ DRC. If operating with VW, by setting *combimode* to VV_ VW;
- **Dynamic Reactive Current (DRC)**: it can be enabled by two different ways. If operating alone, by setting InvControl's *mode* property to DRC. If operating with VV, by setting InvControl's *combimode* property to VV_ DRC;

8.3 Combined Functions

OpenDSS allows the combination of some functions. They are the following:

- **PF + VW**: to enable this mode, define a power factor in a DER element and also enable VW function at the InvControl element (property *mode*) responsible for controlling the corresponding DER. If VW limits the active power output, the constant power factor will be applied on top of the limited active power, such that at the interface with the grid, the constant power factor desired will be kept constant. The same applies if the active power is further limited by the Limit DER Power function;
- **kvar + VW**: to enable this mode, define a kvar in a DER element and also enable VW function at the InvControl element (property *mode*) responsible for controlling the corresponding DER;
- **VV + VW**: to enable this mode, use an InvControl element (property *combimode*) responsible for controlling the corresponding DER. If the inverter capability curve has not been exceeded, the power exchanged with the grid will be the desired active power, which might be limited by the VW function, and the reactive power requested by the VV function;
- **VV + DRC**: to enable this mode, use an InvControl element (property *combimode*) responsible for controlling the corresponding DER. If the inverter capability curve has not been excedeed, the power exchanged with the grid will be the desired active power and the sum of the reactive power requested by the VV and DRC functions individually;

9 Precedence of Functions/Settings

As one may have noticed, there are several types of control functions that can be applied to Storage and PVSystem elements in OpenDSS. Some of those operate on the same electrical measure, i.e. active or reactive power. In these cases, depending on the nature of the control function, they may be allowed to operate simultaneously or they might be mutually exclusive. In the first case, it is necessary to establish an order of precedence. The precedence rules applied in OpenDSS follows the summary of functional descriptions for smart inverters from [6] and also in IEEE 1547-2018 [1] requirements, where applicable. They have been adapted to OpenDSS context and are summarized in Tables 1 and 2 for functions/settings that manage active and reactive power, respectively.

Table 1: Precedence of Watt Related Functions

Priority	**Settings/ Functions**	**Description**
1st: Fundamental Physical Limit	DER Primary Source of Energy	A DER cannot produce/absorb active power that it does not have available. These represent the ultimate limit of the DER. For PVSystem, it is represented by the available active power at a given time instant and for Storage it is represented by the energy capacity available (depending on the relation between $kWhrated$ and $kWhstored$ for charging state and between $\%stored$ and $\%reserve$ for discharging state).
2nd: Nameplate and Device Limits Settings	Max Power Capability Setting	This is the configurable setting establishing the DER's maximum active power input/output: kVA, for PVSystem, and kVA and $kWRated$, for Storage. Higher or lower priority settings/functions may reduce the wattage output below this value, but nothing may increase it above this value.
3rd: Settings Actively Affecting Operating Boundaries	Limit DER Power Function Volt-Watt Function	These functions serve to reduce maximum allowed watt level to some percentage of the Max Power Capability Setting less than 100%. The cause varies: For Volt-Watt function, it's the voltage at the DER terminal (autonomous function). For Limit DER Power Output Function, it's a direct control command (for instance, sent by the operator), specified through property $\%kWRated$ for Storage and $\%Pmpp$ for PVSystem. They may be simultaneously active with the same relative priority. The one requiring the greatest reduction in watts takes precedence. As functions intended to establish operating boundaries, these functions are higher priority than any of the dynamic or steady-state functions. Those functions may be active at the same time as these functions, but must operate (even dynamically) within the boundaries established by these functions.
4th: Dynamic Functions	None at Current Version	These would be Dynamic Real-Power Support and Dynamic Volt-Watt functions. These are dynamic functions that would produce "additional" active power. See [6] for more information.
5th: Steady State Functions	Storage Direct Ch./Dch. Any Storage Dispatch Function	Each of these functions/dispatch modes serve to manage the flow of real power into or out of the DER. These functions are mutually exclusive and cannot be active simultaneously. The first one refers to the direct dispatch command through properties kW, $kvar$, $state$, $\%charge$, and $\%discharge$, whereas the second refers to any of the self-dispatch modes or any mode available through a StorageController CE.

Table 2: Precedence of Vars Related Functions

<table>
<tr><th>Priority</th><th>Settings/ Functions</th><th>Description</th></tr>
<tr><td>1st: Fundamental Physical Limit</td><td>Self-Imposed Limits</td><td>None at current version</td></tr>
<tr><td>2nd: Nameplate and Device Limits Settings</td><td>Max Power Capability Setting</td><td>This is the configurable setting establishing the DER's maximum reactive power input/output: $kvarMax$, $kvarMaxAbs$ and the ascending linear vars limit specified through $\%PminNoVars$ and $\%PminkvarMax$ for both PVSystem and Storage. Higher or lower priority settings may reduce the vars output/input below these values, but nothing may increase it above these values.</td></tr>
<tr><td>3rd: Settings Actively Affecting Operating Boundaries</td><td>None defined for Vars</td><td>None at current version</td></tr>
<tr><td>4th: Dynamic Functions</td><td>DRC Function</td><td>This is a dynamic function, and produces “Additional” reactive current that adds-to or subtracts-from whatever the present reactive current level may be based on one[1] of the 5^{th} priority functions.</td></tr>
<tr><td rowspan="3">5th: Steady State Functions</td><td>Constant PF Function</td><td rowspan="3">These functions instruct the DER as to the desired level of reactive power to produce at any time. For each function, the reactive power level is indirectly related to the watt output. These functions have equal priority, but are never in conflict because they are mutually exclusive and only one may be effective at any time.</td></tr>
<tr><td>Constant kvar Function</td></tr>
<tr><td>Volt-Var Function</td></tr>
</table>

[1] At current version, DRC can only be applied on top of Volt-Var function.

10 Mapping of parameters to IEEE1547-2018

As IEEE 1547-2018 [1] has been widely adopted, Table 3 lists the mapping between the applicable properties from the standard to OpenDSS PVSystem and Storage elements.

Table 3: Mapping of Parameters between OpenDSS and IEEE1547-2018

OpenDSS	**IEEE1547-2018**	**IEEE 1547-2018 Description**
kWRated (for Storage)	Nameplate Active Power Rating	Active power rating in watts at unity power factor
kVA	Apparent Power Maximum Rating	Maximum apparent power rating in voltamperes
kvarMax	Reactive Power Injected Maximum Rating	Maximum injected reactive power rating in vars
kvarMaxAbs	Reactive Power Absorbed Maximum Rating	Maximum absorbed reactive power rating in vars
Not implemented as a specific property in current version. Assumed equal to kWRated	Active Power Charge Maximum Rating	Maximum active power charge in Watts
Not implemented as a specific property in current version. Assumed equal to kVA	Apparent Power Charge Maximum Rating	Maximum apparent power charge rating in voltamperes. May differ from the apparent power maximum rating
kV	AC Voltage Nominal Rating	Nominal AC voltage rating in RMS volts

Note that for PVSystem element, there is currently no $kWRated$ property. However, the property can be modeled with the "Limit DER Power Function", by specifying an appropriate value to $\%Pmpp$. Also note that, for Storage, IEEE1547-2018 states that both the active power charge maximum rating and the apparent power charge maximum rating may differ from their discharging/generation equivalent parameters. The current version of OpenDSS accepts only a single $kWRated$ and a single kVA, which are assumed to be the same for charging and discharging states.

11 Examples

In this section, a few examples are presented to show different aspects of the inverter modelling described throughout this document. For simplicity and easy reproducibility, a small circuit containing a single storage connected to a voltage source will be utilized, as shown in Figure 5.

The base script utilized in all examples is provided below. This script and also all the other scripts used to generate the examples are available in OpenDSS "*Examples\InverterModels\InverterTech–Note* " folder.

```
! Base Circuit with a Single Storage
Clear

New Circuit.Source bus1=A basekv=13.8 phases=3 pu=1 Z0=[10, 10] Z1=[10, 10]

! Inverter Efficiency Curve
New XYCurve.Eff npts=4 xarray=[.1 .2 .4 1.0] yarray=[.86 .9 .93 .97]

New Storage.A phases=3 bus1=A kv=13.8
~ %charge=100 %discharge=100 %reserve=20
~ %effcharge=90 %effdischarge=90
~ %idlingkW=2
~ kWhrated= 10000 %stored=80 state=idling
~ dispmode=default model=1 kVA=1000 kWrated=900 kvarMax=800 %kWRated=100
~ EffCurve=Eff %cutin=5 %cutout=5 varfollowinverter=false wattpriority=True
~ %PminkvarMax = 20 %PminNoVars = 10
~ vminpu = 0.8 vmaxpu= 1.2

New Monitor.Mon_StorageA_State element=Storage.A mode=3
New Monitor.Mon_StorageA_V element=Storage.A mode=0

Set voltagebases = [13.8]
Calcvoltagebases
```

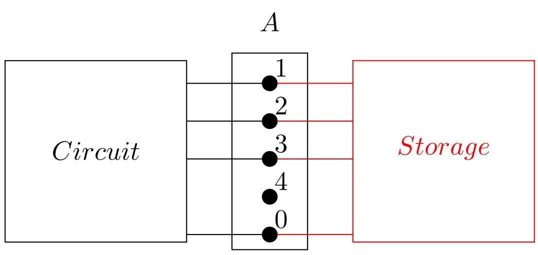


Figure 5: Storage Element Connected directly to a Voltage Source

11.1 Operation with different Priorities: kVA Violation Only

This example illustrates the violation of the inverter kVA rating considering active power, reactive power and power factor priorities. Besides the base script, the following script has been utilized.

```
! kVA Violation Only
New LoadShape.dispatchFollow interval=1 npts=24 mult = [0.0, -0.01, -0.08,
    -0.12, -0.16, -0.30, -0.50, -0.96, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.01,
    0.08, 0.12, 0.16, 0.30, 0.50, 0.96, 0.0, 0.0]

Edit Storage.A dispmode=follow daily=dispatchFollow pf=-0.8

! P Priority
Set casename=Ppriority
Edit Storage.A wattpriority=true

! Q Priority
!Set casename=Qpriority
!Edit Storage.A wattpriority=false

! PF Priority
!Set casename=PFpriority
!Edit Storage.A PFpriority=true

Set mode=Daily
Set maxcontroliter=50
Set stepsize=1h

Solve

Export monitors Mon_StorageA_State
Export monitors Mon_StorageA_V
```

First, a loadshape is specified to drive the storage active power dispatch in "Follow" mode. Then, the storage element definition is edited to enable the operation in the desired mode. Constant PF reactive power dispatch mode is also enabled, with a power factor of -0.8.

Next, *wattpriority* and *PFpriority* are set. Note that only one case can be run at each time. Finally, the solution settings are specified. The simulation is solved in daily mode and the monitors are exported.

Figure 6 shows the PQ plane with all operating points for each of the priorities. They correspond to the state variables *kWOut* and *kWIn* exported from monitor *Mon_StorageA_State*. Note that all operating points lie on the constant power factor line for all three priorities, except during the following time instants:

- The two time instants (one while in charging state and the other while in discharging state) in which the inverter kVA has been violated and for both active and reactive power priorities. These two operating points correspond to the multiplier -0.96 and 0.96 for charging and discharging, respectively. For further details about storage operation in "Follow" dispatch mode, see [3];

- For the time instants when the active power lies within the region between $\%CutIn/\%CutOut$ and $\%PminNoVars$ (W Only), in which only active power dispatch is allowed;

Also note that as $varFollowInverter$ has been set to "false", the operating points for the time instants when the storage is in idling state also lie in the constant power factor line, even though the inverter status is OFF. The small active power that charges the element during this state is due to idling losses (see [3]).

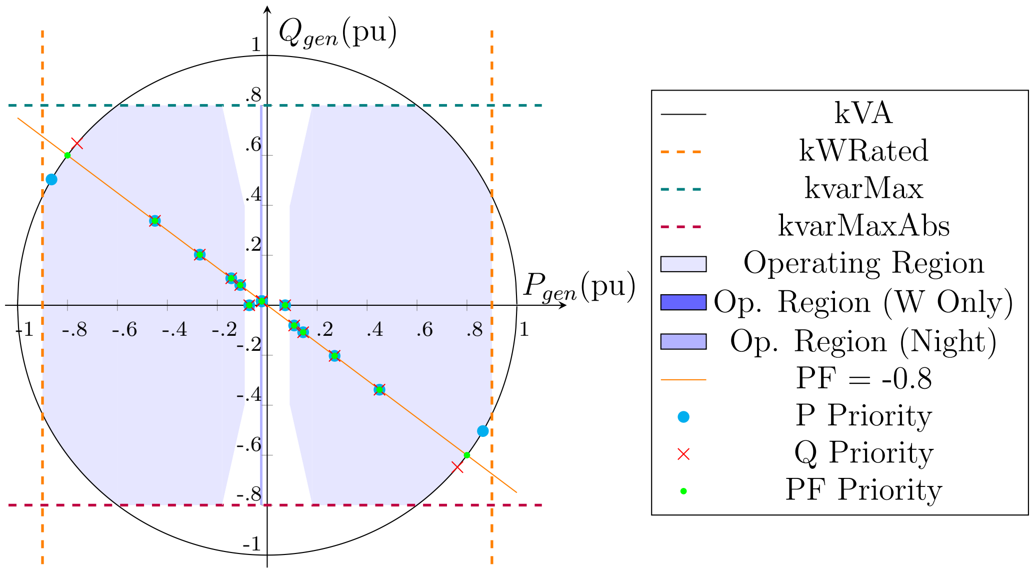


Figure 6: PQ Plane with Inverter Capability Curve and Operating Points under Constant PF Mode (Example 11.1)

11.2 Precedence of Watt Related Functions/Settings

This example illustrates the precedence of watt related functions and the violation of the element's *kW Rated* limit. The following script has been utilized.

```
! kWRated Violation Only
New LoadShape.dispatchFollow interval=1 npts=24 mult = [0, -0.01, -0.08, -0.12,
    -0.16, -0.30, -0.85, -0.96, -1.05, -1.05, 0, 0, 0, 0, 0.01, 0.08, 0.12, 0.16,
     0.30, 0.85, 0.96, 1.05, 0, 0]

Edit Storage.A dispmode=follow daily=dispatchFollow kvar=200

! VW Curves
! VW Curve for Discharging
New XYCurve.vw_curve_dch npts=4 yarray=[1 1 0.0 0.0] xarray=[1 1.05 1.1 1.3]
! VW Curve for Charging
New XYCurve.vw_curve_ch  npts=4 yarray=[0.0 0.0 1 1] xarray=[0.7 0.9  0.95 1]

New InvControl.InvCtrl mode=VOLTWATT voltWatt_curve=vw_curve_dch
~ voltWattCH_curve=vw_curve_ch

! P Priority
Set casename=Ppriority
Edit Storage.A wattpriority=true

! Q Priority
!Set casename=Qpriority
!Edit Storage.A wattpriority=false

! PF Priority
!Set casename=PFpriority
!Edit Storage.A PFpriority=true

Set mode=Daily
Set maxcontroliter=50
Set stepsize=1h

! 1 - 5am
Edit VSource.source pu=1.02
Set number=5
Solve

! 6am
Edit VSource.source pu=0.94
Set number=1
Solve

! 7am
Edit VSource.source pu=0.95
Solve

! 8am
Edit VSource.source pu=0.982
Edit Storage2.A %kWRated=88
Solve
```

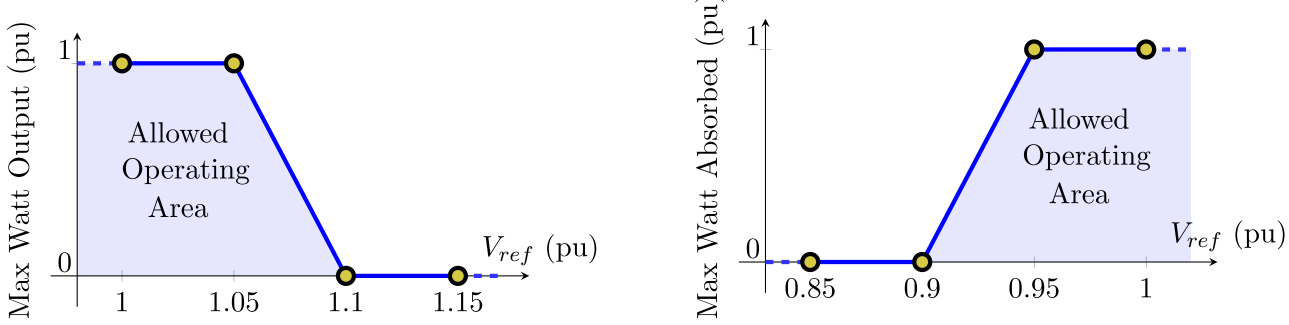
```
! 9am
Edit VSource.source pu=1.0
Edit Storage2.A %kWRated=100
Solve

! 10am - 7pm
Edit VSource.source pu=1.02
Set number=10
Solve

! 8pm
Edit VSource.source pu=1.025
Set number=1
Solve

! 9pm
Edit VSource.source pu=0.98
Edit Storage2.A %kWRated=88
Solve

! 10pm
Edit VSource.source pu=0.97
Edit Storage.A %kWRated=100
Solve

! 11pm - 12am
Edit VSource.source pu=1.02
Set number=2
Solve

Export monitors Mon_StorageA_State
Export monitors Mon_StorageA_V
Export eventlog
```

Similarly to the previous example, the storage element is operated with active power dispatch driven by "Follow" mode, however the reactive power dispatch is set to constant kvar mode, with 200 kvar of reactive power generation. Futhermore, the actual active power dispatch may be limited by the smart inverter VW functionality, which is specified in "InvCtrl" InvControl control element. Note that two different Volt-Watt curves (XYCurve object) have been specified. One for operation in discharging state and the other for operation in charging state, as shown in Figure 7.

The daily simulation is broken in several time intervals with varying sizes (specified through property *number*). The voltage magnitude of the voltage source (*pu* property) is also varied in the simulation. This has been done to force the operation of the VW function in selected time instants in order to highlight the precedence of functions.

Note that there are 3 different inverter functions from Table 1 being applied in this example:

- Volt-Watt Function (3$^{\text{rd}}$ priority): enabled by the InvControl control element;
- Limit DER Power Function (3$^{\text{rd}}$ priority): enabled by setting *%kWRated* to a value less than 100, which is done at 8am and 9pm only;



(a) VW Curve for Discharging

(b) VW Curve for Charging

Figure 7: Volt-Watt Curve for Discharging (a) and Charging (b)

- Storage "Follow" Dispatch Mode (5th priority): enabled when setting $dispmode = follow$;

Figure 8 shows the PQ plane with all operating points for each of the priorities. Note that all operating points lie on the constant power factor line (except for those that fall in the Watts only region) and that there are no differences in the inverter response between all three priorities for the *kWRated* violation, as expected, according to Figure 4b.

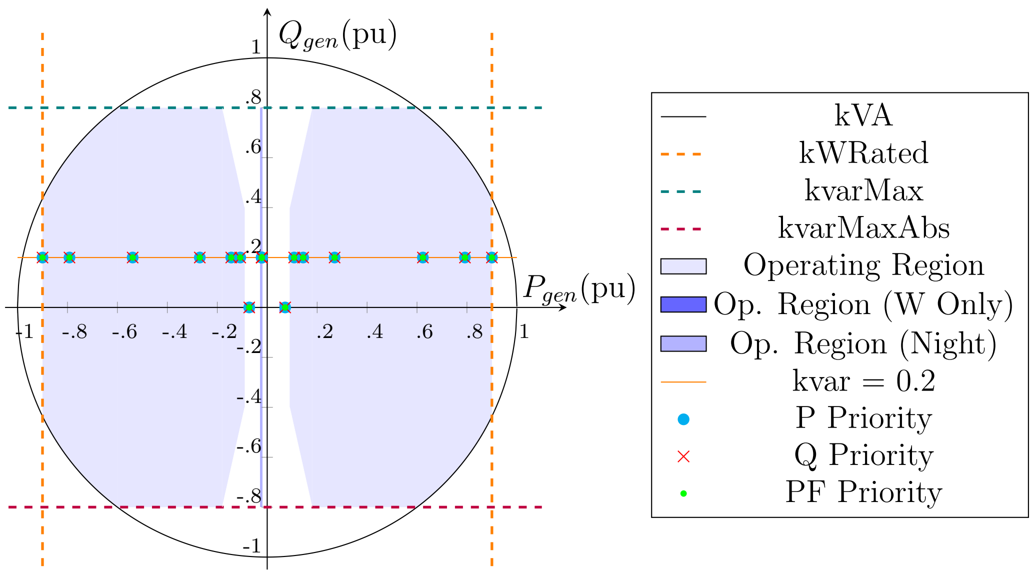


Figure 8: PQ Plane with Inverter Capability Curve and Operating Points under Constant kvar Mode (Example 11.2)

A few rows and columns of the .csv file exported from monitor *Mon_StorageA_State* are shown in Table 4. For a complete description of each column, see [3].

At 6am, the kW desired by the "follow" dispatch mode to charge the element is 270kW, and the average voltage (see InvControl's *monVoltageCalc* property) applied at the element's terminal is 0.9357, which lies within the region where the VW curve for charging tries to limit the active power. The limit imposed can be calculated as $(0.9357 - 0.9) \times \frac{1}{0.05} \times 900 = 642.6kW$, which is greater than the desired output. Thus, the power that charges the element at the grid interface, $kWIn$, is $270kW$.

At 7am, the desired power is 765kW. However, the voltage reference to the VW is 0.9299, which leads to a limit imposed by this function of $(0.92994 - 0.9) \times \frac{1}{0.05} \times 900 = 538.9kW$. Since $\%kWRated$ at this time instant is 100%, the limit imposed by the Limit DER Power Function is 900kW. Thus, as the limit imposed by the VW function requires the greatest reduction and it has a greater priority than the power desired by the "follow" dispatch function, it takes precedence and the actual power with which the element is charged is 538.9kW.

At 8am, $\%kWRated$ has been set to limit the output in 88 percent of the rated active power, which is 792kW. Note that the voltage reference for the VW function is 0.9477, which means the limit of $(0.9477 - 0.9) \times \frac{1}{0.05} \times 900 = 858.6kW$. However, the controller has access to the limit imposed by the Limit DER Power Function, and thus, the power reported in "kW VW Limit" is the lowest between the power calculated from the VW curve and the one imposed by the direct command. As the desired power at this time instant is higher than the limit imposed by $\%kWRated$, the actual power output that charges the element at the grid interface is $792kW$.

At 9am, the power desired is $1.05 \times 900 = 945kW$. As none of the limiting functions impose a lower limit, the actual power at the grid interface is limited by the nameplate device setting, $kWRated$ (2^{nd} priority).

Finally, at 10am, there is not enough energy capacity left to keep charging the element, which corresponds to a Fundamental Physical Limit (1^{st} priority). Therefore, the element enters in idling state, charging only enough power to sustain its idling and associated inverter losses. Note that because there is no energy capacity left, $kWDesired$ shows 0, even though the loadshape multiplier at 10am is -1.05.

Table 4: Selected Rows and Columns of *csv* File Exported from Monitor *Mon_StorageA_State*

Hour	State	kWOut	kWIn	kvarOut	Inv ON	Vref	VW Oper	kW Desired	kW VW Limit	Limit kWOut Function
1	0	0	21.8	200	0	1.0290	0	0	9999	900
2	0	0	21.8	200	0	1.0290	0	-9	9999	900
3	-1	0	72	0	1	1.0163	0	-72	900	900
4	-1	0	108	200	1	1.0246	0	-108	900	900
5	-1	0	144	200	1	1.0227	0	-144	900	900
6	-1	0	270	200	1	0.9357	0	-270	642.6	900
7	-1	0	538.9	200	1	0.9299	1	-765	538.9	900
8	-1	0	792	200	1	0.9477	0	-864	792	792
9	-1	0	900	200	1	0.9599	0	-945	900	900
10	0	0	22.0	200	0	1.0290	0	0	9999	900
11	0	0	21.8	200	0	1.0290	0	0	9999	900
12	0	0	21.8	200	0	1.0290	0	0	9999	900

11.3 Reactive Power Violation

This example illustrates the violation of reactive power limit in several violation regions. It also shows a different inverter capability curve shape from the previous ones.

```
! Reactive Power Violation (linear region, kvarMax, kVA)
New LoadShape.dispatchFollow interval=(1 3600 /) npts=24 mult = [0, -0.01,
    -0.08, -0.12, -0.14, -0.16, -0.30, -0.50, -0.6, -0.8, -0.95, 0, 0.01, 0.08,
    0.12, 0.14, 0.16, 0.30, 0.50, 0.6, 0.8, 0.95, 0, 0]

Edit Storage.A dispmode=follow daily=dispatchFollow %cutin=0 %cutout=0
~ %PminNoVars=0 kvarMaxAbs=600 %idlingkW=0

! VV Curve
New XYCurve.vv_curve npts=5 yarray=[1 1 0 -1 -1] xarray=[0.5 0.92 1.0 1.08 1.5]

New InvControl.InvCtrl combiMode=VV_DRC dbVMin=1 dbVMax=1 arGraLowV=50
~ arGraHiV=50 dynReacAvgWindowLen=2s refReactivePower=VARMAX vvc_curve1=vv_curve
~ varChangeTolerance=0.001

! P Priority
Set casename=Ppriority
Edit Storage.A wattpriority=true

! Q Priority
!Set casename=Qpriority
!Edit Storage.A wattpriority=false

Set mode=Daily
Set maxcontroliter=50
Set stepsize=1s

! 1 - 3am
Edit VSource.source pu=1.0
Set number=3
Solve

! 4am
Edit VSource.source pu=0.98
Set number=1
Solve

! 5am
Edit VSource.source pu=0.96
Solve

! 6am
Edit VSource.source pu=0.94
Solve

! 7am
Edit VSource.source pu=0.92
Solve

! 8am
```

```
Edit VSource.source pu=1.05
Solve

! 9 - 10am
Edit VSource.source pu=1.00
Set number=2
Solve

! 11am
Edit VSource.source pu=0.97
Set number=1
Solve

! 12pm - 3pm
Edit VSource.source pu=1.00
Set number=4
Solve

! 4pm
Edit VSource.source pu=1.03
Set number=1
Solve

! 5pm
Edit VSource.source pu=1.06
Solve

! 6pm
Edit VSource.source pu=1.1
Solve

! 7 - 9pm
Edit VSource.source pu=0.98
set number=3
Solve

! 10pm
Edit VSource.source pu=1.16
set number=1
Solve

! 11pm - 12am
Edit VSource.source pu=1.0
Set number=2
Solve

Export monitors Mon_StorageA_State
Export monitors Mon_StorageA_V
Export eventlog
```

Similarly to the previous example, the storage element is operated with active power driven by "Follow" mode. Properties $\%CutIn$, $\%CutOut$, $\%PminNoVars$ and $\%idlingkW$ have been set to 0 and $kvarMaxAbs$ has been set to 600 kvar to modify the shape of the inverter capability curve.

The reactive power dispatch is driven by an InvControl control element, through VV and DRC smart inverter functions, which have been enabled through property *combimode*. For more details about the other InvControl properties used, see [2]. As in this reactive power dispatch mode constant PF priority is not applicable, the simulation is run considering active and reactive power priorities only. The time step size has been set to 1 second, which is more appropriate for the DRC function.

As in the previous examples, the magnitude of the voltage source is varied throughout the simulation to force the InvControl to requested different reactive power levels to the storage element. In this particular case, the voltage has been intentionally varied such that the inverter operates in all four quadrants throughout the simulation. Figure 9 shows the PQ plane with all operating points for both priorities.

Note that the reactive power reaches several boundaries: kVA, $kvarMax$, $kvarMaxAbs$ and also the boundaries in the region of ascending linear reactive power limit (in quadrants II and IV). Besides that, note that the operating point differs between the two priorities considered for some operating points in which they apparently should be the same (highlighted in Figure 9). There are two reasons for that. The first one is due to the nature of the DRC function, which considers a moving average (with a time window of 2 seconds in this example) of the voltage at the element's terminal to calculate the requested reactive power. The second is that there is a difference between the moving average calculated at some time instants only because they happen right after a time instant in which there has been a kVA violation. Thus, the different priorities set different final complex power operating points, and, by consequence, different voltages, leading to different reactive power requests by the DRC function in the following time steps. As the moving average acts as low-pass filter, the response for the two different priorities eventually converge to the same value after a few later time steps. The user is encouraged to run the examples and verify this fact.

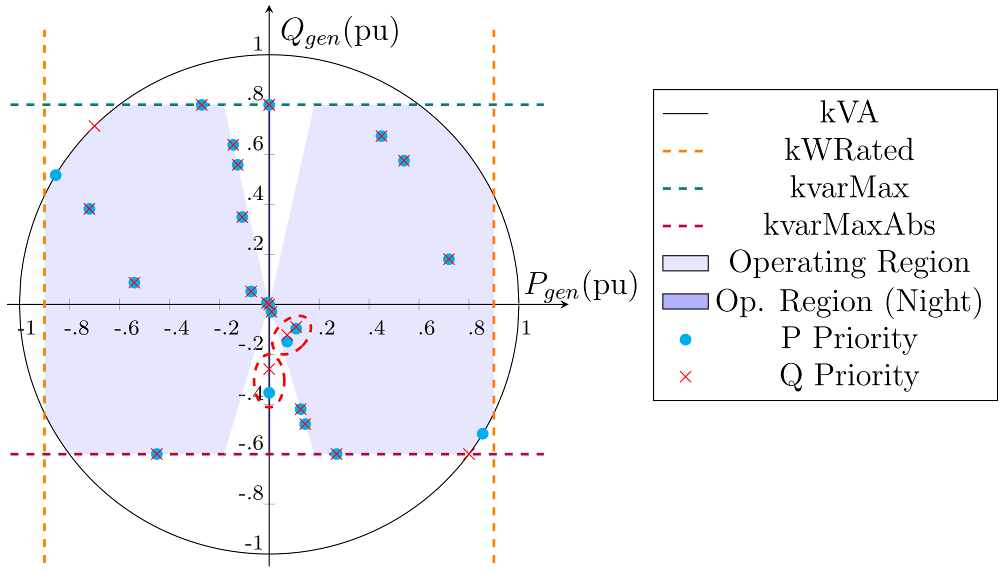


Figure 9: PQ Plane with Inverter Capability Curve and Operating Points for Operation Driven by an InvControl in VV+DRC (Example 11.3)

12 References

[1] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, Std., April 2018.

[2] P. Radatz, W. Sunderman, and C. Rocha, "Opendss pvsystem and invcontrol element models," EPRI, OpenDSS Tech. Note, November 2019.

[3] C. Rocha, J. Peppanen, P. Radatz, M. Rylander, and R. Dugan, "Storage element," EPRI, OpenDSS Tech. Note, November 2019.

[4] R. Dugan and D. Montenegro, "The open distribution system simulator (opendss)," EPRI, OpenDSS Tech. Note, April 2018.

[5] A. Birchfield, "Python to opendss interface for mopdeling control systems," EPRI, OpenDSS Tech. Note, July 2015.

[6] *Common Function for Smart Inverters: 4^{th} Edition*, EPRI, Palo Alto, CA: 2016. :3002008217.