SIMULATION OF SOLAR GENERATION WITH ADVANCED VOLT-VAR CONTROL

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ABSTRACT

Continued improvement in the cost and efficiency of photovoltaic (PV) technology hints at a future in which utilities will need to accommodate high levels of randomly varying generation in distribution systems. High-penetration solar PV on a distribution system can result in objectionable fluctuations in feeder voltage. However, if the PV inverters utilize advanced volt-var control, the voltage variations caused by the solar PV ramping can be reduced. In some cases, an advanced control actually achieves improved overall voltage regulation at the customer and feeder level. It is possible to increase the hosting capacity of distribution systems without excessive voltage fluctuations if the appropriate control were to be built into PV inverters.

INTRODUCTION

In 2009, EPRI's Photovoltaic & Storage Integration Program began a series of studies related to the high penetration of distributed energy resources (DER). One research area in this program was specifically focused on the communication for monitoring and management of DER integration. This research led, in mid 2009, to the launch of a broad industry collaborative [1] to identify a common means by which smart, communicating inverters may be integrated into utility systems. This research effort has since engaged over 400 individuals representing inverter providers, PV and storage manufacturers, utilities, and research organizations.

The central goal of the project was to identify a core set of potential inverter/charger capabilities that, if implemented and made available to distribution management systems, may enable higher penetration levels and enhance the value of grid-tied PV and storage devices.

At the beginning of this PV/Storage Communication Initiative, seven high-priority inverter functions were identified and came to define the scope of the first phase of this work. The seven functions were:

1. Connect/Disconnect from Grid
2. Power Output Adjustment
3. Var Management
4. Storage Management (Charging/Discharging)
5. Event/History Logging
6. Status Reporting/Reading
7. Time Adjustment

Those engaged in the work viewed most of the inverter management functions as "requests" rather than "commands." With the possible exception of grid connect/disconnect command, the ultimate decision as to whether or not a particular function can be supported at a particular point in time would likely be up to the inverter. Many local factors, including device operating condition, device temperature, and battery charge level, can limit the ability of a device to respond to certain requests. In this context, the majority of the commands may be more accurately described as "requests" where the device response indicates the degree to which it was able to comply. In view of this, some of the functions, such as volt/var management, have been created entirely in the form of target settings, toward which devices independently aim. These requests to each device could be made using limited communication capability, where the utility might dispatch the requests only a few times throughout the day.

An EPRI research project under the Distributed Renewable Integration Program 174 is currently carrying forward the work of this initiative by analyzing the effects of advanced voltage control strategies on real distribution systems [2,3]. The specific focus of this analysis is on the use of smart inverters to provide optimized volt/var support. Drawing from a database of distribution circuits throughout the U.S., EPRI is analyzing the impact volt/var control can have when implemented in conjunction with grid-tied solar PV. The purpose of this paper is to summarize some of the results from this analysis.

VOLT/VAR CONTROL

As part of the core functions defined within the PV/Storage Initiative, four various var control "modes" were identified, including

1. Normal Energy Conservation
2. Maximum Var Support
3. Static Var
4. Passive Var

As part of the PV/Storage Communication Initiative, the concept of intelligent var control "modes" was introduced. A mode in this context refers to a certain volt-var characteristic that the inverter system is to follow. A given mode defines what var behaviour is desired as a function of the local service voltage.

The specific volt-var characteristic for each mode is fully configurable and is established by an user-defined array of volt-var points. Inverters may be pre-configured with a number of volt-var modes, and then switched between modes with a single broadcast command. This allows for the possibility that each inverter could have unique volt-var settings for a given mode. In addition, each Mode configuration includes a var ramp rate limit (%/second) and a randomization interval over which mode settings are to be made effective. The following uses of modes have been identified as an example.

Mode 1 could be used as the normal state of operation for an inverter. As indicated in Figure 1, the var behavior for this mode could be configured to vary from capacitive to inductive as system voltage varies over a utility-defined range. The curve shape shown in this figure is one example. Each utility may determine the volt/var settings they prefer by adjusting the (Vx, Qx) pairs in the Mode configuration array. Although four points are shown in this example, the number of points in the configuration arrays is variable so that any characteristic is possible.

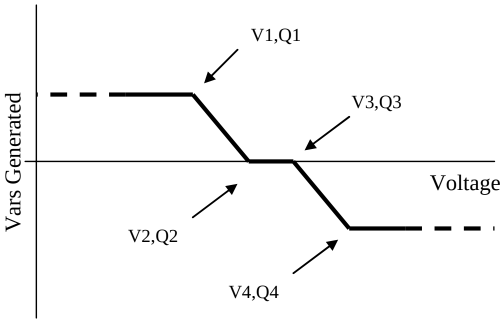

Figure 1. Example Volt/Var Settings for Normal Mode 1

The volt/var characteristic may be identical for all devices on a particular feeder, or may be uniquely set for each device. Regardless, the configuration process is envisioned as being an infrequent(maybe even one-time) event. After configuration is done, large numbers of devices can then be uniquely managed by a single broadcast to “go to Mode 1”. The kind of regulating behavior described in this Mode 1 example is the primary focus of this paper.

Mode 2 could be used to provide var support for transmission system needs or to correct power factor at points of connection between transmission and distribution . The volt-var configurations associated with Mode 2 could thus be made to provide a maximum level of capacitive vars up until the local voltage reaches some upper limit, then reduce the var level above that point.

Modes 3 and so forth could provide for other needs. For example, one mode might be set up to produce a fixed level of vars, irrespective of voltage, and another might be an alternate “normal” mode for use during off-peak periods.

These settings are intended to operate within the IEEE 1547™ [4] normal range of operating voltage, hence the dashed lines shown in Figure 1. Reactive power is assumed to remain at Q1 for voltages below V1, down to the IEEE 1547™ lower cutoff voltage. Likewise, the reactive power is assumed to remain at Q_n for voltages above V_n up to the IEEE 1547™ upper cutoff voltage. For PV systems that are interconnected to MV grids that require additional grid support such as that found in Germany [5], the var response would simply extend beyond these limits.

What is not clear from looking at Figure 1 is that the vertical axis is defined as a percentage of available vars, where “available vars” is the maximum possible for the system at a point in time. Because many inverter systems have a fixed VA limit, available vars may instantaneously increase as watts decrease. This means that even at a single bus voltage (any point on the horizontal axis), the amount of reactive power generated will vary as the solar intensity varies. From the perspective of distribution system management, this allows for the loss of distributed watts injected into the system to be replaced in real-time with vars, thereby helping to improve system regulation.

A volt/var control algorithm has been implemented in the EPRI OpenDSS program [6], which is a comprehensive electrical system simulation tool for electric utility power distribution systems. It has been made available as open source to help the industry evaluate advanced issues in distribution system analysis related to the development of the Smart Grid. It has a number of unique features that are particularly useful for the research environment.

One feature of the program exploited for the subject of this paper is that control elements are modeled separately from the actual current-carrying elements. The capacitor control is separate from the capacitor model, the regulator control is separate from the tap-changing transformer that performs the regulation, etc. The volt/var control is implemented as a control element that controls the power output of a generic generator model.

Utilizing this model, example case studies were considered in which a range of distribution feeder models with high-penetration PV were simulated both with and without the inverters operating under autonomous volt/var control. This paper summarizes the results from one of these cases.

STEADY-STATE VOLTAGE RESPONSE

One sample circuit chosen to evaluate the volt/var functionality is a 12kV distribution circuit comprised of approximately 10 MW of total load distributed throughout 1800 residential and commercial customers. The circuit is mostly overhead, with three feeder regulators in series along the 25 km of 3-phase primary line, with laterals tapping off combining for a total of 150 km of single-phase primary. A one-line diagram of the circuit is shown in Figure 2.

A full three-phase model of this circuit was developed in the OpenDSS, including all conductors, feeder regulators, service transformers and customer loads.

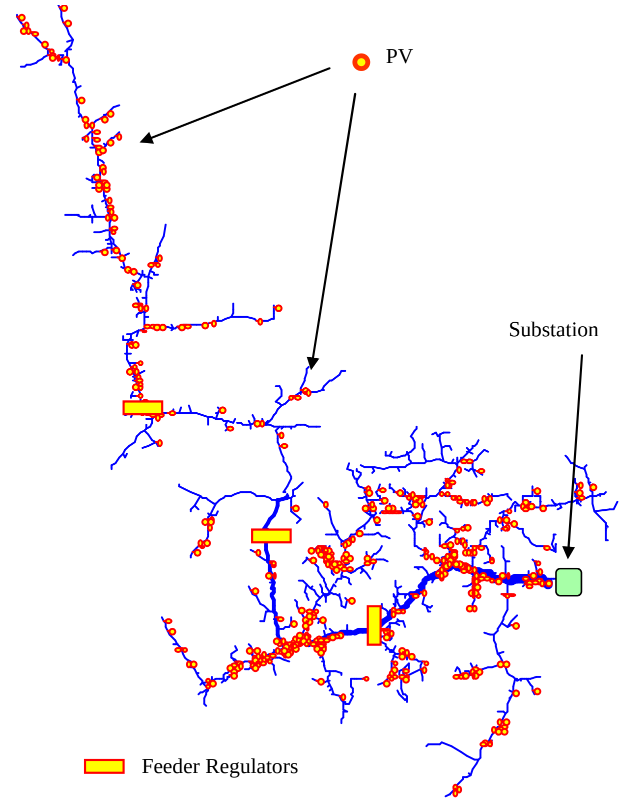

Figure 2. Circuit One-line Diagram

Three separate simulations are performed with the circuit, including:

- Baseline – No PV
- 20% PV (of peak demand)
- 20% PV with volt/var control

The baseline voltage profile without PV for each phase is shown in Figure 3, where voltage is a function of distance from the substation. Due to the long overhead lines, significant voltage drop is experienced along the feeder, thus necessitating the use of three inline feeder regulators seen in Figure 3 at 6, 12, and 18 km.

Due to the circuit consisting of limited existing PV, customer load points are added throughout the feeder to simulate a high-penetration 20% PV scenario. For this scenario, 450 customers were randomly selected to have solar roof-top PV (shown as circles in Figure 2), with each residential customer PV panel having a maximum rating of 4.5 kW and associated inverter rating of 5.4 kVA (1.2 x 4.5). The resulting voltage change, or rise in voltage, from the baseline scenario is shown in Figure 4. At this level of penetration, voltages towards the end of the circuit were found to rise as much as 4-6.5% depending upon penetration for that particular phase.

Autonomous volt/var control is then implemented within the model, with each individual PV operating under the autonomous volt/var schedule as shown in Figure 1 and setpoints defined in Table 1.

Table 1.
Volt/Var Setpoints

$V_{X\,(120V)}$	Q_X
114.0	100.0
119.0	0.0
121.0	0.0
126.0	-100.0

As shown in Figure 5, the voltage change results with volt/var control are found to lessen the voltage variations slightly, with the maximum change (rise) in voltage found to be just below 5.5%. With the level of var compensation from each individual PV inverter being a function of its own terminal voltage, the effective reactive power flow through each inverter varies along the feeder. Furthermore, as the PV active power injection into the grid pushes voltages higher than the setpoint (in this case 1.0 pu), more vars are absorbed by the inverters to bring the voltage back to the desired level. Alternately, if the PV active power injection raises low voltages towards 1.0 pu, the reactive power injection would decrease.

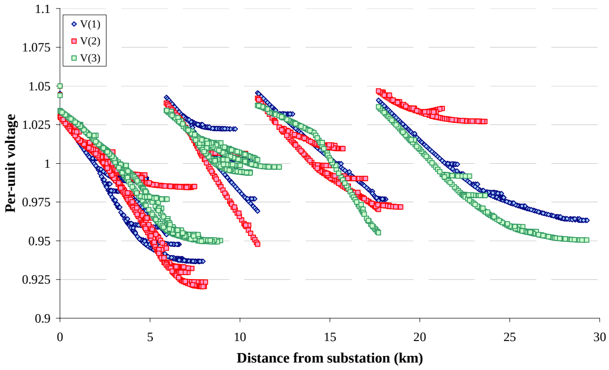

Figure 3. Circuit Medium Voltage Profile - Baseline Without PV (Peak Load Level)

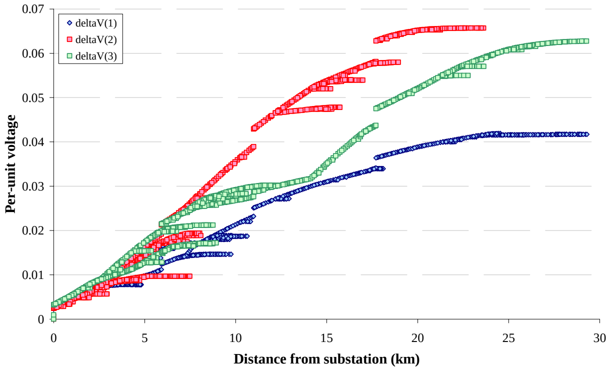

Figure 4. Maximum Change (Rise) in Circuit MV Due to PV Output

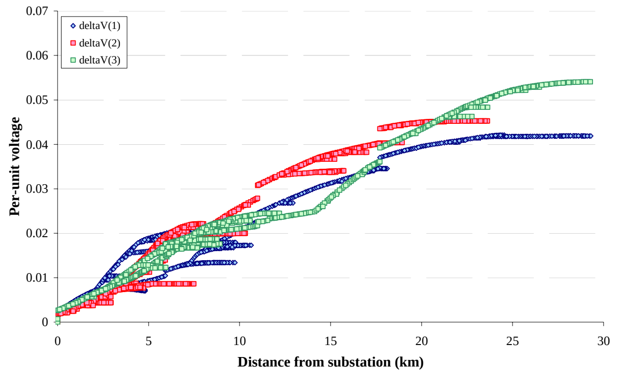

Figure 5. Maximum Change (Rise) in Circuit MV Due to PV with Volt/Var Control

DYNAMIC VOLTAGE RESPONSE

The next series of analysis was to look at the impact volt/var control would have on feeder voltages as the load and PV vary throughout the data and interact to effect system voltage. This type of analysis is often referred to as long-term dynamic or quasi-static load flow analysis. Utilizing measured data extracted from the energy management system, customer loads are assigned load shapes that represent a typical peak load day. A typical solar resource shape is then selected to represent PV variations throughout the day, with the aggregate solar and customer load shapes shown in Figure 6. The same three simulation scenarios as that considered for the steady-state analysis are performed.

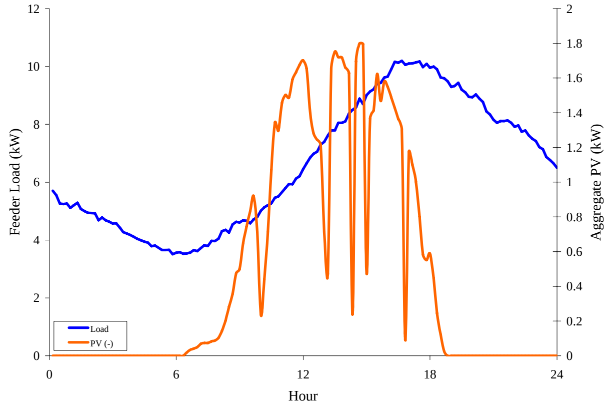

Figure 6. 24-Hour Aggregate Feeder Load and Solar PV Profile

The MV system voltage results for all three cases are plotted in Figure 7. Note the primary circuit voltage shown is just upstream from the first feeder regulator, approximately 5 km from the distribution substation. The baseline scenario with no PV illustrates voltages varying throughout the day from 91% to 101% due to normal load variations. The addition of PV to the system provides as much as 5% voltage rise throughout the daylight hours, with fairly significant voltage fluctuations occurring during periods when the PV production reduces due to cloud passage.

In this example, the use of the inverter volt/var control is found to reduce the voltage fluctuations caused by the PV. With each PV providing just a small amount of reactive power throughout the day, the results also indicate the volt/var control flattens feeder voltage response to normal load changes as well.

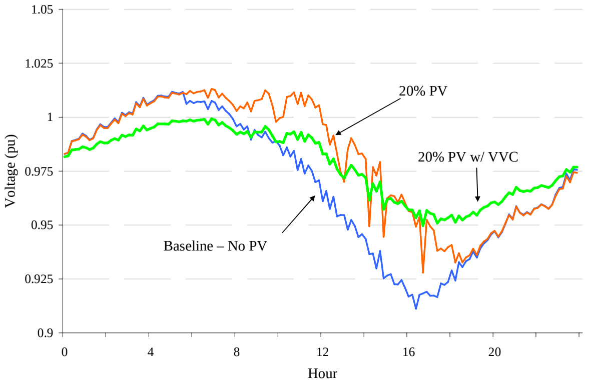

Figure 7. 24-Hour Medium Voltage Simulation Results

Additional circuits have been analyzed in a similar manner, with results indicating that use of autonomous volt/var control can significantly increase the level of PV that is allowable on distribution circuits for which voltage constraints are the limiting factor.

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