ADVANCED INVERTER CONTROLS FOR DISTRIBUTED RESOURCES

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ABSTRACT

The increasing application of inverter-connected distributed resources to the distribution system creates a need to define improved means for integration of these resources without adversely impacting power quality or reliability. Since 2009, EPRI has been facilitating a collaborative initiative to develop standard functions and a standard language for grid integration of smart solar and storage inverters along with the US DOE, Sandia National Laboratories, and the Solar Electric Power Association. The initiative was designed around an open process and a large interest group became engaged, including inverter manufacturers, system integrators, research organizations and utilities. This paper illustrates three of the advanced inverter control standard functions that were identified using simulation of a distribution system containing large solar PV installations.

INTRODUCTION

With increasing penetration of inverter-connected distributed resources to the distribution system, such as solar photovoltaic (PV) generation and energy storage, advanced functionality can play an important role in applying those inverter-connected resources. Project participants in the EPRI-facilitated collaborative identified a key set of high priority advanced inverter functions: [1,2]

- basic intelligent volt-var,
- volt-watt,
- dynamic reactive current,
- dynamic volt/watt,
- peak power limiting and
- voltage ride-through.

This paper will discuss three of these: the Basic Intelligent Volt-Var, Intelligent Volt-Var with Adaptive Set-Point, and Dynamic Reactive Current advanced inverter control. The functionality is demonstrated via simulation based on an actual North American distribution system that has existing large scale solar PV generation resources connected to it. Actual measurements of power output of the solar PV resources are employed in the simulations.

The MV distribution system used to demonstrate the functionality is a 12.47 kV multi-grounded neutral, wye-connected system that is typical of many North American MV systems. It has a peak load of 6 MW and a minimum load of approximately 0.7 MW.

The feeder has 93 km of primary (MV) lines and covers an area of approximately 91 square km. For voltage regulation and reactive power support, the feeder has a substation load-tap-changer (LTC), three feeder voltage regulators, and two fixed and three voltage-controlled capacitor banks, respectively.

The distribution system is modeled, along with the advanced inverter functionality illustrated here, in the EPRI OpenDSS program, an open-source program that particularly useful for simulating distribution systems with advanced controls. [3]

The inverter-based resources that are modeled are solar PV systems modeled with the *PVSystem* class in OpenDSS. PVSystem-class elements model photovoltaic resources for distribution planning purposes. The models include the major components of the PV panel(s)/array(s), efficiency considerations related to the PV panel(s)/array(s), efficiency curves for the inverter, and a basic representation of the inverter characteristics, suitable for distribution planning studies.

BASE-LINE SIMULATION

Using the OpenDSS program, we apply an irradiance shape that describes the insolation on a partly cloudy day measured at one of the PV facilities on the distribution circuit in May 2012. The distribution circuit has four large-scale PV installations totalling 1.7 MW of peak generation capacity divided between two interconnect transformers that are physically near each other.

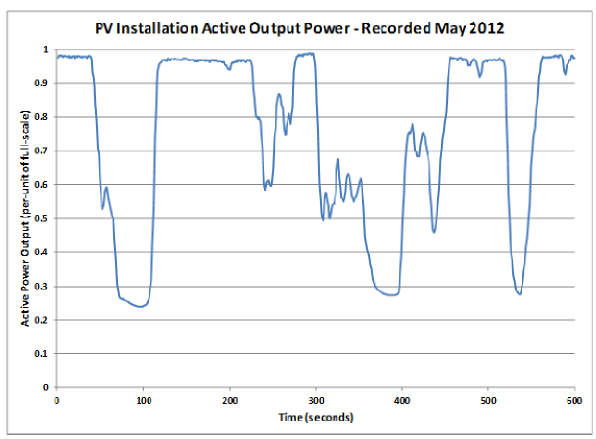

Figure 1. Recorded PV Active Power Output Used to Drive the Simulation.

The active power output from the irradiance shape that is applied to all four PV systems is shown in Figure 1. The resulting voltage, active power, and reactive power for the

PV #3 installation are shown in Figure 2. We will focus on the PV #3 installation in this paper.

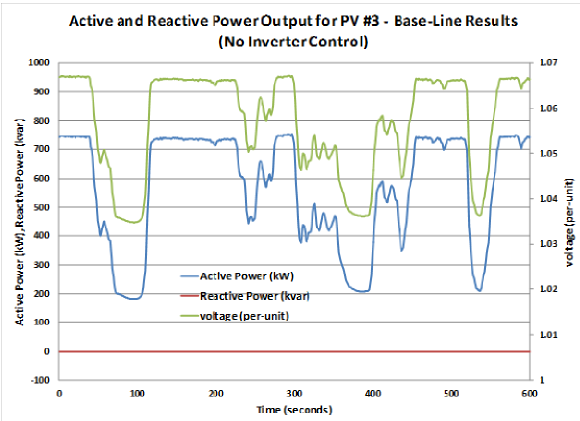

Figure 2. Active and Reactive Power Output, and Terminal Voltage for PV #3 for Base-Line Conditions.

INTELLIGENT VOLT-VAR

The Basic Intelligent Volt-Var functionality uses one, or more, volt-var curves to define the response of a inverter-based distributed resource to steady-state voltage levels at the interconnection point of the inverter with the AC grid. One example of a volt-var curve is shown in Figure 3.

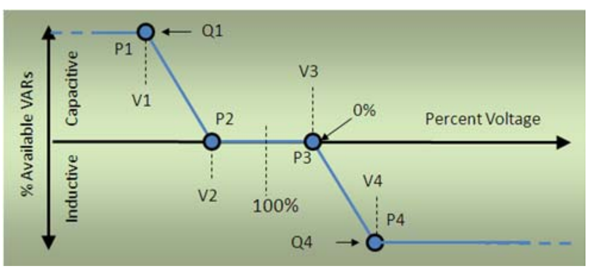

Figure 3. Example Intelligent Volt-Var Settings Curve

This volt-var curve defines the reactive power output level (on the y-axis) in terms of the percent available reactive power, which is determined by the inverter maximum apparent power output level and the present active power output level.

The given percentage of available reactive power output is a function of the voltage present at the interconnection point of the inverter. The voltage (on the x-axis) is defined in percent of either the nominal system voltage rating, or, alternatively, a rolling average of the voltage over a given period of time.

The implementation of a rolling average window is particularly useful when the voltage at the point on the distribution system where an inverter is connected is not operating at nominal value. It may be operating at a level that is higher or lower than nominal rated voltage due to loading, circuit characteristics, and settings on distribution system voltage regulation equipment. One example might be where a distribution system is being operated at reduced voltage levels under a conservation voltage reduction, or voltage optimization, scheme.

Intelligent Volt-Var with Hysteresis

Another approach to intelligent volt-var inverter control identified by the collaborative is the Intelligent Volt-Var with Hysteresis concept illustrated in Figure 4. This approach uses additional voltage and reactive power points that define a hysteresis region. When voltage levels are rising at the inverter interconnection point, the inverter reactive power characteristic follows the curve defined by points P1 through P4.

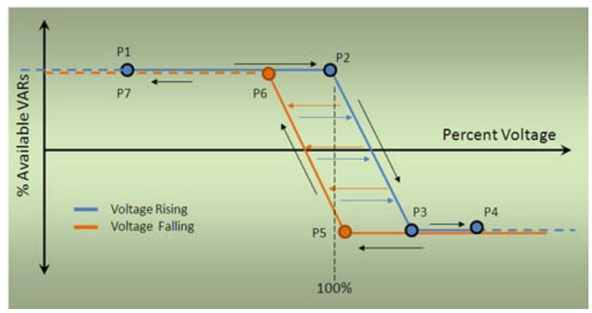

Figure 4. Example Intelligent Volt-Var Settings with Hysteresis

If the voltage trend changes direction and begins reducing in magnitude, the reactive power output level is held constant at its' last value, and the volt-var response changes to the volt-var curve defined by the points P5 through P6.

There is a region between the two curves during which the reactive power output level will remain constant. This continues until the voltage level intersects one of the two curves depending on whether the voltage is increasing or decreasing in magnitude

Example Output from Basic Intelligent Volt-Var Inverter Control

Using the distribution system and irradiance shape previously described, we enable the Basic Intelligent Volt-Var Control functionality with the volt-var curve shown in Figure 5.

For voltages less than 1.0 pu, the intelligent volt-var control with this volt-var curve will attempt to provide reactive power to the grid, depending on the voltage and the available reactive power in the inverter. This action attempts to correct the voltage to the nominal value, given the characteristics of the volt-var curve used for this example. For voltages greater than 1.0 pu, The Intelligent Volt-Var Control will absorb reactive power from the grid, thereby attempting to counteract higher than nominal voltages.

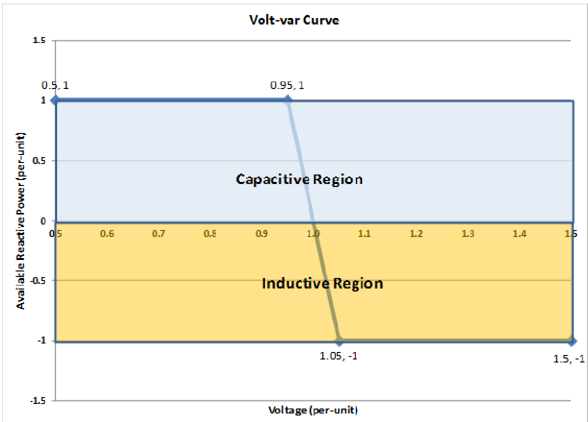

Figure 5. Volt-Var Curve Used for Illustrating Operation of Basic Intelligent Volt-Var Control Mode.

Results from the simulation with this functionality engaged are shown in Figure 6. By comparing to Figure 2, there is a reduction in the overall average voltage during the simulation (green curve). Reactive power absorption from the grid occurs throughout the entire simulation, due to the terminal voltages always being at a level greater than 1.0 per-unit. When the voltage begins to drop due to reduced active power output from the PV #3, the reactive power absorption reduces correspondingly, following the volt-var curve.

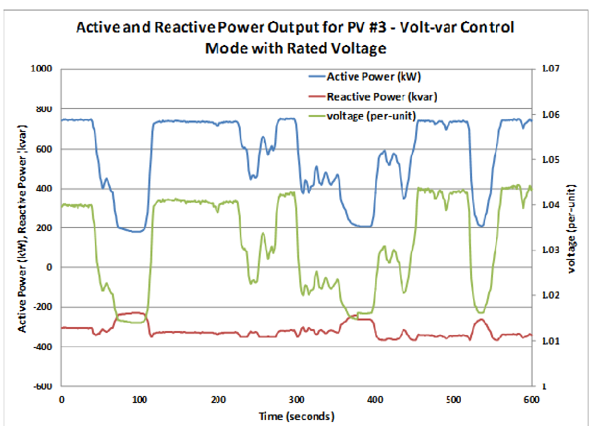

Figure 6. Average Phase Voltage and Active and Reactive Power Output for PV # 3, for Volt-Var Control Mode without Hysteresis

Example Output from Intelligent Volt-Var Inverter Control with Adaptive Set-Point

A slight alteration in the Basic Intelligent Volt-Var Control method is to implement it with an adaptive set-point. Although not specifically defined in the workshops, a rolling average window can be used to have the 1.0 pu point on the voltage axis correspond to the 'normal' terminal voltages that the PV system has.

We apply the same irradiance shape as indicated in the base-line section, and enable the Intelligent Volt-Var Control functionality with the volt-var curve with adaptive voltage set-point as shown in Figure 5.

For the adaptive voltage set-point we choose a rolling average window with a length of 120 s. The total simulation time is 600 s. The resulting average phase voltage and active and reactive power output levels are shown in Figure 7. Note the start-up period, particularly evident in the reactive power absorption level as the 120-s rolling average window buffer begins to fill up with data points. The overall fluctuation in the range of voltages seen at the terminals of PV system #3 are less than observed in other simulations shown thus far.

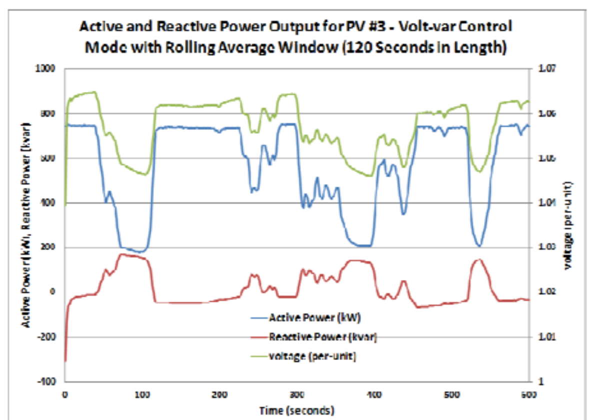

Figure 7. Average Phase Voltage and Active and Reactive Power Output for PV # 3, for Volt-Var Control Mode without Adaptive Voltage Set-point.

DYNAMIC REACTIVE CURRENT

The final advanced inverter function that will be illustrated in this paper is the Dynamic Reactive Current functionality. This inverter function attempts to counteract more rapidly-occurring fluctuations in voltage by means of more rapid injection of reactive power into the grid for low voltage conditions, or more rapid absorption of reactive power from the grid for high voltage conditions.

At a high-level, its operation can be described by Figure 8.

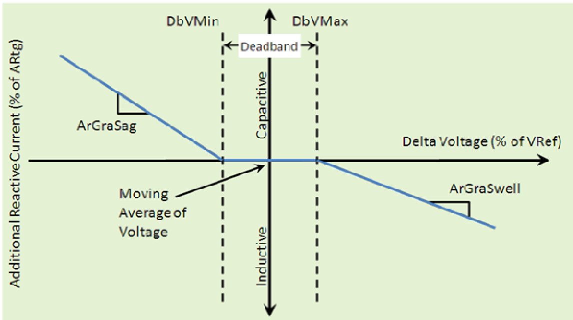

Figure 8. Dynamic Reactive Current Support Function, Basic Concept.

As the present terminal voltage begins to move farther outside of the dead band, two constants, ArGraSag and ArGraSwell, determine what percentage of reactive current should be injected into the system, or absorbed from the system. The reactive current is a percentage of the nameplate rating of the inverter. The deadband is itself moving, being a rolling average of the voltage.

For instance, if the voltage difference (delta voltage) between the moving average voltage and the present terminal voltage is -5%, and is outside the deadband, it is multiplied times the ArGraSag constant to determine the amount of reactive power that is rapidly injected into the grid to counteract the low voltage. The injection typically occurs on a time interval on the order of a 1 s, or longer.

This is illustrated by invoking this functionality with the ArGraSag and ArGraSwell constants set to 10.0 (percent reactive power per percent change in voltage) and setting the dead-band to a width of 5% around the center-point of the moving average of the voltage. Then by applying a high impedance fault during the simulation, we can see the effects of the dynamic reactive current function as it attempts to inject reactive power to the grid and increase the terminal voltages during the event. Two lines are shown in Figure 9, with the lower line (blue) showing the voltage sag magnitude without any advanced inverter control engaged. The upper line (red) shows the voltage sag magnitude with the reactive power injected to the grid with the Dynamic Reactive Current functionality engaged.

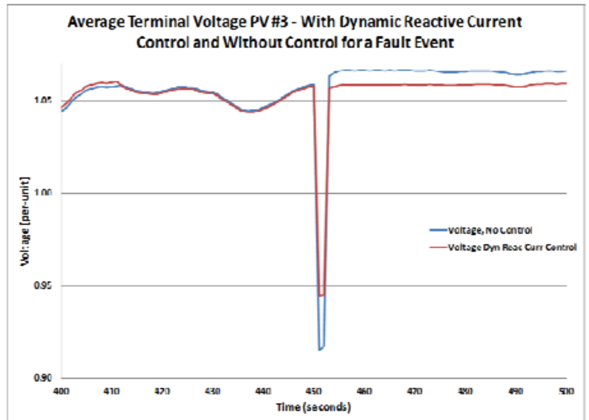

Figure 9. Average Phase Voltage for PV #3, for Dynamic Reactive Current Control Mode with a 120-s Rolling Average Window, and a 2-s High Impedance Fault.

CONCLUSION

We have illustrated two of the advanced inverter control functions that have been identified through the EPRI-organized workshops on advanced inverter functions since 2009, as well as one variant method developed by EPRI personnel.
As time and funding permits, additional functions will be added to the OpenDSS distribution analysis platform to allow further investigation of advanced inverter control functions. The effects of these advanced inverter functions will be tested on a variety of distribution systems taking into account parameters such as voltage deviation, possibilities of increasing hosting capacity, and interactions between control modes.

REFERENCES

[1] EPRI, 2011, *Common Functions for Smart Inverters.* EPRI, Palo Alto, USA. Report ID: 1023059.

[2] EPRI, 2012, *Common Functions for Smart Inverters, Version 2*. EPRI, Palo Alto, USA, Report ID: 1026809.

[3] EPRI, 2008-2012, *OpenDSS Computer Program, The Open Source Distribution System Simulator,*. URL: http://sourceforge.net/projects/electricdss/