Modeling High-Penetration PV for Distribution Interconnection Studies

Smart Inverter Function Modeling in OpenDSS, Rev. 2

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Technical Update, October 2013

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ABSTRACT

A great deal of work has been done by the Electric Power Research Institute (EPRI) and others with respect to the analysis of high-penetration photovoltaics at the distribution level (such as hosting capacity determinations). EPRI has also, over the past few years, been leading an effort to develop a common set of smart inverter grid-support functions. The objective of this project, summarized in this report, is an effort to combine these two initiatives by implementing the grid support functions that have been identified within the industry and model them so that the industry can evaluate function efficacy, investigate the potential impact on distribution feeder operation and hosting capacity, and eventually implement these functions in commercially available software.

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 photovoltaics 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 an actual distribution feeder and local solar measurements.

Keywords

Distributed solar photovoltaics (PV)
Distribution planning
Hosting capacity
OpenDSS
Open-source distribution software
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 solar PV (see Figure 1-1). This particular report is essentially an updated report to that published last year [5], including functionality added and/or modified to the OpenDSS models previously developed in and documented in 2012.

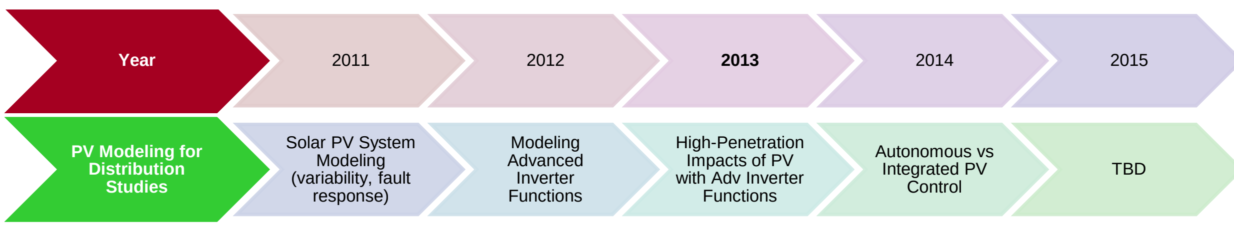

Figure 1-1
Timeline of 2012 Effort Relative to Project's Past/Future Efforts

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 Relative to Hosting Capacity for PV

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 PV hosting capacity at the local distribution level. These functions include maximum generation limit, fixed power factor, intelligent volt-var, volt-watt, dynamic reactive current, and watt-power factor. Each of these specific functions, with the exception of watt-power factor which was recently added in 2012 [6], are the focus of this effort.

The particular smart inverter functions that have been identified in this effort are summarized in Table 1-1.

Table 1-1
Smart Inverter Functions

Smart Inverter Function	Summary	Application
Connect/Disconnect	utility control for connect/disconnect	PV/ES
Maximum Generation Limit	reduce maximum output of DER	PV/ES
Charge/Discharge Management	managing charge/discharge of ES	ES
Fixed Power Factor	fixed power factor regardless of voltage or watt output	PV/ES
Intelligent Volt-var	var output based upon local voltage and watt output	PV/ES
Volt-watt	watt output based upon local voltage and watt output	PV/ES
Frequency-Watt	frequency-based watt control	PV/ES
Watt-Power Factor**	watt-based PF control	PV/ES
Low/High Voltage Ride Through	ability to remain online during low and high voltage events	PV/ES
Dynamic Reactive Current	"fast" var response to sudden voltage conditions	PV/ES
Real Power Smoothing	controlling charge/discharge to reduce watt fluctuations	ES
Dynamic Volt-Watt	"fast" watt response to sudden voltage conditions	ES
Load/Generation Following	dispatching of DER to match load and/or other generation	ES

Impacts PV-Related Hosting Capacity

* New in 2012

Previous Work

Previous work [7] has investigated the use of volt-var and the potential feeder voltage improvement that can be realized when utilized along with solar PV. Results had shown the volt-var control, when implemented with PV connected to a voltage-constrained feeder, can have a significant impact on system voltage. The functional definition of volt-var control implemented previously has since been updated to include additional control options such as hysteresis. This additional control will be highlighted in this report.

Project Summary

This report describes work that involves implementing the smart inverter, grid-support functions in distribution system analysis software. The smart inverter function 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.

Work Moving Forward

The next phase of this effort will be to apply these functions in actual distribution feeder models that are seeing low hosting capacities for PV and evaluate the use of these functions for increasing hosting capacity. Among other things, this could include:

- Use stochastic PV analysis (DPV Feeder approach) on a wide range of feeder configurations using various smart inverter functions
- Time series analysis to determine % observable improvement in feeder response under various smart inverter function implementation
- Use of smart inverters for coordination with conservation voltage reduction (CVR)
- Smart inverter functions are only as effective as the settings that are employed for a given feeder. Parameter optimization of such functions could allow for a determination of which settings work more effective under given conditions (time of day, type of solar PV variability day, location of PV along the feeder, etc)
- Autonomous vs integrated control

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.

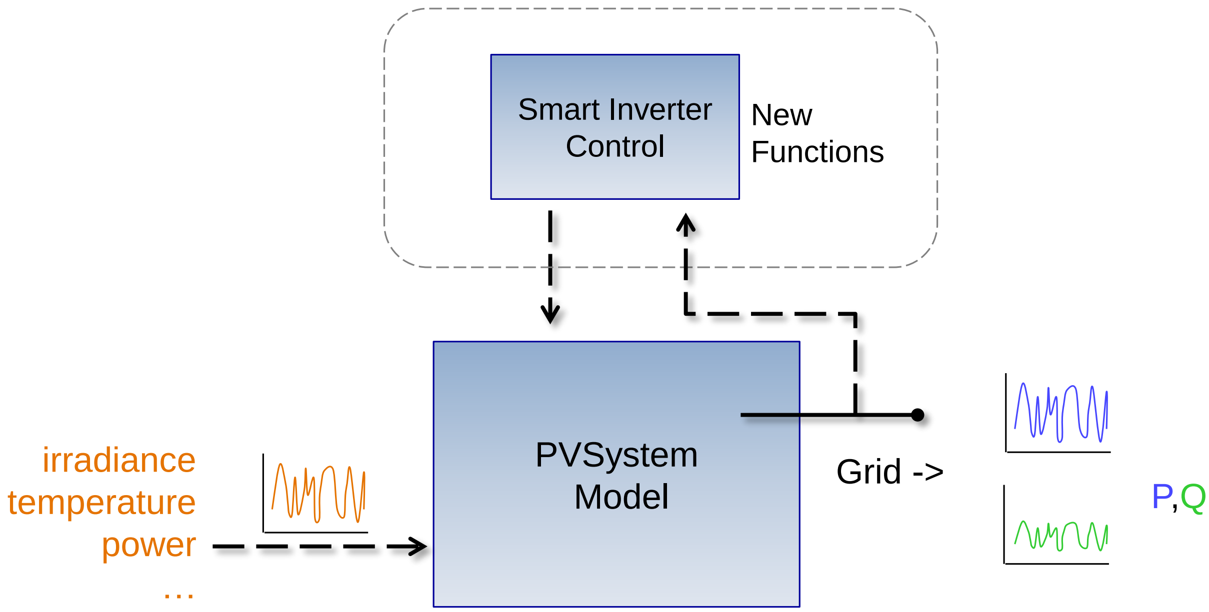

Figure 2-1
Simplified Block Diagram of the Entire PV System and new Inverter Control

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, Pmpp, at a selected temperature and an irradiance of 1.0 kW/m2. 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 Pmpp varies with T relative to the temperature chosen for the rated Pmpp at 1 kW/m2. 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 Pmpp 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].

A 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) to 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 utility-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 more narrow range of setpoints to provide much tighter voltage regulation. The reactive power output values are 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.

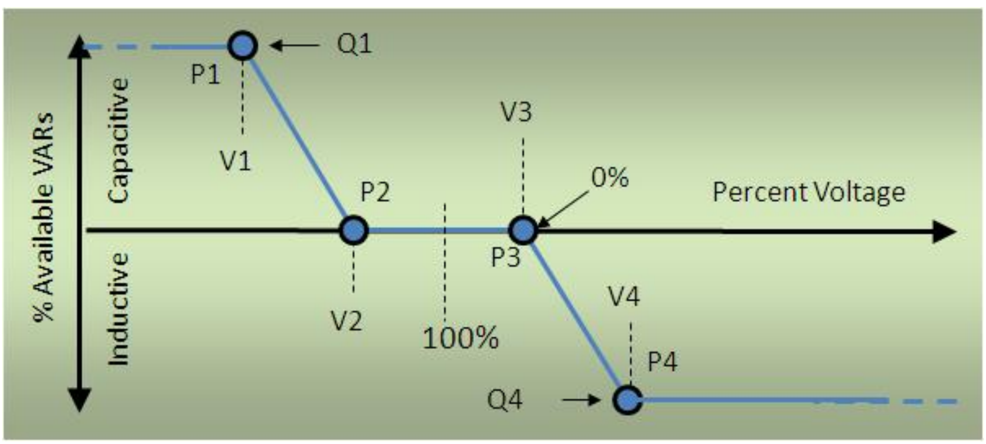

Figure 3-1
Example Array Settings to Describe Desired Volt-var Behavior

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.

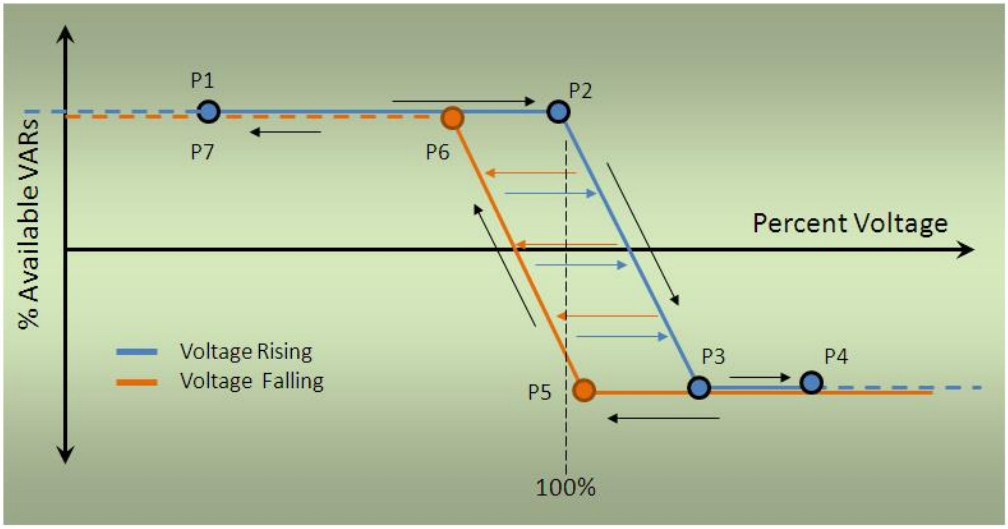

Figure 3-2
Example Array Settings with Hysteresis

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.

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. 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. 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.

$$\boldsymbol{kvar_{available}} = \sqrt{(\boldsymbol{kva\_rating})^2 - (\boldsymbol{present\_kW})^2} \qquad \textbf{Eq. 3-1}$$

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.

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 (as a percentage of available vars)
  - 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 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 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 the control modes VOLTWATT and VOLTVAR, 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: 0s
- Possible values: an integer (whole number) 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 an individual PVSystem may reach the tolerance within different numbers of control iterations.
  - Optional/Required: Optional.
  - Default value: 0.025 (per unit of available vars)
  - 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 an individual PVSystem 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: **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 available var output within plus or minus 'x' per-unit available vars 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, we will introduce here a radial distribution circuit that has four existing PV installations. 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^2

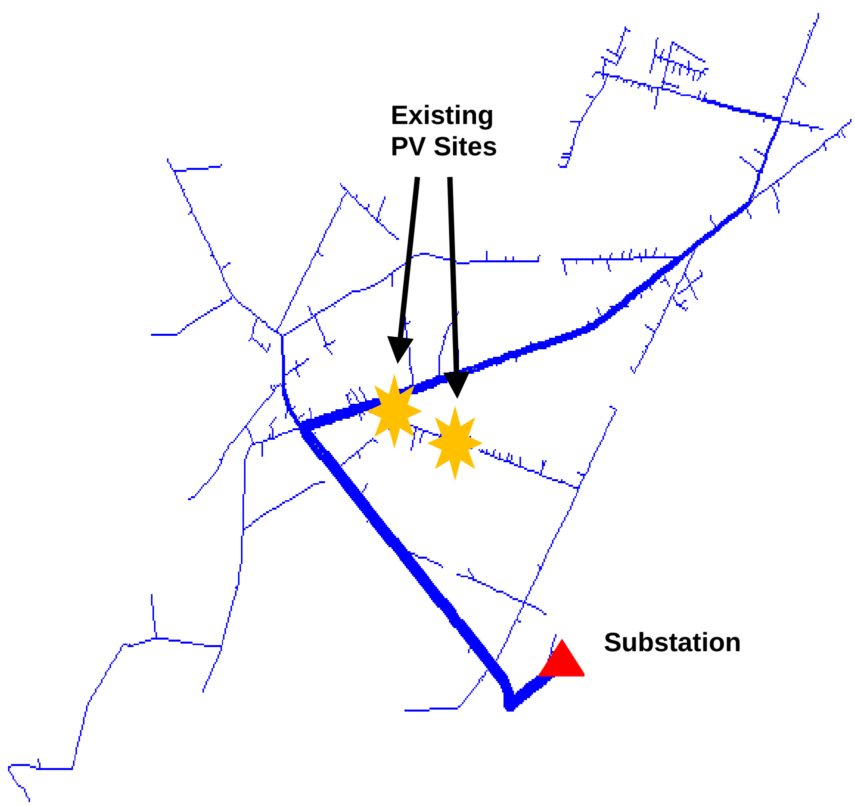

Figure 3-3
Distribution Circuit Showing Locations of Existing PV Installations

For our purposes here, we utilize a ten minute window of AC output power collected at one of the four PV installations on this circuit, 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.

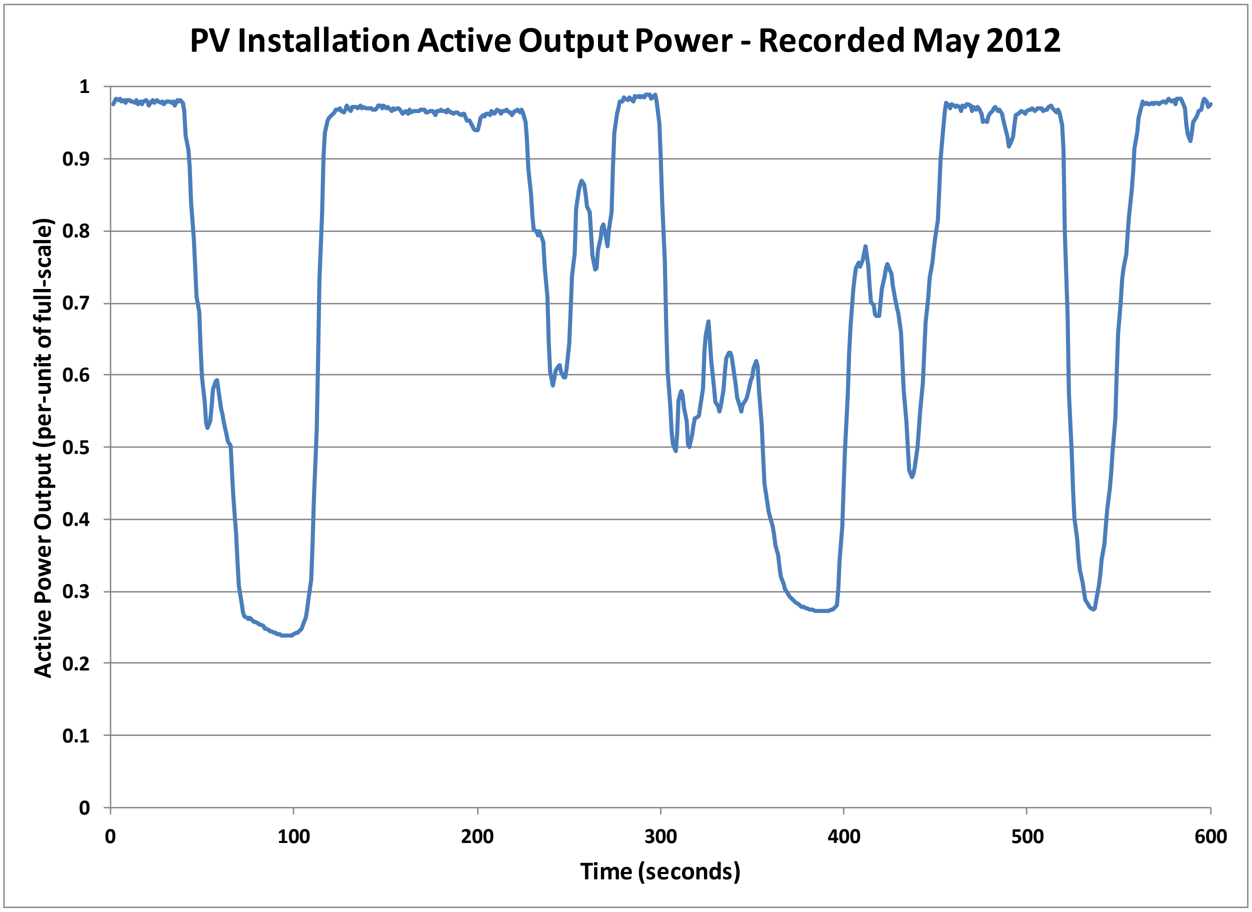

Figure 3-4
Active Power Output Recorded at an Existing PV Installation in May 2012 on the Distribution Circuit

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), we will define four PVSystem objects to represent the four PV installations on this circuit. These four PVSystem objects are defined in the following OpenDSS script.

```
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, we run the 600 seconds of simulation time 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. 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.

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.

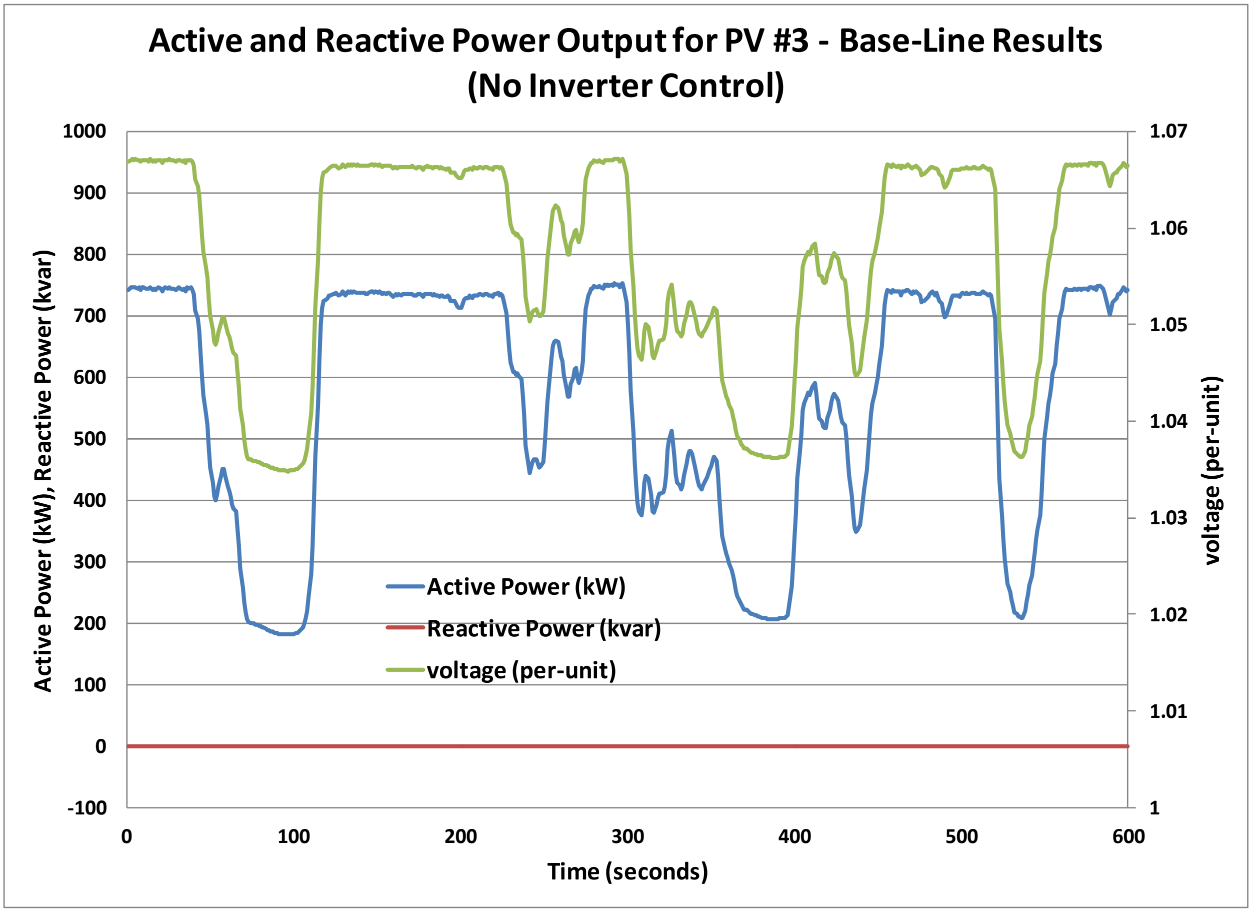

Figure 3-5
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating without any Inverter Control

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_curvex_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.

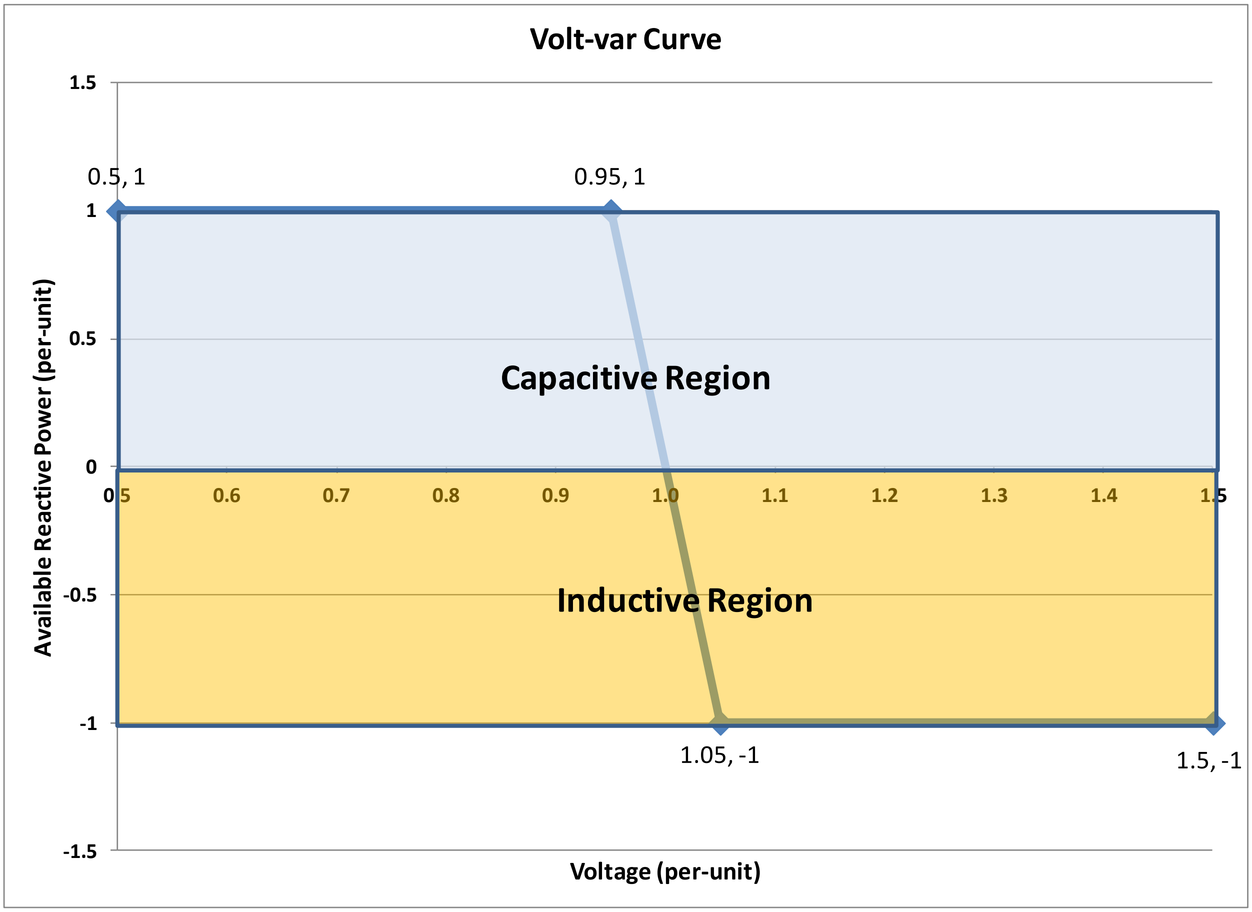

Figure 3-6
Volt-var Curve Utilized for Illustrating Operation of Basic Volt-var Control Mode

Illustration of Operation

Continuing with the same active power input curve, applied to all 4 PV systems in the circuit, we now run the simulation 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.

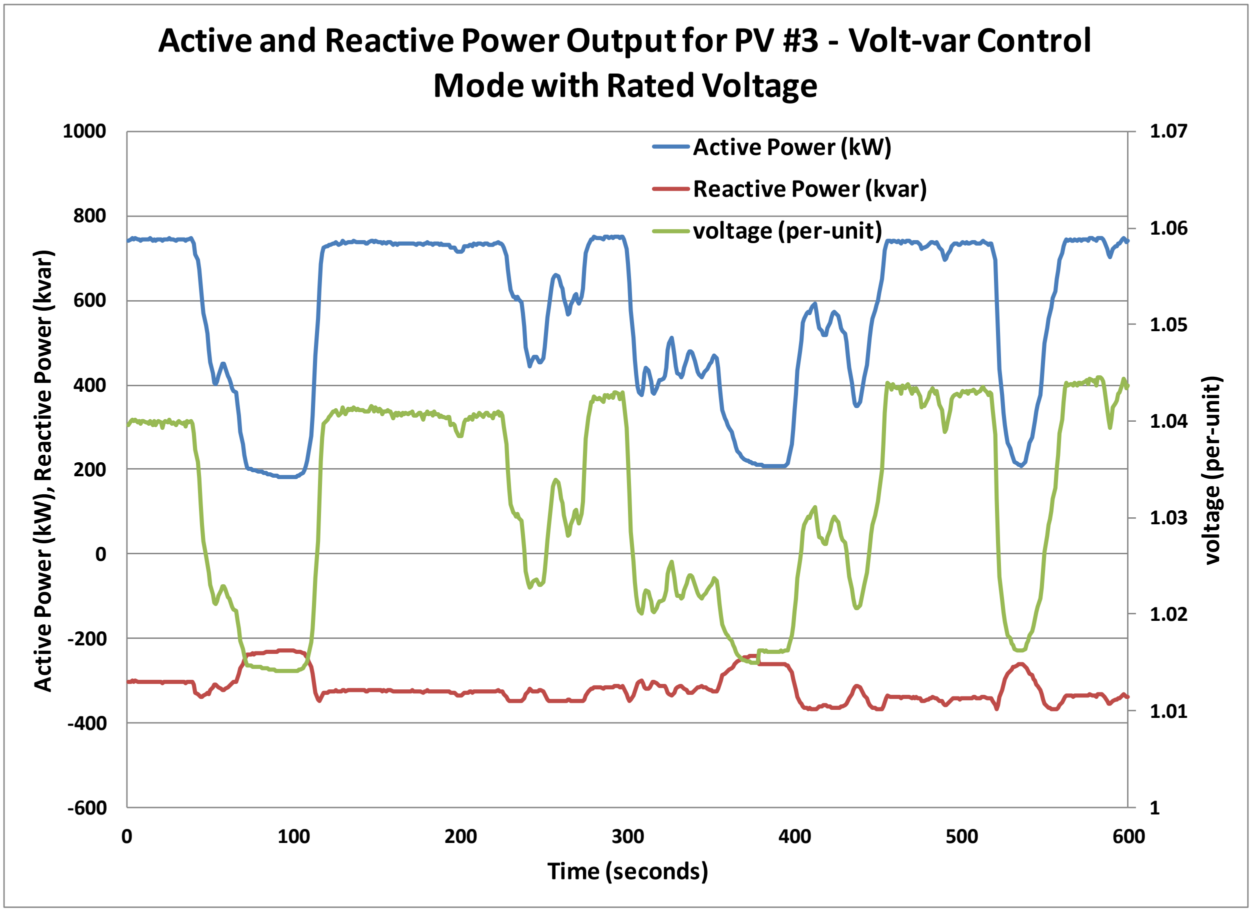

Figure 3-7
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-var Control Mode without Hysteresis

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 our example here, we will define a hysteresis offset of -0.025 pu voltage. In order to preserve symmetry around the 1.0 pu voltage value, we will re-define the number one curve to be 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.

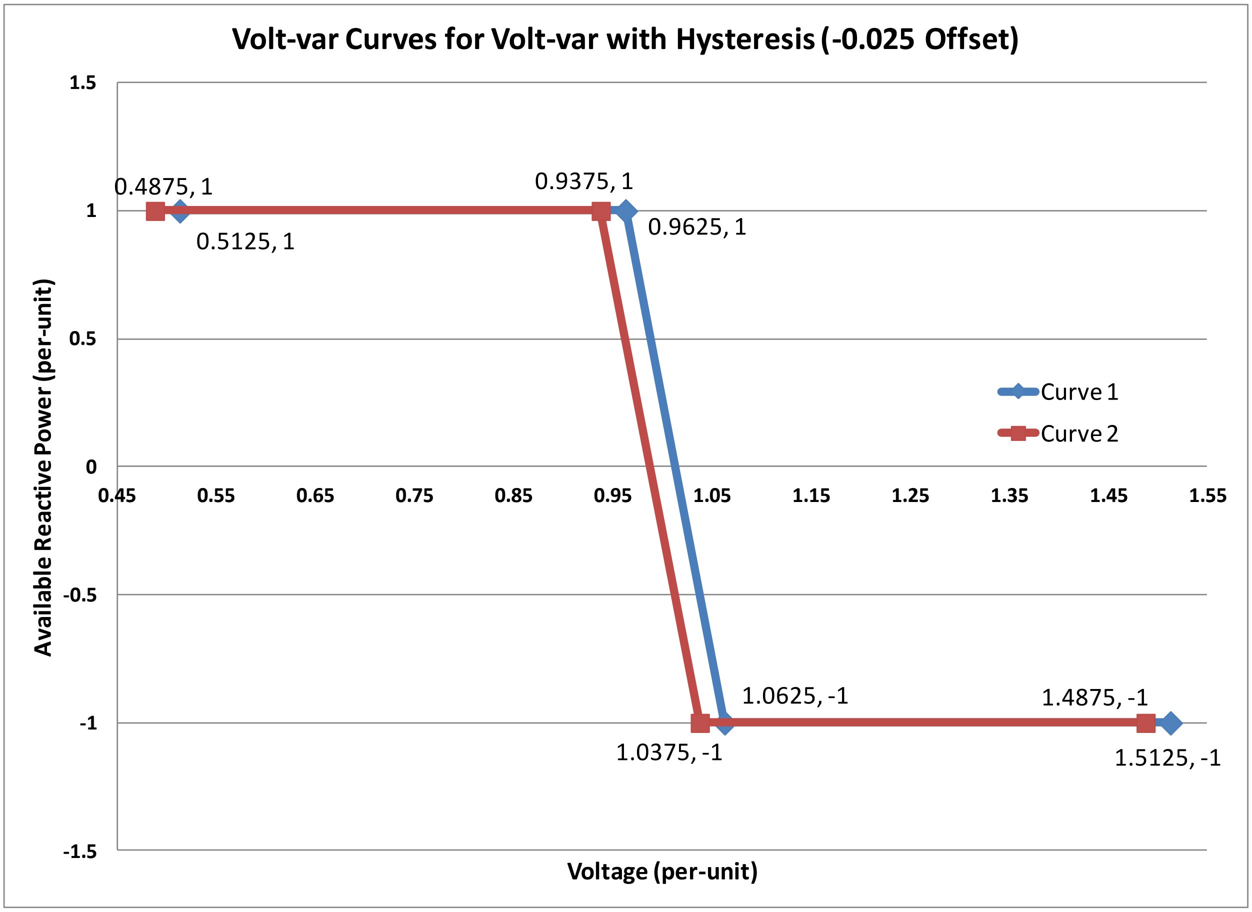

Figure 3-8
Volt-var Curves Utilized for Illustrating Operation of Volt-var Control Mode with Hysteresis

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_curvex_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, we can also plot the output reactive power (in per unit of available vars) as a function of voltage, against the two volt-var curves (Figure 3-10). 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.

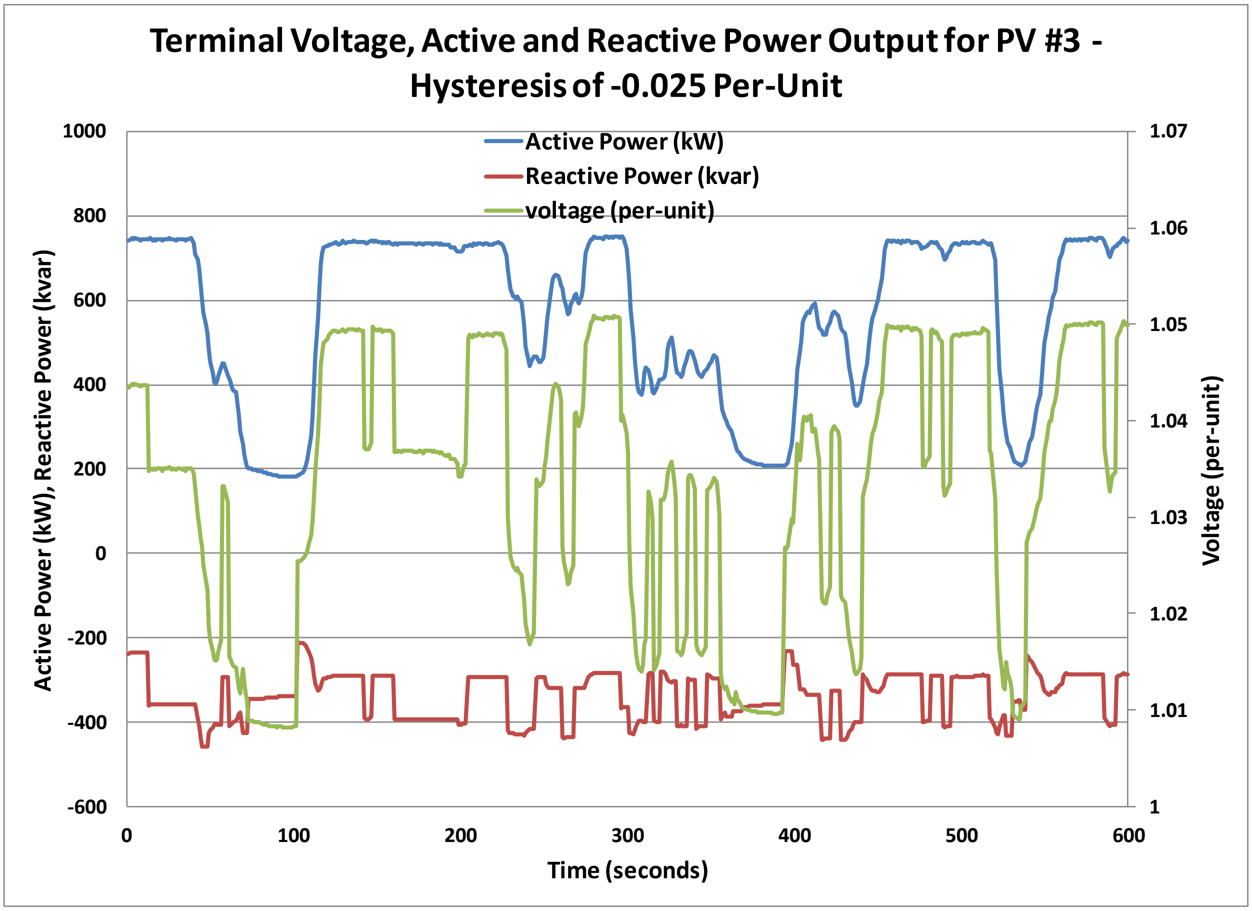

Figure 3-9
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-var Control Mode with Hysteresis Offset of -0.025 Per-Unit Voltage

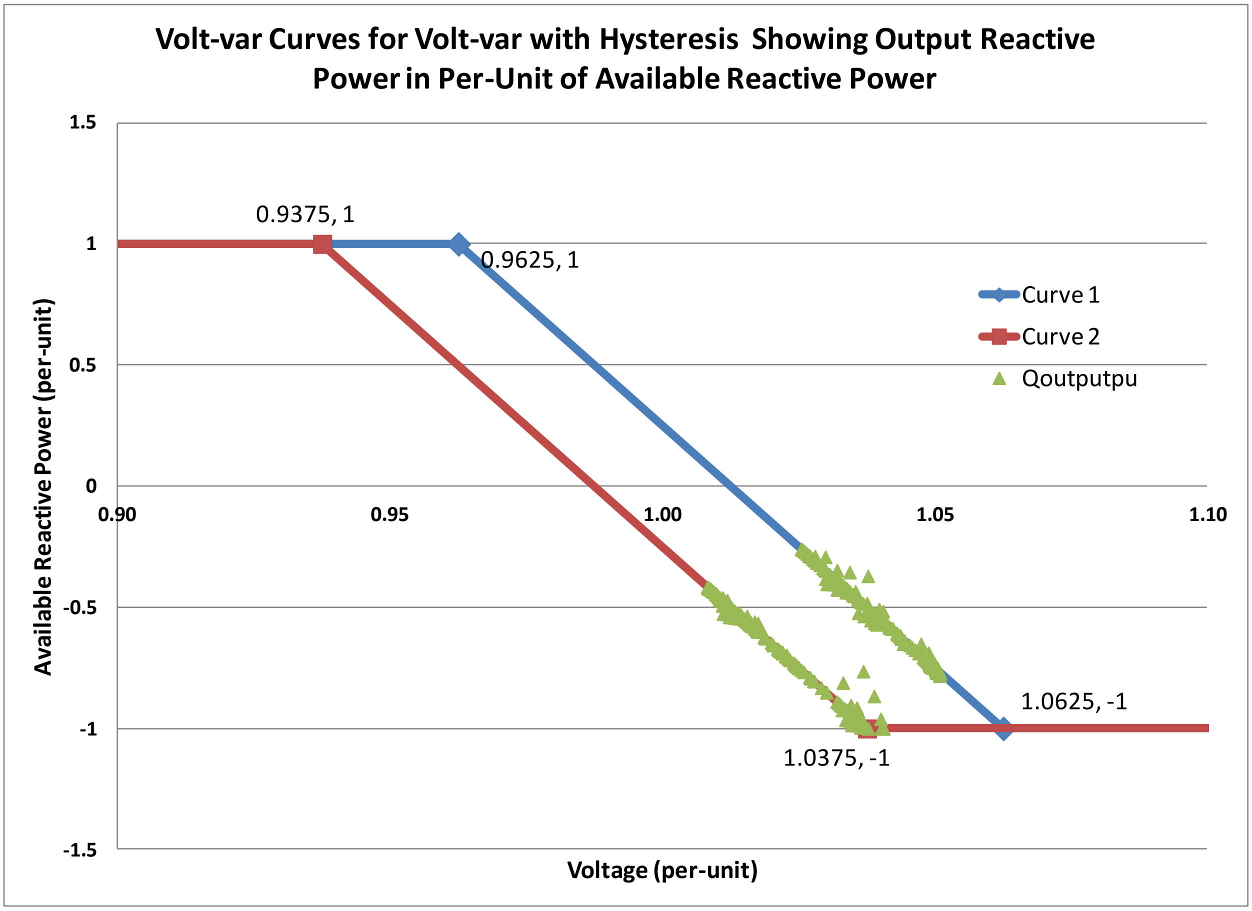

Figure 3-10
Reactive Power Output in Per unit of Available Vars and the Two Volt-var Curves Utilized for Illustrating Operation of Volt-var Control Mode with Hysteresis

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. This curve is shown in Figure 3-6 with the capacitive and inductive reactive power regions indicated.

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 we will be utilizing a rolling average window 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.

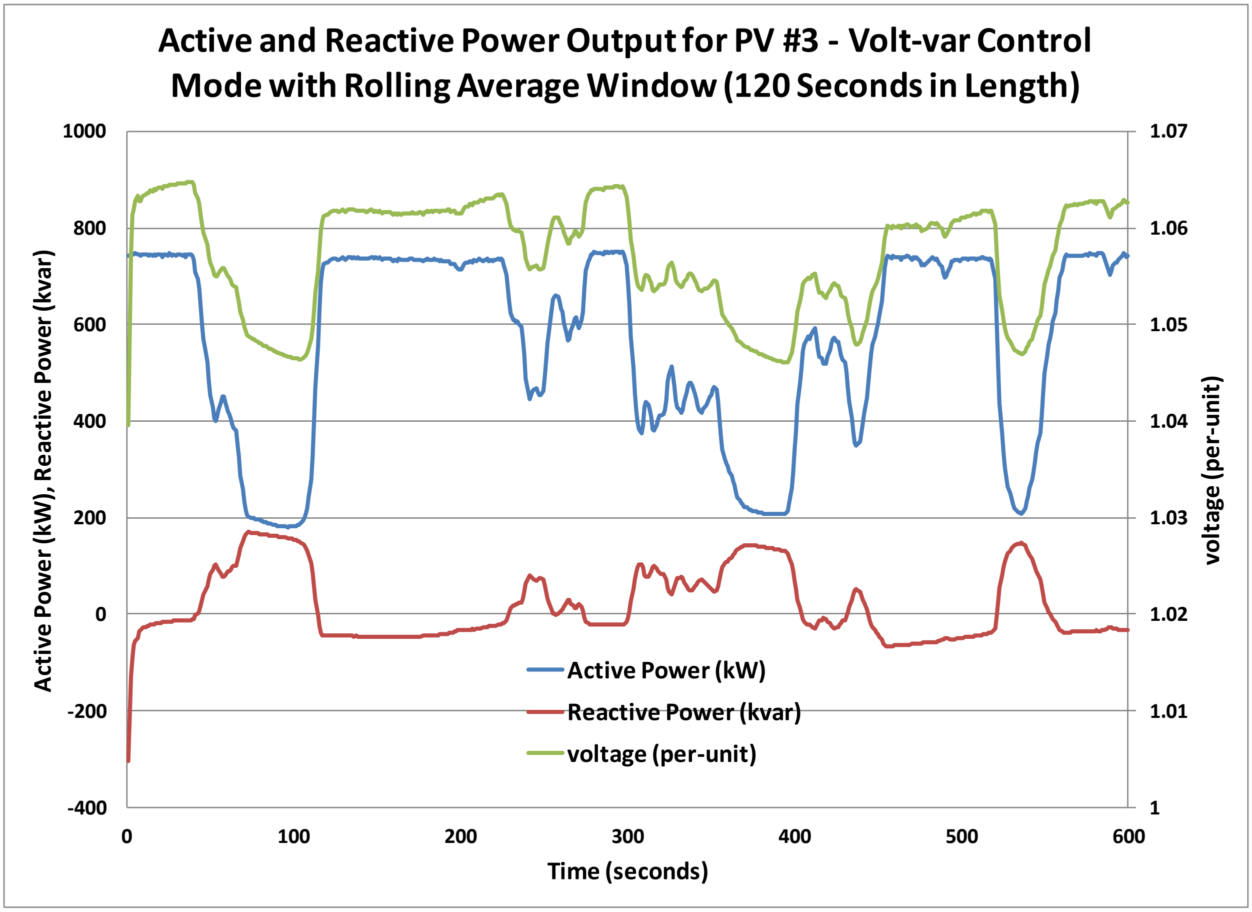

Figure 3-11
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-Var Control Mode with Rolling Average Window with Length of 120 seconds

So the adaptive set-point attempts to follow the average terminal voltage over time. Should our simulation have been performed on a system with conservation voltage reduction (CVR) in effect, we 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 Low-Pass Filter Rate-of-Change Limiting

Implementation in OpenDSS Script

The following script shows how to utilize the low-pass filter rate-of-change limit function and how to set its' time constant (tau).

```
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=rated
~ vvc_curve1=vv_curve RateofChangeMode=LPF LPFTau=5 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, 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, by default, are defined in per unit of the rated voltage of the PVSystem object since no parameters were included to change from default behavior. This indicates that we will be utilizing a rolling average window to provide an adaptive voltage set-point. The volt-var curve to be utilized is the one named vv_curve.

The rate-of-change mode is set to mimic the behavior of an RC low-pass filter with tau=5 seconds.

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 per-unit of available vars) from a simulation with normal VOLTVAR mode operation is shown in the blue curve. The red curve shows the effects of adding the low-pass filter rate-of-change limit with the time constant (tau) of the filter set to five-seconds.

The effects of the rate-of-change limiting function in the form of a low-pass filter with tau=5 seconds are evident in the smoothness of the red curve compared to the more highly variable output from the normal VOLTVAR mode operation. (Figure 3-12).

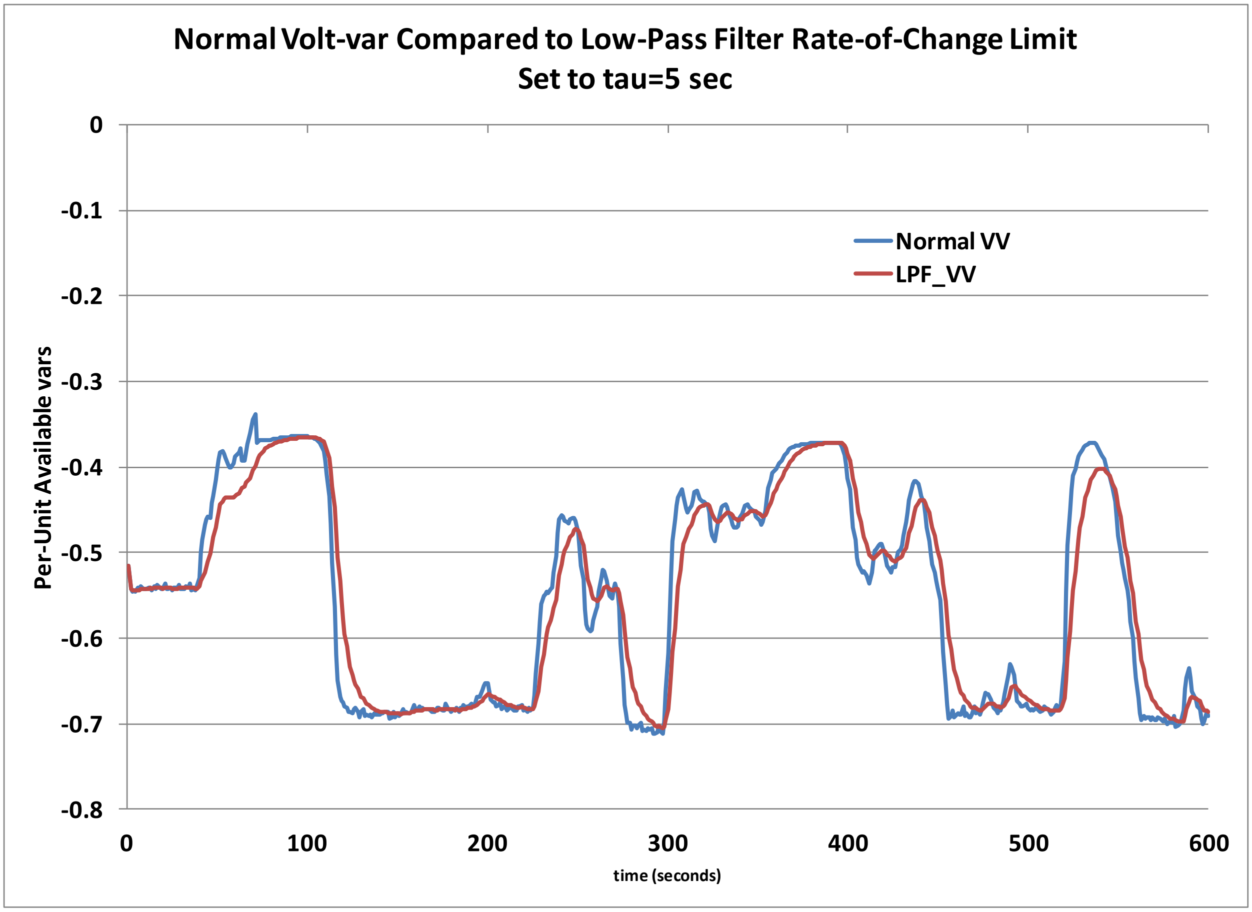

Figure 3-12
Per-Unit Available Reactive Power Output for PV Number 3, Results when Operating under Normal Volt-Var Control Mode, and with Low-Pass Filter Rate-of-Change Limit Engaged (tau=5 seconds)

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.

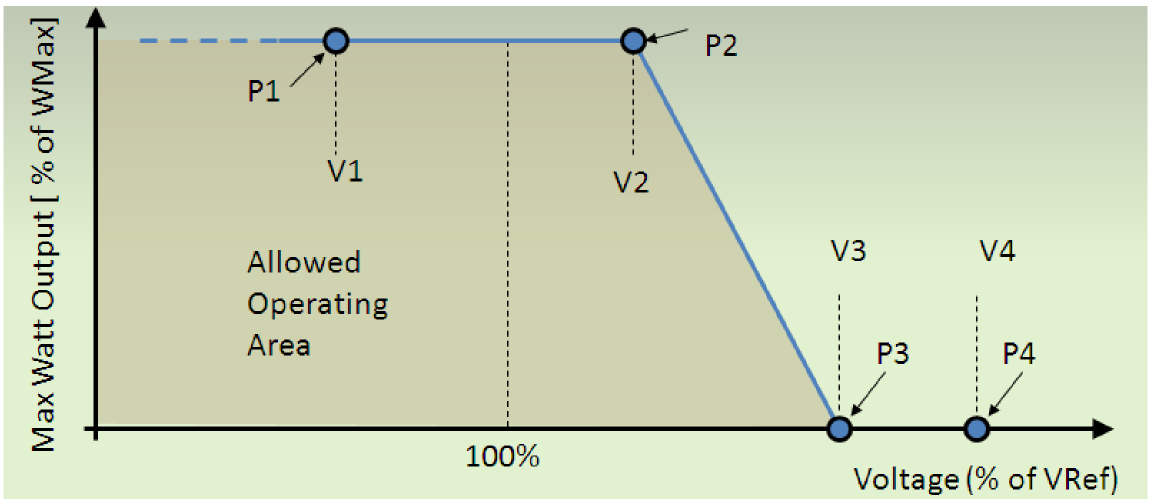

Figure 4-1
Example Volt-watt curve

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-var 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 reactive power as a function of the terminal voltage at the PVSystem object.

The y-axis units for the XYCurve are, unlike that which is indicated in Figure 4-1, in per unit of the present active power output for the PVSystem object(s) under control. 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 we set the y-axis point at 1.1 pu voltage at a level of, say, 80% of rated maximum active power (0.8 pu), and we are 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. A sample set of points is shown in Figure 4-1 for a simple volt-watt curve. Note, again, that the y-axis is in per unit of present active power output.

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 objectss, 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), 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: 0s
  - Possible values: an integer (whole number) 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.
  - Optional/Required: Optional.
  - Default value: PMPPPU
  - Possible values: PMPPPU | PAVAILABLEPU

- 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 either available active power output or full-scale active power output, within plus or minus 'x' per-unit available or full-scale 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 available, or full-scale active power output per second in both the inductive and capacitive direction. 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

We will utilize the same distribution circuit and PVSystem objects as for the VOLTVAR control mode cases, modifying as needed for the VOLTWATT control mode. See Figure 3-3 for a one-line diagram of the circuit, and see the section titled: **Sample Usage in OpenDSS** 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_curvex_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 present active power (‘y’ value) for each of the four points. This volt-watt curve is shown in Figure 4-1.

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.

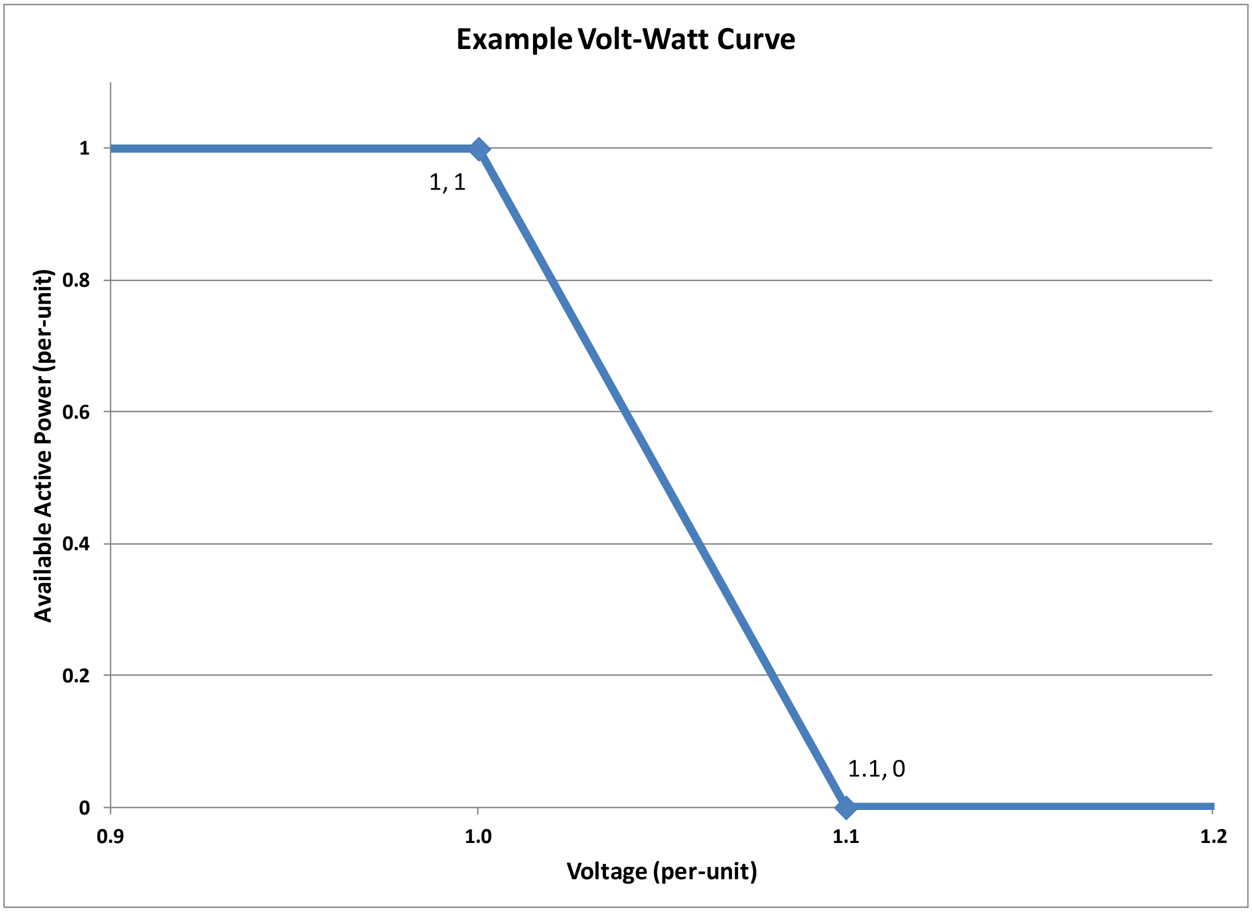

Figure 4-2
Volt-Watt Curve Utilized for Illustrating Operation of Volt-Watt Control Mode with Rated Voltage

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. Even with an ‘aggressive’ volt-watt curve that begins to decline after 1.0 pu voltage, resulting in substantial active power output reduction, there is only a slight reduction in voltage due to decreased active power output.

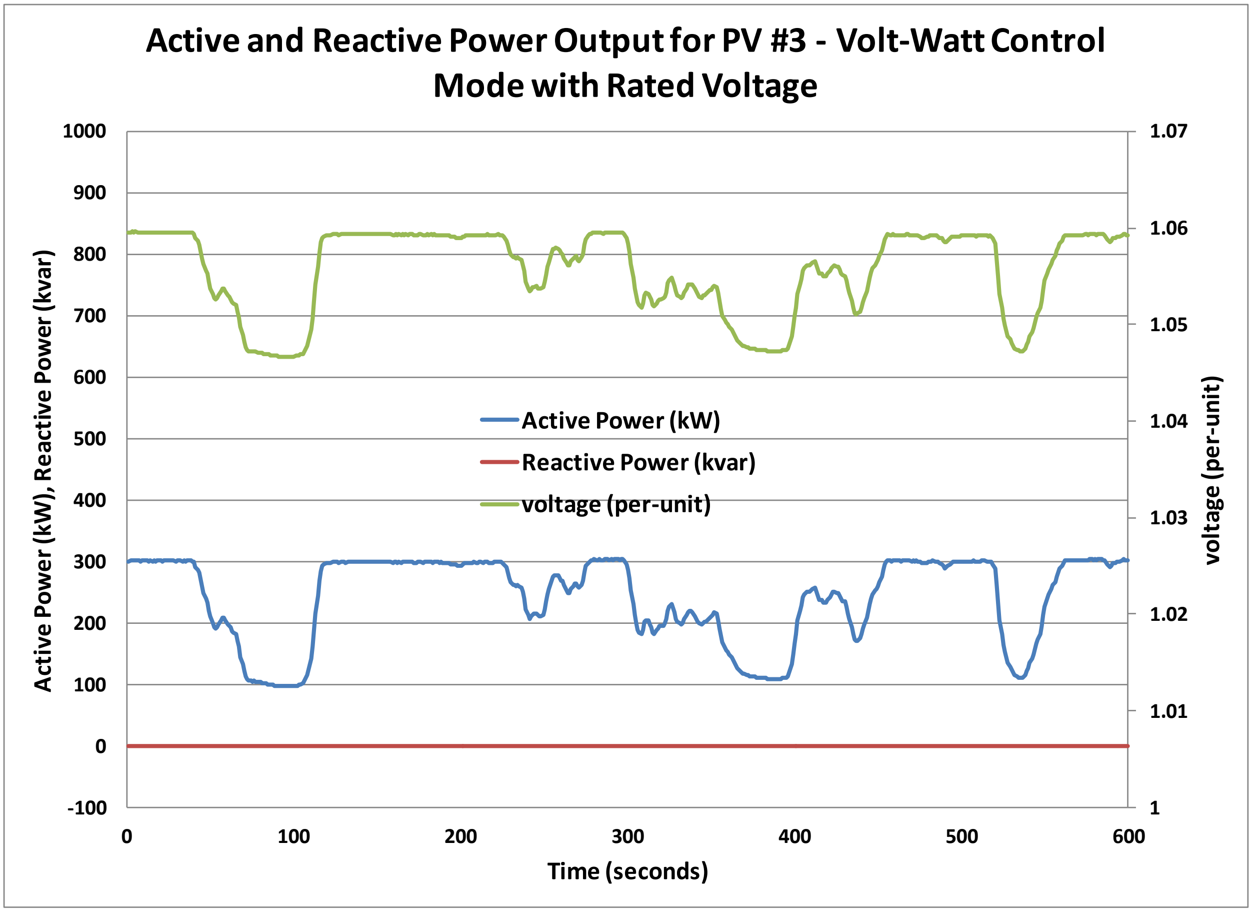

Figure 4-3
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Volt-Watt Control Mode with Rated Voltage Utilized

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 Pmpp, 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 Pmpp per second, the rise/fall rate-of-limit function will limit the change in output to 0.02 per-unit Pmpp 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 Pmpp) 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 Pmpp per second (Figure 4-4)

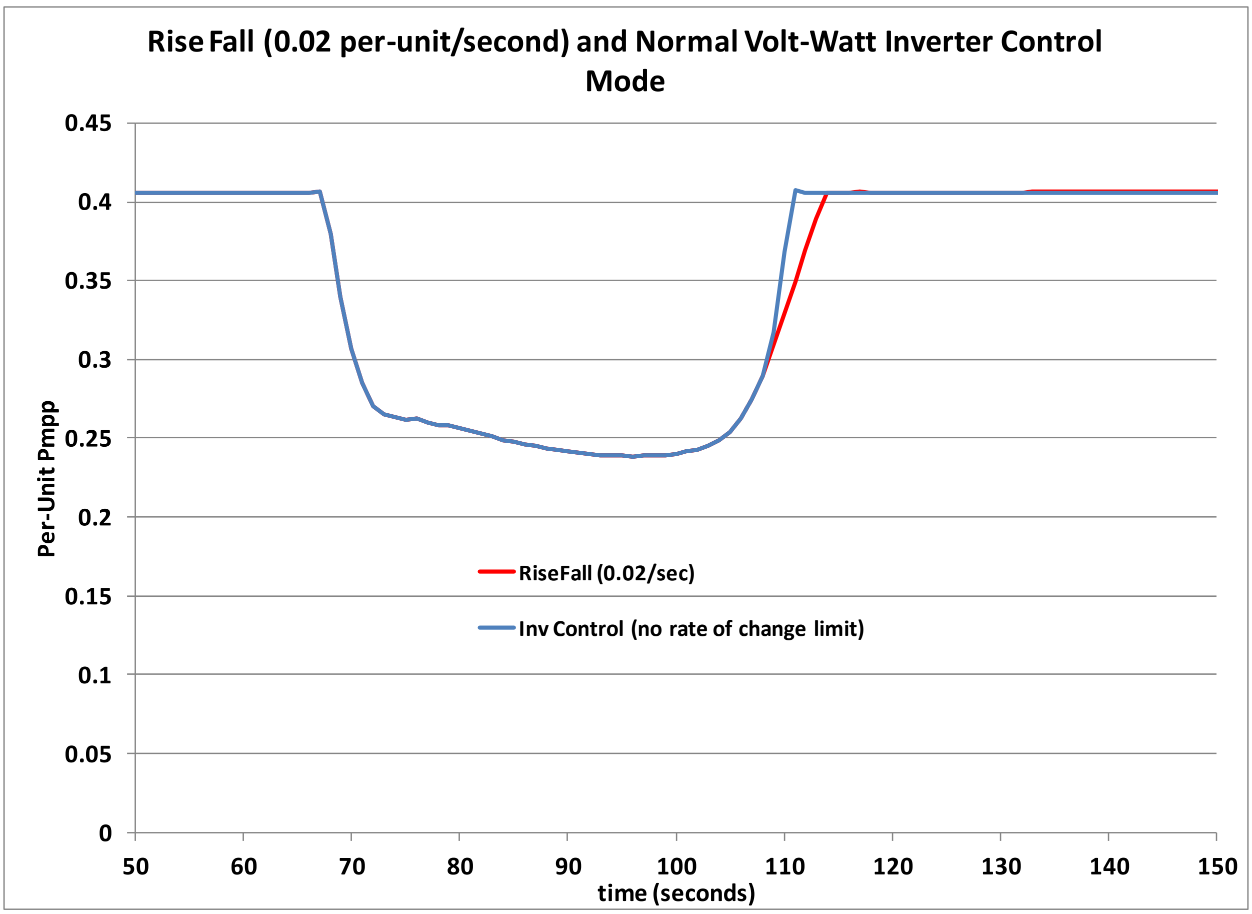

Figure 4-4
Per-Unit Pmpp of Active Power Output for PV Number 3, Results when Operating under Normal Volt-Watt Control Mode, and with Rise/Fall Rate-of-Change Limit Engaged (0.02 p.u. Pmpp per second)

5
DYNAMIC REACTIVE CURRENT FUNCTION

Function Scope

This function is intended to provide a flexible mechanism through which inverters may be configured to provide reactive current support in response to dynamic 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 [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.

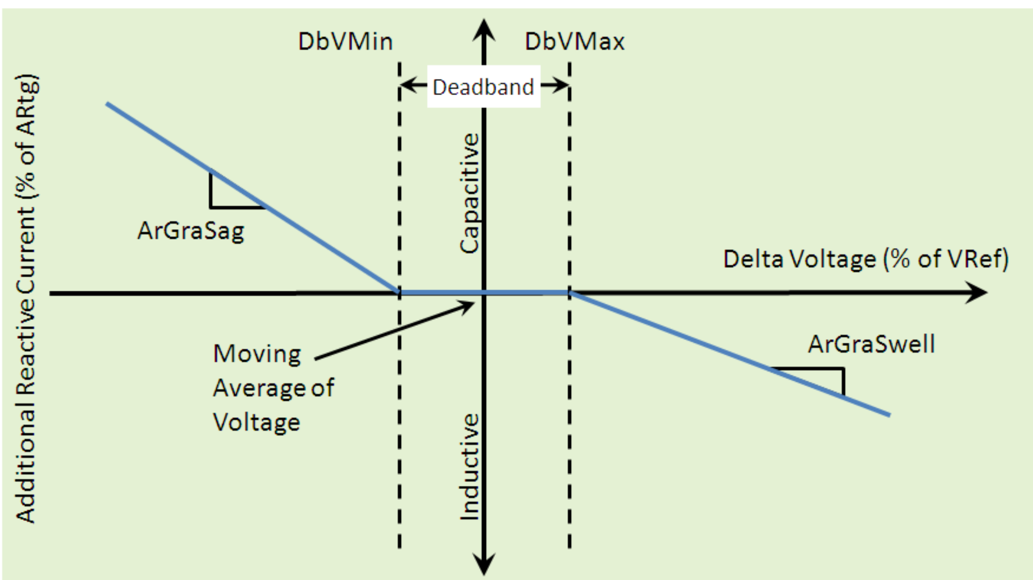

Figure 5-1
Dynamic Reactive Current Support Function, Basic Concept

Function Application

This is a type of dynamic system stabilization function. Such functions create an effect that is in some ways similar to momentum or inertia, in that it resists rapid change in the controlling parameter.

Power quality, such as flicker, may be improved by the implementation of functions of this type and 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 due to faults, sudden switching off or on of capacitors, or due to abnormal voltage regulator actions.
  - 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: 0s
  - Possible values: an integer (whole number) 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 (per unit of available vars)
  - 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

An example implementation is shown in script as follows.

```
New InvControl.InvTestPVCtrl mode=DYNAMICREACCURR DbVMin=0.975 DbVMax=1.025
~ ArGraLowV=10.0 ArGraHiV=10.0 DynReacavgwindowlen=120s EventLog=yes
```

This 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 dynamic reactive current control mode.

The minimum and maximum voltage values which define the dead-band are 0.975 pu and 1.025 pu, referenced to rated voltage. We have chosen to set the high voltage and low voltage gradients to 10.0. This means that for every percent of deltaV, which is calculated by subtracting the rolling average window value from the present voltage (and dividing by the PVSystem object's rated voltage), we want 10.0 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 dead-band we are on. This is illustrated in Figure 5-2.

The dynamic reactive current rolling average window length is set to 120 seconds, or two minutes in length. 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.

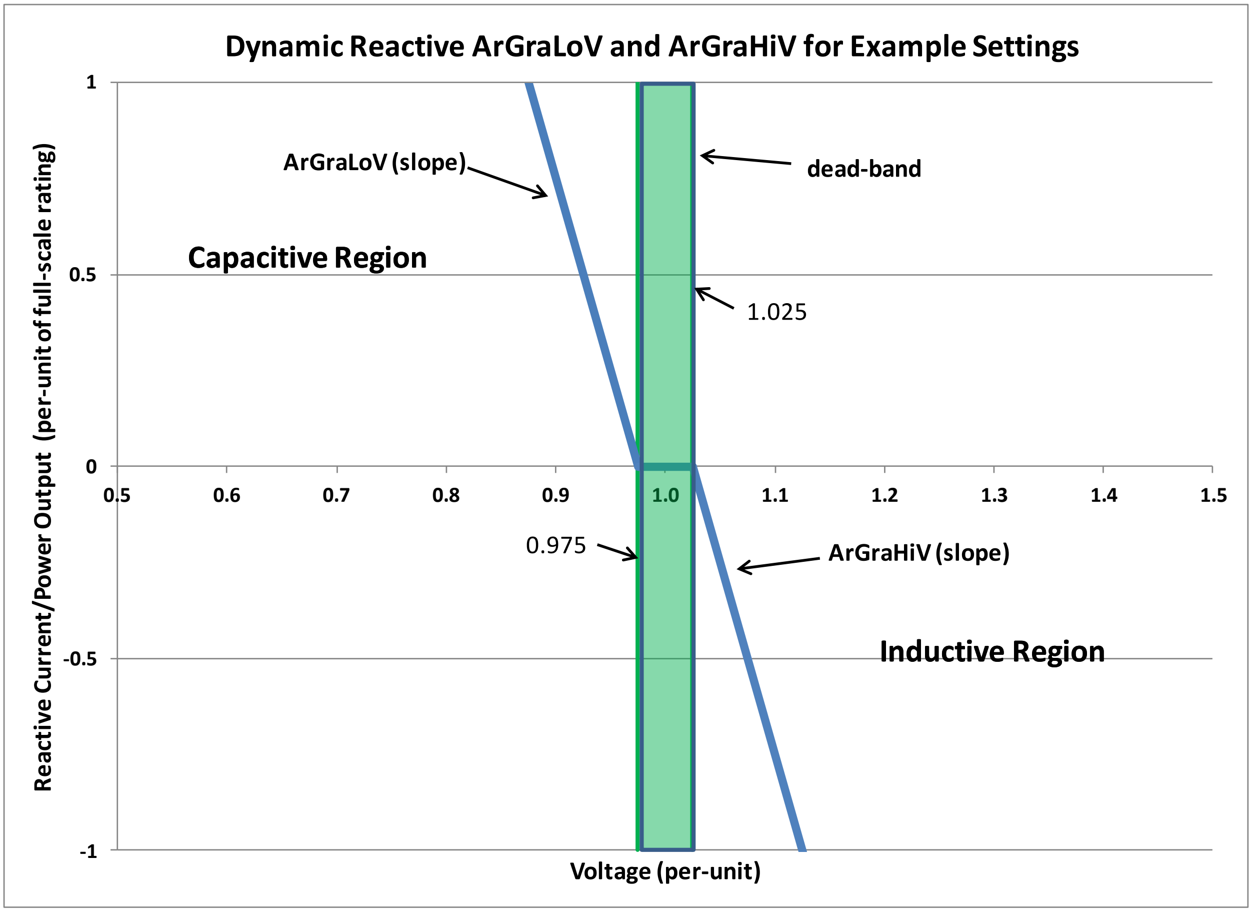

Figure 5-2
Dynamic Reactive Current Control Output (Shown in Blue) for Different Values of DeltaV

Dynamic Reactive Current

In order to simulate a low-voltage event, we apply a relatively high-impedance three-phase-ground fault a couple of spans away from the interconnect transformer at about 450 seconds into the simulation. The fault is left on the system for two seconds and then removed Figure 5-3 shows the depth to which the voltage drops during the fault event. Note that the PV are operating at unity power factor, without any control.

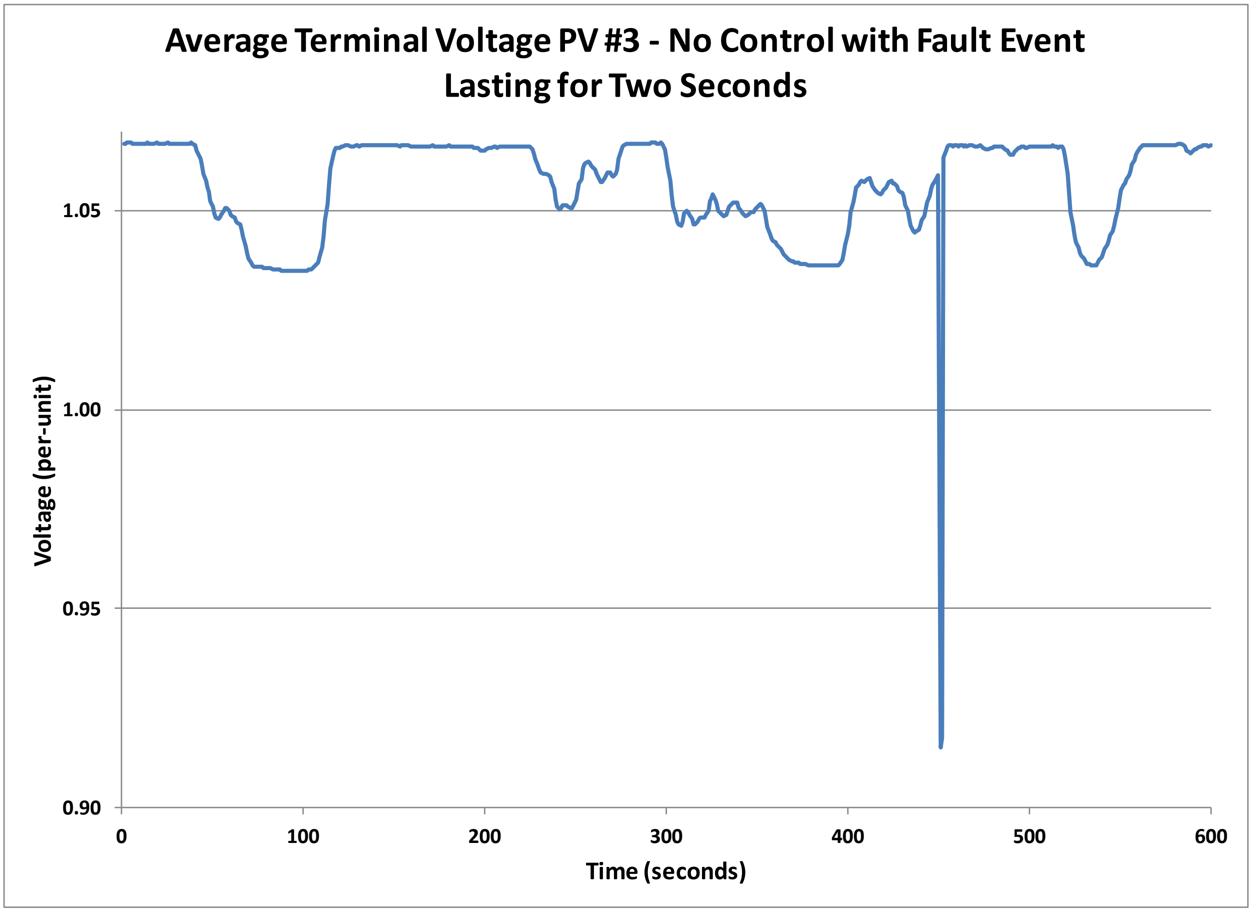

Figure 5-3
High-Impedance Three-Phase Fault Occurring at about 450 seconds into the Simulation, Fault Duration = 2 seconds

Illustration of Operation

Now the InvControl object is activated, using a window length of 120 seconds (2 minutes) with the settings given above in the OpenDSS script. A plot of the active and reactive power output as well as the terminal voltage is shown in Figure 5-4. For a view of the amount of reduction in the depth of the voltage drop due to the fault, by implementing dynamic reactive current control mode, Figure 5-5 shows the voltage drop with and without the control mode engaged. This is a composite of Figure 5-3 (no control) and a portion of Figure 5-4.

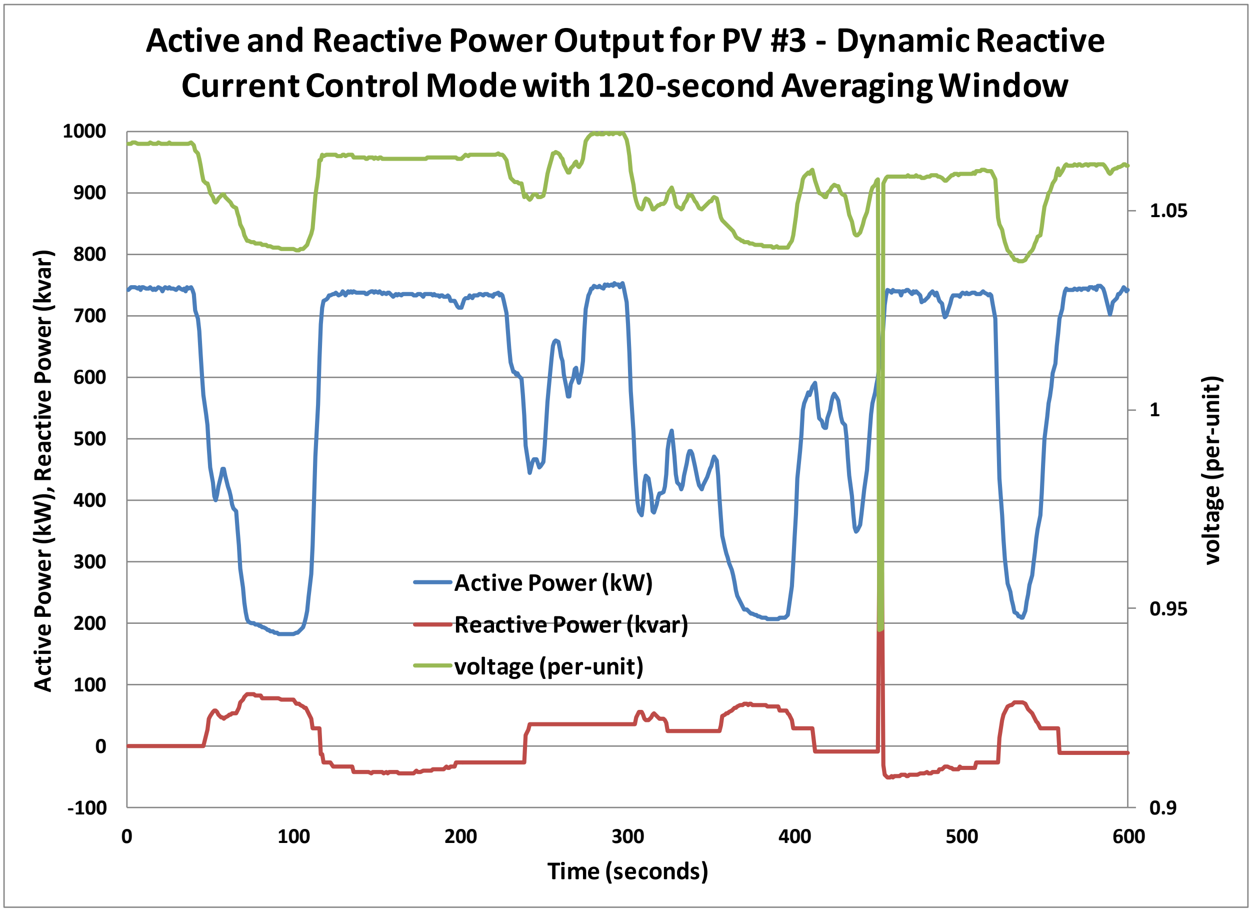

Figure 5-4
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Dynamic Reactive Current Control Mode with a 120-second Rolling Average Window

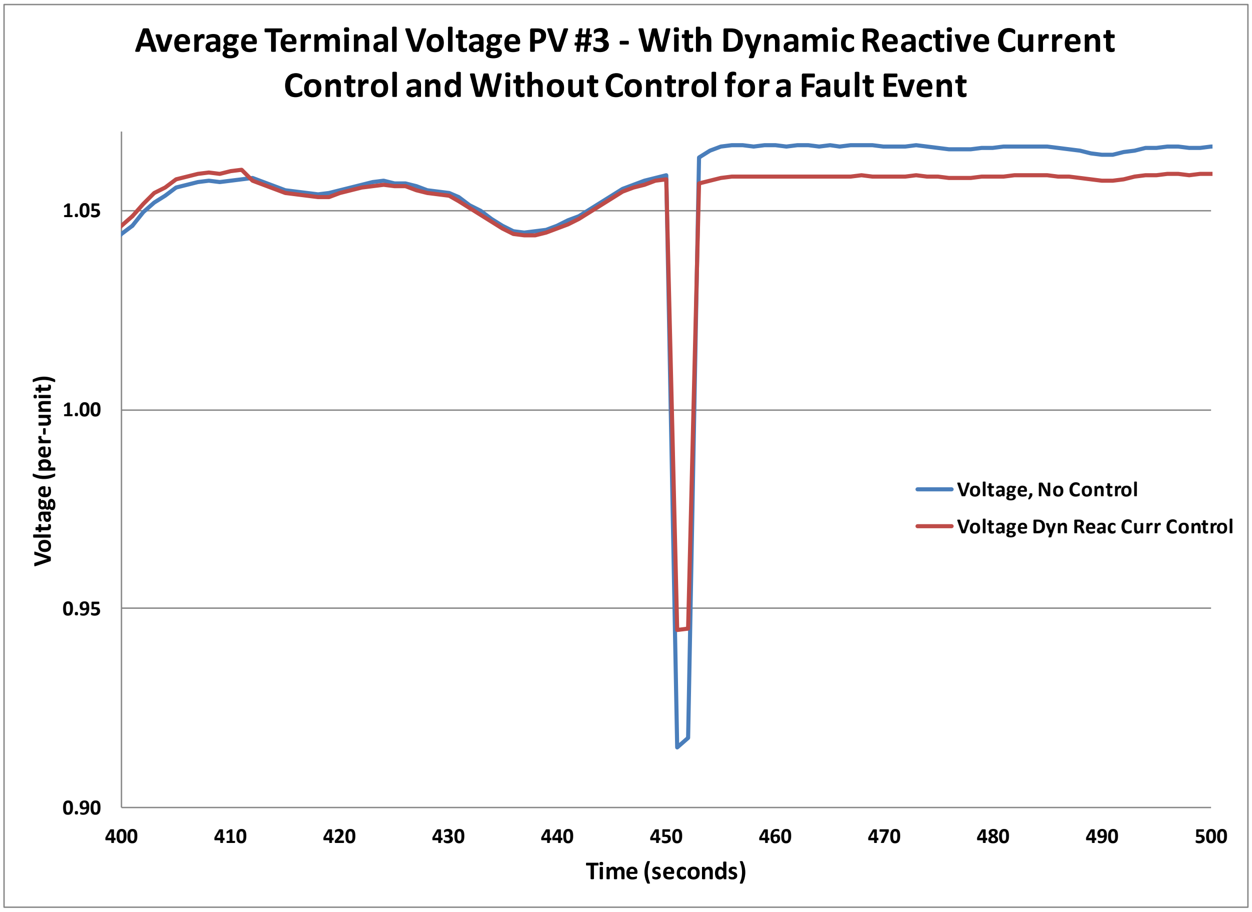

Figure 5-5
Average of Three Phases Terminal Voltage for PV Number 3, Results when Operating under Dynamic Reactive Current Control Mode with a 120-second Rolling Average Window, and when Operating without Control during a Two-second High Impedance Fault

6
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 6-1 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 3-5, 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.

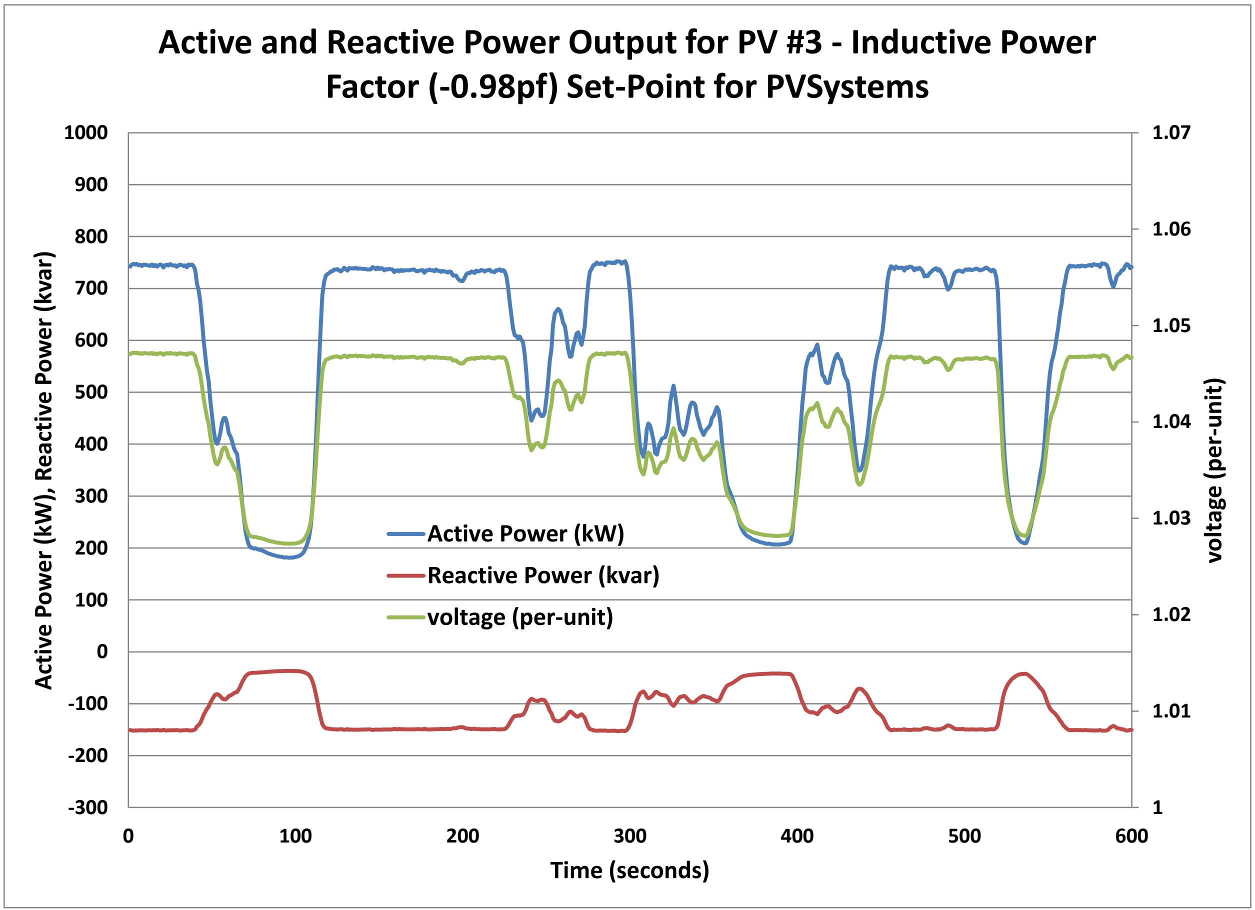

Figure 6-1
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under Fixed Power Factor Set-point for the PV Systems, with Power Factor Set to -0.98 (Inductive Reactive Power)

7
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 7-1 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.

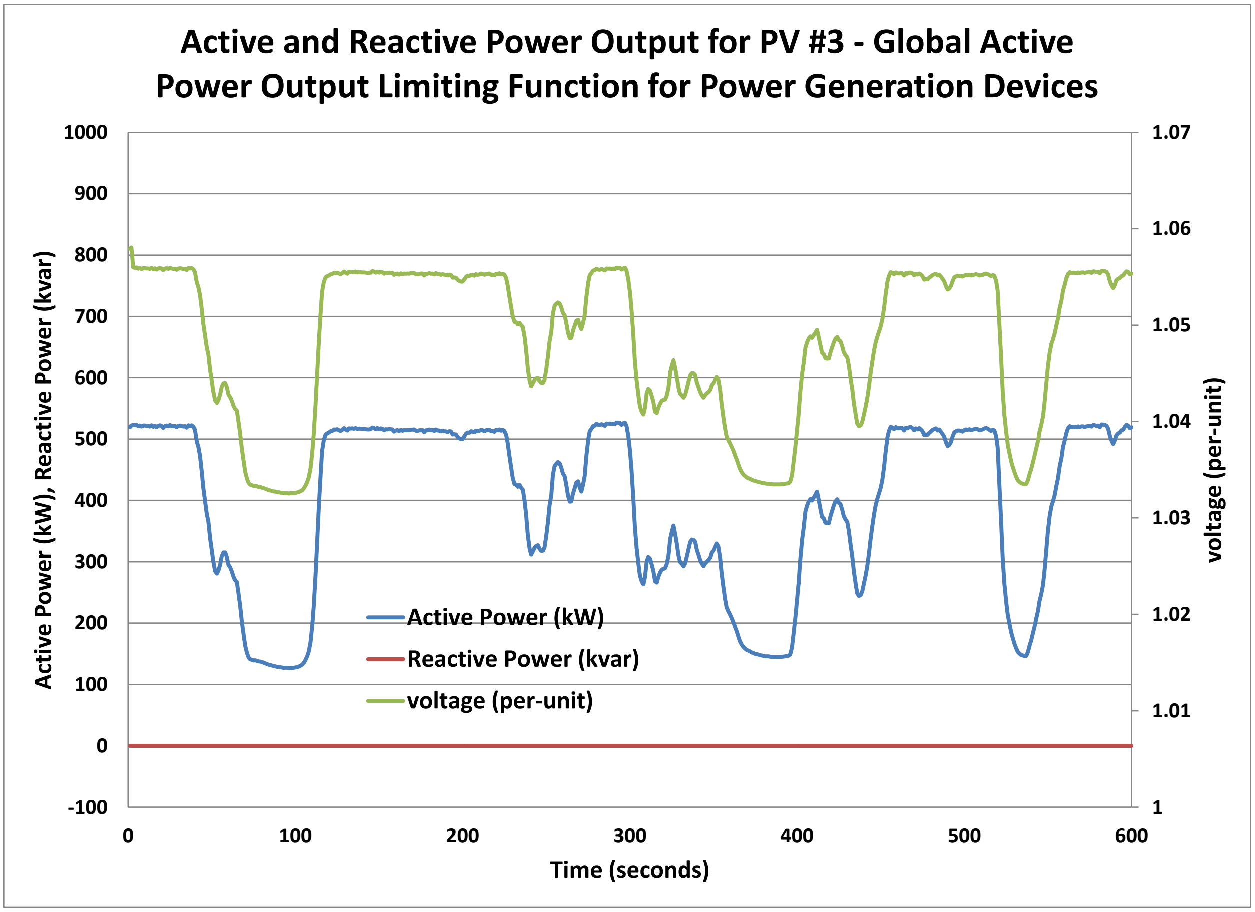

Figure 7-1
Average of Three Phases Terminal Voltage and Active and Reactive Power Output for PV Number 3, Results when Operating under a Maximum Power Generation Limiting of 70% for the PV Systems

8

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 8-1 for this example of usage.

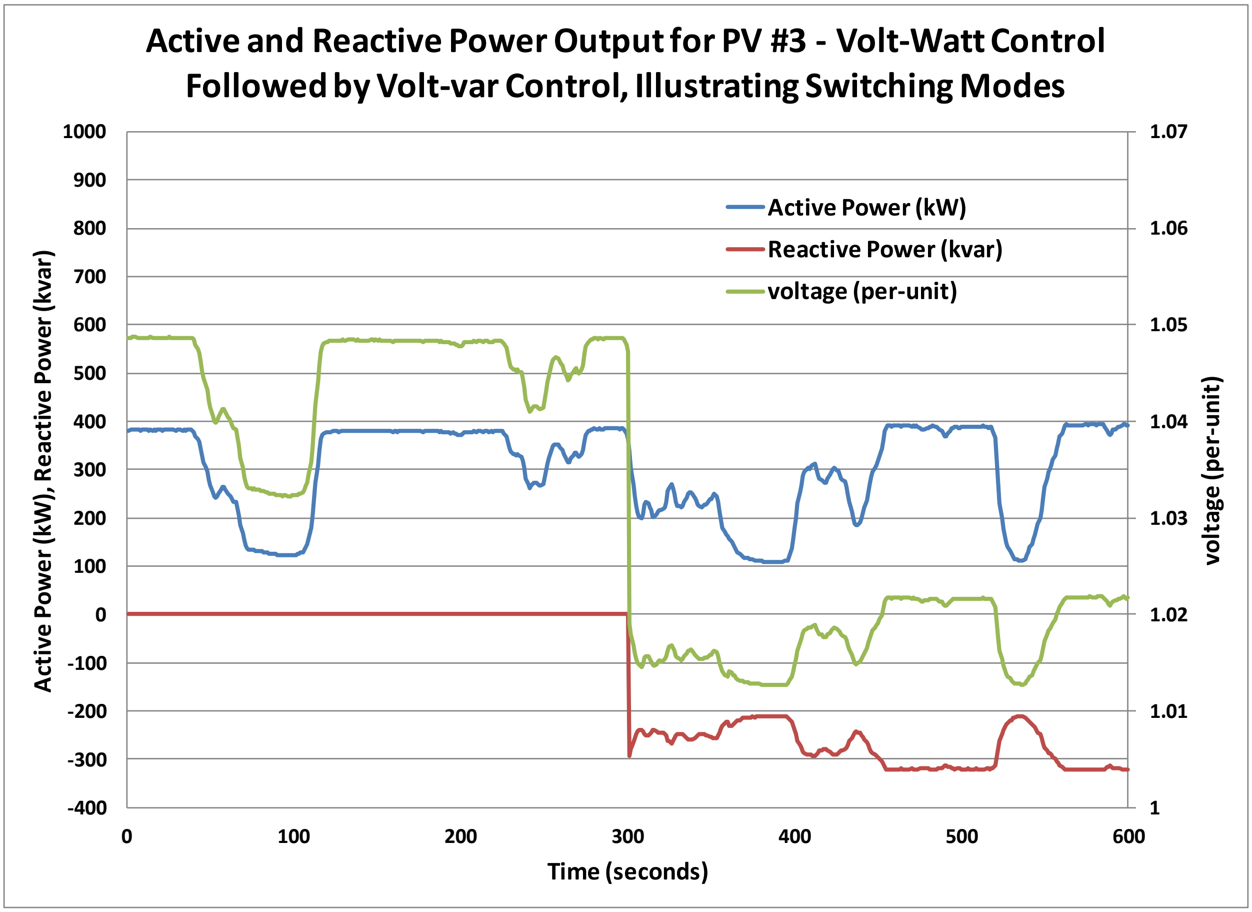

Figure 8-1
Switching from Volt-Watt Mode to Volt-Var Mode at 300 seconds

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.

9
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.

10
REFERENCES

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