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Multi-Inverter Interaction with Advanced Grid Support Functions

H.LI*, J.SMITH, M.RYLANDER
Electric Power Research Institute (EPRI)
U.S.A

SUMMARY

Inverter grid-support functions can help mitigate the adverse impacts of solar photovoltaics (PV) to the power system. The US power industry has recognized the need for this functionality, however, the potential interactions between inverters needs to be addressed. This work studies the inverter interactions based on two solar PV inverters with volt-var control function on a utility feeder. The impacts of three factors: volt-var setting, controller parameters and terminal voltage averaging time period are evaluated by varying the settings for these factors. The simulation results show that small voltage fluctuations due to the inverter interactions occur in some cases and the three studied factors have influence on the inverter's potential interaction. Results indicate high sensitivity of reactive power with respect to voltage deviations and aggressive inverter response times can result in some level of inverter interaction being observed. Results also indicate that making minor changes, such as averaging the input voltage to the control, can help dampen oscillations. The study shows there is potential interaction between grid-support inverters, and settings need to be carefully selected to prevent potential adverse impact on the system. While not covered in this paper, additional work is being done in which actual field monitoring of the simulated PV inverters is performed to observe the extent, if any, interactions occur.

KEYWORDS

Grid-support, Inverter, Interactions, Photovoltaics, Smart, Volt-var control

*hli@epri.com

Introduction

The penetration of inverter-based solar PV in the power system are increasing significantly as the industry moves toward cleaner energy. The solar PV impact to voltage related issues have made more and more utilities recognize the need for inverter technologies to provide grid-support. The vast majority of commercial, inverter-based solar PV systems have the capability of fast and flexible active and reactive power control. The grid-support functions fully utilize solar PV inverters' capabilities to better serve the grid and prevent costly grid renovations.

A common set of the inverter grid support functions have been developed [1]. Power factor control, volt-var control, and volt-watt control are the most common grid support functions targeting voltage related issues at the distribution level. While the industry is moving towards adopting solar PV inverters with grid-support functions, it is important to identify and understand fully the potential impacts and issues introduced by these functions. The control of a single solar PV inverter with grid-support functions has been well developed. However, little work has been done to address the potential dynamic interactions between these inverters, especially those within electrical proximity to one another. This paper presents some simulation findings of the interactions between two close solar PV inverters on a utility feeder in the smart inverter demo project funded by the US Department of Energy [2].

Modeling

A 12.47 kV distribution feeder is selected to enable solar PV inverters with advanced grid-support functions. A total 1.7 MW of solar PV is installed at two sites 0.6 miles away on the feeder with PV1 consisting of 475 kW and PV2 of 1235 kW. The inverter ratings are 475 kVA and 1235 kVA, respectively. To focus on the inverter interactions, the loads and capacitor banks on this feeder are aggregated. The simplified feeder model in Matlab Simulink is shown in Figure 1. The solar PV with inverter interfaces at each site are connected to the feeder via a 480 V/12.47 kV transformer.

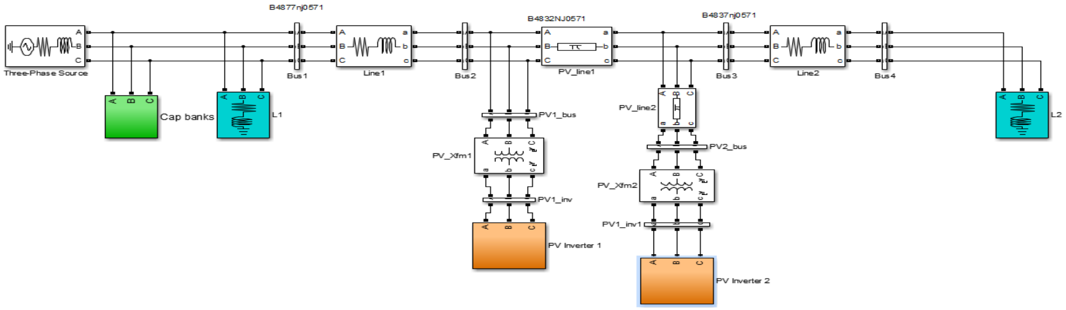


Figure 1 Feeder model with solar PV inverters

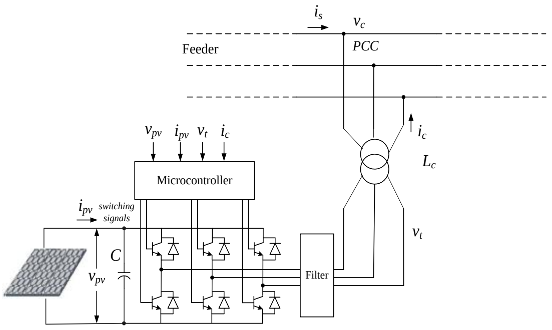
The solar PV inverter is modelled as a common three-phase single-stage inverter [3] as shown in Figure 2. The AC power out of the inverter is filtered to reduce harmonics and then is fed to the grid via a transformer with equivalent inductance L_c at the point of common coupling (PCC). The PCC voltage is v_c and the PV inverter terminal voltage and current (after the filter) are v_t and i_c, respectively. The active and reactive power output of the PV inverter to the grid can be expressed as Equations (1) and (2), respectively, when the phase angle α between the PCC voltage and inverter terminal voltage is small.

$$P = \frac{V_t V_c}{X_l} \sin\alpha \approx \frac{V_t V_c}{X_l} \alpha \tag{1}$$

$$Q = \frac{V_t}{X_l}(V_t - V_c \cos\alpha) \approx \frac{V_t}{X_l}(V_t - V_c) \tag{2}$$

where V_t and V_c are the magnitudes of the terminal voltage v_t, and inverter PCC voltage v_c, and α is the phase angle difference of v_c and v_t.

Equations (1) and (2) show that the active power flow can be controlled by regulating the phase angle α of v_t and the reactive power can be controlled by regulating the amplitude of v_t. Although there are many different inverter control methods the basic principles under them are similar. In this study, a simple PI based control is implemented for active and reactive power control based on Equation (1) and (2) shown in Figure 3.



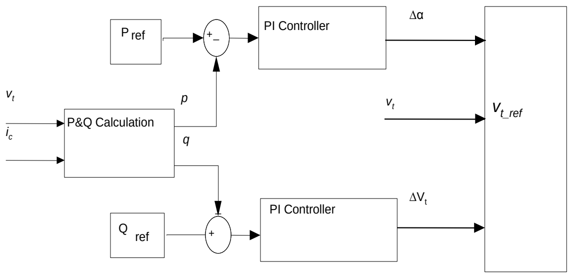


Figure 2 Solar PV inverter model

Figure 3 Solar PV inverter Control

Volt-Var Control

The volt-var control function allows each individual DER system to provide a unique var response according to 1) to the voltage at the point of connection (the terminals of the DER system), 2) either the available or the absolute apparent power capacity of the DER at that point in time, and 3) the utility-defined volt-var setpoints such as the example illustrated in Figure 4.

Some of the uses of the volt-var functionality are to attempt to maintain the voltage at the terminal of the DER system within ANSI limits for a variety of circumstances. For example, absorption of reactive power (inductive vars) can be called upon if the voltage begins to exceed a pre-determined upper level (as defined by a volt-var curve). Conversely, if lower than normal voltages are present at the terminals of the DER 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.

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 0.95 pu 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 DER system. The points can also be defined with or without a “deadband” such that the DER provides continuous var control from V1 to V4.

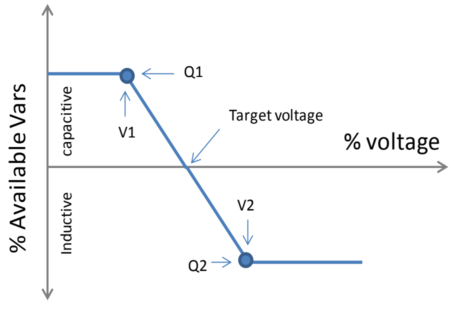


Figure 4 Example volt-var curve

The volt-var control flow used in this study is shown in Figure 5. The PV inverter terminal voltage is averaged over a moving fixed-width time window and then the average voltage is fed to the volt-var curve function to determine how much reactive power should be generated. The inverter controller then adjusts its switching command according to the needed reactive power. The reactive power control flow indicates that the volt-var curve setting, the inverter controller parameters and the voltage averaging time could have impacts on the interactions of the grid-support inverters. In the following, the inverter interactions will be examined with respect to these factors.

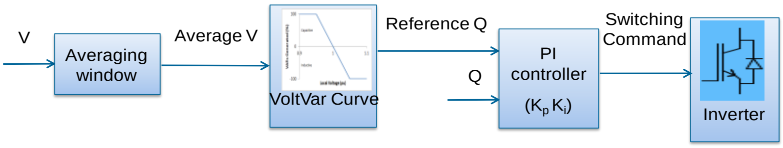


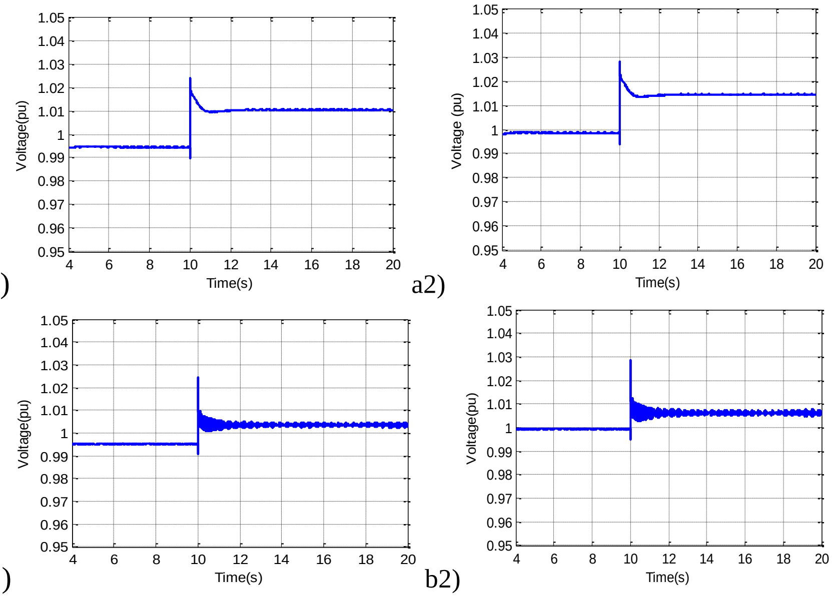
Figure 5 Volt-var control flow

Potential Interactions Between Inverters with Advanced Functions

In this study, the volt-var grid support function will be used as an example to investigate the potential inverter interactions. To simplify the simulation test, a step-voltage change is created on the feeder such that both PV systems experience the voltage fluctuation, and respond according to their own controls. To introduce the voltage fluctuation, capacitor banks are switched online.

A. Comparison of single vs both PV inverters with volt-var function

The simulations are conducted in Matlab Simulink. The maximum active power output of the two PV arrays in the simulation is limited to 400 kW and 1000 kW such that the inverters have remaining capacity to provide reactive power to the grid at full active power output. The DC output from the panel is held constant over the course of the simulation, which is reasonable considering the simulation is performed over a 10 second period. Figure 6 shows the voltages at the PV inverters terminals of two different cases A) only PV1 provides volt-var control; and B) both PV1 and PV2 provide volt-var control. The target voltages at both terminals are 1 pu. Voltages rise due to the capacitor switching on at 10 s, and then reduce slightly according to the volt/var response of PV1. As can be seen in case A), in which PV1 is only providing var control, the terminals of PV2 also see the voltage reduction due to PV1. In case B), where both PV systems operated under volt/var control, one can observe the voltages at both terminals being reduced even further after the capacitor switching. In this case, both inverters are helping to regulate the voltage. However, one also observes oscillations in the voltage, which would indicate there are interactions between the two close PV inverters when both PV inverters provide volt-var support function according to local voltages.



a1) a2) b1) b2)

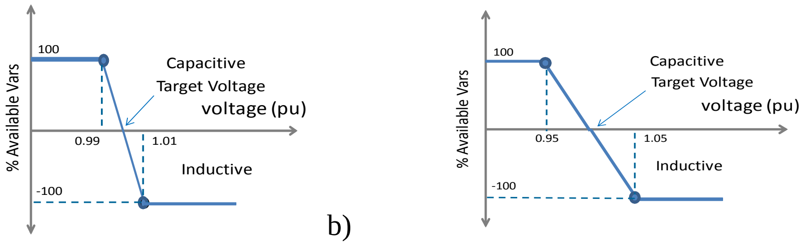
Figure 6 Voltages a1) V at terminal1 when only PV1 provides var a2) V at terminal2 when only PV1 provides var b1) V at terminal1 when both PVs provide var b2) V at terminal2 when both PVs provide var

B. Sensitivity to control settings

Results indicate that interaction between inverters, albeit, small, do occur. In this section, simulation results will be shown in which different control parameters are varied in order to examine the interaction response. Three scenarios are examined, 1) volt-var curve set point adjustment, 2) inverter control parameters, and 3) voltage averaging time period. The case B) in section A is selected as the base case. It has the volt-var setting shown in Figure 7(a), controller parameters kp=0.3 and ki=3 and 0.05 s voltage averaging window.

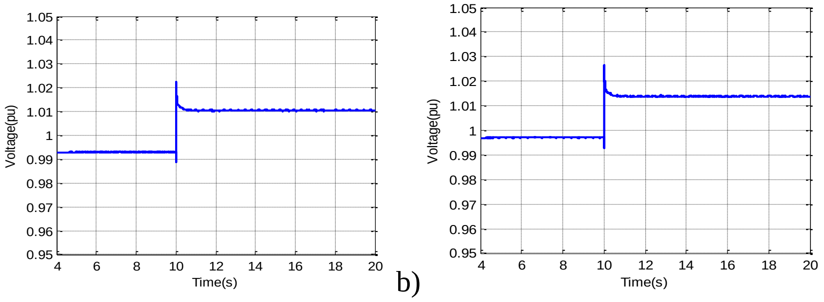
1) Volt-var curve

Figure 7 (a) and (b) show two volt-var settings with the same 1.0 pu target voltage but different slopes. The terminal voltages of both PV inverters having volt-var curve setting 2 are shown in Figure 8. Other than the volt-var curve settings, the other simulation settings are the same for the two scenarios. By comparing Figure 6 (b1)- (b2), which utilizes volt-var setting 1, and Figure 8, one observes more inverter interaction under volt-var setting 1. The comparison of the two scenarios indicates that steeper volt-var slopes tend to cause the PV inverters to chase against each other around the target points. In the case that the available reactive power of the PV inverters on the feeder is substantial, the voltage fluctuations as a result of the inverters control chasing may start to cause adverse impacts on the feeder. It should be noted here the volt-var curve slope is only one of the parameters to define a volt-var curve and there are many other ways to define a volt-var curve. The simulation conducted here is to confirm that the volt-var setting affects the inverter interactions. How each parameter affects the interactions depends on the specific volt-var curve characteristic and needs further study.



a) b)

Figure 7 Volt-var settings a) Volt-var setting 1 b) Volt-var setting 2

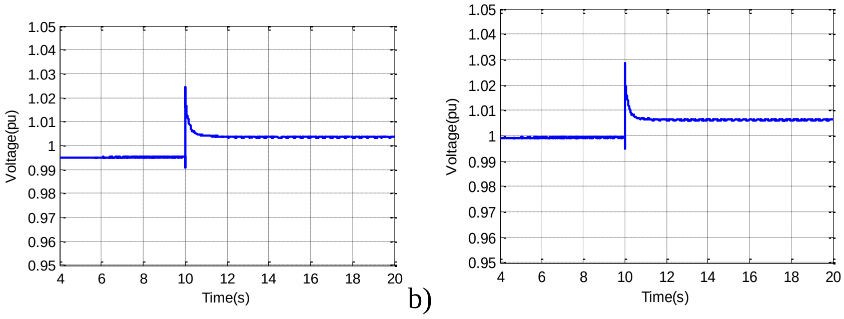


a) b)

Figure 8 Voltages a) V at terminal1 with volt-var setting 2 b) V at terminal2 with volt-var setting 2

2) Inverter controller parameters

In this test, the controller parameters kp and ki that decide the controller response speed, reduced from (0.3, 3) in base case to (0.1, 1) to compare the voltage responses under different controller parameters. It is shown in Figure 9 that the voltages fluctuations caused by the inverters' interaction do not occur with reduced controller parameters.



a) b)

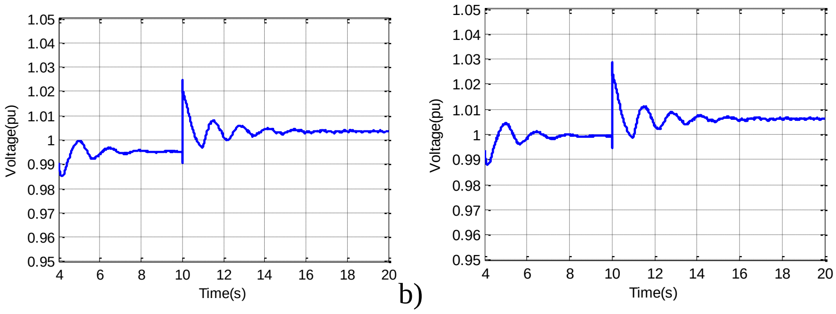
Figure 9 Voltages a) V at terminal1 with kp=0.1 ki=1 b) V at terminal2 with kp=0.1 ki=1

Since smaller PI control parameters make the response speed slower, the results suggest that the voltage oscillations occur slowing the controller response to allow for smaller var adjustments at each control iteration could help eliminate inverter "chasing".

3) Voltage averaging time period

The voltage fed to the volt-var curve function to determine the amount of reactive power could be averaged over a longer period of time for stable voltage measurement readings. However, this averaging time period could impact the inverters interaction. Figure 10 shows the voltage response for when the input voltage is averaged over a 1s window. It should be noted that the voltage displayed in Figure 10 is still the RMS voltage, not an averaged RMS value. As can be seen by comparing Figure 10 and Figure 6 (b1), (b2) the scenario with longer averaging time period has larger voltage oscillations initially but eventually the oscillations dampen out. The averaging time period has different impacts in the volt-var control process. Initially, the var amount based on the average voltages over a long time tends to exceed what is actually needed at that moment because the average voltages are biased by the old voltage data which generate higher var demands. Thus, a larger voltage fluctuation occurs. However, as the control process further proceeds especially when the voltages start to oscillate around a central point, averaging voltages over a long time period could filter out some oscillations and the reactive power production as a result will be smoother compared with the scenarios with very short averaging windows. The voltage oscillations damp out under the smooth reactive power production. The two different influences of the averaging time period need to be well balanced when picking up the averaging time period parameter.

However, averaging the voltage input to the volt-var function slows the function's response time, and although it may be one way to reduce inverter interactions, may not be desirable overall. More research is needed in this area.



a) b)

Figure 10 a) V at terminal1 with 1 s window b) V at terminal2 with 1 s window

Conclusions

The global electric power industry has recognized the need for PV system inverters to provide grid-support functions. The potential interaction between grid-supportive inverters, however, can pose challenges to reliable operation in the power system. This paper is to raise awareness on this issue. The simulation results show that there can be interaction with two large inverters located electrically close to one another. The parameters of volt-var settings, the inverter controller parameters and the voltage averaging window can cause more/less oscillations. Results seem to indicate that aggressive volt/ var slopes (high sensitivity of reactive power with respect to voltage deviation) and fast-response times tend to cause the inverters to interact more significantly. Results also seem to indicate that averaging terminal voltages can damp oscillations but it may introduce larger voltage fluctuation initially and may be undesirable in terms of slowing the reactive power response time of the inverters. The results presented assumes the worst case where both inverters operate simultaneously. Slightly asynchronous operation could reduce the interactions. More systematic studies and field demonstration/measurements of the common set of grid-support functions are needed to better understand the potential interactions and to provide insights on how to prevent any possible adverse impacts.

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