

# **Modeling High-Penetration PV for Distribution Interconnection Studies**

*Smart Inverter Function Modeling in OpenDSS, Rev. 3*

**3002011305**





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# ABSTRACT

Utilities are currently facing potential adverse impacts from high penetration of distributed energy resources, namely inverter-based photovoltaics (PV). Smart inverter functionality is seen as a potential solution to mitigate some of these adverse impacts, but modeling and analysis are needed to determine smart inverter effectiveness.

The objective of this project, and summarized in this report, is to merge the impacts from PV with the benefits from smart inverters. This is achieved by modeling the grid support functions identified within the industry and analyzing them such that the industry can evaluate smart inverter efficacy, investigate potential impact on distribution feeder operation, and determine eventual implementation in commercially available distribution system analysis software. This year's update includes the addition of simultaneous volt-var/dynamic reactive power function modes as well as other features that allow simultaneous activity of multiple operating functions.

The smart inverter functions currently implemented reduce the impact of PV to the distribution system, allowing for increased levels of hosting capacity. All modeling is performed in the publicly available open-source distribution system simulator (OpenDSS). With each function, sample cases illustrating usage and application are shown using an actual distribution feeder and local solar measurements.

## **Keywords**

Distributed PV

Hosting capacity

OpenDSS

Open-source distribution software

Simultaneous modes

Smart inverter





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# 1

## INTRODUCTION

### Background

A great deal of work has been done by EPRI and others with respect to analysis of high-penetration PV at the distribution level (e.g., hosting capacity determinations) [1,2,3]. Likewise, EPRI has also, over the past few years, been leading an effort to develop a common set of smart inverter, grid-support functions [4]. The objective of this project, and summarized in this report, is an effort to marry these two initiatives by implementing the grid support functions that have been identified within the industry and model them in an open-source platform such that industry can evaluate function efficacy, investigate potential impact on distribution feeder operation and hosting capacity, as well as eventual implementation in commercially available software.

This effort is part of an ongoing effort related to the modeling of inverter-based generation. This particular report is essentially an updated report to that published in 2013 [5], including functionality added and/or modified to the OpenDSS models previously developed in and documented in 2012.

### ***Common Functions for Smart Inverters***

Since 2009, EPRI has been facilitating an industry collaborative initiative that is working to define common functions and communication protocols for integration of smart distributed resources with the grid. The goal is to enable high-penetration scenarios in which a diversity of resources (for example, photovoltaic and battery storage) in varying sizes and from varying manufacturers can be integrated into distribution circuits in a manageable and beneficial way.

Since 2009, EPRI has facilitated a collaborate team, working together with the Department of Energy, Sandia National Laboratories, and the Solar Electric Power Association define common functions and communication protocols for integration of smart distributed resources with the grid.

### ***Smart Inverter Functions***

The intended application for a number of the functions includes both solar PV and energy storage, however **this particular effort focuses on the smart inverter functions that have the greatest impact on improving feeder response at the local distribution level.** These functions include maximum generation limit, fixed power factor, intelligent volt-var, volt-watt, dynamic reactive current, volt-watt/volt-var, volt-var/dynamic reactive power.

### ***New Functionality in DSS***

The new functionality in the OpenDSS for the InvControl consists mainly of the addition of the ability to have multiple operating functions active simultaneously. These are the simultaneous volt-var/volt-watt function, explained in Chapter 6, and the simultaneous volt-var/dynamic reactive power function, explained in Chapter 7.

Additional changes include:

- The y-axis for the volt-var curve can have different units now, instead of just being in per-unit of the available vars. See the **VV\_RefReactivePower** parameter in Chapter 3, Chapter 6, and Chapter 7.
- The y-axis for the volt-watt curve has one added unit. See the **VoltwattYAxis** parameter in Chapter 4.

## Project Summary

This report describes work that involves implementing the smart inverter, grid-support functions in distribution system analysis software. The smart inverter functions chosen are focused on those relative to reducing the impact of PV to the distribution system, thus allowing for increased levels of hosting capacity. All modeling is performed in the publicly available open-source distribution system simulator (OpenDSS).

With each function, sample cases illustrating usage and application are shown using a real distribution feeder and local solar measurements. A more detailed write-up describing the actual function can be further found in Seal's work [6]. If the reader is familiar with this effort, they will recognize many of the naming of configuration parameters are the same, for the project team made a concerted effort to use the same nomenclature.

## Industry Impact

This particular effort is part of an ongoing effort to evaluate the use of inherent PV inverter controls for mitigating grid-related issues caused by PV, as well as examining increased levels of hosting capacity via smart inverter functionality. Simulations can be used to evaluate the efficacy of said functions, as well as determine the best parameters to utilize in a given situation.

In order to evaluate such functions, the industry must have the tools that are capable of simulating PV systems that operate in such a manner.

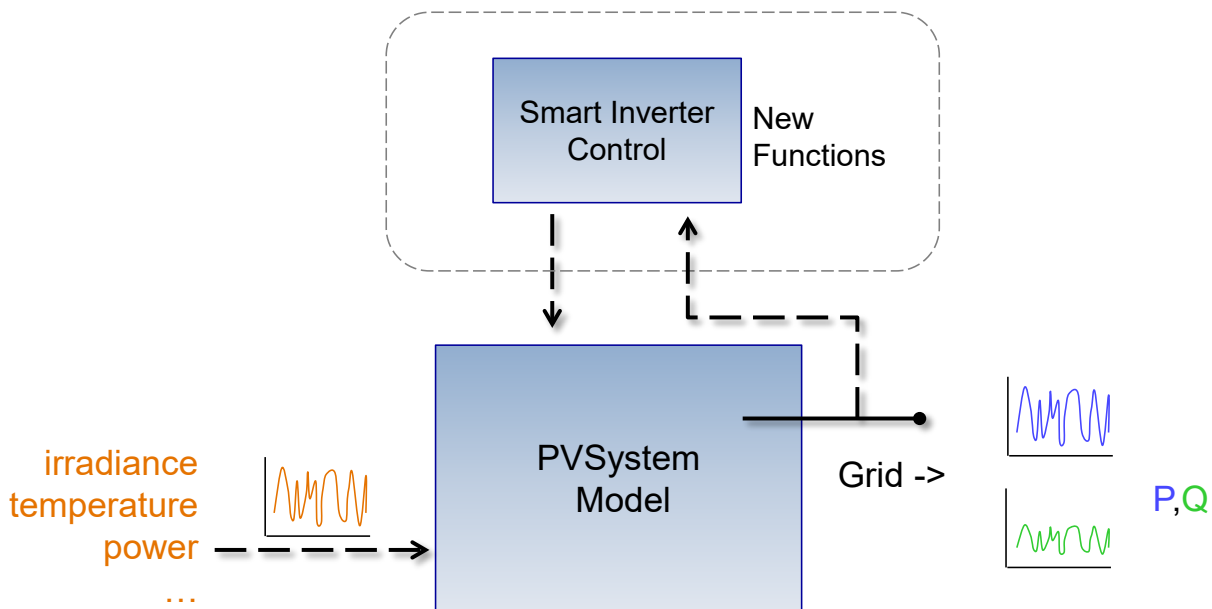
This particular project enables these efforts to allow the evaluations of such functions. Because the modeling approach utilizes open-source software (OpenDSS), the evaluations can be performed by utilities, research organizations, universities, and consultants without the need for proprietary software. In addition, the modeling work can eventually be used to seed implementation in commercially available software used for day-to-day planning.

# 2

## PVSYSTEM MODEL

In order to cover the new InvControl model capability in the OpenDSS, it is prudent to first start by discussing the actual PVSystem model for which the InvControl model interfaces to the grid model. A solar PV system is composed of many elements which allow for the conversion of sunlight ultimately to AC power suitable for interconnection with the electric utility system (often referred to as ‘the grid’) [8].

A simplified block diagram for the entire PV system, from solar cell(s) to the grid is illustrated in **Figure 2-1**. The Inverter Control, which provides volt-var, volt-watt, and dynamic reactive current control modes is shown as well in the figure.



**Figure 2-1**  
**Simplified Block Diagram of the Entire PV System and new Inverter Control**

A PV system consists of one or more solar cell modules or panels, that take insolation from the sun (direct and indirect) and convert that into a DC signal which is passed on to an input filter capacitor. Following the input filter capacitor, a DC to AC inverter transforms the current from the DC stage into an AC signal that is synchronized with the grid.

In the OpenDSS modeling program most of these components are represented in a simplified manner in the PVSystem device class. The present version of the PVSystem model is useful for simulations generally greater than 1s time steps. The model assumes the inverter is able to find the max power point (mpp) of the panel quickly. This simplifies the modeling of the individual components (PV panel(s) and inverter) and should be adequate for most interconnection impact studies.

The interface to the circuit model is the same as any Power Conversion (PC) element in the OpenDSS program. It basically appears the same to the circuit model as a Generator or Load or Storage device would, producing or consuming power according to some function.

In this case, the active power,  $P$ , is a function of the Irradiance (insolation from the sun), temperature ( $T$ ), and rated power at the maximum power point,  $P_{mpp}$ , at a selected temperature and an irradiance of  $1.0 \text{ kW/m}^2$ . In addition, the efficiency of the inverter at the operating power and voltage is applied.

The PVsystem model uses XYcurve objects to describe certain characteristics of the PV panels and inverters. XYcurve objects are new with this version of OpenDSS. The user may enter x-y curves as either an array of points or as separate arrays of x and y values. The following two examples are equivalent:

```
// curve in separate x, y array
New XYCurve.MyEff npts=4 xarray=[0.1 0.2 0.4 1.0] yarray=[0.86 0.9 0.93 0.97]

// curve as array of x,y values, in sequence
New XYCurve.MyEff npts=4 points=[0.1, 0.86 0.2, 0.9 0.4, 0.93 1.0, 0.97]
```

XYcurve objects are interpolated linearly between defined points to determine the actual value. For curves used in the PVsystem model, it is usually sufficient to enter only 4 or 5 points because the curves are relatively smooth and monotonic.

An array of points is entered to describe how the  $P_{mpp}$  varies with  $T$  relative to the temperature chosen for the rated  $P_{mpp}$  at  $1 \text{ kW/m}^2$ . This is a per unit factor for discounting the panel power output for temperature. The factor is 1.0 for the temperature for which the  $P_{mpp}$  is defined. This curve normally declines for higher temperatures and increases for lower temperatures.

An array of points is also used to represent the efficiency curve for the inverter. While this is a family of curves depending on the dc bus voltage, the model uses only a single curve at this time, using a curve near the typical operating voltage of a given array. This model may be made more sophisticated in future revisions, but this simplified model appears adequate for distribution impact studies [9,10].

An InvControl device works with PVSystem objects by controlling them in a manner to provide three main advanced inverter functions.

# 3

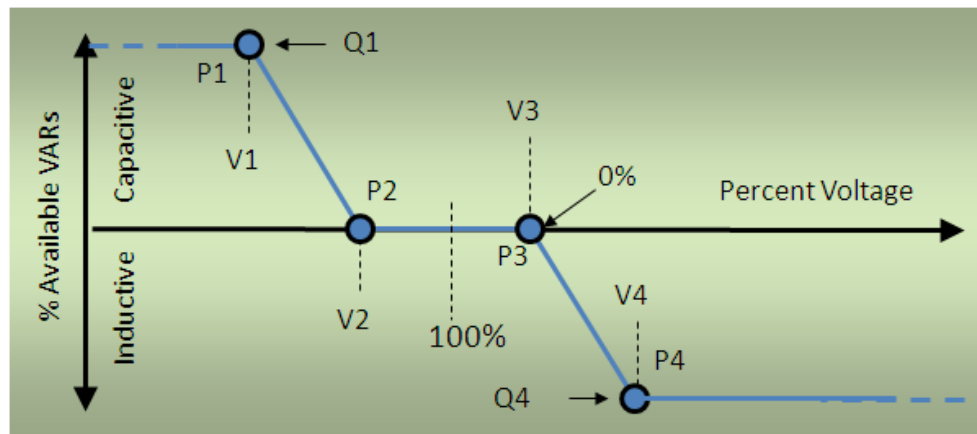
## INTELLIGENT VOLT-VAR FUNCTION

### Function Scope

The volt-var control function allows each individual PV system to provide a unique var response according to 1) the voltage at the point of connection (the terminals of the PV system), 2) the available apparent power capacity of the inverter at that point in time, and 3) the user-defined volt-var setpoints as illustrated in **Figure 3-1**.

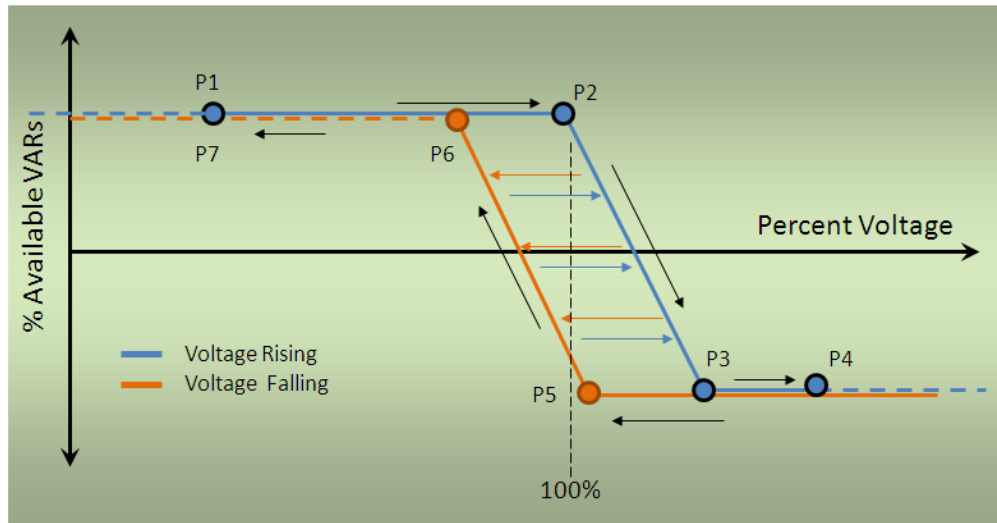
The user may define a variable number of points in the form of a volt-var curve. For example, the setpoints can be defined such that the inverter provides maximum possible reactive power at the full range of allowable voltage (V1 of 0.95pu and V4 of 1.05 pu), or possibly a narrower range of setpoints to provide much tighter voltage regulation. The reactive power output values are, by default, defined as a percentage of available vars given the present active power output and the full-scale apparent power rating of the PV system's inverter. The points can also be defined with or without a "deadband" such that the inverter provides continuous var control from V1 to V4.

Capacitive vars are assumed to be positive, while inductive vars are assumed to be negative in defining the curve.



**Figure 3-1**  
**Example Array Settings to Describe Desired Volt-var Behavior**

In some cases, it may be desired to support and employ a hysteresis in the volt-var settings. This is accommodated as illustrated in **Figure 3-2**, by extending the volt-var configuration array with additional points that trace back toward the left after reaching the highest point.



**Figure 3-2**  
**Example Array Settings with Hysteresis**

### Function Application

Some of the uses of the volt-var functionality are to attempt to maintain the voltage at the terminal of the PV system within ANSI limits for a variety of circumstances. Absorption of reactive power (inductive vars) can be called upon if the voltage begins to exceed a pre-determined upper level (as defined by the volt-var curve). Conversely, if lower than normal voltages are present at the terminals of the PV system, say due to a reduction in active power output, reactive power can be delivered to the grid (capacitive vars) to help boost the voltage back to normal levels.

With hysteresis, one can define a voltage-reactive power region, in which reactive power output will not change, until the voltage drops or rises enough to encounter the line segments defined by the volt-var curve or the line segments defined by the hysteresis (or ‘voltage falling’) points. This might be desirable when no sudden changes in reactive power are needed. The region in between the voltage rising curve and the voltage falling curve is somewhat analogous to a ‘dead-band’ except rather than cease reactive power output; the reactive power output is maintained at the last calculated level [11].

With the adaptive voltage set-point, the PV system has access to a rolling average window (of user-defined length) that will slowly adjust to the ‘normal’ system voltage, over time, depending on the length of the window. This will be especially useful on circuits where conservation voltage reduction (CVR) is in effect throughout the day. Rather than having to define a custom volt-var curve whose 0 var point is centered on the CVR set-point, the rolling average window, when set appropriately, will slowly move the center-point (the curve’s 1.0 per-unit voltage point) of the volt-var curve to the normal, or average, voltage that the circuit is operating at, via regulators’ and/or capacitors’ set-points. It is worth noting that the adaptive voltage set-point is an additional option added that is not currently defined within the set of common smart inverter functions [4].

## Model Requirements

- PVSystem (one or more)
- XYcurve (one per inverter control)

### PVSystem

Utilizing the inverter control (referred to by its class name in OpenDSS: InvControl) in volt-var control mode the user should first define one or more PVSystem objects that will be controlled by an InvControl element.

The PVSystem object(s), which represent entire PV systems including PV panel(s)/array plus the inverter, should have their full-scale kVA rating and Pmpp defined. Pmpp is the rated maximum power of the PV array for 1.0 kW/sq-m irradiance and a user-selected array temperature. The power factor should be set to unity for the PVSystem element. If desired, the kvarLimit property can be set in the PVSystem element to define a maximum reactive power injection/absorption limit. The kvarLimit can also work with the InvControl's VV\_RefReactivePower property, when that property is set to either VARMAX\_VARS or VARMAX\_WATTS. Other settings that would be helpful to be defined are the cut-out (switch the inverter off) kVA level and the cut-in (switch the inverter on) kVA level to define the power levels below and above which the inverter switches off or on.

### XYCurve

In addition to the PVSystem model, the volt-var function requires the user to define one or more XYcurve objects. There should be one XYcurve instance per InvControl instance. The XYCurve object defines the output reactive power as a function of the terminal voltage at the PVSystem object.

The y-axis units for the XYcurve are in per unit of available kvar, by default. Given the nominal kVA rating of the PVSystem and the present active power output of the PVSystem, the power electronics in the inverter only allow a certain amount of reactive power to be generated. It is assumed for the model that the full range of reactive power is available to be sent to the grid (capacitive reactive power) or absorbed from the grid (inductive reactive power). The available reactive power (to be sent or absorbed) at any moment in the simulation is governed by the following equation (**Equation 3-1**). To convert to per unit, one divides the actual reactive power output by this quantity.

$$kvar_{available} = \sqrt{(kva\_rating)^2 - (present\_kW)^2} \quad \text{Equation 3-1}$$

A positive sign for reactive power output (in per unit, pu) for the y-array values indicates capacitive vars, or reactive power flowing in the same direction as active power. A negative sign for reactive power output indicates inductive vars, or reactive power flowing in the opposite direction as the active power.

Other y-axis units are available for the volt-var curve by altering the VV\_RefReactivePower property in the InvControl. The default setting, which has already been described, is VARAVAL\_WATTS. This setting indicates that the y-axis units are in per-unit of available reactive power (as just described). The second portion of the default setting indicates that active power has precedence over reactive power, should the kVA rating of the PVSystem's inverter be

exceeded. The other two settings are VARMAX\_VARS and VARMAX\_WATTS. These settings, in conjunction with the kvarLimit of the PVSystem indicate that the y-axis units of the volt-var curve are in per-unit of the kvarLimit value (kvarLimit is given in kvar). The only difference between these two are the precedence of reactive power or active power should limits be reached of the inverter capability.

For the x-axis, the units are in per unit of the terminal voltage of the PVSystem object. However, the quantity to convert from volts to per-unit voltage can be set by the user. The default setting is to use the rated voltage of the PVSystem object to ‘per-unitize’ the voltage. An alternate option is to use a rolling average window, of user-defined length, to convert the terminal voltage of the PVSystem from volts to per-unit voltage.

For PVSystem objects having more than one phase, the terminal voltage is represented by the average of the ‘number of phases’ line-neutral voltages.

There should be an equal number of x-array points as y-array points so as to define the reactive power output as a function of the terminal voltage. A sample set of points is shown in **Figure 3-1** for a simple volt-var curve without hysteresis.

Regardless of the number of points given, the XYCurve object in the OpenDSS will interpolate between given volt-var (x,y) point pairs. The XYCurve object will also extrapolate beyond the limits of the given points if the voltage at the terminals of the PV system exceeds the minimum or maximum value, based on a linear extrapolation of the last line segment that is defined.

Given the possibility of extrapolation beyond the extents of the XYCurve, it is often advisable to have a point at a fairly low voltage value like 0.5 pu corresponding to 1.0 pu available reactive power output, and another point at a fairly high voltage value like 1.5 per unit corresponding to -1.0 pu available reactive power output, to avoid undesirable dispatching behavior. Note that in these regions, the PVSystem model will typically have reverted to a constant impedance representation.

### ***Hysteresis (Optional)***

Hysteresis is optionally available to the user so as to define a ‘dead-band’ within which the reactive power output remains constant. The InvControl model allows one to utilize a second curve that is of the same shape and number of points as the basic volt-var curve defined by the XYCurve object, but it is offset by a certain per-unit voltage. This offset, which should be specified as a negative value, allows for the creation of the second XYCurve. If no hysteresis offset is defined, it is assumed that the offset is 0, and therefore no hysteresis is utilized. While the user cannot actually create a separate XYCurve, in the OpenDSS implementation, the second curve is essentially “created” by use of the hysteresis offset. The practical effect from an operational stand-point is the same as just adding an additional curve of the same shape to the existing volt-var curve.

The functionality of the hysteresis option is as follows. If the prior two power-flow solutions show that the terminal voltages are moving in a positive direction and the latest power-flow solution shows continued movement in the positive direction (increasing terminal voltage), the reactive power output will follow the XYCurve defined (referred to as XYCurve 1).



If the most recent power-flow solution shows the terminal voltage decreasing we shift to the hysteresis curve (referred to as XYCurve 2, which is internal to the OpenDSS program only; i.e., it is not defined by the user explicitly), but maintain the same reactive power output. The reactive power output will remain the same until such time as the voltage decreases enough that we have encountered the boundary of XYCurve 2. At that point, if the voltage is still going in a negative direction we follow XYCurve 2 for determining the reactive power output.

Similarly, if we are utilizing XYCurve 2 (due to decreasing terminal voltages) and the terminal voltages from the last power flow solution, compared to the prior, change direction and start moving in the positive direction, we shift to utilizing XYCurve 1. However, as before, the reactive power output does not change until such time as the terminal voltage level encounters a point on the XYCurve 1. Only at that point do we begin to follow XYCurve 1.

## Model Input Parameters and Configuration Options

For an InvControl object, the following input parameters can be set and utilized by the user for operating the InvControl device to control one or more PVSystem objects under volt-var control mode. The default value and whether the parameter is optional or required are indicated along with a description of each parameter and its usage.

- **Parameter: PVSystemList**
  - Description: A list of one or more PVSystem objects' names (excluding the class specifier of PVSystem) that will be under the control of the present InvControl device.
  - Optional/Required: Optional.
  - Default value: Blank, empty list.
    - Note: If blank then all PVSystem objects in the circuit are brought under the control of the present InvControl device.
  - Possible Values: pvname1,pvname2,pvname3.
- **Parameter: Mode**
  - Description: The control mode under which the InvControl device will control the PVSystem objects listed following the PVSystemList parameter, or all PVSystem objects in the circuit if PVSystemList is not specified.
    - Note: VOLTVAR control mode controls one or more PVSystem objects to follow a volt-var curve and varies the reactive power output of the individual PVSystem objects, independently from each other, according to a user-defined volt-var curve that correlates terminal voltage with reactive power.
  - Optional/Required: Optional. If no value is specified, then VOLTVAR mode is assumed.
  - Default value: VOLTVAR.

- Possible Values: VOLTVAR | VOLTWATT | DYNAMICREACCURR. Unique abbreviations may be used.
- Parameter: **vvc\_curve1**
  - Description: The name of an XYCurve that defines the reactive power output level (in pu of available reactive power) in terms of the terminal voltage(s) at each individual PVSystem.
  - Optional/Required: Required for VOLTVAR control mode. Otherwise, not required.
  - Default value: None. Must be specified for VOLTVAR control mode.
  - Possible values: The name of a defined XYCurve object.
- Parameter: **hysteresis\_offset**
  - Description: An offset, in per-unit voltage, to generate a second volt-var curve (internal to the application) that defines the behavior of the volt-var function with a dead-band equal to the hysteresis\_offset value. See **Figure 3-2** for an example of volt-var curves illustrating hysteresis.
  - Optional/Required: Optional. Required if hysteresis is to be utilized.
  - Default value: 0.0. If equal to zero, then hysteresis functionality is not utilized.
  - Possible values: Any floating point number less than or equal to 0.0.
- Parameter: **voltage\_curvex\_ref**
  - Description: For several modes, this defines the denominator that converts the terminal voltage into a per-unit value.
    - If 'rated' is specified as the value, or if no value is entered, the rated voltage of the PVSystem device(s) under the control of the InvControl device are used as the denominator.
    - If 'avg' is specified as the value for this parameter, a rolling average window voltage value is used as the denominator to convert the voltage into a per-unit value.
    - Information regarding the rolling average window is provided in the for the parameter 'avgwindowlen', which is listed next in this section.
  - Optional/Required: Optional.
  - Default value: rated.
  - Possible values: rated | avg.

- Parameter: **avgwindowlen**

- Description: For several control modes, this defines the length of the rolling average window in units of simulation time.
  - A rolling average window contains the voltages from each PVSystem object (independently) that is under the control of a given InvControl object for the most recent power-flow solution and sufficient prior power-flow solutions to cover the number of seconds, minutes, or hours for which the window length is specified.
  - Note: At time 0 in the simulation, there are no power-flow solution voltages and, therefore, the rolling average window length value is 0.0.
  - Prior to the initial filling of the rolling average window buffer with a full set of voltages (i.e., voltages covering power-flow simulation time equal to the avgwindowlen parameter value), we calculate an average voltage using the set of voltage samples in the buffer.
  - The rolling average window discards the oldest set of voltages (across all PVSystem objects under control of this InvControl object), as simulation time progresses, filling in the empty ‘slot’ with the most recent set of terminal voltages.
- Optional/Required: Optional.
- Default value: 1s.
- Possible values: an integer (whole number), greater than 0, followed by a specifier of second (s), minute (m), or hour (h); as in 1s (one second), 5m (five minutes), 3h (three hours).

- Parameter: **VarChangeTolerance**

- Description: This value is the difference between the desired target vars (in per unit) of the PVSystem and the present reactive power output (in per unit), as an absolute value (without sign). This reactive power tolerance per-unit value plus the voltage tolerance value (VoltageChangeTolerance) determine, together, when to stop control iterations by the InvControl. If an InvControl is controlling more than one PVSystem, each PVSystem has this quantity calculated independently, and so individual PVSystems may reach the tolerance within different numbers of control iterations.
- Optional/Required: Optional.
- Default value: 0.025 (per-unit).
- Possible values: Positive numerical values.

- Parameter: **VoltageChangeTolerance**

- Description: This is the change in voltage from one control iteration solution to the next that is one determining parameter to stop additional control iterations. This is the difference between the present per-unit voltage at the terminals of the PVSystem and the prior control iteration PVSystem terminal voltage(s) (in per-unit), as an absolute value (without sign). This voltage tolerance value plus the var tolerance value (VarChangeTolerance) determine, together, when to stop control iterations by the InvControl. If an InvControl is controlling more than one PVSystem, each PVSystem has this quantity calculated independently, and so individual PVSystems may reach the tolerance within different numbers of control iterations.
- Optional/Required: Optional.
- Default value: 0.0001 (per-unit voltage).
- Possible values: Positive numerical values.

- Parameter: **deltaQ\_factor**

- Description: Used in the VOLTVAR and DYNAMICREACCURR modes. This parameter sets the maximum change (in per unit of the y-axis of the volt-var curve or y-axis of the DRC mode) from the prior reactive power output level to the desired reactive power output level during each control iteration.

If numerical instability is noticed in solutions such as the reactive power sign changing from one control iteration to the next and/or voltages oscillating between two values with some separation, this is an indication of numerical instability (use the EventLog to diagnose).

If the maximum control iterations are exceeded, and no numerical instability is seen in the EventLog or via monitors, then try increasing the value of this parameter to reduce the number of control iterations needed to achieve the control criteria, and move on to the power flow solution.

- Optional/Required: Optional.
- Default value: 0.7 (70% change to desired reactive power per control iteration).
- Possible values: Positive numerical values. It is generally best not to set deltaQ\_factor lower than 0.2, so that there is enough change in voltage and reactive power to continue control iterations to achieve the desired reactive power level based on the volt-var curve and the voltage and the available headroom.

- **Parameter: VV\_RefReactivePower**

- Description: A parameter that defines the reference for the y-axis for the volt-var curve and any other function that has the capability to directly change reactive power injection/absorption. Also determines precedence of active or reactive power when other limits are reached.
- There are three possible values:
  - The first (and default value), VARAVAL\_WATTS, defines the y-axis of the volt-var curve and the y-axis any other function that changes reactive power to be in units of per-unit of available reactive power. See **Equation 3-1** for a definition of available reactive power. If the volt-var function requests more reactive power than is available (due to terminal voltage and the volt-var curve and the inverter kva limit), then reactive power (vars), will be reduced until the combination of active and reactive power does not exceed the inverter kva limit.
  - The next, VARMAX\_VARS, defines the y-axis of the volt-var curve and the y-axis for any other function that changes reactive power to be in units of per-unit of the value of kvarLimit set on each PVSystem. Since each PVSystem can have an individual kvarLimit, the y-axis changes for each PVSystem under control of the InvControl. If the volt-var function requests more reactive power than is available (due to terminal voltage and the volt-var curve and the inverter kva limit), then active power (watts), will be reduced until the requested reactive power is achieved.
  - The last, VARMAX\_WATTS, defines the y-axis of the volt-var curve and the y-axis for any other function that changes reactive power to be in units of per-unit of the value of kvarLimit set on each PVSystem. Since each PVSystem can have an individual kvarLimit, the y-axis changes for each PVSystem under control of the InvControl. If the volt-var function requests more reactive power than is available (due to terminal voltage and the volt-var curve and the inverter kva limit), then reactive power (vars), will be reduced until the combination of active and reactive power does not exceed the inverter kva limit.
- Optional/Required: Optional.
- Default value: VARAVAL\_WATTS.
- Possible values: VARAVAL\_WATTS|VARMAX\_VARS|VARMAX\_WATTS.

- **Parameter: RateofChangeMode**

- Description: A parameter that adds rate-of-change limiting functionality to the VOLTVAR control mode. Two types of rate-of-change limit functions are available to the user: (1) rise/fall rate-of-change limit, (2) low-pass filter rate-of-change limit. The rise/fall rate-of-change limit keeps the change in reactive power within plus or minus 'x' per-unit reactive power (units depend on

VV\_RefReactivePower setting) per second. The low-pass filter implements a simple RC filter in the discrete time-domain and the user can set the low-pass filter time constant in seconds. The low-pass filter time constant is defined such that it mimics a simple RC filter with time constant equal to tau.

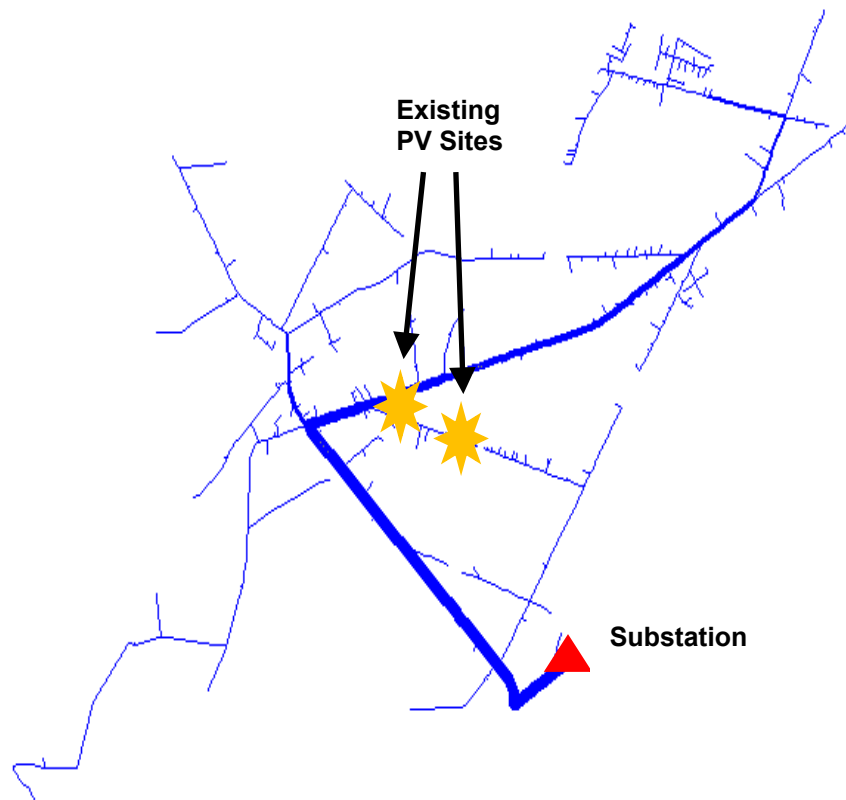
- Optional/Required: Optional.
- Default value: INACTIVE.
- Possible values: INACTIVE|LPF | RISEFALL.
- **Parameter: LPFtau**
  - Description: The tau time constant for the discrete-time implementation of a low-pass filter such that it mimics a simple RC filter with time constant equal to tau.
  - Optional/Required: Optional.
  - Default value: 0.001.
  - Possible values: Positive numerical values.
- **Parameter: RiseFallLimit**
  - Description: The rate-of-change limit defined in terms of change in per-unit available vars output per second in both the inductive and capacitive direction.
  - Optional/Required: Optional.
  - Default value: 0.001.
  - Possible values: Positive numerical values.
- **Parameter: EventLog**
  - Description: A flag that determines whether or not entries are added to the Event log for actions taken by the InvControl device.
  - Optional/Required: Optional.
  - Default value: Yes.
  - Possible values: Yes/True | No/False.

### Sample Usage in OpenDSS

For purposes of illustrating the sample usage of an InvControl object, across all control modes, a radial distribution circuit that has four existing PV installations is used. The four existing PV installations are tied into the distribution system via two (2) interconnect transformers – 2 PV systems per interconnect transformer. The basic characteristics of the distribution circuit are outlined in **Table 3-1**. A one-line diagram of the 12.5 kV distribution circuit is shown in **Figure 3-3**.

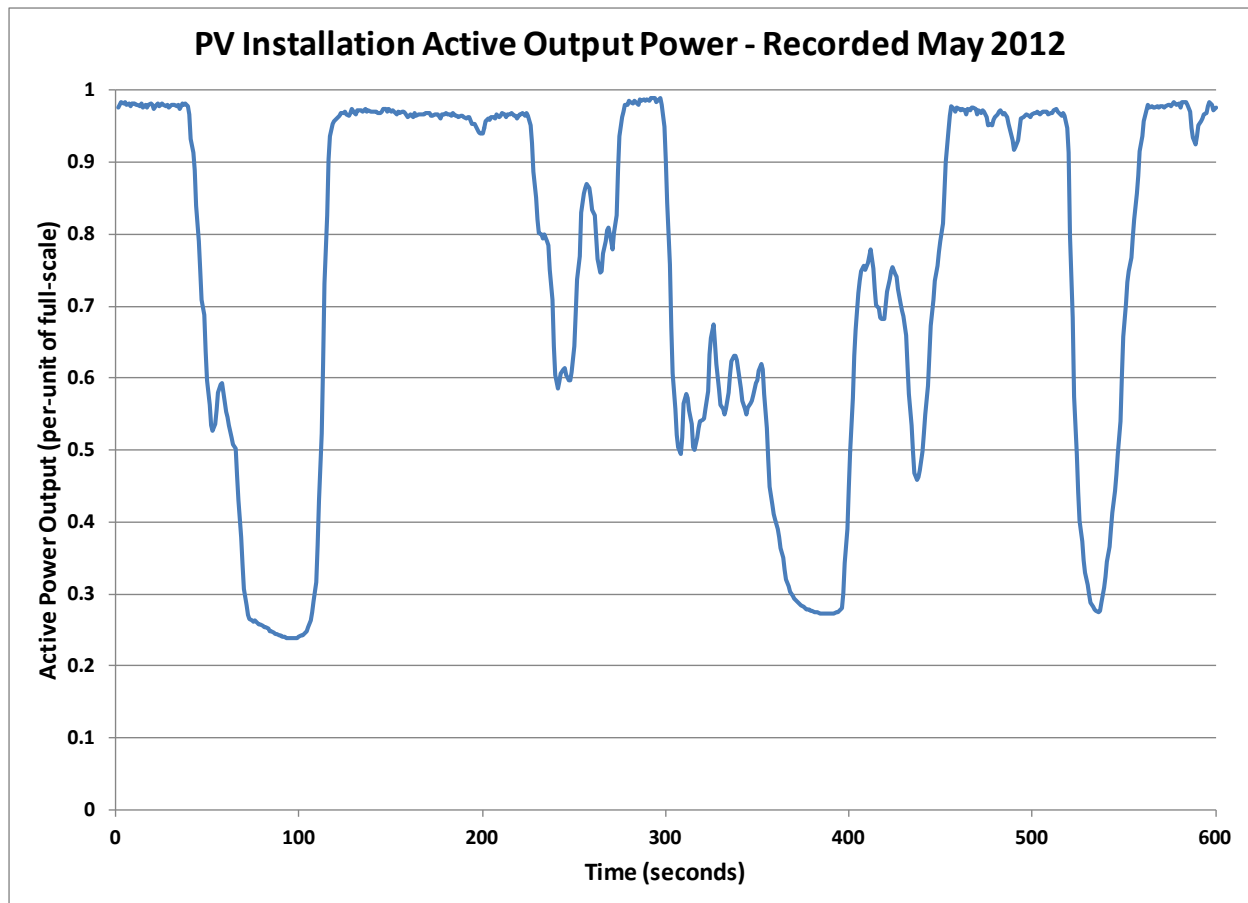
**Table 3-1**  
**Distribution Circuit Characteristics used for Illustrating Inverter Control Functionality**

Feeder Characteristics	
Voltage (kV)	12.47
Peak Load	~ 6 MW
Minimum Load	0.7 MW
Existing PV	1.7 MW
Substation LTC	Yes
Feeder Regulators	3
Capacitors	2 – fixed 3 – voltage controlled
Total Circuit Miles	58
Feeder “Footprint”	35 mi <sup>2</sup>



**Figure 3-3**  
**Distribution Circuit Showing Locations of Existing PV Installations**

For the purposes here, a ten-minute window of AC output power collected at one of the four PV installations on this circuit is used, across all four PV (i.e., identical solar output is applied to each of the four PV so that they are operating together). The AC output power, which corresponds to irradiance data collected in May of 2012 on this circuit, on a partly cloudy day, is shown in per-unit of full-scale active output power in **Figure 3-4**.



**Figure 3-4**  
Active Power Output Recorded at an Existing PV Installation in May 2012 on the Distribution Circuit

To establish a base-line of the response that one would expect from a PV installation with ‘off-the-shelf’ settings (including the power factor set at unity), four PVSystem objects are defined in the following OpenDSS script to represent the four PV installations on this circuit.

```
New PVSystem.3P_ExistingSite4 phases=3 bus1=B51854_sec kV=0.4157 kVA=523
~ irradiance=1 Pmpp=475 pf=1 %cutin=0.1 %cutout=0.1 yearly=PV_ls

New PVSystem.3P_ExistingSite1 phases=3 bus1=X_5865228330A kV=0.4157 kVA=314
~ irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1 yearly=PV_ls

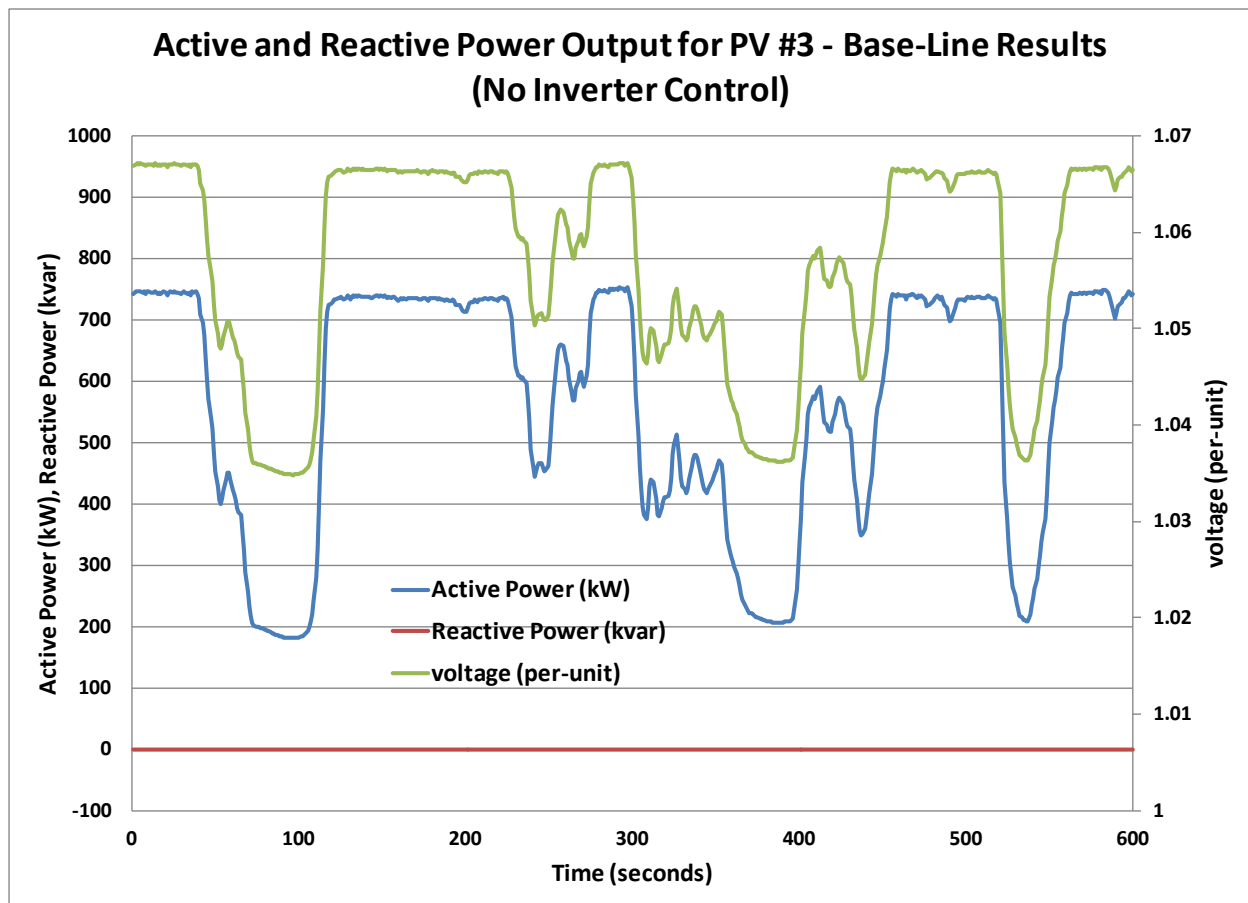
New PVSystem.3P_ExistingSite3 phases=3 bus1=X_5891328219_Cust1 kV=0.4157
~ kVA=836 irradiance=1 Pmpp=760 pf=1 %cutin=0.1 %cutout=0.1 yearly=PV_ls

New PVSystem.3P_ExistingSite2 phases=3 bus1=B4832_sec kV=0.4157 kVA=209
~ irradiance=1 Pmpp=190 pf=1 %cutin=0.1 %cutout=0.1 yearly=PV_ls
```



Next, the 600 seconds of simulation time are run, at a time period when the loading on the circuit is relatively light. The power output and terminal voltage (average of three phases) is shown in **Figure 3-5**. All quantities throughout this report will be reported at the terminals of the PV #3. PV #3 is located at the end of a length of secondary cable and the rated voltage is 240V (line-neutral).

Voltages will be shown in per-unit values on a 240V base. Active power will be shown with a positive sign if delivering power to the grid. Similarly, for reactive power, a positive value will indicate supplying reactive power to the grid (capacitive vars) and a negative value will indicate absorbing reactive power from the grid (inductive vars). Again, all quantities reported will be at the terminals of PV #3 throughout this report.



**Figure 3-5**  
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating without any Inverter Control

### ***Volt-Var Control***

#### **Implementation in OpenDSS Script**

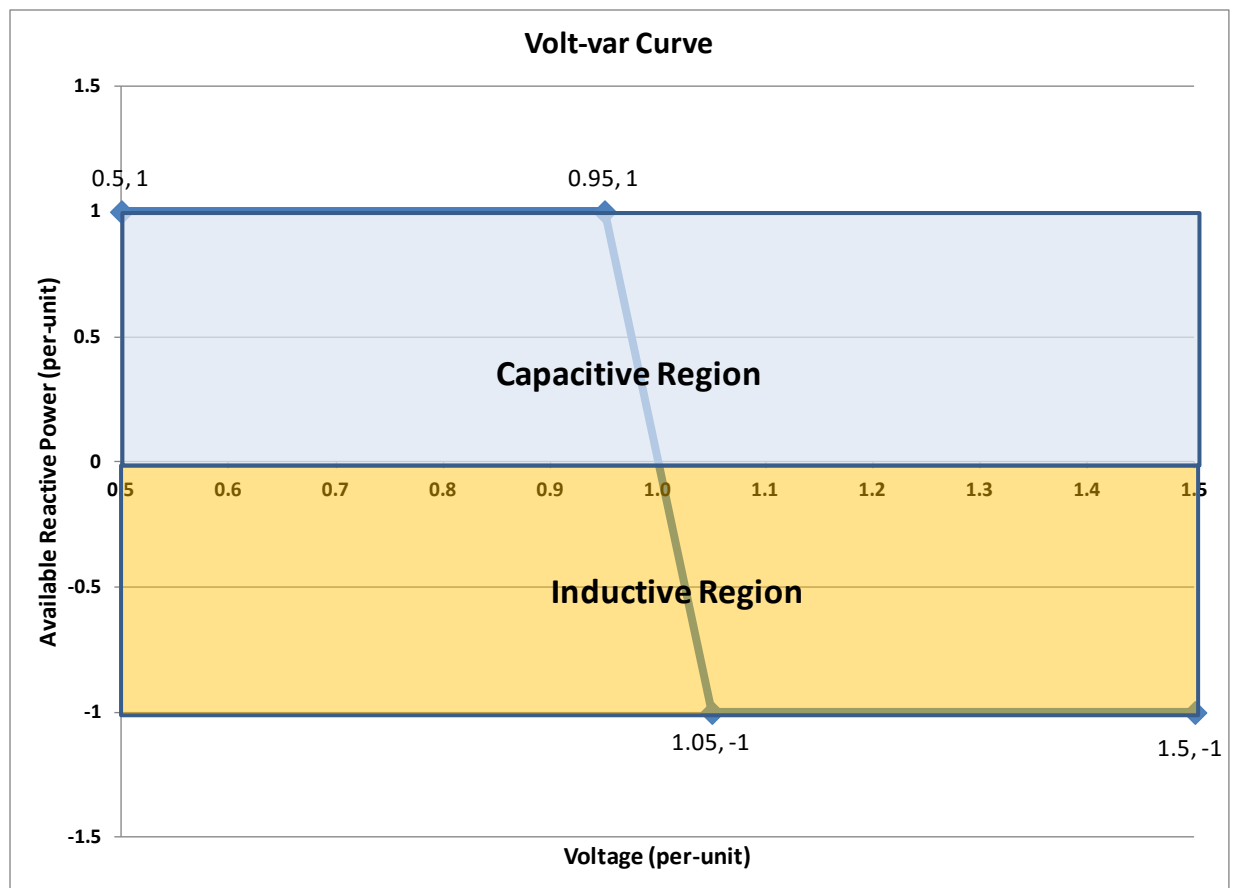
As indicated earlier, the user should define a volt-var curve, first, followed by the InvControl model definition. This is shown in script as follows.

```
New XYCurve.vv_curve npts=4 Yarray=(1.0,1.0,-1.0,-1.0)
~ XArray=(0.5,0.95,1.05,1.5)
```

```
New InvControl.InvPVCtrl mode=VOLTVAR voltage_curve_x_ref=rated
~ vvc_curve1=vv_curve EventLog=yes
```

The first line defines an XYCurve object called *vv\_curve* that consists of a per-unit voltage ('x' value) and a per-unit available reactive power ('y' value) for each of the four points. This curve is shown in **Figure 3-6** with the capacitive and inductive reactive power regions indicated.

The second line of OpenDSS script defines the inverter control. No PV systems are listed by name, so by default, all PV in the circuit will be under the control of this InvControl object. The mode is explicitly set to VOLTVAR control mode. The x-values are set to be defined in per unit of the rated voltage of the PVSystem object, which is 240V in this case (line-neutral). The volt-var curve to be utilized is the one named *vv\_curve*. Lastly, entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.



**Figure 3-6**  
**Volt-var Curve Utilized for Illustrating Operation of Basic Volt-var Control Mode**

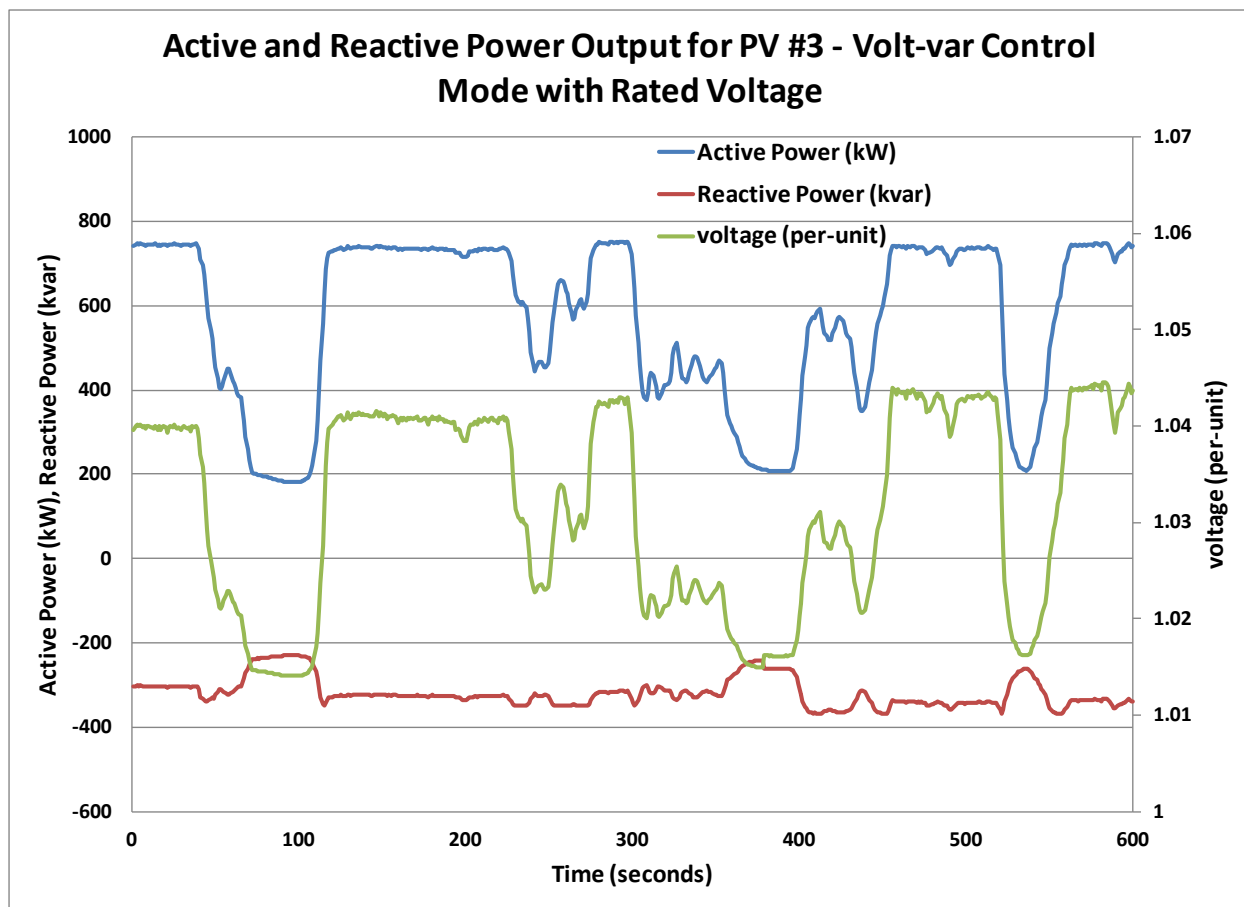
### Illustration of Operation

Continuing with the same active power input curve, applied to all 4 PV systems in the circuit, the simulation progresses for 600 seconds with volt-var control in operation. The terminal voltage

and output powers are shown in **Figure 3-7**. The terminal voltage utilizes the right-hand y-axis for its range of values.

Based on the volt-var curve and the maximum voltage has been reduced from almost 1.07 pu down to about 1.045 pu by absorption of vars from the grid following the volt-var curve and control algorithm.

The absorption of vars (inductive vars) is shown in the red line in the second figure, and varies according to the terminal voltage value. During times when the voltage had previously been above 1.05 pu, the inverter control directed the PV systems to perform the maximum absorption of vars, based on the available ‘head-room’ given the active power output and nominal kva ratings of the PV systems.

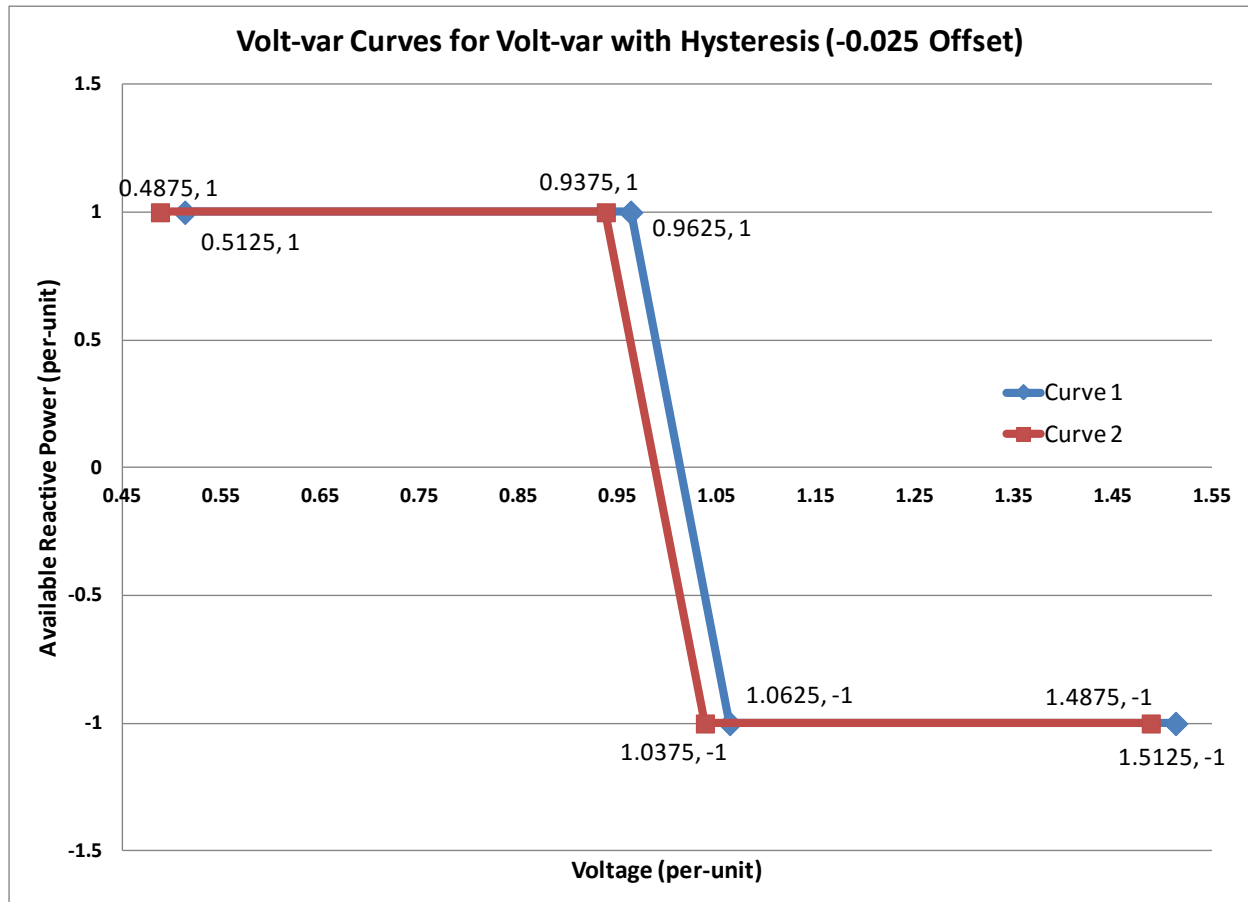


**Figure 3-7**  
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-var Control Mode without Hysteresis

### ***Volt-Var Control with Hysteresis***

Utilizing hysteresis requires the user to define a hysteresis offset value in per-unit voltage for which an XYCurve will be generated with the appropriate offset from the user-defined XYCurve for vvc\_curve1. The second XYCurve has the same shape as the vvc\_curve1, and is offset along the x-axis by the user chosen offset value. The second curve is not accessible for editing by the user, and so is only internal to the OpenDSS application.

For the example here, a hysteresis offset of -0.025 pu voltage is defined. In order to preserve symmetry around the 1.0 pu voltage value, the number one curve is shifted to the right (along the x-axis) by one-half of the hysteresis offset value. Graphically, the two curves appear as shown in **Figure 3-8**.



**Figure 3-8**  
**Volt-var Curves Utilized for Illustrating Operation of Volt-var Control Mode with Hysteresis**

### Implementation in OpenDSS Script

```
New XYCurve.vv_curve npts=4 Yarray=(1.0,1.0,-1.0,-1.0)
~ XArray=(0.5125,0.9625,1.0625,1.5125)
```

```
New InvControl.InvPVCtrl mode=VOLTVAR voltage_curve_ref=rated
~ vvc_curve1=vv_curve hysteresis_offset=-0.025 EventLog=yes
```

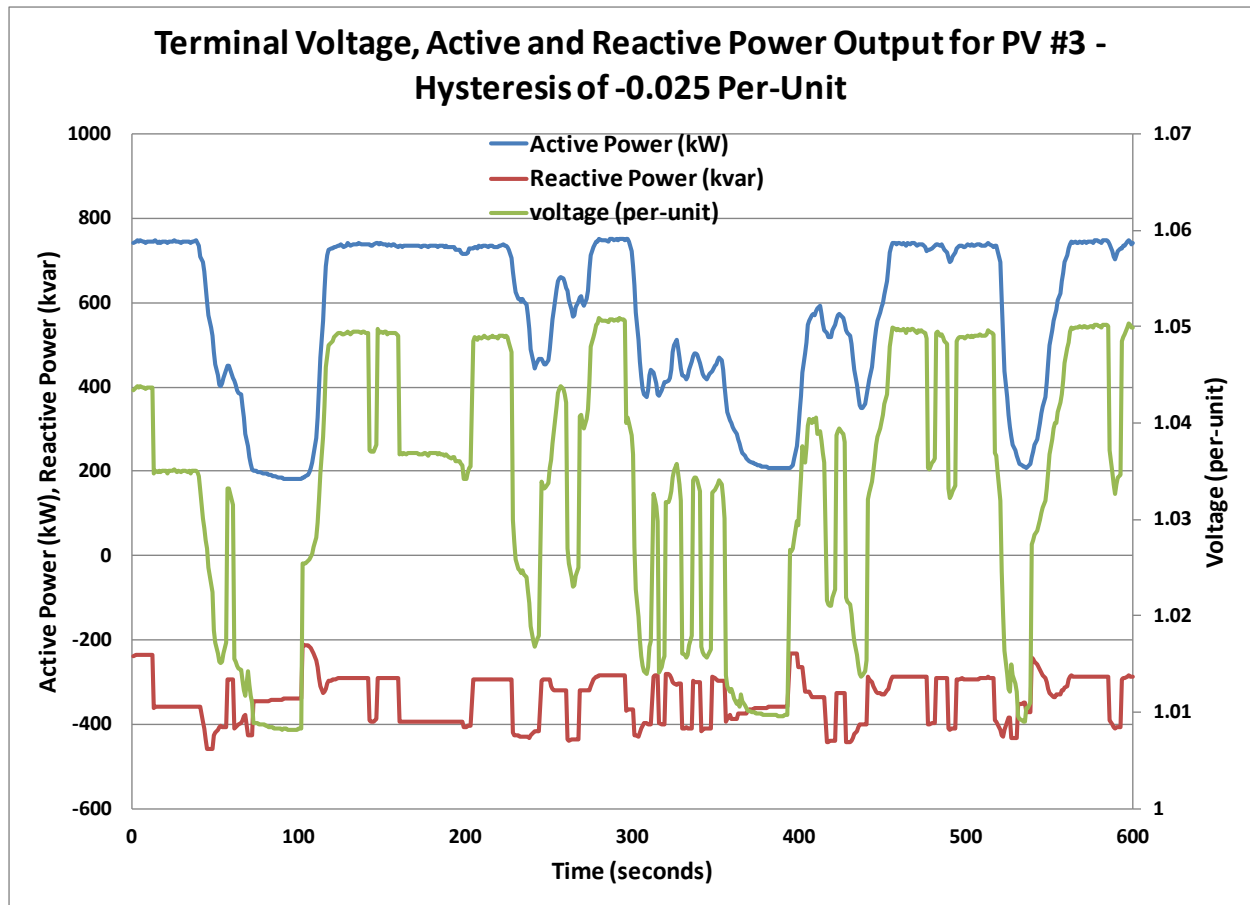
The first line defines an XYCurve object called vv\_curve that consists of a per-unit voltage ('x' value) and a per-unit available reactive power ('y' value) for each of the four points. This curve is shown in **Figure 3-8** with the blue lines.

The second line of OpenDSS script defines the inverter control. No PVSystem objects are listed by name, so by default, all PV in the circuit will be under the control of this InvControl object. The mode is explicitly set to VOLTVAR control mode. The x-values are set to be defined in per unit of the rated voltage of the PVSystem, which is 240V in this case (line-neutral). The volt-var curve to be utilized is the one named vv\_curve. A hysteresis offset of -0.025 is specified, so, internally, a second volt-var curve is generated (as shown with the red lines in **Figure 3-8**) and utilized. Lastly, entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.

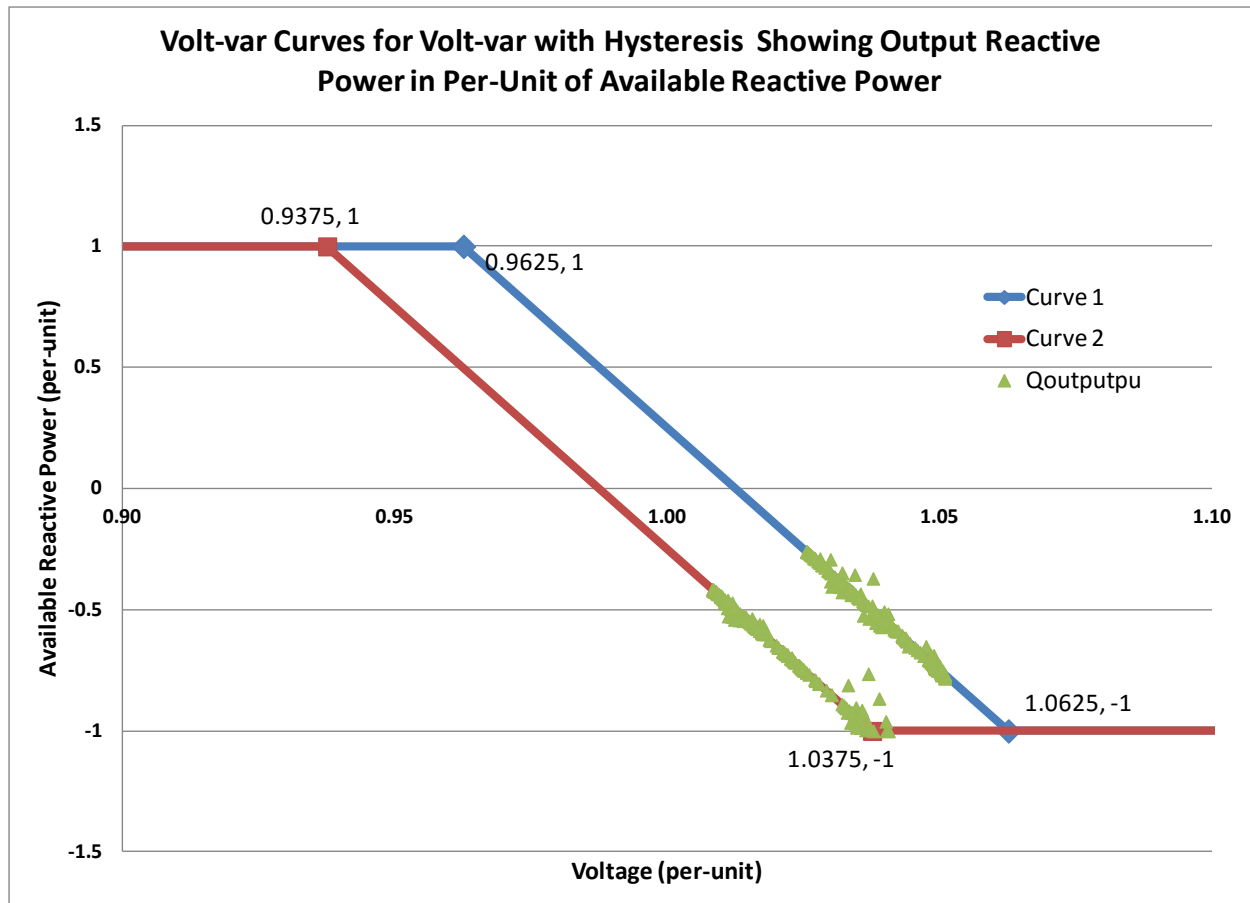
### Illustration of Operation

The terminal voltage and output powers are shown in **Figure 3-9**. The terminal voltage utilizes the right-hand y-axis for its range of values.

To see the effects of the hysteresis function, the output reactive power (in per unit of available vars) is plotted as a function of voltage, against the two volt-var curves **Figure 3-9**. One can see that when the terminal voltage is at one or the other of two curves, it follows that curve for determining the reactive power output level. However, when the power-flow solution's terminal voltages are in between the curves, the reactive power output level stays constant (in per unit of available vars) until such time as the voltage reaches one or the other curves.



**Figure 3-9**  
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-var Control Mode with Hysteresis Offset of -0.025 Per-Unit Voltage



**Figure 3-10**  
**Reactive Power Output in Per unit of Available Vars and the Two Volt-var Curves Utilized for Illustrating Operation of Volt-var Control Mode with Hysteresis**

### ***Volt-var Control with Adaptive Setpoint***

#### **Implementation in OpenDSS Script**

Utilizing volt-var control mode with an adaptive set-point requires setting the rolling average window length. This is shown in script as follows.

```
New XYCurve.vv_curve npts=4 Yarray=(1.0,1.0,-1.0,-1.0)
~ XArray=(0.5,0.95,1.05,1.5)
```

```
New InvControl.InvPVCtrl mode=VOLTVAR voltage_curvex_ref=avg avgwindowlen=2m
~ vvc_curve1=vv_curve EventLog=yes
```

The first line defines an XYCurve object called *vv\_curve* that consists of a per-unit voltage ('x' value) and a per-unit available reactive power ('y' value) for each of the four points.

The second line, beginning with the 'New' keyword of the OpenDSS script defines the inverter control. No PV systems are listed by name, so by default, all PV in the circuit will be under the control of this InvControl object. The mode is explicitly set to VOLTVAR control mode. The x-values are set to be defined in per unit of the average voltage of the PVSystem object. This indicates that a rolling average window will be used to provide an adaptive voltage set-point. The

length of the window is defined as two minutes, so a rolling average window, containing up to 120 seconds of power flow solution terminal voltages will be continually updated. For the first 119 seconds, the rolling average window will not be full, but the average of the terminal samples in the buffer will be calculated. The volt-var curve to be utilized is the one named `vv_curve`. Lastly, entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.

### Illustration of Operation

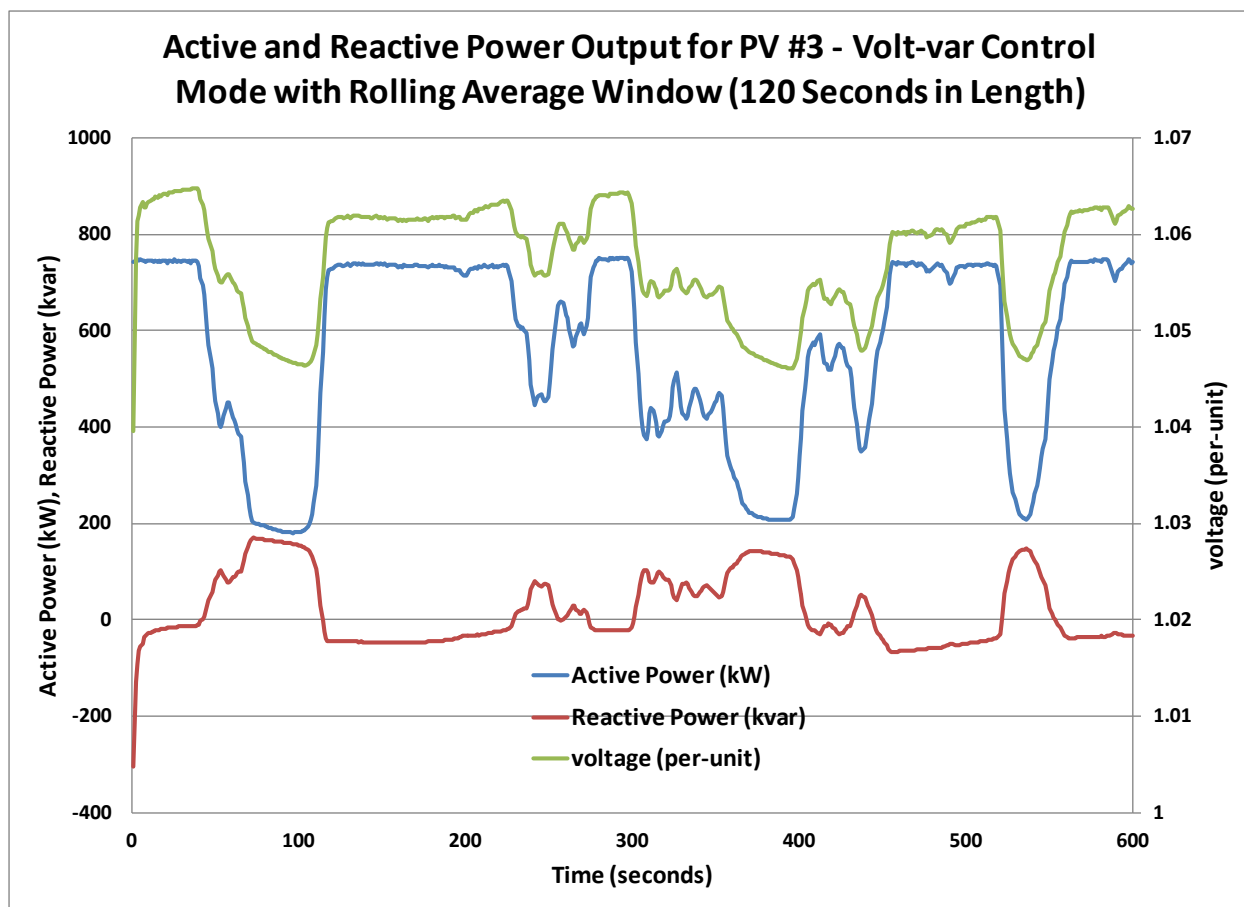
The terminal voltage and output powers are shown in **Figure 3-11**. The terminal voltage utilizes the right-hand y-axis for its range of values.

The effects of the rolling average window are evident in the var output that is dispatched **Figure 3-11**. Rather than the volt-var curve having its 1.0 pu voltage, and corresponding 0.0 pu available var output being at 240V (rated voltage of the PVSystem), the 1.0 pu voltage point is defined by taking the average of the terminal voltages and dividing by the rolling average window value, at each step during the simulation.

Some start-up delay is evident near 0 seconds on the x-axis of the figure, as the rolling average window initially has a value 0 because no power flow solutions have been performed. As the simulation progresses, the rolling average tracks the ‘normal’ voltage at the terminals of the Number 3 PV. Since its ‘normal’ voltage is near 1.06 pu over most of the simulation, the var dispatch is generally in the direction of sending reactive power to the grid (capacitive vars) even when the voltage is above 1.05 pu.

When the active power output of the Number 3 PV system increases, the dispatch of reactive power reverses direction in order to absorb vars from the grid (appearing inductive to the grid) to maintain near 1.06 pu output, rather than allowing the voltage to increase further.





**Figure 3-11**

**Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-Var Control Mode with Rolling Average Window with Length of 120 seconds**

So the adaptive set-point attempts to follow the average terminal voltage over time. If the simulation had been performed on a system with conservation voltage reduction (CVR) in effect, one would see that the reactive power dispatch would follow slowly (depending on the window length), the voltage set-point on the circuit as reflected in the terminal voltage at the PV systems. This adaptive voltage set-point is useful to adjust the output of the PV systems to follow, rather than ‘buck’ or ‘boost’ against slow, normal, system voltage variations due to regulator and/or load action.

### ***Volt-var Control with Y-Axis Reference Changed to Per-Unit of PVSystem kvarLimit***

#### **Implementation in OpenDSS Script**

The following scripts show how to utilize the y-axis reference in the InvControl for the volt-var control function in conjunction with the kvarLimit property of each of the PVSystems under its’ control.

First, the kvarLimit, in units of kvar (see help for PVSystem), is defined for each of the PVSystems in the circuit.

```

New PVSystem.3P_ExistingSite4 phases=3 bus1=B51854_sec kV=0.4157 kVA=523
~ irradiance=1 Pmpp=475 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=215
~ early=PV_ls

New PVSystem.3P_ExistingSite1 phases=3 bus1=X_5865228330A kV=0.4157 kVA=314
~ irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=130
~ yearly=PV_ls

New PVSystem.3P_ExistingSite3 phases=3 bus1=X_5891328219_Cust1 kV=0.4157
~ kVA=836 irradiance=1 Pmpp=760 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=345
~ yearly=PV_ls

New PVSystem.3P_ExistingSite2 phases=3 bus1=B4832_sec kV=0.4157 kVA=209
~ irradiance=1 Pmpp=190 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=85 yearly=PV_ls

New XYCurve.vv_curve npts=4 Yarray=(1.0,1.0,-1.0,-1.0)
~ XArray=(0.5,0.95,1.05,1.5)

New InvControl.InvPVCtrl mode=VOLTVAR voltage_curve_ref=rated
~ vvc_curve1=vv_curve VV_RefReactivePower=VARMAX_WATTS EventLog=yes

```

The first four lines show the definitions of the PVSystems. The only difference is that the kvarLimit (in kvar) has been added to each definition.

The fifth line defines an XYCurve object called `vv_curve` that consists of a per-unit voltage ('x' value) and a per-unit reactive power value ('y' value) for each of the four points.

The sixth line, beginning with the 'New' keyword of the OpenDSS script defines the inverter control. No PV systems are listed by name, so by default, all PV in the circuit will be under the control of this InvControl object. The mode is explicitly set to VOLTVAR control mode. The x-values, are defined in per unit of the rated voltage of the PVSystem object. The volt-var curve to be utilized is the one named `vv_curve`.

The `VV_RefReactivePower` parameter is set to `VARMAX_WATTS`. This setting means that the y-axis values of the volt-var curve are understood to be in per-unit of the kvarLimit for each PVSystem (independently). For instance, for the Existing Site 1, the units for the y-axis of the volt-var curve are in per-unit of 130 kvar. Similarly, for the Existing Site 2, the units for the y-axis are in per-unit of 85 kvar.

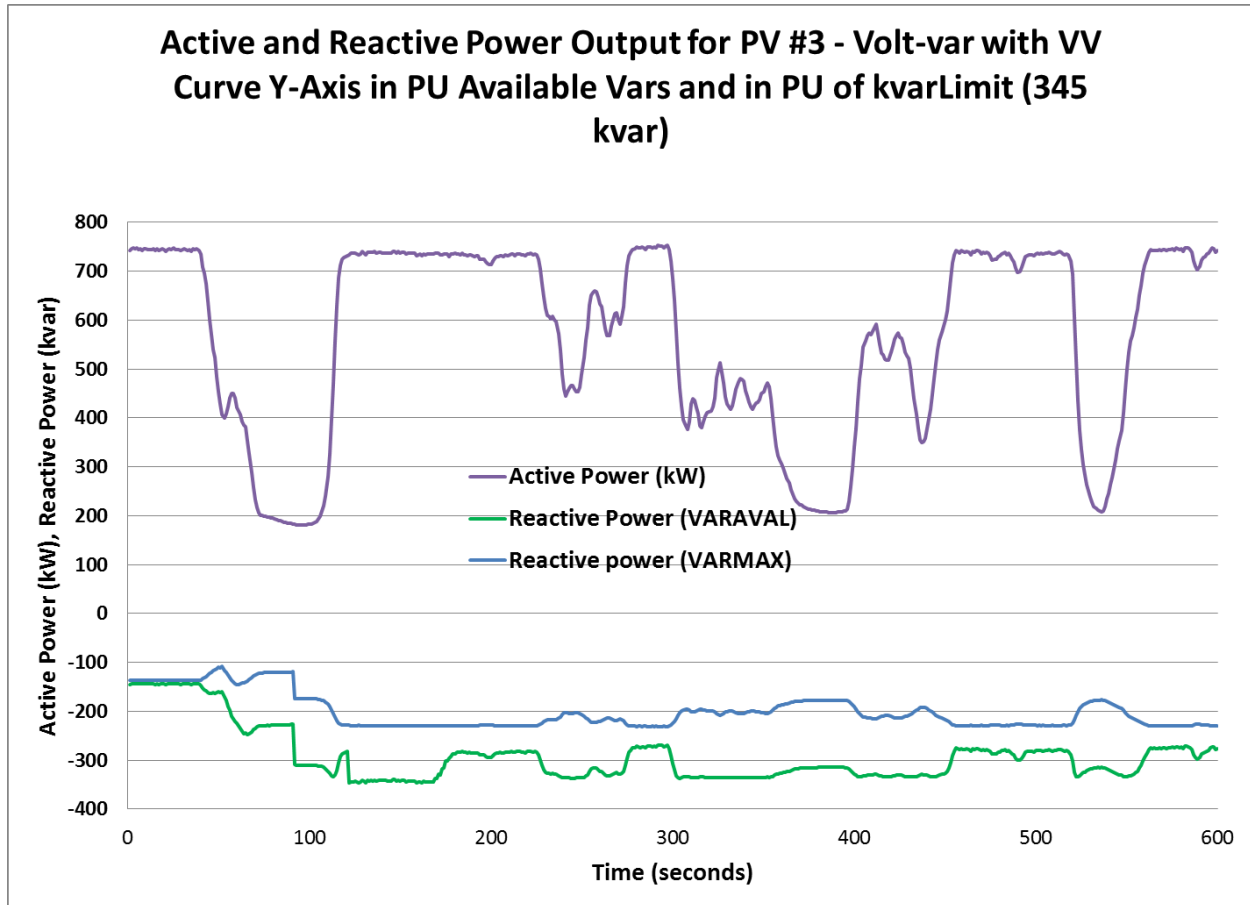
The "`_WATTS`" portion of the `VV_RefReactivePower` parameter indicates that active power has precedence over reactive power. This means that if the combination of active and reactive power exceeds the kVA rating of the PVSystem, the reactive power absorption/injection will be reduced such that the kVA rating of the PVSystem is not exceeded. Active power injection will not be reduced.

Lastly, entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.

## Illustration of Operation

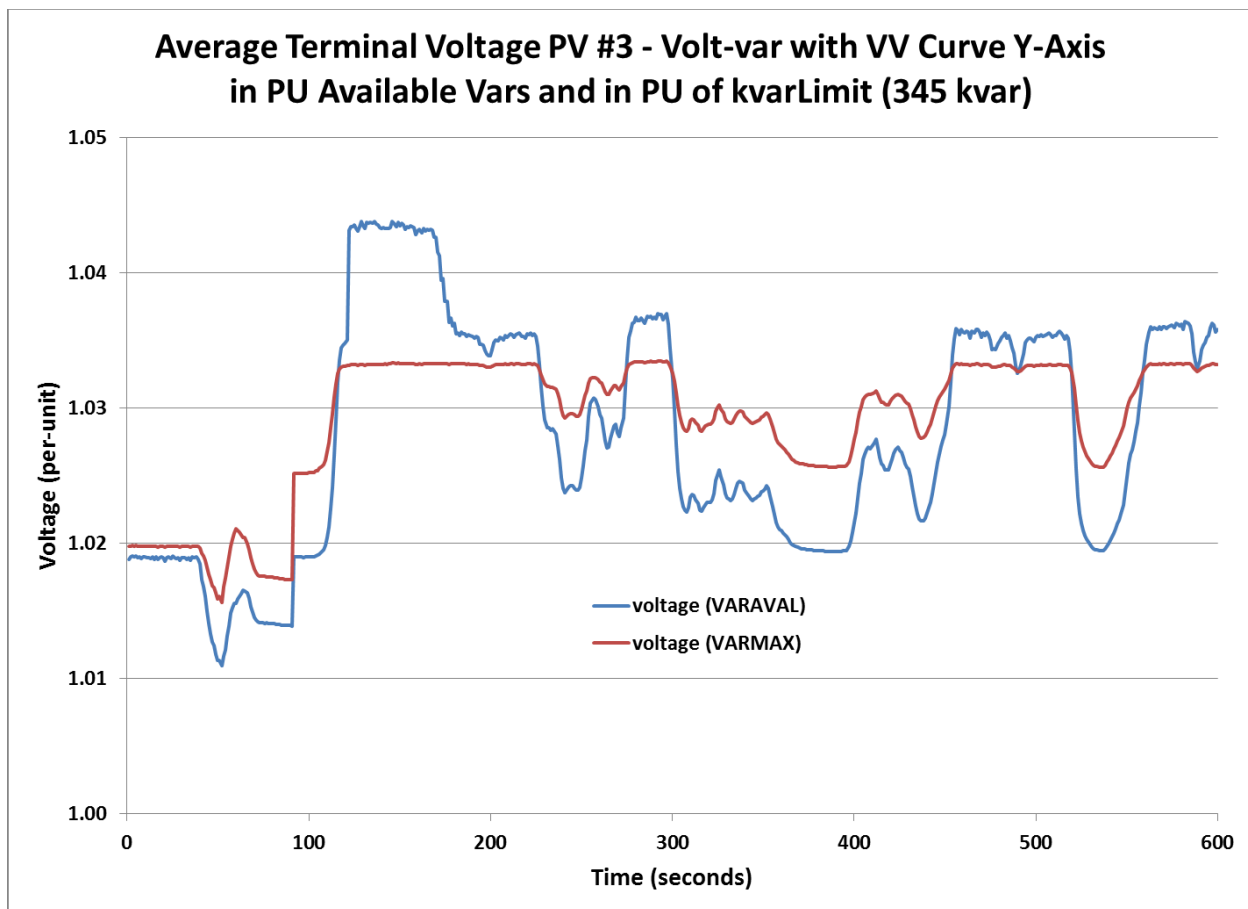
The reactive power output (in kvar) from a simulation with VOLTVAR mode operation with the y-axis of the volt-var curve in per-unit of available vars (VARAVAL\_WATTS) is shown with the green curve. The results from the same simulation, but with the y-axis of the volt-var curve in per-unit of the kvarLimit of the PVSystem (VARMAX\_WATTS) for PV#3 is shown in the blue curve. The purple curve shows the active power in kW.

The following figure shows the voltages resulting from the two y-axis settings (independently) at the terminals of PV #3.



**Figure 3-12**

**Active and Reactive Power Output for PV Number 3, Results when Operating under Normal Volt-Var Control Mode, y-axis on volt-var curve changed between available reactive power and the kvar limit.**



**Figure 3-13**  
Voltages for PV Number 3, Results when Operating under Normal Volt-Var Control Mode, y-axis on volt-var curve changed between available reactive power and the kvar limit.

# 4

## VOLT-WATT FUNCTION

### Function Scope

This function is intended to provide a flexible mechanism through which a general volt-watt function could be configured. The user may define a set of voltage-active power (x,y) points that define the output of active power under various terminal voltage values (see **Figure 4-1**). The volt-watt function only adjusts the output of active power, it does not adjust reactive power output actively.

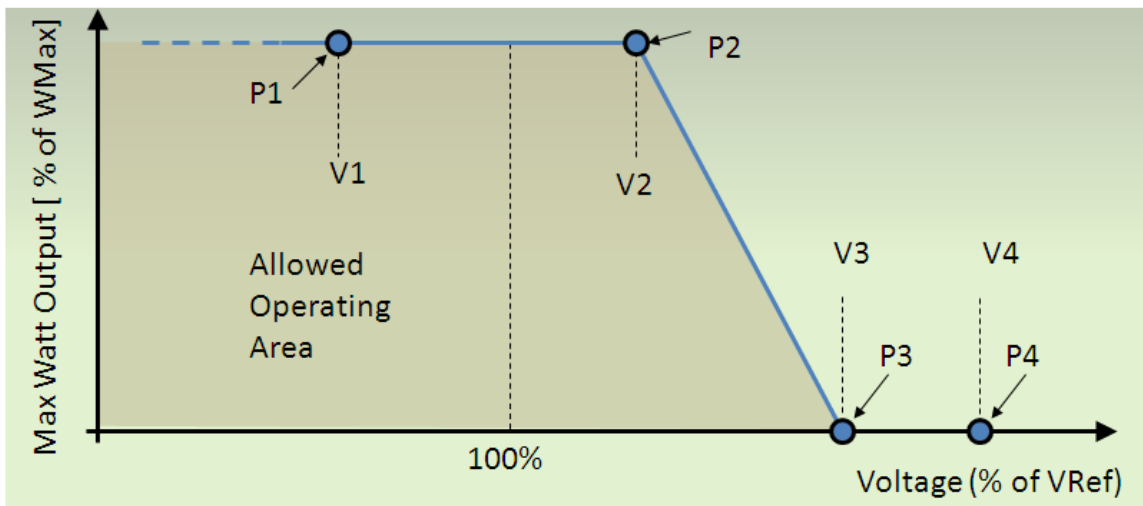


Figure 4-1  
Example Volt-watt curve

### Function Application

As indicated in report [4], a couple of applications are listed here:

- **High Penetration at the Distribution Level, Driving Feeder Voltage Too High.** Under circumstances where high PV output and low load is causing feeder voltage to rise too high at certain times, the volt-watt functionality might be utilized to reduce active power output levels on a PV system by PV system basis. This might especially be needed where existing distribution controls are not able to prevent the occurrence of these high voltages.
- **Localized High Service Voltage.** Under circumstances where a large number of customers served by the same distribution transformer have PV, local service voltage may rise too high. This may result is certain PV inverters that do not turn on at all. Therefore, reducing active power output by PV systems via a volt-watt function may allow more of the PV to ‘share’ the load on the distribution transformer.

## Model Requirements

- PVSystem (one or more)
- XYcurve (one per inverter control)

### **PVSystem**

Utilizing the inverter control in volt-watt control mode the user should first define one or more PVSystem objects that will be controlled by the InvControl device.

The PVSystem object(s), which represent an entire PV system including PV panel(s)/array plus the inverter, should have their full-scale kVA rating and Pmpp defined. Pmpp is the rated maximum power of the PV array for 1.0 kW/sq-m irradiance and a user-selected array temperature. The power factor should be set to unity for the PVSystem object. Other settings that would be helpful to be defined are the cut-out (switch the inverter off) kVA level and the cut-in (switch the inverter on) kVA level to define the power levels below and above which the inverter switches off or on.

### **XYCurve**

In addition to the PVSystem model, the volt-watt function requires the user to define one or more XYCurve objects. There should be one XYcurve instance per InvControl device instance. The XYCurve object defines the output active power as a function of the terminal voltage at the PVSystem object.

The y-axis units for the XYCurve can vary (see settings below), unlike that which is indicated in **Figure 4-1**. The reason for the change from the specification is as follows.

It is assumed that the terminal voltage at a PV system is due to two components: (1) system voltage, as reflected through the interconnect transformer with some drop due to the transformer's impedance plus any drop due to the secondary conductors between the transformer secondary terminals and the PV system; and (2) the active power output of the PV.

The terminal voltages, given the impedance characteristics are highly dependent on the active and reactive power output (or absorption, in the case of reactive power) of the PV system at any moment in time. If the voltage is at a higher than normal level, we cannot control, using the inverter control, the system voltage component, but we can control the active and reactive power output levels.

Given that the active power output level varies throughout the day as a function of (principally) irradiance on the PV panels, it seems that to provide finer control over the portion of the voltage rise due to active power output, we should define the y-axis in terms of present active power output.

For instance, if the y-axis point is set at 1.1 pu voltage at a level of, say, 80% of rated maximum active power (0.8 pu), and the PVSystem is already below that level in actual active power output, the PVSystem object(s) under the control of the inverter control in VOLTWATT mode will not reduce active power output to try to bring the voltage nearer to a reasonable voltage level of, say, 1.05 pu. The inverter will not cause a change in active power output that may be useful to mitigate high voltages at the terminals of the PV system. As mentioned previously, this is a deviation from the existing function definition in the reference document [4], however future

implementations will allow for the output scaling to be based upon actual PV system output at the given time.

The possible values for the y-axis are from 1.0 pu, which indicates that the PVSystem object will maintain the full (present) active power output level based on the irradiance level, to 0.0 pu, which indicates no active power output to the grid. Values in between 1.0 pu and 0.0 pu can also be used. For instance, a value of 0.4 pu would signify limiting the output to a level of 40% of the present irradiance level, taking into account any losses in the PVSystem model.

For the x-axis, the units are in per unit of the terminal voltage of the PVSystem object. However, the quantity to convert from volts to per-unit voltage can be set by the user. The default setting is to use the rated voltage of the PVSystem object to ‘per-unitize’ the voltage. An alternate option is to use a rolling average window, of user-defined length, to convert the terminal voltage of the PVSystem object from volts to per-unit voltage.

For PVSystem objects having more than one phase, the terminal voltage is represented by the average of the ‘number of phases’ line-neutral voltages.

When entered separately, there should be an equal number of x-array points as y-array points to define the active power output as a function of the terminal voltage. Users may also define an XYCurve object using the Points property to define an array of x,y points.

## Model Input Parameters and Configuration Options

For an InvControl object, the following input parameters can be set and utilized by the user for operating the InvControl object to control one or more PVSystem objects under volt-watt control mode. The default value and whether the parameter is optional or required are indicated along with a description of each parameter and its’ usage.

- Parameter: **PVSystemList**
  - Description: A list of one or more PVSystem-object names (excluding the class specifier of PVSystem) that will be under the control of the present InvControl object.
  - Optional/Required: Optional.
  - Default value: Blank, empty list.
    - Note: If blank then all PVSystem objects in the circuit are brought under the control of the present InvControl object.
  - Possible Values: pvname1,pvname2,pvname3,...
- Parameter: **Mode**
  - Description: The control mode under which an InvControl object will control the PVSystem objects listed following the PVSystemList parameter, or all PVSystem objects in the circuit if PVSystemList is not specified.
    - Note: VOLTWATT control mode controls one or more PVSystem objects to follow a volt-watt curve and varies the active power output of the

individual PVSystem objects, independently from each other, according to a user-defined volt-watt curve that correlates terminal voltage with active power output (in per unit of present active power output).

- Optional/Required: Required for VOLTWATT control mode. If no value is specified, then VOLTVAR mode is assumed.
  - Default value: VOLTVAR.
  - Possible Values: VOLTVAR | VOLTWATT | DYNAMICREACCURR.
- Parameter: **voltwatt\_curve**
  - Description: The name of an XYCurve that defines the active power output level in terms of the terminal voltage(s) at each individual PVSystem object.
  - Optional/Required: Required for VOLTWATT control mode. Otherwise, not required.
  - Default value: None. Must be specified for VOLTWATT control mode.
  - Possible values: The name of a defined XYCurve object.
- Parameter: **voltage\_curvex\_ref**
  - Description: For VOLTWATT and VOLTVAR modes, defines the denominator that converts the terminal voltage into a per-unit value.
    - If 'rated' is specified as the value, or if no value is entered, the rated voltage of the PVSystem object(s) under the control of the InvControl object are used as the denominator.
    - If 'avg' is specified as the value for this parameter, a rolling average window voltage value is used as the denominator to convert the voltage into a per-unit value.
    - Information regarding the rolling average window is provided in the for the parameter 'avgwindowlen', which is listed next in this section.
  - Optional/Required: Optional.
  - Default value: rated.
  - Possible values: rated | avg.
- Parameter: **avgwindowlen**
  - Description: For the control modes VOLTWATT and VOLTVAR, this defines the length of the rolling average window in units of simulation time, which is utilized to convert voltages in units of volts to voltages in units of per-unit voltage.



- A rolling average window contains the voltages from each PVSystem object (independently) that is under the control of a given InvControl object for the most recent power-flow solution and sufficient prior power-flow solutions to cover the number of seconds, minutes, or hours for which the window length is specified.
  - Note: At time 0 in the simulation, there are no power-flow solution voltages and therefore the rolling average window length value is 0.0 for this time-frame.
  - Prior to the initial filling of the rolling average window buffer with a full set of voltages (i.e., voltages covering power-flow simulation time equal to the avgwindowlen parameter value), an average voltage is calculated using the set of voltage samples in the buffer.
  - The rolling average window discards the oldest set of voltages (across all PVSystem objects under control of this InvControl object), as simulation time progresses, filling in the empty 'slot' with the most recent set of terminal voltages.
- Optional/Required: Optional.
- Default value: 1s.
- Possible values: an integer (whole number), greater than zero, followed by a specifier of second (s), minute (m), or hour (h); as in 1s (one second), 5m (five minutes), 3h (three hours).
- **Parameter: VoltwattYAxis**
  - Description: A flag that determines the units used for the y-axis of the volt-watt curve. If set to PMPPPU then the y-axis units for the volt-watt curve are understood to be in per unit of the Pmpp value for the PVSystem. When set to PAVAILABLEPU the y-axis for the volt-watt curve is understood to be in per unit of available power at any given time given Pmpp rating, efficiency factor of the PVSystem, and present irradiance. When set to PCTPMPPPU the y-axis for the volt-watt curve is understood to be in per unit of the Pmpp rating of the PVSystem multiplied by the pctPmpp parameter of the PVSystem.
  - Optional/Required: Optional.
  - Default value: PMPPPU.
  - Possible values: PMPPPU | PAVAILABLEPU|PCTPMPPPU.
- **Parameter: deltaP\_factor**
  - Description: Used in the VOLTWATT mode. This parameter sets the maximum change (in per unit of the y-axis of the volt-watt curve) from the prior active power output level to the desired active power output level during each control iteration.

If numerical instability is noticed in solutions such as the active power sign changing from one control iteration to the next and/or voltages oscillating between two values with some separation, this is an indication of numerical instability (use the EventLog to diagnose).

If the maximum control iterations are exceeded, and no numerical instability is seen in the EventLog or via monitors, then try increasing the value of this parameter to reduce the number of control iterations needed to achieve the control criteria, and move on to the power flow solution. The change in voltage from one control iteration solution to the next is the determining parameter to stop additional control iterations. This is the difference between the present per-unit voltage at the terminals of the PVSystem and the prior control iteration PVSystem terminal voltage(s) (in per-unit), as an absolute value (without sign).

If an InvControl is controlling more than one PVSystem, each PVSystem has this quantity calculated independently, and so individual PVSystems may reach the tolerance within different numbers of control iterations.

- Optional/Required: Optional.
  - Default value: 1.0 (100% change from prior pu active power value (based on y-axis units of volt-watt curve to desired active power per control iteration).
  - Possible values: Positive numerical values. It is generally best not to set deltaP\_factor lower than 0.2, so that there is enough change in voltage and active power to continue control iterations to achieve the desired active power level based on the volt-watt curve and the voltage.
- Parameter: **RateofChangeMode**
    - Description: A parameter that adds rate-of-change limiting functionality to the VOLTWATT control mode. Two types of rate-of-change limit functions are available to the user: (1) rise/fall rate-of-change limit, (2) low-pass filter rate-of-change limit. The rise/fall rate-of-change limit keeps the change in active power output, within plus or minus 'x' per-unit active power per second. The low-pass filter implements a simple RC filter in the discrete time-domain and the user can set the low-pass filter time constant in seconds. The low-pass filter time constant is defined such that it mimics a simple RC filter with time constant equal to tau.
    - Optional/Required: Optional.
    - Default value: INACTIVE.
    - Possible values: INACTIVE|LPF | RISEFALL.
  - Parameter: **LPFtau**
    - Description: The tau time constant for the discrete-time implementation of a low-pass filter such that its' output of active power mimics a simple RC filter with

time constant equal to tau given the input irradiance and VoltwattYAxis setting.  
Note: The PVSystem does not contain energy storage.

- Optional/Required: Optional.
- Default value: 0.001.
- Possible values: Positive numerical values.
- Parameter: **RiseFallLimit**
  - Description: The rate-of-change limit defined in terms of change in per-unit active power output per second. Note: The PVSystem does not contain energy storage.
  - Optional/Required: Optional.
  - Default value: 0.001.
  - Possible values: Positive numerical values.
- Parameter: **EventLog**
  - Description: A flag that determines whether or not entries are added to the Event log for actions taken by the InvControl object.
  - Optional/Required: Optional.
  - Default value: Yes.
  - Possible values: Yes/True | No/False.

## Sample Usage in OpenDSS

The same distribution circuit and PVSystem objects as for the VOLTVAR control mode cases are used, modifying as needed for the VOLTWATT control mode. See **Figure 3-3** for a one-line diagram of the circuit, and see the description under **Figure 3-4**: for the definition of the four PVSystem objects in the circuit.

### ***Volt-Watt Control***

#### Implementation in OpenDSS Script

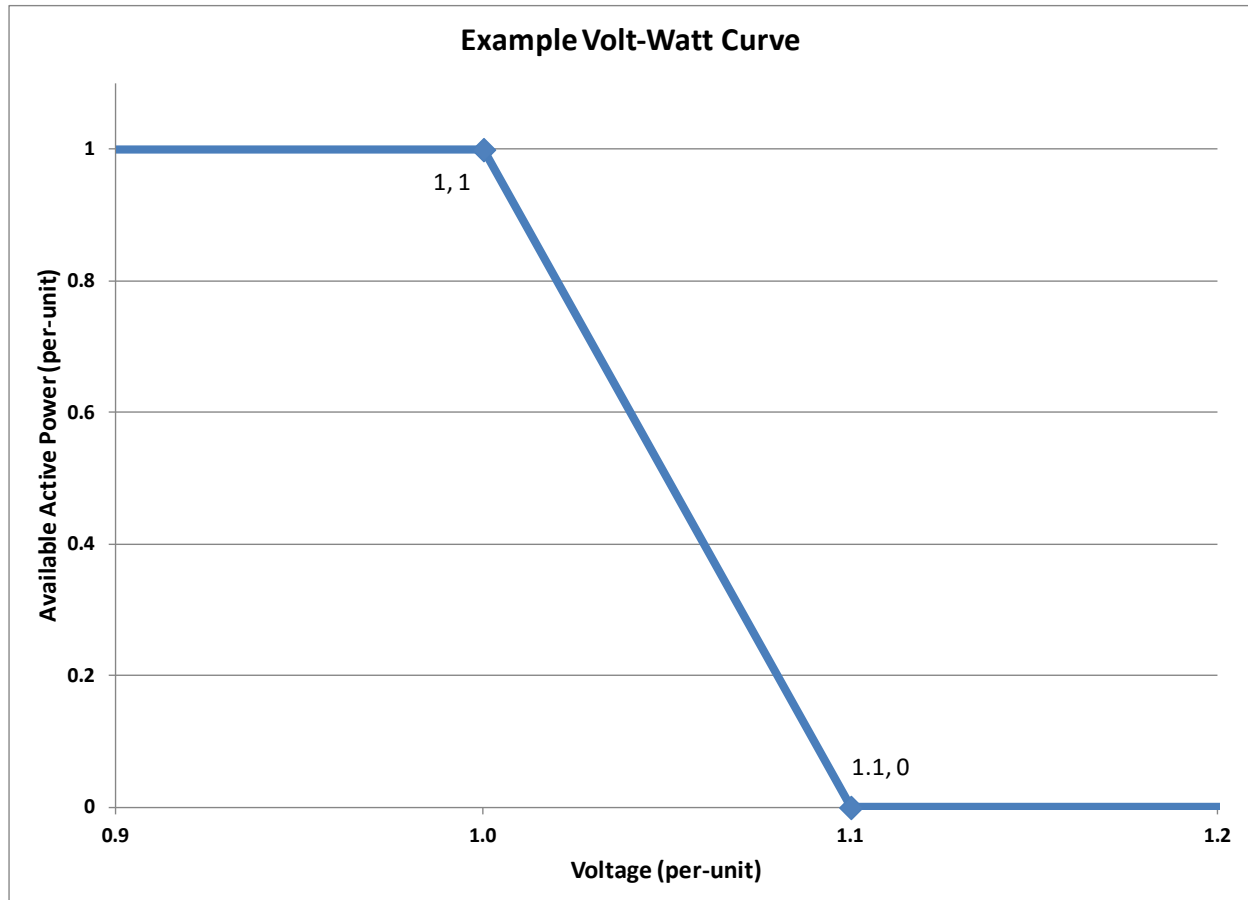
As indicated earlier, the user should define a volt-watt curve, first, followed by the InvControl object. This is shown in script as follows.

```
New XYCurve.examplevoltwattcurve npts=4 Yarray=(1.0,1.0,0.0,0.0)
~ XArray=(0.0,1.0,1.1,2.0)

New InvControl.InvPVCtrl mode=VOLTWATT voltage_curve_ref=rated
~ voltwatt_curve=examplevoltwattcurve EventLog=yes
```

The first line defines an XYCurve object called examplevoltwattcurve that consists of a per-unit voltage ('x' value) and a per-unit active power ('y' value) for each of the four points. This volt-watt curve is shown in **Figure 4-2**.

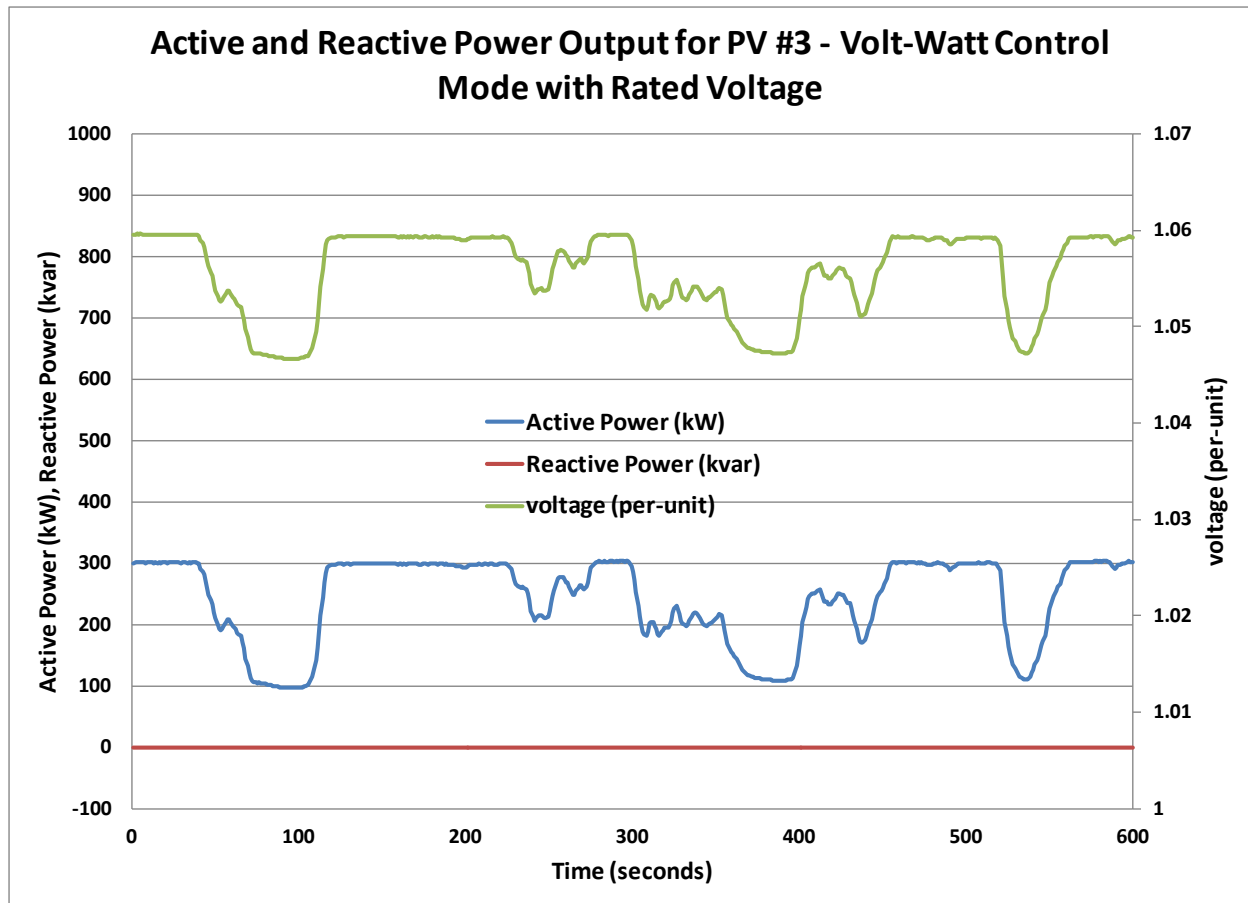
The second line of OpenDSS script defines the inverter control. No PVSystem objects are listed by name, so by default, all PV in the circuit will be under the control of this InvControl. The mode is explicitly set to VOLTWATT control mode. The x-values are set to be defined in per unit of the rated voltage of the PVSystem object, which is 240V in this case (line-neutral). The volt-watt curve to be utilized is the one named examplevoltwattcurve. The last parameter sets the program such that entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.



**Figure 4-2**  
**Volt-Watt Curve Utilized for Illustrating Operation of Volt-Watt Control Mode with Rated Voltage**

#### Illustration of Operation

The terminal voltage and output powers are shown in **Figure 4-3**. The terminal voltage utilizes the right-hand y-axis for its range of values.



**Figure 4-3**  
**Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-Watt Control Mode with Rated Voltage Utilized**

### ***Volt-watt Control with Rise/Fall Rate-of-Change Limiting***

#### **Implementation in OpenDSS Script**

The following script shows how to utilize the rise/fall rate-of-change limiting functionality with VOLTWATT control mode.

```
New XYCurve.vw_curve npts=4 Yarray=(1.0,1.0,0.0,0.0)
~ XArray=(0.5,0.95,1.05,1.5)

New InvControl.InvPVCtrl mode=VOLTWATT voltwatt_curve=vw_curve
~ VoltwattYAxis=PMPPPU RateofChangeMode=RISEFALL RiseFallLimit=.02
~ EventLog=yes
```

The first line defines an XYCurve object called *vw\_curve* that consists of a per-unit voltage ('x' value) and a per-unit active power ('y' value) for each of the four points.

The second line, beginning with the 'New' keyword of the OpenDSS script defines the inverter control. No PV systems are listed by name, so by default, all PV in the circuit will be under the control of this InvControl object. The mode is explicitly set to VOLTWATT control mode. The y-values are defined to be in per-unit of the Pmpp rating (for each of the PVSystems under

control, individually), also called full-scale active power rating. The volt-watt curve to be utilized is the one named `vw_curve`.

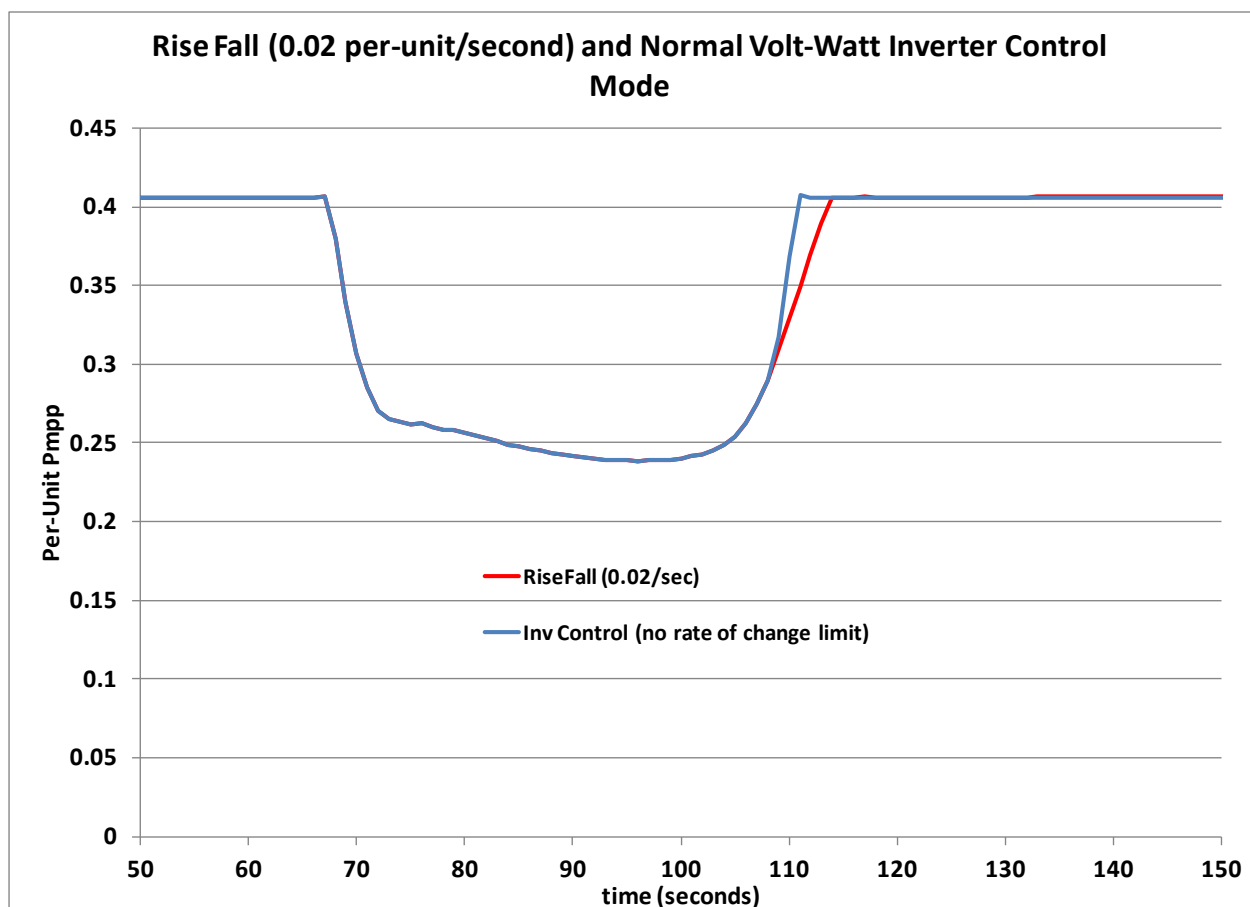
The rate-of-change mode is set to limit the change in per-unit of  $P_{mpp}$ , for active power to not exceed 0.02 per-second. For instance, if the irradiance increases at a rate that causes the active power output of the PVSystem to increase faster than 0.02 per-unit  $P_{mpp}$  per second, the rise/fall rate-of-limit function will limit the change in output to 0.02 per-unit  $P_{mpp}$  per second until such time as we have matched what the active output power would settle to given irradiance, efficiency, etc.

Lastly, entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.

### Illustration of Operation

The active power output (in per-unit of  $P_{mpp}$ ) from a simulation with normal VOLTWATT mode operation is shown in the blue curve. The red curve shows the effects of adding the rise/fall rate-of-change limit and setting the limit to a maximum change of 0.02 per-unit  $P_{mpp}$  per second

**Figure 4-4.**



**Figure 4-4**  
Per-Unit  $P_{mpp}$  of Active Power Output for PV Number 3, Results when Operating under Normal Volt-Watt Control Mode, and with Rise/Fall Rate-of-Change Limit Engaged (0.02 p.u.  $P_{mpp}$  per second).

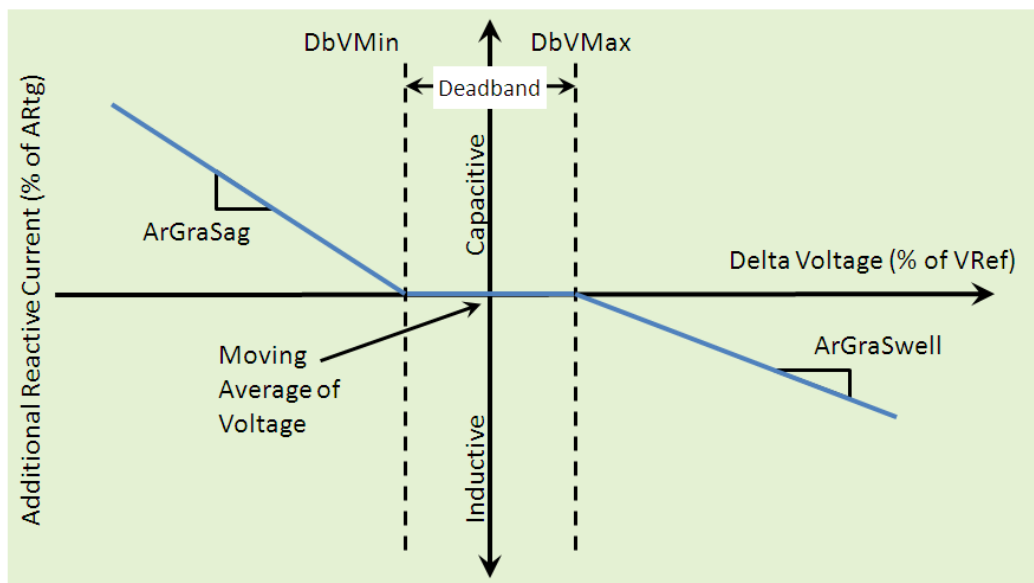
# 5

## DYNAMIC REACTIVE CURRENT FUNCTION

### Function Scope

The dynamic reactive current (DRC) function is intended to provide a flexible mechanism through which inverters may be configured to provide reactive current support in response to variations in voltage. This function is distinct from the existing steady-state volt-var function described earlier in this document, in that the controlling parameter is the change in voltage rather than the voltage level itself. In other words, the power system voltage may be above normal, resulting in a general need for inductive vars, but if it is also falling rapidly, this function could produce capacitive reactive current to help counteract the dropping of the voltage. The ultimate impact is the attempt to smooth voltage variation [4].

A figure that will be utilized to describe this functionality is shown in **Figure 5-1**. This figure will be explained throughout the text in more detail.



**Figure 5-1**  
**Dynamic Reactive Current Support Function, Basic Concept**

### Function Application

This is a type of voltage stabilization function. Such functions create an effect that is in some ways similar to momentum or inertia, in that it resists change in the controlling parameter (voltage). By adjusting the control settings, the control can be tuned to react only fast (dynamic) events or also slower changes in system voltage.

When implemented in fast-responding solid-state inverters, these functions may provide other (slower) grid equipment with time to respond [4].

## Model Requirements

- PVSystem (one or more)
- InvControl (one or more)

## Model Input Parameters and Configuration Options

For an InvControl object, the following input parameters can be set and utilized by the user for operating the InvControl object to control one or more PVSystem objects under dynamic reactive current control mode. The default value and whether the parameter is optional or required are indicated along with a description of each parameter and its' usage.

- Parameter: **PVSystemList**
  - Description: A list of one or more PVSystem object names (excluding the class specifier of PVSystem) that will be under the control of the present InvControl object.
  - Optional/Required: Optional.
  - Default value: Blank, empty list.
    - Note: If blank then all PVSystem objects in the circuit are brought under the control of the present InvControl object.
  - Possible Values: pvname1,pvname2,pvname3,...
- Parameter: **Mode**
  - Description: The control mode under which the InvControl device will control the PVSystem object listed following the PVSystemList parameter, or all PVSystem objects in the circuit if PVSystemList is not specified.
    - Note: DYNAMICREACCURR control mode controls one or more PVSystem object to respond in a fairly rapid time frame to low or high voltages that might occur.
  - Optional/Required: Required for DYNAMICREACCURR control mode. If no value is specified, then VOLTVAR mode is assumed.
  - Default value: VOLTVAR.
  - Possible Values: VOLTVAR | VOLTWATT | DYNAMICREACCURR. Unique abbreviations may be used.
- Parameter: **DbVMin**
  - Description: The minimum dead-band voltage value which, along with DbVMax, defines a dead-band in which no reactive power is generated.
  - Optional/Required: Required for dynamic reactive current control mode. Otherwise, not required.



- Default value: 0.95 pu voltage.
- Possible values: Any numerical value in per unit of rated voltage of the PVSystem object.
- Parameter: **DbVMax**
  - Description: The maximum dead-band voltage value which, along with DbVMin, defines a dead-band in which no reactive power is generated.
  - Optional/Required: Required for dynamic reactive current control mode. Otherwise, not required.
  - Default value: 1.05 pu voltage.
  - Possible values: Any numerical value in per unit of rated voltage of the PVSystem object.
- Parameter: **ArGraLowV**
  - Description: A unit-less value which is defined as a gradient in percent of capacitive reactive power production divided by percent delta-voltage. It defines how ‘quickly’ the capacitive reactive power production is increased as the percent delta-voltage value decreases below DbVMin.
    - Percent delta-voltage is defined as the present PVSystem terminal voltage minus the moving average voltage, expressed as a percentage of the rated voltage for the PVSystem object.
    - Note: This parameter name replaces the ArGraSag parameter shown in **Figure 5-1**, in order to emphasize the point that the functionality is only applicable for simulation time scales of one second or longer.
  - Optional/Required: Required for dynamic reactive current control mode. Otherwise, not required.
  - Default value: 0.1 (unit-less).
  - Possible values: Any positive numerical value.
- Parameter: **ArGraHiV**
  - Description: A unit-less value which is defined as a gradient in percent of inductive reactive power absorption divided by percent delta-voltage. It defines how ‘quickly’ the inductive reactive power production is increased as the percent delta-voltage value increases above DbVMax.
    - Percent delta-voltage is defined as the present PVSystem object terminal voltage minus the moving average voltage, expressed as a percentage of the rated voltage for the PVSystem object.

- Note: This parameter name replaces the ArGraSag parameter shown in **Figure 5-1**, in order to emphasize the point that the functionality is only applicable for simulation time scales of one second or longer.
  - Optional/Required: Required for dynamic reactive current control mode. Otherwise, not required.
  - Default value: 0.1 (unit-less).
  - Possible values: Any positive numerical value.
- Parameter: **DynReacavgwindowlen**
  - Description: For the control mode DYNAMICREACCURR, this defines the length of the rolling average window in units of simulation time, which is utilized to calculate deltaV, along with the present terminal voltage.
    - A rolling average window contains the voltages from each PVSystem object (independently) that is under the control of a given InvControl object for the most recent power-flow solution and sufficient prior power-flow solutions to cover the number of seconds, minutes, or hours for which the window length is specified.
    - Note: At time 0 in the simulation, there are no power-flow solution voltages and therefore the rolling average window length value is 0.0 for this time-frame.
    - Prior to the initial filling of the rolling average window buffer with a full set of voltages (i.e., voltages covering power-flow simulation time equal to the avgwindowlen parameter value), we calculate an average voltage using the set of voltage samples in the buffer.
    - The rolling average window discards the oldest set of voltages (across all PVSystem objects under control of this InvControl object), as simulation time progresses, filling in the empty ‘slot’ with the most recent set of terminal voltages.
  - Optional/Required: Required for dynamic reactive current mode.
  - Default value: 1s.
  - Possible values: an integer (whole number) greater than 0, followed by a specifier of second (s), minute (m), or hour (h); as in 1s (one second), 5m (five minutes), 3h (three hours).
- Parameter: **VarChangeTolerance**
  - Description: This value is the difference between the desired target vars (in per unit) of the PVSystem and the present reactive power output (in per unit), as an absolute value (without sign). If an InvControl is controlling more than one PVSystem, each PVSystem has this quantity calculated independently, and so an

individual PVSystem may reach the tolerance within different numbers of control iterations.

- Optional/Required: Optional.
- Default value: 0.025 (pu).
- Possible values: Positive numerical values.

- Parameter: **deltaQ\_factor**

- Description: Used in the VOLTVAR and DYNAMICREACCURR modes. This parameter sets the maximum change (in per unit of the y-axis of the volt-var curve or y-axis of the DRC mode) from the prior reactive power output level to the desired reactive power output level during each control iteration.

If numerical instability is noticed in solutions such as the reactive power sign changing from one control iteration to the next and/or voltages oscillating between two values with some separation, this is an indication of numerical instability (use the EventLog to diagnose).

If the maximum control iterations are exceeded, and no numerical instability is seen in the EventLog or via monitors, then try increasing the value of this parameter to reduce the number of control iterations needed to achieve the control criteria, and move on to the power flow solution.

- Optional/Required: Optional.
- Default value: 0.7 (70% change to desired reactive power per control iteration).
- Possible values: Positive numerical values. It is generally best not to set deltaQ\_factor lower than 0.2, so that there is enough change in voltage and reactive power to continue control iterations to achieve the desired reactive power level based on the volt-var curve and the voltage and the available headroom.

- Parameter: **VV\_RefReactivePower**

- Description: A parameter that defines the reference for the y-axis for the volt-var curve and any other function that has the capability to directly change reactive power injection/absorption. Also determines precedence of active or reactive power when other limits are reached.
- There are three possible values:
  - The first (and default value), VARAVAL\_WATTS, defines the y-axis of the volt-var curve and the y-axis any other function that changes reactive power to be in units of per-unit of available reactive power. See **Equation 3-1** for a definition of available reactive power. If the volt-var function requests more reactive power than is available (due to terminal voltage and the volt-var curve and the inverter kva limit), then reactive power

(vars), will be reduced until the combination of active and reactive power does not exceed the inverter kva limit.

- The next, VARMAX\_VARS, defines the y-axis of the volt-var curve and the y-axis for any other function that changes reactive power to be in units of per-unit of the value of kvarLimit set on each PVSystem. Since each PVSystem can have an individual kvarLimit, the y-axis changes for each PVSystem under control of the InvControl. If the volt-var function requests more reactive power than is available (due to terminal voltage and the volt-var curve and the inverter kva limit), then active power (watts), will be reduced until the requested reactive power is achieved.
- The last, VARMAX\_WATTS, defines the y-axis of the volt-var curve and the y-axis for any other function that changes reactive power to be in units of per-unit of the value of kvarLimit set on each PVSystem. Since each PVSystem can have an individual kvarLimit, the y-axis changes for each PVSystem under control of the InvControl. If the volt-var function requests more reactive power than is available (due to terminal voltage and the volt-var curve and the inverter kva limit), then reactive power (vars), will be reduced until the combination of active and reactive power does not exceed the inverter kva limit.

- Optional/Required: Optional.
- Default value: VARAVAL\_WATTS.
- Possible values: VARAVAL\_WATTS|VARMAX\_VARS|VARMAX\_WATTS.

- **Parameter: RateofChangeMode**

- Description: A parameter that adds rate-of-change limiting functionality to the DYNAMICREACCURR control mode. Two types of rate-of-change limit functions are available to the user: (1) rise/fall rate-of-change limit, (2) low-pass filter rate-of-change limit. The rise/fall rate-of-change limit keeps the change in reactive power within plus or minus 'x' per-unit reactive power (units depend on VV\_RefReactivePower setting) per second. The low-pass filter implements a simple RC filter in the discrete time-domain and the user can set the low-pass filter time constant in seconds. The low-pass filter time constant is defined such that it mimics a simple RC filter with time constant equal to tau.
- Optional/Required: Optional.
- Default value: INACTIVE.
- Possible values: INACTIVE|LPF | RISEFALL.

- **Parameter: LPFtau**

- Description: The tau time constant for the discrete-time implementation of a low-pass filter such that it mimics a simple RC filter with time constant equal to tau.

- Optional/Required: Optional.
- Default value: 0.001.
- Possible values: Positive numerical values.
- Parameter: **RiseFallLimit**
  - Description: The rate-of-change limit defined in terms of change in per-unit available vars output per second in both the inductive and capacitive direction.
  - Optional/Required: Optional.
  - Default value: 0.001.

Possible values: Positive numerical values.

- Parameter: **EventLog**
  - Description: A flag that determines whether or not entries are added to the Event log for actions taken by the InvControl object.
  - Optional/Required: Optional.
  - Default value: Yes.
  - Possible values: Yes/True | No/False.

## Sample Usage in OpenDSS

### Implementation in OpenDSS Script

The following scripts show how to utilize the y-axis reference in the InvControl for the DRC control function in conjunction with the kvarLimit property of each of the PVSystems under its' control.

First, the kvarLimit, in units of kvar (see help for PVSystem), is defined for each of the PVSystems in the circuit.

```
New PVSystem.3P_ExistingSite4 phases=3 bus1=B51854_sec kV=0.4157 kVA=523
~.irradiance=1 Pmpp=475 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=215
~.early=PV_ls
```

```
New PVSystem.3P_ExistingSite1 phases=3 bus1=X_5865228330A kV=0.4157 kVA=314
~ irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=130
~ yearly=PV_ls
```

```
New PVSystem.3P_ExistingSite3 phases=3 bus1=X_5891328219_Cust1 kV=0.4157
~ kVA=836 irradiance=1 Pmpp=760 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=345
~ yearly=PV_ls
```

```
New PVSystem.3P_ExistingSite2 phases=3 bus1=B4832_sec kV=0.4157 kVA=209
~ irradiance=1 Pmpp=190 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=85 yearly=PV_ls
```

The four preceding lines show the definitions of the PVSystems. The only difference between these definitions, and the initial ones presented is that the kvarLimit (in kvar) has been added to each PVSystem definition.

The following line defines the inverter control to enable the dynamic reactive current (DRC) function. Further description follows the line of script.

```
New InvControl.InvTestPVCtrl Mode=DYNAMICREACCURR.voltage_curve_ref=rated
~ VV_RefReactivePower=VARMAX_WATTS DbVMin=1.0 DbVMax=1.0 ArGraLowV=40
~ ArGraHiV=40 DynReacavgwindowlen=10s.deltaQ_factor=0.5 EventLog=yes
```

No PV systems are listed by name, so by default, all PV in the circuit will be under the control of this InvControl object. The mode is explicitly set to dynamic reactive current control mode. The x-values, are defined in per unit of the rated voltage of the PVSystem object

The VV\_RefReactivePower parameter is set to VARMAX\_WATTS. This setting means that the y-axis values of the volt-var curve are understood to be in per-unit of the kvarLimit for each PVSystem (independently).

The “\_WATTS” portion of the VV\_RefReactivePower parameter indicates that active power has precedence over reactive power. This means that if the combination of active and reactive power exceeds the kVA rating of the PVSystem, the reactive power absorption/injection will be reduced such that the kVA rating of the PVSystem is not exceeded. Active power injection will not be reduced.

The minimum and maximum voltage values which define the dead-band are both set to 1.0 per-unit voltage, meaning that there is no dead-band. The high voltage and low voltage gradients are both set to 40. This means that for every percent of deltaV, which is calculated by subtracting the DRC rolling average window value from the present voltage (and dividing by the PVSystem object’s rated voltage), 40.0 pu of capacitive or inductive vars per per-unit deltaV (i.e., multiplied by the deltaV value and full-scale current rating to arrive at reactive output), depending on which side of the 1.0 pu deltaV value the calculated deltaV is on.

The dynamic reactive current rolling average window length is set to 10 seconds. The deltaQ\_factor is set to 0.5, indicating that there should be no more than a 50% change between the prior reactive power output level and the ‘desired’ reactive power output level based on the DRC settings, per control iteration. The last parameter sets the OpenDSS application in a mode such that entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.

## ***Dynamic Reactive Current***

### **Illustration of Operation**

The output power of the 4 PV systems is changed such that there is a constant active power output level until approximately 300 seconds. The constant output active power level is set to 0.8 per-unit of the Pmpp for each PV system. For PV system Number 3, this equates to about 608 kW. At 300 seconds, the active power output level is reduced to 0.2 per-unit of the Pmpp for each PV system. For PV system Number 3, this equates to about 152 kW. The active power output is left at this level for 5 seconds and then the active power output of all the PVSystems is returned to 0.8 per-unit of Pmpp.

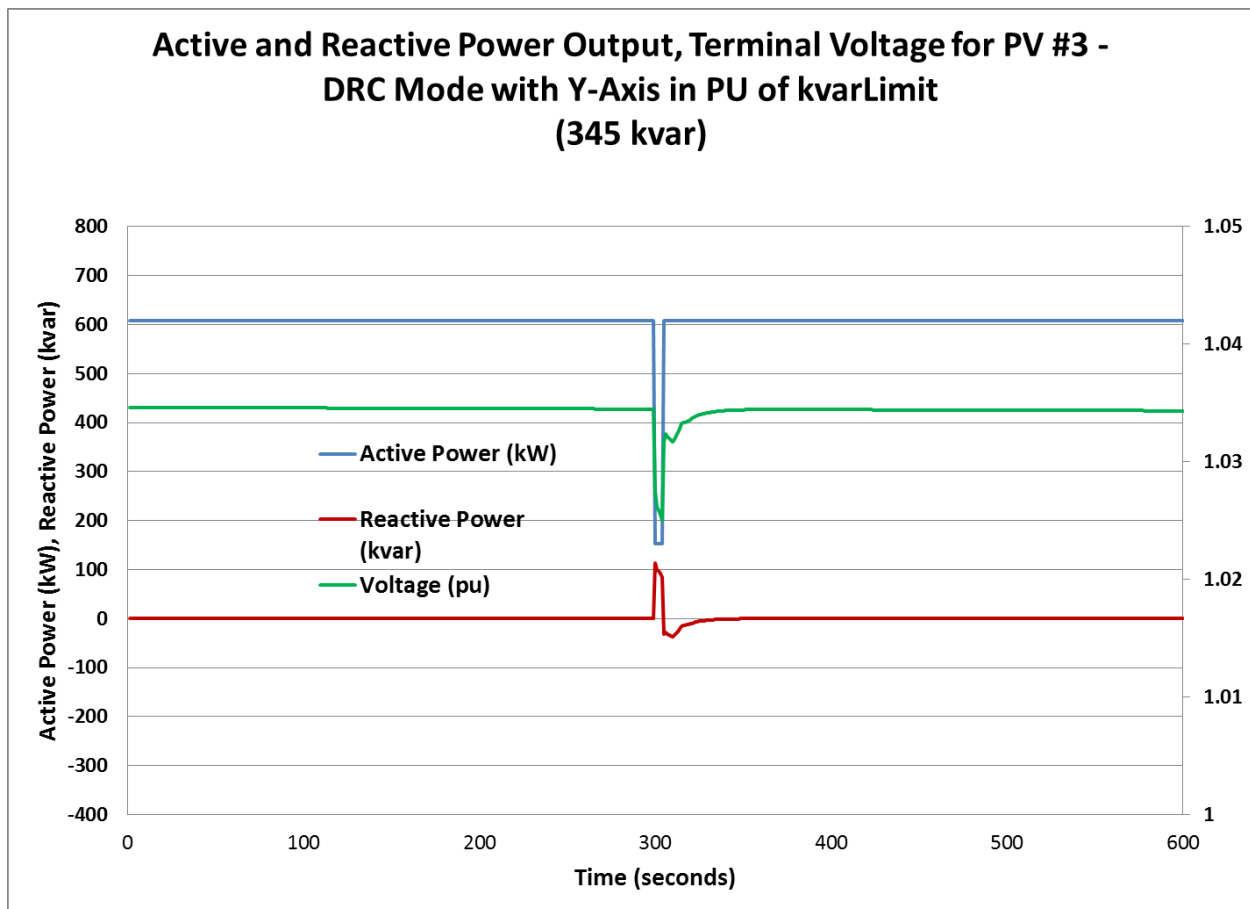
The regulators in the circuit are set at fixed taps and not allowed to change taps (their controls are disabled), so as to focus on just the DRC action in the simulation.

A plot of the active and reactive power output as well as the terminal voltage is shown in **Figure 5-2**.

The response of the DRC control mode, with the settings given above is to provide no reactive power output while the voltage is steady at 1.035 pu voltage. When the voltage drops, due to the step reduction in active power output, the DRC injects a peak of about 113 kvar into the system to reduce the voltage drop.

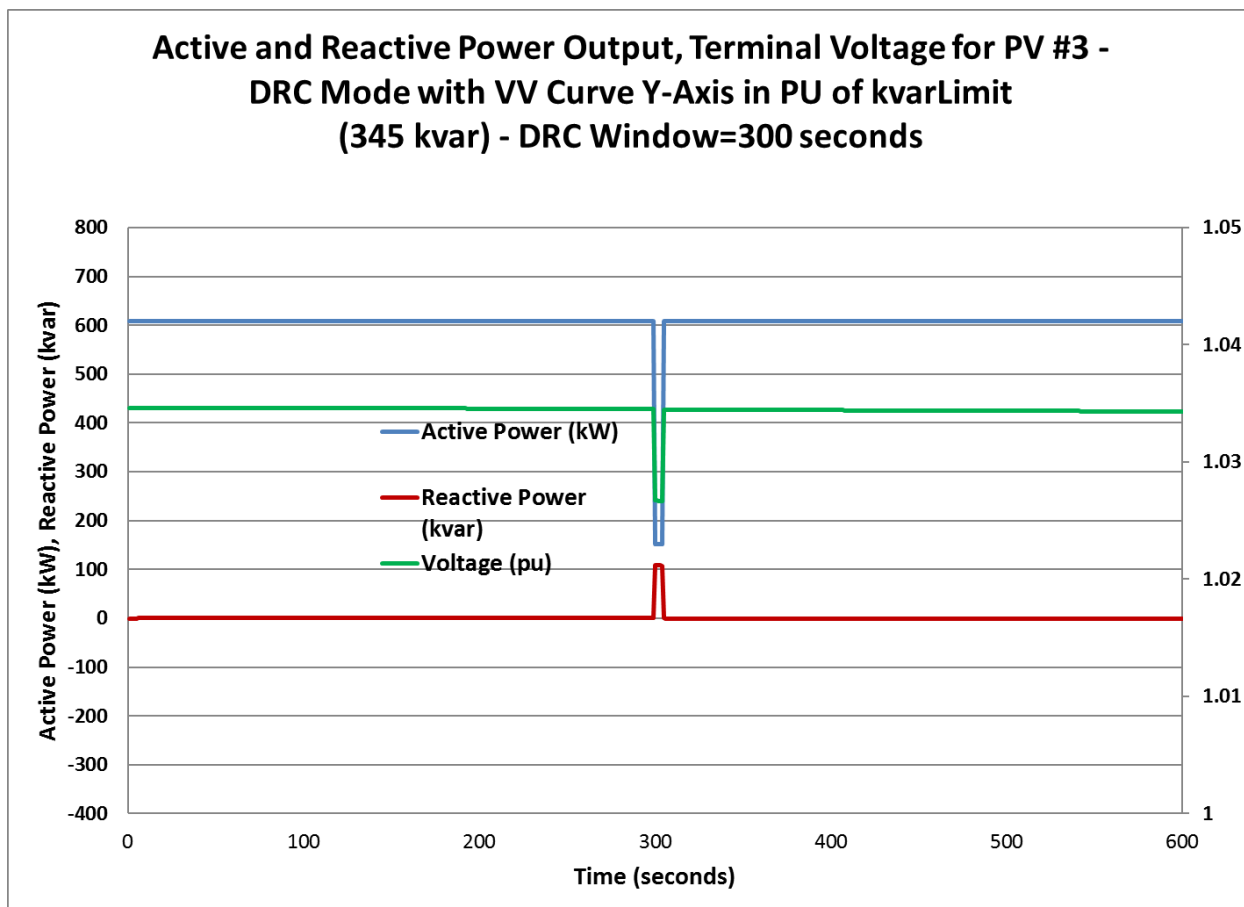
The reactive power injection drops slightly as the  $\Delta V$  decreases due to the ‘recent’ lower voltage values being added to the DRC rolling average window (10 sec. length). Then when the active power is brought back to about 608 kvar, and the voltage begins to increase suddenly, the DRC function switches to the inverter absorbing reactive power from the system (inductive) to counteract the fast increase in voltage. Finally, the reactive power output settles back down to 0 after a short period of time, related to the length of the DRC averaging window.

In this previous example, the DRC rolling average voltage changes during the dynamic event due to the small average window length. If the average window length had been longer (e.g., 300s), the inverter reactive output would be more constant during the event and zero after the event clears as shown in **Figure 5-3**. A longer rolling average window may be desired to smooth voltage while shorter rolling average windows may chase a moving DRC voltage target.



**Figure 5-2**  
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Dynamic Reactive Current Control Mode with a 10-second Rolling Average Window





**Figure 5-3**  
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Dynamic Reactive Current Control Mode with a 300-second Rolling Average Window



# 6

## SIMULTANEOUS VOLT-VAR/VOLT-WATT MODE

### Function Scope

The simultaneous volt-var/volt-watt control function allows each individual PV system to provide a unique active and reactive power response according to 1) the voltage at the point of connection (the terminals of the PV system), 2) the available apparent power capacity of the inverter at that point in time, and 3) the user-defined volt-var setpoints as illustrated in **Figure 3-6** and the user-defined volt-watt setpoints as illustrated in **Figure 4-2**.

The functionality of each individual control discussed in earlier chapters applies together in this combined control.

### Function Application

Similar to the individual use of volt-var and volt-watt, the combined control attempts to maintain the voltage at the terminal of the PV system. However, the combined control can adjust both active and reactive power simultaneously.

Although additional benefit can be attained, settings must be chosen carefully such that the two functions don't have conflicting targets. For example, the user would not want to curtail active power to zero with the volt-watt control when the volt-watt control is operating in the capacitive mode. The feasible combined setting would curtail real power only when in the inductive volt-var region, thus volt-watt and volt-var are working together to prevent unwanted voltage rise.

### Model Requirements

- PVSystem (one or more)
- XYcurve (two per inverter control – one for volt-watt and one for volt-var)

### PVSystem

Utilizing the inverter control (referred to by its class name in OpenDSS: InvControl) in simultaneous volt-var/volt-watt control mode the user should first define one or more PVSystem objects that will be controlled by an InvControl element.

The PVSystem object(s), which represent entire PV systems including PV panel(s)/array plus the inverter, should have their full-scale kVA rating and Pmpp defined. Pmpp is the rated maximum power of the PV array for 1.0 kW/sq-m irradiance and a user-selected array temperature. The power factor should be set to unity for the PVSystem element. If desired, the kvarlimit property can be set in the PVSystem element to define a maximum reactive power injection/absorption limit. The kvarlimit can also work with the InvControl's RefReactivePower property, when that property is set to either VARMAX\_VARS or VARMAX\_WATTS. Other settings that would be helpful to be defined are the cut-out (switch the inverter off) kVA level and the cut-in (switch the inverter on) kVA level to define the power levels below and above which the inverter switches off or on.

## XYCurve

In addition to the PVSystem model, both the volt-var function and the volt-watt function require the user to define an XYcurve object for each simultaneous mode. There should be two XYcurve instances per InvControl instance (one for volt-var and one for volt-watt). The XYCurve objects defines the output reactive and active powers as a function of the terminal voltage at the PVSystem object.

A positive sign for reactive power output (in per unit, pu) for the y-array values indicates capacitive vars, or reactive power flowing in the same direction as active power. A negative sign for reactive power output indicates inductive vars, or reactive power flowing in the opposite direction as the active power.

For the x-axis, the units are in per unit of the terminal voltage of the PVSystem object. However, the quantity to convert from volts to per-unit voltage can be set by the user. The default setting is to use the rated voltage of the PVSystem object to ‘per-unitize’ the voltage. An alternate option is to use a rolling average window, of user-defined length, to convert the terminal voltage of the PVSystem from volts to per-unit voltage.

For PVSystem objects having more than one phase, the terminal voltage is represented by the average of the ‘number of phases’ line-neutral voltages.

There should be an equal number of x-array points as y-array points in the curve for reactive power output as a function of the terminal voltage. Similarly, there should be an equal number of x-array points as y-array points in the curve for active power output as a function of the terminal voltage.

## Model Input Parameters and Configuration Options

For an InvControl object operating in simultaneous volt-var/volt-watt mode, most of the input parameters that can be used are the same as in the Intelligent volt-var function chapter and the volt-watt function chapter. The **Mode** parameter should not be used for the simultaneous modes. The only parameter that is different is the CombiMode parameter, that indicates simultaneous modes are in effect. It is described here.

- Parameter: **CombiMode**
  - Description: The simultaneous control mode under which the InvControl device will control the PVSystem objects listed following the PVSystemList parameter, or all PVSystem objects in the circuit if PVSystemList is not specified. There are two simultaneous modes available at present: volt-var/volt-watt (VV\_VW) and volt-var/dynamic reactive current (VV\_DRC).
    - Set to VV\_VW for simultaneous volt-var/volt-watt mode.
  - Optional/Required: Required if simultaneous modes desired.
  - Default value: ‘’ (empty string = no simultaneous mode).
  - Possible Values: ‘’\* | VV\_VW | VV\_DRC.

## Sample Usage in OpenDSS

The same distribution circuit used for the previous control mode cases is used again. See **Figure 3-3** for a one-line diagram of the circuit.

### ***Volt-Var/Volt-Watt Simultaneous Control***

#### Implementation in OpenDSS Script

The following scripts shows how to utilize the simultaneous volt-var/volt-watt function.

First, the kvarLimit, in units of kvar (see help for PVSystem), is defined for each of the PVSystems in the circuit. Aside from this change, the PVSystems are the same as what has been used in previous implementations.

```
New PVSystem.3P_ExistingSite4 phases=3 bus1=B51854_sec kV=0.4157 kVA=523
~.irradiance=1 Pmpp=475 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=215
~.yearly=PV_ls

New PVSystem.3P_ExistingSite1 phases=3 bus1=X_5865228330A kV=0.4157 kVA=314
~ irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=130
~ yearly=PV_ls

New PVSystem.3P_ExistingSite3 phases=3 bus1=X_5891328219_Cust1 kV=0.4157
~ kVA=836 irradiance=1 Pmpp=760 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=345
~ yearly=PV_ls

New PVSystem.3P_ExistingSite2 phases=3 bus1=B4832_sec kV=0.4157 kVA=209
~ irradiance=1 Pmpp=190 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=85 yearly=PV_ls
```

The following line defines an XYCurve object called *vv\_curve* that consists of a per-unit voltage ('x' value) and a per-unit reactive power value ('y' value) for each of the four points. Positive values indicate capacitive reactive power, or injecting reactive power from the PV system inverter into the power system, and negative values indicate inductive reactive power, or absorbing reactive power from the power system.

```
New XYCurve.vv_curve npts=4 Yarray=(1.0,1.0,-1.0,-1.0)
~ XArray=(0.5,0.95,1.05,1.5)
```

The user should define a volt-watt curve, as well. This is shown in script as follows.

```
New XYCurve.vw_curve npts=4 Yarray=(1.0,1.0,0.0,0.0)
~ XArray=(0.0,1.0,1.05,2.0)
```

The preceding line defines an XYCurve object called *vw\_curve* that consists of a per-unit voltage ('x' value) and a per-unit present active power ('y' value) for each of the four points. This volt-watt curve is similar to the one shown in **Figure 4-2**, except that the desired zero per-unit active power value begins at 1.05 per-unit voltage.

The line immediately following this paragraph, beginning with the 'New' keyword of the OpenDSS script defines the inverter control. No PV systems are listed by name, so by default, all PV in the circuit will be under the control of this InvControl object. The CombiMode is explicitly set to VV\_VW control mode.

```
New InvControl.InvTestPVCtrl CombiMode=VV_VW.voltage_curve_x_ref=rated  
~ VV_RefReactivePower=VARMAX_WATTS  
~ vvc_curve1=vv_curve voltwatt_curve=vw_curve EventLog=yes
```

Continuing with the description of the preceding line of OpenDSS script, the x-values are defined in per unit of the rated voltage of the PVSystem object.

The VV\_RefReactivePower parameter is set to VARMAX\_WATTS. This setting means that the y-axis values of the volt-var curve are understood to be in per-unit of the kvarLimit for each PVSystem (independently). For instance, for the Existing Site 1, the units for the y-axis of the volt-var curve are in per-unit of 130 kvar. Similarly, for the Existing Site 2, the units for the y-axis are in per-unit of 85 kvar.

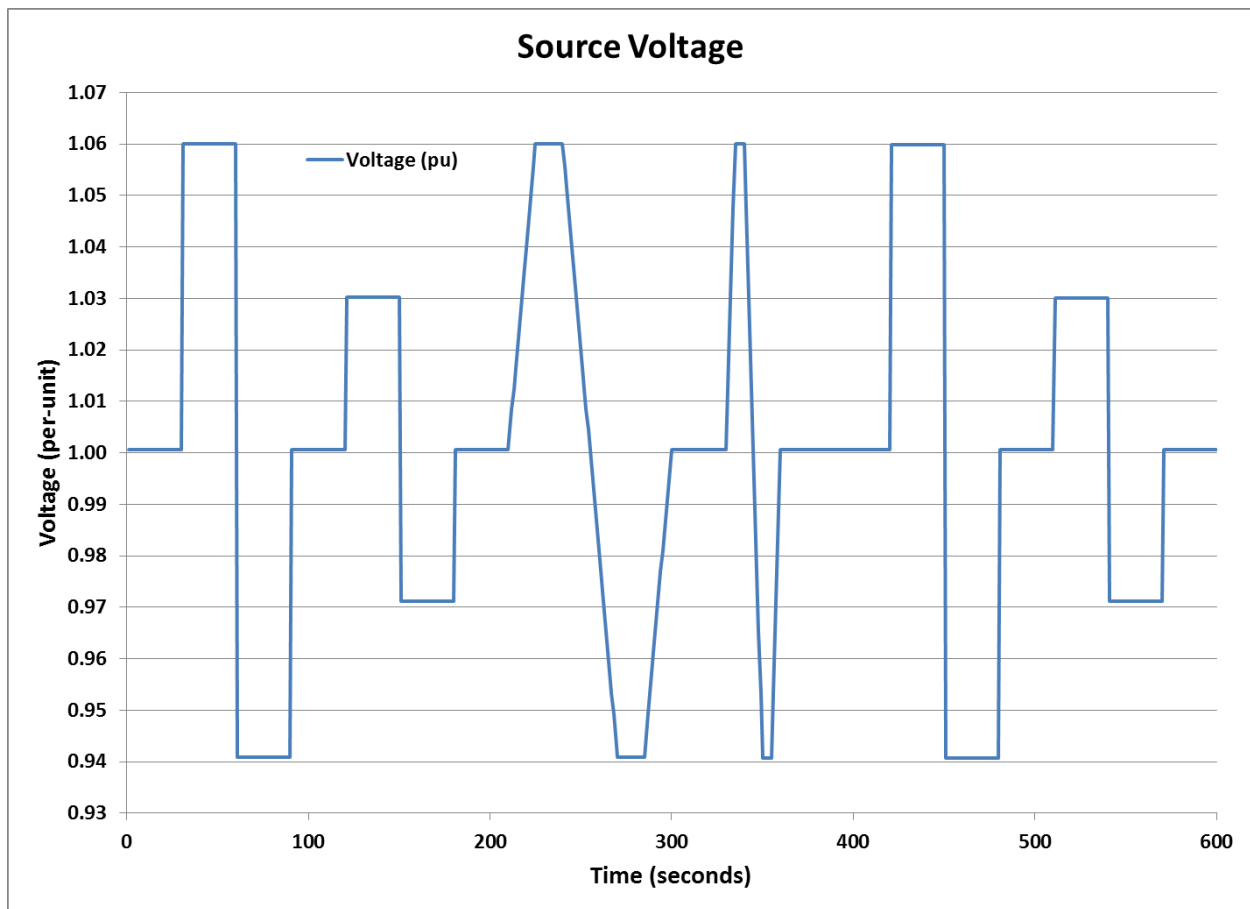
The volt-var curve to be utilized is the one named vv\_curve.

The volt-watt curve to be utilized is the one named vw\_curve. Since no value is explicitly set for the parameter VoltwattYAxis, the default value of PMPPPU is used. This default setting indicates that the y-axis units for the volt-watt curve are understood to be in per unit of the Pmpp value for the PVSystem.

Lastly, entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.

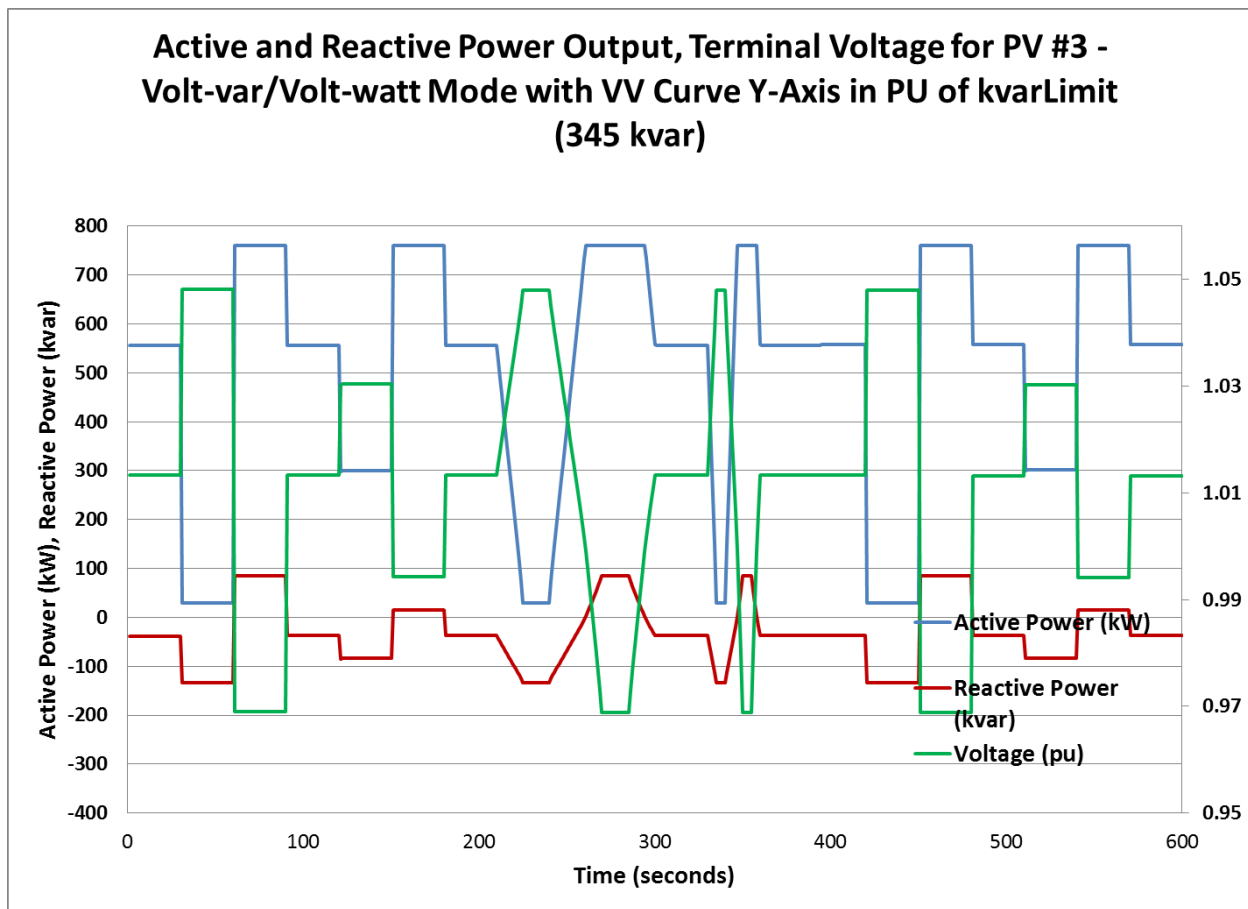
### Illustration of Operation

In this example of operation of the combined volt-var/volt-watt mode, the circuit has been altered. In this example, the irradiance has been set to a constant value of 1.0 per-unit for the 600 seconds of the simulation. The voltage source has been set to follow the shape shown in **Figure 6-1**. So, in this case, only the voltage is the variable that is being changed to see what changes occur in reactive and active power output.



**Figure 6-1**  
Average of Three Phases Source Voltage That is Being Varied During the Simulation (irradiance is fixed).

The terminal voltage and output powers are shown in **Figure 6-2** for the simultaneous volt-var/volt-watt combination. The terminal voltage utilizes the right-hand y-axis for its range of values.



**Figure 6-2**  
**Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-var/Volt-watt Control Mode**

As can be seen clearly in **Figure 6-2** the active power is at its' peak value when the voltage is low. When the voltage increases above 1.0 per-unit, the active power decreases according to the volt-watt curve. Similarly, the reactive power becomes inductive when the terminal voltage is high and it becomes capacitive ('boosting' the voltage) when the terminal voltage drops below 1.0 per-unit.



# 7

## SIMULTANEOUS VOLT-VAR/DYNAMIC REACTIVE CURRENT

### Function Scope

The simultaneous volt-var/dynamic reactive current (VV/DRC) function allows each individual PV system to provide a reactive power response according to 1) the voltage at the point of connection (the terminals of the PV system), 2) the available apparent power capacity of the inverter at that point in time, 3) the user-defined volt-var setpoints and, 4) the change in voltage from the present voltage as compared to a rolling average window voltage and the settings for the DRC.

The functionality of each individual control discussed in earlier chapters applies together in this combined control.

The reactive power response is a summation of the value determined from the volt-var mode and from the DRC mode.

### Function Application

Similar to the individual use of volt-var and DRC, the combined control attempts to maintain the voltage at the terminal of the PV system. However, the combined control can adjust reactive power based on either/both controls simultaneously. The advantage of the combined functionality is that it allows the best qualities in each to be attained.

At many times, the best operation of the inverter would be to have no reactive output. This can be attained by implementing a wide bandwidth/deadband in the volt-var curve while allowing reactive power output at/toward the ANSI limits. Within the deadband, the DRC can provide support to mitigate any unwanted changes in voltage. Together, the DRC smooths voltage variation when inside some range while volt-var adds additional reactive mitigation when voltage moves outside that acceptable range.

### Model Requirements

- PVSystem (one or more)
- XYcurve (one per inverter control – for volt-var)

### *PVSystem*

Utilizing the inverter control (referred to by its class name in OpenDSS: InvControl) in simultaneous volt-var/volt-watt control mode the user should first define one or more PVSystem objects that will be controlled by an InvControl element.

The PVSystem object(s), which represent entire PV systems including PV panel(s)/array plus the inverter, should have their full-scale kVA rating and Pmpp defined. Pmpp is the rated maximum power of the PV array for 1.0 kW/sq-m irradiance and a user-selected array temperature. The power factor should be set to unity for the PVSystem element. If desired, the kvarlimit property

can be set in the PVSystem element to define a maximum reactive power injection/absorption limit. The kvarlimit can also work with the InvControl's RefReactivePower property, when that property is set to either VARMAX\_VARS or VARMAX\_WATTS. Other settings that would be helpful to be defined are the cut-out (switch the inverter off) kVA level and the cut-in (switch the inverter on) kVA level to define the power levels below and above which the inverter switches off or on.

## **XYCurve**

In addition to the PVSystem model, the volt-var function requires the user to define an XYcurve object. The XYCurve object defines the reactive power as a function of the terminal voltage at the PVSystem object.

A positive sign for reactive power output (in per unit) for the y-array values indicates capacitive vars, or reactive power flowing in the same direction as active power. A negative sign for reactive power output indicates inductive vars, or reactive power flowing in the opposite direction as the active power.

For the x-axis, the units are in per unit of the terminal voltage of the PVSystem object. However, the quantity to convert from volts to per-unit voltage can be set by the user. The default setting is to use the rated voltage of the PVSystem object to 'per-unitize' the voltage. An alternate option is to use a rolling average window, of user-defined length, to convert the terminal voltage of the PVSystem from volts to per-unit voltage.

For PVSystem objects having more than one phase, the terminal voltage is represented by the average of the 'number of phases' line-neutral voltages.

There should be an equal number of x-array points as y-array points so as to define the reactive power output as a function of the terminal voltage.

## **Model Input Parameters and Configuration Options**

For an InvControl object operating in simultaneous volt-var/dynamic reactive current mode, most of the input parameters that can be used are the same as in the Intelligent volt-var function chapter and the dynamic reactive current function chapter.

The **Mode** parameter should not be used for the simultaneous modes. The only parameter that is different is the CombiMode parameter, that indicates simultaneous modes are in effect. It is described here.

- Parameter: **CombiMode**
  - Description: The simultaneous control mode under which the InvControl device will control the PVSystem objects listed following the PVSystemList parameter, or all PVSystem objects in the circuit if PVSystemList is not specified. There are two simultaneous modes available at present: volt-var/volt-watt (VV\_VW) and volt-var/dynamic reactive current (VV\_DRC).
    - Set to VV\_DRC for simultaneous volt-var/dynamic reactive current mode.
  - Optional/Required: Required if simultaneous modes desired.

- Default value: '' (empty string = no simultaneous mode).
- Possible Values: '\*' | VV\_VW | VV\_DRC.

## Sample Usage in OpenDSS

The same distribution circuit as for the previous control mode cases will be utilized.

### ***Volt-Var/Dynamic Reactive Current Simultaneous Control***

#### Implementation in OpenDSS Script

The following scripts shows how to utilize the simultaneous volt-var/dynamic reactive current function.

First, the kvarLimit, in units of kvar (see help for PVSystem), is defined for each of the PVSystems in the circuit. Aside from this change, the PVSystems are the same as what has been used in previous implementations.

```
New PVSystem.3P_ExistingSite4 phases=3 bus1=B51854_sec kV=0.4157 kVA=523
~.irradiance=1 Pmpp=475 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=215
~.yearly=Pv_ls
```

```
New PVSystem.3P_ExistingSite1 phases=3 bus1=X_5865228330A kV=0.4157 kVA=314
~ irradiance=1 Pmpp=285 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=130
~ yearly=Pv_ls
```

```
New PVSystem.3P_ExistingSite3 phases=3 bus1=X_5891328219_Cust1 kV=0.4157
~ kVA=836 irradiance=1 Pmpp=760 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=345
~ yearly=Pv_ls
```

```
New PVSystem.3P_ExistingSite2 phases=3 bus1=B4832_sec kV=0.4157 kVA=209
~ irradiance=1 Pmpp=190 pf=1 %cutin=0.1 %cutout=0.1 kvarLimit=85 yearly=Pv_ls
```

The following line defines an XYCurve object called *vv\_curve* that consists of a per-unit voltage ('x' value) and a per-unit reactive power value ('y' value) for each of the four points. Positive values indicate capacitive reactive power, or injecting reactive power from the PV system inverter into the power system, and negative values indicate inductive reactive power, or absorbing reactive power from the power system. Note that there is a 'dead-band' in the volt-var curve between 0.99 pu voltage and 1.01 pu voltage.

```
New XYCurve.vv_curve npts=6 Yarray=(1.0,1.0,0.0,0.0,-1.0,-1.0)
~ XArray=(0.5,0.9,0.99,1.01,1.05,1.5)
```

The line immediately following this paragraph, beginning with the 'New' keyword of the OpenDSS script defines the inverter control. No PV systems are listed by name, so by default, all PV in the circuit will be under the control of this InvControl object. The CombiMode is explicitly set to VV\_DRC control mode.

```
New InvControl.InvTestPVCtrl CombiMode=VV_DRC.voltage_curve_ref=rated
VV_RefReactivePower=VARMAX_WATTS vvc_curve1=vv_curve DbVMin=1.0 DbVMax=1.0
ArGraLowV=20 ArGraHiV=20 DynReacavgwindowlen=1s.deltaQ_factor=0.5
EventLog=Yes
```

Continuing with the description of the preceding line of OpenDSS script, the x-values are defined in per unit of the rated voltage of the PVSystem object.

The VV\_RefReactivePower parameter is set to VARMAX\_WATTS. This setting means that the y-axis values of the volt-var curve are understood to be in per-unit of the kvarLimit for each PVSystem (independently). For instance, for the Existing Site 1, the units for the y-axis of the volt-var curve are in per-unit of 130 kvar. Similarly, for the Existing Site 2, the units for the y-axis are in per-unit of 85 kvar.

The volt-var curve to be utilized is the one named vv\_curve.

For the DRC portion of the simultaneous control mode both DbVMin and DbVMax are set to 1.0 pu voltage. This indicates that there is no voltage dead-band for the DRC portion.

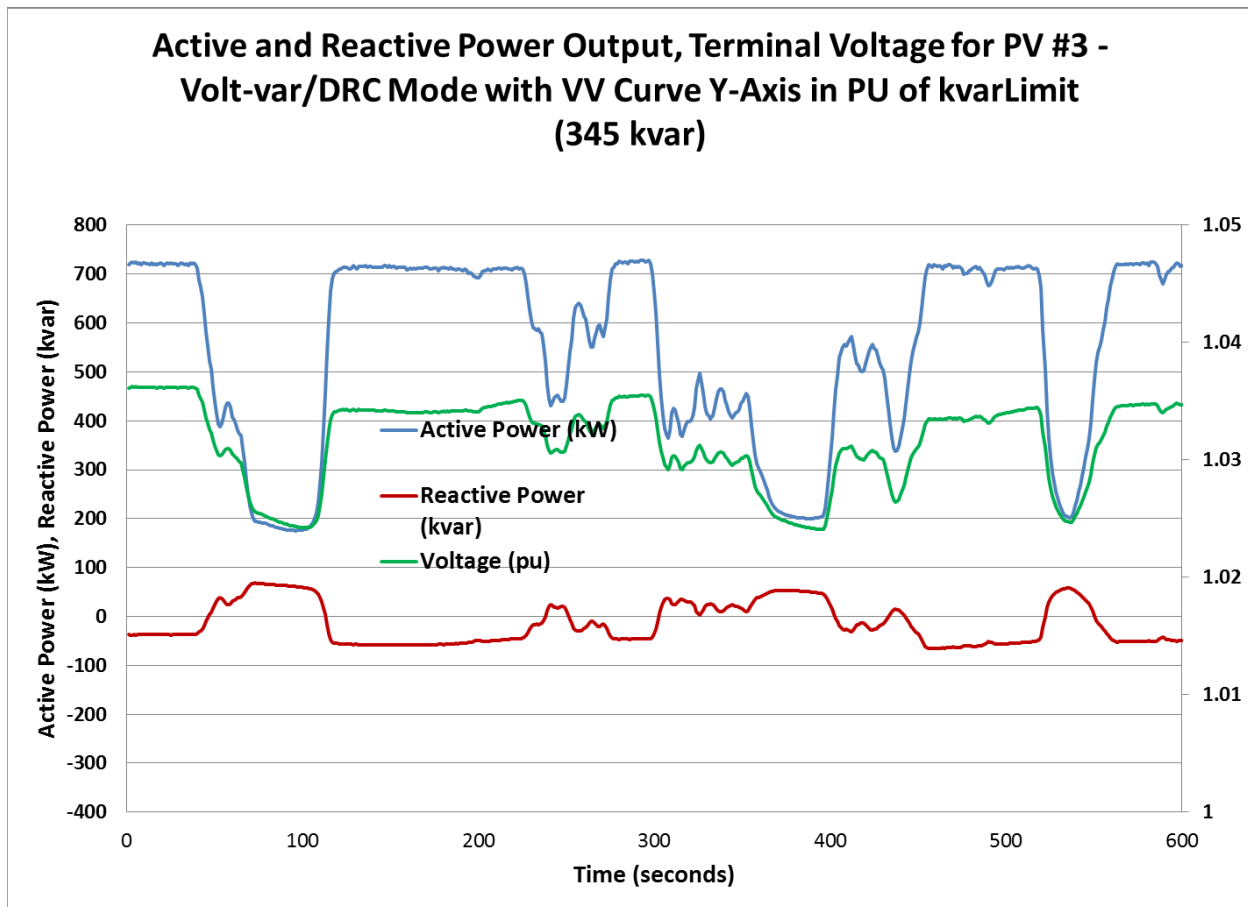
ArGraLowV and ArGraHiV are both set to 20. This means that for every percent of deltaV, which is calculated by subtracting the DRC rolling average window value from the present voltage (and dividing by the PVSystem object's rated voltage), it is desired to produce 20.0 pu of capacitive or inductive vars per per-unit deltaV (i.e., multiplied by the deltaV value and full-scale current rating to arrive at reactive output), depending on which side of the 1.0 per-unit deltaV line we are on.

The dynamic reactive current rolling average window length is set to 1 second in length.

Lastly, entries are allowed to be made into the EventLog for any control actions taken (or anticipated to be taken) by the inverter control.

### Illustration of Operation

Continuing with the same active power input curve, applied to all 4 PV systems in the circuit, we now run the simulation for 600 seconds with VV\_DRC simultaneous control mode in operation. However, in this case, we 'widen' the dead-band in the volt-var portion of the control to not operate between 0.93 and 1.03 pu voltage. The terminal voltage and output powers are shown in **Figure 7-1**. The terminal voltage utilizes the right-hand y-axis for its range of values.



**Figure 7-1**  
**Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-var/DRC Control Mode**

This simulation shows the additive combination of the simultaneous volt-var/dynamic reactive current functions during the first 80 seconds or so. Then once the voltage drops below 1.03 pu we see the action just due to the DRC, although it has a long window length of 120 seconds, as it pursues continuing to inject capacitive reactive power even though the voltage is not changing much between 80 and 100 seconds. Then once the voltage increases above the 1.03 pu voltage level the volt-var portion is absorbing reactive power (inductive vars) more-so than the DRC. A few returns to capacitive reactive power occur when the voltage dips due to DRC action.

Also note that when the voltage is relatively steady, the reactive power absorption is almost exclusively due to the volt-var response.



# 8

## FIXED POWER FACTOR FUNCTION

### Function Scope

This function is intended to provide a simple mechanism through which the power factor of a DER may be set to a fixed value [4].

### Function Application

One typical use for the fixed power factor function is to help provide means of voltage regulation, by setting the fixed power factor to a value such that the PV system appears slightly inductive to the grid. By setting to a value near unity, but absorbing reactive power from the grid as a function of active power output, this tends to provide voltage regulation capabilities, with minimal ‘specialized’ functionality needed in the PV Inverter controls.

### Model Requirements

- PVSystem object (one or more)
- No InvControl object is required

### Model Input Parameters and Configuration Options

For this mode the only model input parameters that are required are those within the PVSystem object itself. The user will set the pf (power factor parameter) to any positive or negative number between (but not including) -1.0 and 1.0 (including this value for unity power factor; i.e., no reactive power output).

When reactive power has the opposite sign of active power, the power factor parameter should be negative. A positive power factor signifies that the PVSystem element produces reactive power (capacitive vars) as is typical for a generator.

### Sample Usage in OpenDSS

#### Implementation in OpenDSS Script

An example implementation is shown in script as follows.

```
New PVSystem.3P_ExistingSite4 phases=3 bus1=B51854_sec kV=0.4157 kVA=523
~.irradiance=1 Pmpp=475 pf=-0.98 %cutin=0.1 %cutout=0.1 yearly=PV_ls

New PVSystem.3P_ExistingSite1 phases=3 bus1=X_5865228330A kV=0.4157 kVA=314
~ irradiance=1 Pmpp=285 pf=-0.98 %cutin=0.1 %cutout=0.1 yearly=PV_ls

New PVSystem.3P_ExistingSite3 phases=3 bus1=X_5891328219_Cust1 kV=0.4157
~ kVA=836 irradiance=1 Pmpp=760 pf=-0.98 %cutin=0.1 %cutout=0.1 yearly=PV_ls

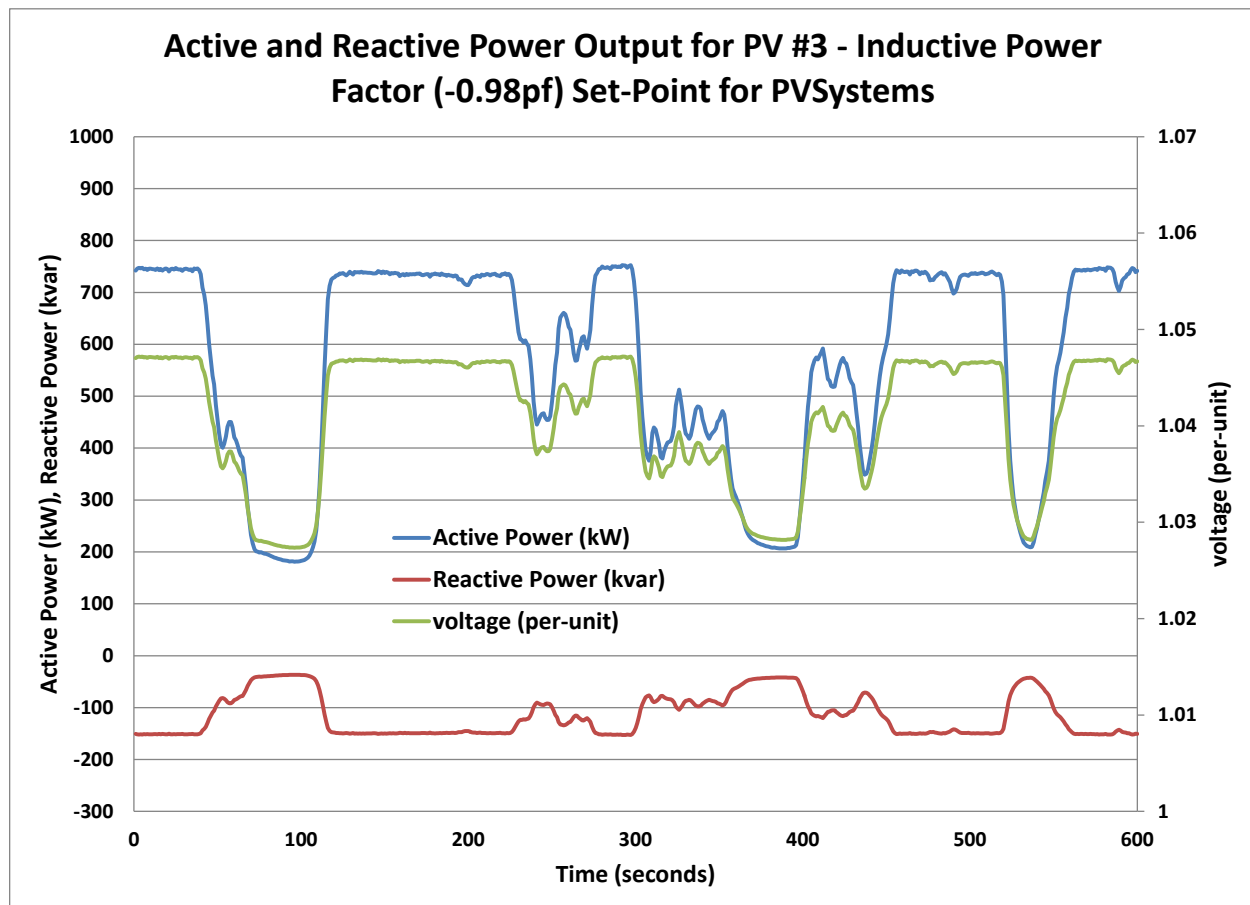
New PVSystem.3P_ExistingSite2 phases=3 bus1=B4832_sec kV=0.4157 kVA=209
~ irradiance=1 Pmpp=190 pf=-0.98 %cutin=0.1 %cutout=0.1 yearly=PV_ls.
```

The lines of OpenDSS script specifies that the PVSystem objects will operate at a 0.98 power factor, such that the PVSystem objects will be absorbing vars from the system (inductive vars). No other changes are made to the PVSystem object definitions. Note that there is no InvControl object for this mode of operation.

### Illustration of Operation

Now that the PVSystem objects have been defined to run at an inductive power factor, we will repeat the simulation and determine what effects on voltage variations we see. **Figure 8-1** shows the output of the PV Number 3 with respect to active and reactive power, and the resulting terminal per-unit voltage. Comparing this to **Figure 4-3**, we see that a simple, fixed inductive power factor set-point has a positive effect by lowering the terminal voltage level.

Note that for this case, all four PVSystem objects had the same power factor set-point. Given the electrical locations of the PVSystem elements, the other PV system that is served from the same interconnect transformer as PV Number 3, also has an effect on the terminal voltage seen at PV Number 3.



**Figure 8-1**  
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Fixed Power Factor Set-point for the PV Systems, with Power Factor Set to -0.98 (Inductive Reactive Power)



# 9

## MAXIMUM GENERATION LIMIT FUNCTION

### Function Scope

This function operates as a control, to establish an upper limit on the active power that the PV system can produce (deliver to the grid) from its terminals [4].

### Function Application

Some example applications are:

- **Localized (Customer Side of the Distribution Transformer) Overvoltage Conditions.** This function could be used to reduce DG output to prevent localized overvoltage conditions.
- **Localized Asset Stress.** This function could be used to limit the maximum output from DG to prevent the overloading of local assets such as transformers.
- **Feeder Overvoltage Conditions.** This function could be used across a large number of devices to prevent high-penetration of PV systems from driving distribution system voltages too high during periods of light load.

### Model Requirements

- PVSystem (one or more)
- No InvControl is required

### Model Input Parameters and Configuration Options

A maximum generation limit function is available on each PVSystem object through use of the pctPmpp property that the user may set in OpenDSS script. The pctPmpp can be set as a percentage value (e.g., 70.0) to which the Pmpp will be limited.

Since the active power output at any moment in time is a function of the Pmpp and the irradiance (minus any efficiency losses due to temperature and any other factors), this has the effect of limiting the active power output to a percentage of what its present value would be otherwise, by multiplying by the percentage value specified by the pctPmpp property.

### Sample Usage in OpenDSS

#### *Implementation in OpenDSS Script*

An example implementation is shown in script as follows.

```
New PVSystem.3P_ExistingSite4 phases=3 bus1=B51854_sec kV=0.415692194 kVA=523
~ irradiance=1 Pmpp=475 kvar=0.00 pctPmpp=70.0 %cutin=0.1 %cutout=0.1
~ yearly=PV_ls
```

```
New PVSystem.3P_ExistingSite1 phases=3 bus1=X_5865228330A kV=0.415692194
~ kVA=314 irradiance=1 Pmpp=285 kvar=0.00 pctPmpp=70.0 %cutin=0.1 %cutout=0.1
~ yearly=PV_ls
```

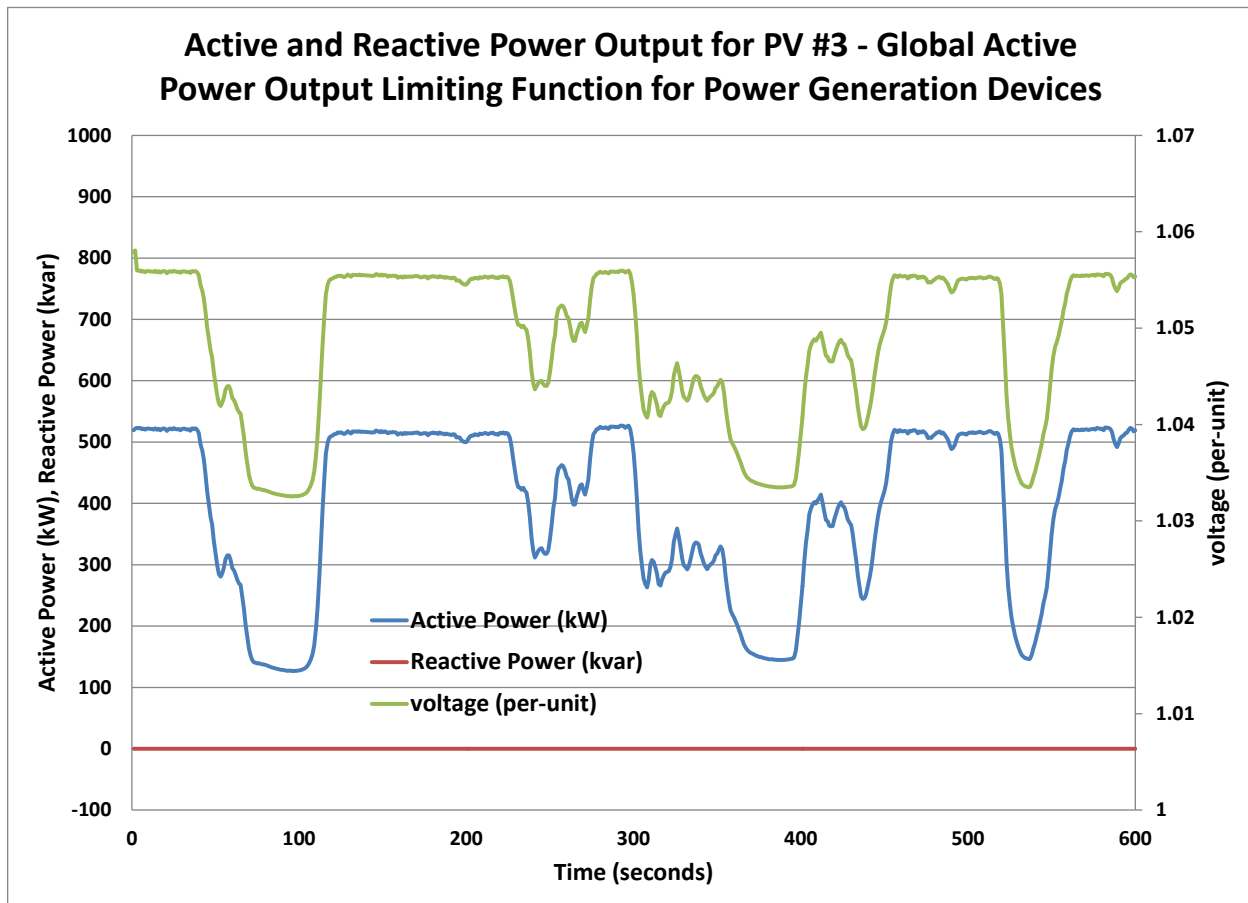
```
New PVSystem.3P_ExistingSite3 phases=3 bus1=X_5891328219_Cust1 kV=0.415692194
~ kVA=836 irradiance=1 Pmpp=760 kvar=0.00 pctPmpp=70.0 %cutin=0.1 %cutout=0.1
~ yearly=PV_ls
```

```
New PVSystem.3P_ExistingSite2 phases=3 bus1=B4832_sec kV=0.415692194 kVA=209
~ irradiance=1 Pmpp=190 kvar=0.00 pctPmpp=70.0 %cutin=0.1 %cutout=0.1
~ yearly=PV_ls
```

The lines of OpenDSS script specifies that the PVSystem objects will operate at a 70% of Pmpp and will generate 0 kvar of reactive power.

### ***Illustration of Operation***

Now that the PVSystem objects have been defined to run at a maximum of 70% of Pmpp, we will repeat the simulation and determine what effects on voltage variations we see. **Figure 9-1** shows the output of the PV Number 3 with respect to active and reactive power, and the resulting terminal per-unit voltage. The terminal voltage uses the right-hand y-axis for its range of values.



**Figure 9-1**  
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under a Maximum Power Generation Limiting of 70% for the PV Systems

# 10

## GENERAL MODEL USAGE

The following sections will provide additional general usage information related to the Inverter Control (InvControl model).

### Applicable Solution Modes

The InvControl model is intended to be used at simulation time-scales of one second or longer. It does not yet have functionality for operating in the OpenDSS 'dynamic' mode, which generally uses sub-second intervals. Therefore, the solution modes in which the InvControl model is applicable are:

- Snapshot
- Daily
- Yearly
- DutyCycle

### Changing Functions and Settings Mid-Simulation

Scheduling functionality is intended to be introduced into the InvControl model in the OpenDSS at some point in the future. In the meantime, the user is able to change functions and settings in the middle of the simulation to mimic scheduling, or to mimic messages being sent to the inverter controls to change their output or control in some fashion.

As a simple illustration of this, we will take the 600 second simulation time frame for which we have irradiance data, and divide this simulation into two segments. During the first 300 seconds, the InvControl device is operating in volt-watt control mode utilizing rated voltage of a PVSystem object to define 1.0 pu voltage. After the first 300 seconds, we change the control mode to simple volt-var control mode (without hysteresis).

In OpenDSS script this can be achieved as follows.

```
New XYCurve.myvw_curve npts=4 Yarray=(1.0,1.0,0.0,0.0)
~ XArray=(0.5,1.0,1.05,1.5)

New InvControl.InvTestPVCtrl mode=VOLTWATT voltage_curvex_ref=rated
~ voltwatt_curve=myvw_curve EventLog=yes

set casename= voltwatt300_voltvar300

solve mode=yearly number=300 stepsize=1s

New XYCurve.myvv_curve npts=4 Yarray=(1.0,1.0,-1.0,-1.0)
~ XArray=(0.5,0.95,1.05,1.5)

InvControl.INVPVCTRL.mode=VOLTVAR

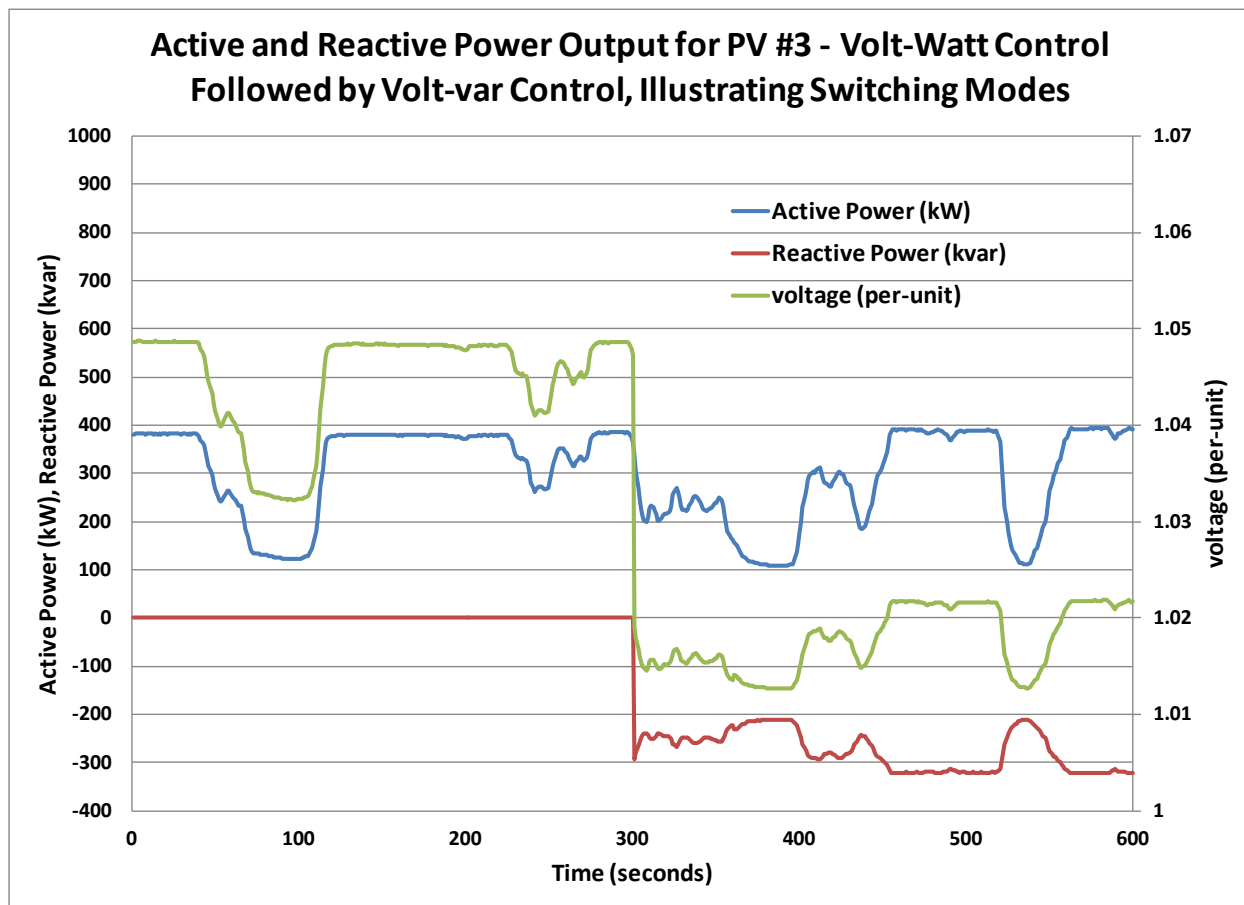
InvControl.INVPVCTRL.voltage_curvex_ref=rated

InvControl.INVPVCTRL.vvc_curve1=myvv_curve
```

```
set number=300
```

```
solve
```

The resulting output is shown in **Figure 10-1** for this example of usage.



**Figure 10-1**  
**Switching from Volt-Watt Mode to Volt-Var Mode at 300 seconds**

### Maximum Number of Inverter Controls

There are theoretically, no limits on the number of inverter controls that can be included in a given circuit model. Practically, the maximum number is limited by the available memory in the computer and the available addressable memory of the operating system and the OpenDSS program. The maximum available addressable memory tends to be limited by the Operating System and the number of bits for which the OpenDSS executable has been compiled.

For the 32-bit version of the OpenDSS, the maximum number of inverter controls would be limited to the maximum addressable memory available to the OpenDSS operating under either a 32-bit operating system or a 64-bit operating system.

For the 64-bit version of the OpenDSS, the maximum number of inverter controls should be a much higher number since the amount of memory that is addressable is significantly greater.

Note that with the EventLog being maintained in memory (for speed purposes), one may encounter an out-of-memory error in the 32-bit version of the OpenDSS if the inverter control(s) insert a large number of messages into the event log. This would be more likely to happen with either a large number of inverter controls or a large number of PVSystem objects under the control of a single inverter control. The EventLog parameter can be set to No or False to inhibit the insertion of entries into the event log.

### **Combining Control Modes**

Control modes cannot be combined in a single InvControl element at present, although this may be considered for future functionality.

### **Time of Day Scheduling**

Presently time-of-day scheduling can be implemented by solving the circuit for a certain period of time in either daily or yearly solution mode, and then switched to another mode by script. This would need to be repeated at any point in time when the scheduled operation mode is desired to be changed.

Future versions of the InvControl model may add the functionality to define time periods throughout the day and those functions that should be applied during those time periods.



# 11

## FUTURE WORK

As time and budget allows, additional functionality may be added to the InvControl model. This section of the document lists a few of the functions or options that may be added in the future:

- Ramp rate control
  - At the time-series power-flow solution time frame, add the capability to limit the change of the quantity being controlled (active power, reactive power, reactive current) such that it is allowed to change a certain percentage (of full-scale rating or possibly present available output level) per second, per minute, or per hour.
  - This may make the modes, especially dynamic reactive current control mode, slightly more stable from an operational (i.e., ‘in the field’) and numerical solution stand-point.
  - This may also allow for mitigation against high variability in solar resource output, although it may require added energy storage devices for this behavior, under certain circumstances.
- Combined function usage
  - Certain utility groups have indicated an interest in perhaps combining control modes, given a user-defined control mode hierarchy.
  - For instance, a user may want to operate a PV system with inverter control in volt-var mode, but change to dynamic reactive current control mode if the voltage at the terminals of the PV system change by more than a certain percentage in a short period of time. Once the event has passed, the user may wish to return to volt-var control mode.
- Time-of-day scheduling of modes
  - Scheduling of modes based on time-of-day may help to better coordinate with load-level changes throughout the day, and may also be beneficial for reducing losses, say at light loading periods by changing control modes.

Additionally, future analyses will likely look at the effectiveness of the inverter control modes described in this Technical Update with respect to hosting capacity limits on distribution feeders.





# 12

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