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Determination of Smart Inverter Control Settings to Improve Distribution System Performance

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SUMMARY

The interconnection rate of inverter-based photovoltaic (PV) generation to the power system is increasing exponentially in the US. The penetration level nation-wide remains low, but locally in places such as California and Hawaii the penetration and impact to the distribution system are considerable.

Due to the potential for integration benefits, the utility industry is moving toward the adoption of active and reactive power control capabilities of inverters. Currently the IEEE 1547a standard for interconnecting distributed generation has been modified to allow inverter-based generation to actively participate in voltage regulation.

The regulatory rules that allow this control are only the first step in the process of implementation. While defining the need for such functions is necessary, determining appropriate settings is critical to ensure smart inverters provide the response that is anticipated.

This paper presents an automated routine for determining the best smart inverter settings based on volt-var, volt-watt, or off-unity power factor control. This is done with a three step process consisting of 1) modeling the distribution feeder, 2) simulation with various load levels, solar variability, and smart inverter control settings, and finally 3) processing the feeder response to find the control settings that achieve the performance objective. The determination of best settings is ultimately done by observing the feeder response to multiple variables and selecting the best control settings based on performance metrics and voltage constraints.

KEYWORDS

Distribution, Inverter, Photovoltaics, Smart, Volt-var

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Introduction

The interconnection rate of inverter-based photovoltaic (PV) generation to the power system is increasing exponentially in the US [1]. The penetration level nation-wide remains low, but locally in places such as California and Hawaii the penetration and impact are considerable [2]. The impacts can be mitigated by operating the PV inverters to absorb or inject reactive power. Inverter reactive power control can be enabled by either operating inverters at an off-unity power factor or in a closed-loop control where reactive power is dependent on voltage (volt-var mode) [3,4].

Due to the potential for integration benefits, the utility industry is moving toward the adoption of active and reactive power control capabilities of inverters. Currently the IEEE 1547a standard for interconnecting distributed generation has been modified to allow inverter-based generation to actively participate in voltage regulation [5]. States within the US with high penetration have been more proactive as well to update interconnection requirements, such as California Rule 21, and have begun to adopt this capability as seen necessary to meet their solar renewable targets while mitigating adverse impacts [6].

The regulatory rules that allow this control are only the first step in the process of implementation. While defining the need for such functions is necessary, determining appropriate settings is critical to ensure smart inverters provide the response that is anticipated. Figure 1 shows the primary node voltage response at the inverter point of interconnect for a wide range of volt-var control settings on a specific day. The voltage response without PV (No PV) and with PV at unity power factor (PV base) are shown as well. One noticeable aspect of this example is that volt-var control is capable of significantly altering the feeder voltage as soon as the inverter comes online for the day. The inverter in this example is only capable of reactive power support when the inverter is online during active power generation. From this illustration alone, the best settings would be hard to determine.

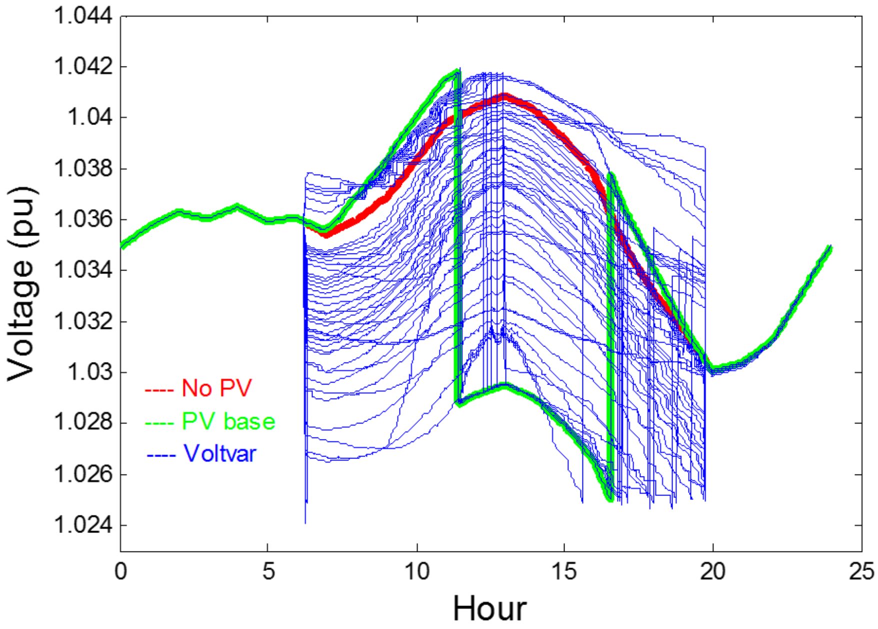


Figure 1. Variety of Voltage Responses Resulting from Different Volt-var Settings

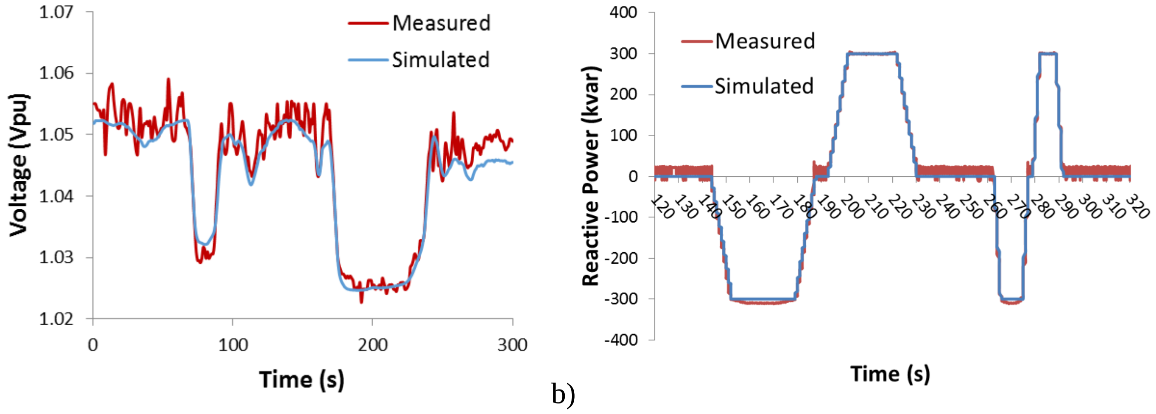
This paper presents a routine for determining the best smart inverter settings based on volt-var, volt-watt, or off-unity power factor control. This is done by observing the feeder response to multiple variables and ranking the control settings based on performance metrics and voltage constraints.

Modeling

Modeling is essential to determine the best smart inverter settings. The accuracy of the model has a direct impact on how accurate the simulated results will be to the field response when the control is implemented in the field. The model consists of the detailed feeder with load and solar characteristics as well as the unique capabilities of each inverter. Inverter vendors have a wide variety of options for smart inverter functionality. The type of control scheme such as volt-var is a high level setting, but inverters can also have options such as making real or reactive power priority when capacity constrained. Producing an accurate and detailed model is critical to determine appropriate settings. The details of how the inverter is modeled in OpenDSS has been covered in detail elsewhere, and will not be addressed here [7,8].

The Feeder

This proposed method for inverter setting analysis uses a feeder model capable of time-series analysis. In the time-series model, all control modes must be implemented such as capacitor control modes setpoints, and delays. The model also incorporates voltage regulation control such as substation load tap changers, line drop compensation, and line regulators. These controls involve voltage setpoints, transformer ratios, bandwidths, and delays. The majority of feeder data is provided in a utility steady-state model; however, additional data must be acquired and incorporated for the time-series analysis. The time-series response of the model can be compared to measurement data for validation. An example of validation for a feeder is shown in Figure 2a where simulated and measured voltage are compared at a solar site [9].



a) b)

Figure 2. Time-series Model Validation a) Feeder Model Comparison to Field Measurements b) Inverter Model Comparison to Lab Measurements

The Inverter

The accuracy of the inverter model is also critical to determine the best smart inverter control settings. The lab tested inverter is therefore validated to the model. Based on similar volt-var control settings and interconnect voltage, the resulting simulated and measured reactive power response is shown in Figure 2b. The control response is nearly identical besides some reactive power fluctuation at unity power factor. This reactive power fluctuation in the actual inverter is commonly used for detecting island conditions.

Methodology for Simulating Smart Inverter Impacts

The feeder impact is examined by performing a daily time-series simulation using two load profiles, three solar profiles, and a wide range of inverter control setting. The load profiles are acquired from measurement data and include the peak and minimum load days. The solar profiles are also acquired from measurement data and include one of each highly variable, clear, and overcast day. Additional load and solar profiles would further benefit the selection of best inverter settings. The inverter settings cover a range of possibilities discussed in the next section. The simulation is conducted at the one minute resolution for a 24 hour period in each combination of load/solar/control scenario.

Inverter Control Settings

The control settings analyzed are not all inclusive as the number of possibilities is infinite. Therefore, a range of possibilities has been chosen to represent a wide spectrum of possibilities. An example set of volt-var control curves are shown in Figure 3a. These settings are linear and span both the capacitive and reactive control regions. Additional possibilities include dead bands when the inverter lies idle, only inductive/capacitive, and nonlinear variation in the inductive/capacitive regions.

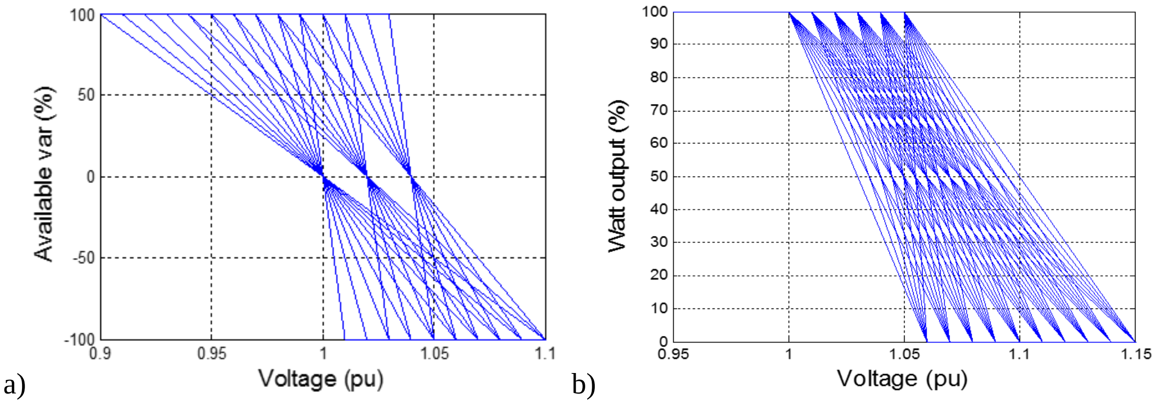


Figure 3. Example Control Settings for a) Volt-var and b) Volt-watt

Example control curves used for the volt-watt analysis are shown in Figure 3b. These curves shown are also not inclusive of all possibilities but sufficiently examine a wide range of those that are practical. Curtailment of real power is not anticipated at lower voltages while some fraction of curtailment might be expected when voltages begin to exceed the ANSI 105% voltage threshold. Power curtailment only occurs if the inverter power output is greater than the percent allowed at the specific voltage on the curve. Additional options that are not analyzed include nonlinear curves.

The power factor control examines specific setpoints on the inverters. These inductive setpoints vary from 0.9 to 1.0 in 0.01 increments. Finer resolution could be examined but general trends are expected using these analyzed values.

Methodology for Assessing Grid Performance

The method for analysis of simulation results includes optimizing the distribution feeder performance objective and maintaining adequate voltages. The objective is optimized by analyzing the feeder response through one or more performance metrics. Adequate voltages are maintained by observing voltage constraints.

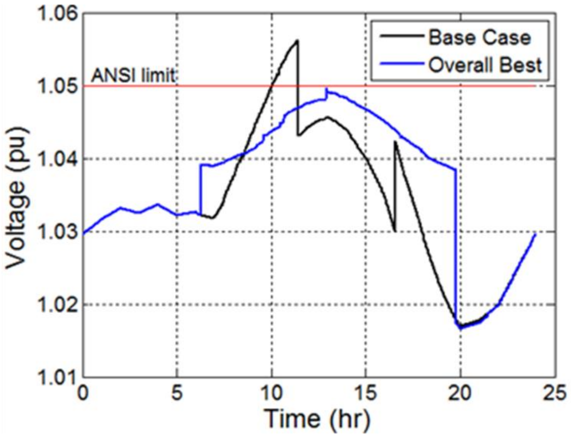
Performance Metric and Voltage Constraints

Performance metrics consist of data points taken throughout the feeder. These include point of interconnect impact, feeder-head impact, feeder-end impact, and feeder-wide impact. Feeder-wide impact can include overall feeder metrics such as absolute maximum voltages, losses, consumption, and voltage drop across the feeder. Several performance metrics are shown in Figure 4a. Ideally the impact on the metrics would improve with the advanced inverter control.

Optimizing a particular performance metric without taking into account other factors could potentially cause adverse impacts to occur. Therefore, voltage constraints are also applied when selecting the best settings. An illustration of voltage constraints are shown in Figure 4b. The ANSI limit is chosen as the limit in this example, but more restrictive thresholds could be applied. As long as the voltage is within limits, the inverter settings is considered adequate. There is no additional benefit for voltage further within ANSI unless defined as a specific performance metric.

Feeder Impact Criteria
Tap Operations
Cap Operations
Feeder Losses (kWh)
Feeder Consumption (MWh)
Max Feeder-Wide Voltage (pu)
Time Above ANSI Max Voltage (sec)
Min Feeder-Wide Voltage (pu)
Time Below ANSI Min Voltage (sec)
Voltage Variability Index

a)



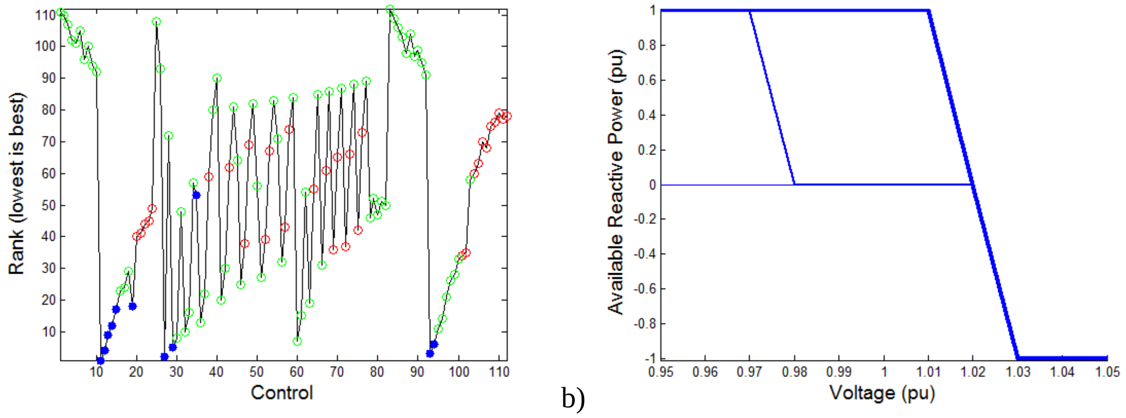
b)

Figure 4. Feeder Impact a) Performance Metrics b) Voltage Constraints

Selecting Best Inverter Settings

The selection of best settings is done by ranking the control based on the performance metrics and then down-selecting based on voltage constraints. An example of the volt-var control ranking is illustrated in Figure 5a.

The ranking labels the most optimal control settings to the least optimal control settings. The control with the lowest overall rank identifies the control that consistently provides a better benefit with respect to the optimized metric/s. The magnitude of rank is dependent on the total number of control settings analyzed and will be dependent whether volt-var, volt-watt, or power factor is analyzed. In the graph shown in Figure 5a, a total of 110 different volt-var control settings are considered. The solid blue circles identify control settings that did not cause a primary node voltage violation (outside ANSI min/max). Unfilled green circles identify control that caused primary node voltage violation but for a length of time less than or equal to the baseline PV at unity power factor scenario. Unfilled red circles identify settings that caused primary node voltage violations for a length of time greater than the baseline PV scenario.



a) b)

Figure 5. Volt-var Control Setting a) Ranking b) Top Three Curves

Trends can be seen in the ranking based on control setting analyzed, as shown by the black lines. These trends occur because the control settings utilized sample through different characteristics involving setpoints, bandwidths, and slopes that are somewhat similar.

An illustration of the three best volt-var curves is illustrated in Figure 5b. All three curves have identical shape in the lower half of the figure. Fortunately in this example, the best control settings (lowest magnitude rank) do not cause any violations. Throughout the analysis, however, there will be situations that the lowest ranked control settings only reduce, or potentially increase, voltage violations. In these conditions, the recommended best settings would be based on lowest rank as well as whether a reduction or elimination of voltage violations is required.

Additionally, if best settings are to be determined for several performance metrics or for several solar/load conditions, the ranking can be weighted based on the probability of that occurrence. Weighting based on performance metric can be applied because multiple performance metrics can be examined simultaneously yet some metrics can be more important to the overall objective. Weighting is also adjusted based on solar/load condition to determine the overall impact over a longer time horizon where some conditions are more likely to occur than others.

The analysis is aimed at determining the best control settings, but to give perspective, the method also identifies that there are control settings that result in adverse grid impacts.

Conclusion

The utility industry is moving toward the adoption of active and reactive power control capabilities of inverters. Currently the IEEE 1547a standard for interconnecting distributed generation has been modified to allow inverter-based generation to actively participate in voltage regulation. These regulatory rules that allow this control now make it necessary to determine appropriate settings to ensure smart inverters provide the response that is anticipated.

This paper discussed a routine for determining the best smart inverter settings that can be applied for volt-var, volt-watt, or off-unity power factor control. The routine is a three step process consisting of

1) modeling the distribution feeder,
2) simulation with various load levels, solar variability, and smart inverter control settings, and
3) processing the feeder response to achieve the performance objective.

The determination of best settings is ultimately done by observing the feeder response to multiple variables and selecting the best control settings based on performance metrics and voltage constraints.

The methodology proposed allows for a wide range of inverter settings, load conditions, as well as solar resource characteristics. However, such detailed analyses require significant effort and are not feasible for every application. Ongoing work will streamline this approach such that more simplified techniques are derived to be broadly applied.

Acknowledgement

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