Advanced Inverter Controls to Dispatch Distributed PV Systems

John Seuss[1], Matthew J. Reno[2], Matthew Lave[2], Robert J. Broderick[2] and Santiago Grijalva[1],

[1] Georgia Institute of Technology, Atlanta, GA, USA

[2] Sandia National Laboratories, Albuquerque, NM, 87185-1033, USA

***Abstract* — The research presented in this paper compares five real-time control strategies for the power output of a large number of distributed PV systems in a large distribution feeder circuit. Both real and reactive power controls are considered with the goal of minimizing network over-voltage violations caused by high penetrations of PV generation. The control parameters are adjusted to maximize the effectiveness of each control. The controls are then compared based on their ability to achieve multiple objectives. These objectives include minimizing the total number of voltage violations, minimizing the total amount of PV energy curtailed or reactive power generated, and maximizing the fairness of any control action among all PV systems. The controls are simulated on the OpenDSS platform using time series load and spatially-distributed irradiance data.**

I. Introduction

As photovoltaic (PV) generation becomes increasingly common on distribution networks, recent research has sought to find the physical constraints on the amount of PV that existing distribution networks can handle [1, 2]. Advanced inverter controls could allow the PV inverters to provide reactive power support when available or curtail their real power output when necessary to keep the network within operational constraints. The goal of this research is to study how smart inverter controls can be used to mitigate the rise in network voltage caused by a large amount of PV distributed throughout a distribution feeder. Several PV inverter control strategies are compared that will either curtail the real power output or provide reactive power support based on network conditions. The goal of each control strategy is to <u>mitigate</u> all over-voltage violations caused by PV anytime during the year, <u>minimize</u> the total amount of PV energy curtailed or reactive power generated, and <u>maximize</u> the fairness of any control action among all PV systems. Both controls that only utilize local measurements and those that require a robust communication network are tested.

Recent research has shown that the addition of passive voltage monitoring local controls to the PV inverter can mitigate many of the adverse effects caused by distributed PV systems [3, 4]. Improved functionality may be possible if some level of communication exists between the inverters [5-7] by using optimal dispatch of PV inverter reactive power [8] or optimal dispatch of both real and reactive power [9]. Ideally, control of PV inverters should be coordinated with existing voltage regulators to achieve the best results [10, 11]. Optimal power dispatch approaches are typically computationally intensive and only study short time periods. Local control approaches are more easily studied over large time series, but the tuning of their control parameters that yield the best results is not straightforward [12]. A comparison between the performances of local versus centralized control over long time periods is therefore complicated by the vast difference in simulation times.

The studied control types are each introduced in Section II. The base case simulation data and methodology is introduced in Section III, and the control type simulations are presented in Section IV. The results are then compared in Section V, and conclusions discussed in Section VI.

II. Control Types Investigated

To investigate the effectiveness of control types on curtailment we explored five different control types: 1) Zero Current Injection, 2) Local Voltage-Based PV Curtailment, 3) Local Voltage-Based Var Control, 4) Centralized Fair Curtailment Dispatch and 5) Curtailment Dispatch via PV Voltage Sensitivities [13]. Each control is designed to mitigate over-voltages while being compared based on the amount of control action used, either power curtailed or vars produced, and the fairness of how the control action is applied across the population of PVs in the network.

Zero Current Injection (ZCI): The PV system is limited to only producing enough power to supply the local load, but never inject power into the distribution network. This control prevents reverse power flow and the voltage rise associated with it. It is the most conservative case to be used as a baseline.

Local Voltage-Based PV Curtailment: Using only locally available measurements, the output of each PV system can be curtailed based on the point of common coupling (PCC) voltage of its respective phase. To maintain smooth control operations, the curtailment is typically performed as a ramping down of active power output beginning at some measured voltage, v_1, as shown below in Figure 1. If voltage continues to rise, the inverter will continue to ramp down its output until it is completely curtailed at measured voltage v_2. This type of control curve is called a “Volt/Watt droop”.

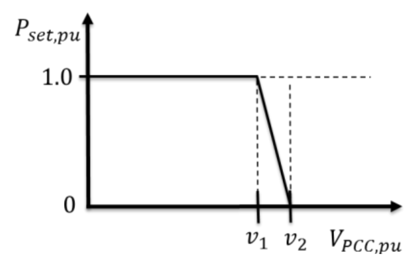

Figure 1. Volt/Watt droop curve used for local PV power curtailment.

Local Voltage-Based Var Control: A PV grid-tie inverter can supply reactive power to the grid to help regulate the line voltage by phase shifting the current it injects with respect to the voltage at its PCC. However, the capability for the inverter to provide vars is limited by its rating. In this work, it is assumed that the inverter is rated equivalent to the maximum power point its PV panels are capable of achieving, P_{MPP}. Neglecting non-idealities, the amount of reactive power available to the inverter is represented by the diagram in Figure 2 where the radius of the circle represents the rating of the inverter. The reduced power level can either be due to the PVs panels operating below P_{MPP} due to lack of rated incident irradiance or due to active curtailment from a control, such as Volt/Watt. PV panels are seldom operating at P_{MPP}, so there is typically some reactive power available to the inverter. The var limits from the left of Figure 2 determine the per-unit scale of the Volt/Var curve, shown in the right of Figure 2, which dictates how the inverter supplies its available reactive power based on the voltage measured at the PCC.

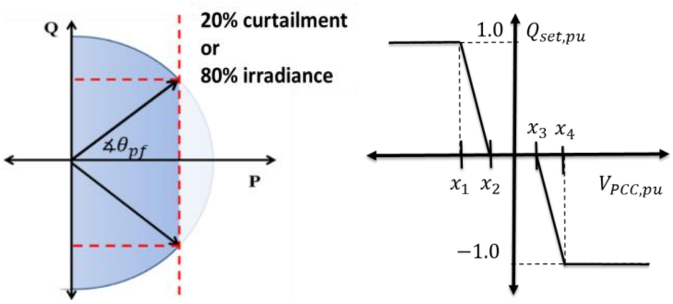

Figure 2. (left) Assumed relationship between real power output and reactive power available to PV inverter. (right) Volt/Var droop curve used for reactive power support.

Centralized Fair Curtailment Dispatch: The previous two control methods have assumed that no communication network exists to assist in controlling the PV inverters, so they must rely on local measurements only. If the PV inverters are able to communicate with a centralized controller, this controller would then have knowledge of all network voltages and could strategically dispatch control signals to the specific inverters that would be best suited to mitigate over-voltage violations. However, simply controlling the inverters that will mitigate over-voltages first may unfairly target a few PV installations on the network. With a centralized approach, knowledge of each inverter in the network means that fairness of the control can also be taken into consideration in the control algorithm itself.

The first centralized method is investigated to see how well inverters can mitigate over-voltages by curtailing them all in equal proportion at each time step. To this end, a regulator (1) is developed to determine the percent each PV should curtail from its available power at each time instant based on the deviation from a desired voltage limit of the maximum voltage in the network, V_{lim}. The curtailment ratio α in (1) is dispatched to each inverter at each discrete time step, k. An inertia gain, K_Φ, can be adjusted to weight the importance of the past step. The speed of this regulator can be set by the gain K_R, which must be tuned depending on the rate at which the signal is dispatched to the PV. Since this is a discrete controller with physical constraints, there is an upper limit to K_R beyond which the control will oscillate between saturated states. This upper limit is proportional to the rate at which the control updates and the rate at which the inverters respond. The local implementation of the control is given in (2). When inverter i receives the central curtailment ratio $\alpha(k)$, it sets its power reference signal, $P_i(k)$, as a function its maximum power point (MPP) power and the local irradiance at that time step $I_i(k)$ to curtail its power output proportionally.

$$\alpha(k+1) = K_\Phi \alpha(k) + K_R(\max(V_i(k)) - V_{lim}) \tag{1}$$

$$\begin{gathered} P_i(k) = \alpha(k) P_{i,max}(k) \\ P_{i,max}(k) = I_i(k) P_{MPP,i} \end{gathered} \tag{2}$$

Curtailment Dispatch via PV Voltage Sensitivities: Based on established linear voltage sensitivities, the PV systems can be more optimally dispatched to mitigate over-voltage with the least amount of total PV energy curtailed on the feeder. This comes at the cost of fairness to customers that may be curtailed more. The first-order approximation assumes the change in network voltage at each measured bus can be approximated via (3).

$$\Delta \boldsymbol{V} \approx \boldsymbol{A} \Delta \boldsymbol{P} + \boldsymbol{B} \Delta \boldsymbol{Q} \tag{3}$$

In (3), the coefficient matrix $\boldsymbol{A}$ is found by curtailing each PV system j by a percentage of its per-unit rating, Δp, such that $P_j = P_{j0} - \Delta p$. The columns of the real power sensitivity matrix can then be populated with the resulting difference in voltage from the zero-curtailment case, $\boldsymbol{V_0}$, as in (4). The reactive power sensitivity matrix $\boldsymbol{B}$ is found similarly by adjusting the output of each PV system by some Δq.

$$\begin{gathered} \boldsymbol{A} = [\boldsymbol{a_1}\ \boldsymbol{a_2} \ldots \boldsymbol{a_j} \ldots \boldsymbol{a_n}] \\ \boldsymbol{a_i} = \boldsymbol{V_i} - \boldsymbol{V_0} \end{gathered} \tag{4}$$

Due to some assumed limitations in the type of measurements and communication available, as well as the scope of the time data to be studied, a true optimal solution at each time step was not considered. Instead, a similar approach as the centralized fair curtailment is developed to integrate the desired change in power of each PV inverter $\Delta\boldsymbol{P}$ over time. Thus, the curtailment of each inverter, ΔP_j, becomes a state variable to be updated and passed between time steps and then dispatched to the PV at the appropriate interval. The time step k represents either 1-minute or 5-minute dispatch to the PV in the later simulations. The curtailment vector is updated by the inverse sensitivity matrix times the desired change in voltage and a tunable gain K_A, as shown below in (5).

$$\Delta\boldsymbol{P}(k+1) = \Delta\boldsymbol{P}(k) + K_A\boldsymbol{A}^{-1}(\boldsymbol{V}(k) - V^*)$$
$$s.t\ \ (-1 \le \Delta\boldsymbol{P}(k) \le 0) \tag{5}$$
$$|\Delta\boldsymbol{P}(k+1) - \Delta\boldsymbol{P}(k)| \le \Delta P_{lim}$$

The inequality constraints in (5) are added to keep the control actions bounded to physical constraints. The 2nd line in (5) represents the fact that an inverter cannot curtail or produce more power than that flowing through it. To prevent oscillations between controllers, the amount each PV can ramp between iterations is limited to 20% of its rated power per minute, which is achieved by setting $\Delta P_{lim} = 0.2$ in the 3rd line of (5). The desired voltage V^* to regulate in (5) is initially set to the ANSI limit of 1.05, however, this value can be reduced to account for inaccuracies of the linear approximation and mitigate any remaining voltage violations. In addition to V^*, the control in (5) can be tuned by the gain variable K_A and the curtailment change limiter ΔP_{lim}.

III. Base Case Simulation

This paper focuses on the application of smart inverter controls to a large number of highly distributed PV systems in a realistic distribution network. To effectively study the time-dependent and unpredictable nature of PV, a full year of irradiance and load data is studied. A sufficient amount of PV generation is placed on the network to ensure over-voltage problems during daytime periods throughout the year.

A real distribution feeder is modeled in OpenDSS to test the PV controls [14]. The circuit, designated Feeder CO1, is a rural 12kV distribution feeder with one voltage regulator about halfway down the feeder and five switching capacitors. A map showing the layout of the feeder topology and the existing voltage regulating devices is shown in Figure 3. The feeder has a peak load of 6.41MW and a minimum load of 1.29MW.

In total, 2079 single-phase PV systems are placed on the feeder, one at each load, shown as the yellow stars in Figure 3. Each PV system is sized to represent 60% of the peak value of the local load to which it is connected. This is equivalent to 250% of the minimum daytime load within the year, which means there will be reverse power flows and voltage rises. The average per-phase PV system rating is 1.74kW, and the total feeder aggregate installed PV is 3.62MW. To create unique simulated irradiance time series for each PV system, 1-year of global horizontal irradiance (GHI) measured in Albuquerque, NM was time-shifted by the appropriate time offset from historical daily cloud speeds, and the irradiance measurements were translate to plane of array irradiance for south-facing fixed-latitude-tilt PV systems. Figure 4 demonstrates the voltage-rise effect of the PV during a period of low load and high irradiance. For a given load level, the bottom three lines without yellow stars are the voltage profiles of the feeder without PV, and the top three lines are with PV.

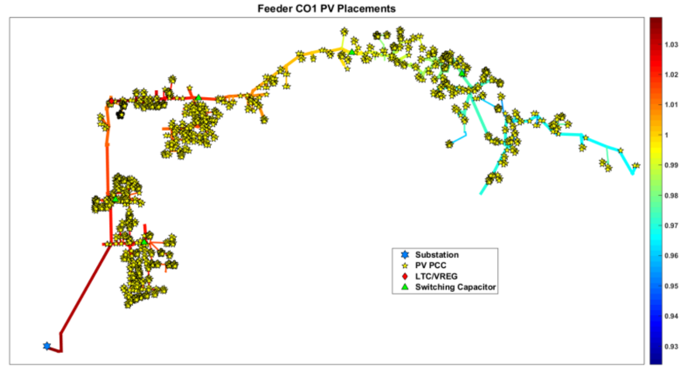

Figure 3. Map of feeder CO1 with PV placements indicated and lines colored by per-unit voltage.

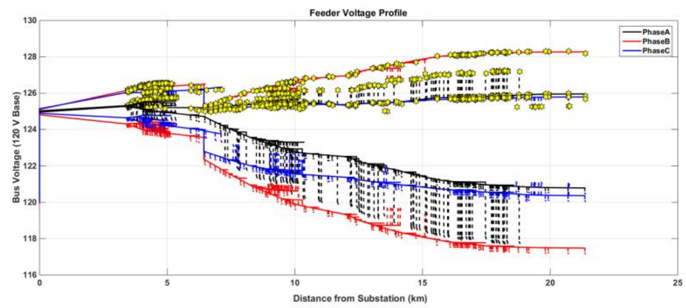

Figure 4. Feeder voltage profile at minimum load without PV and with PV, represented as yellow stars.

IV. Control Parameter Tuning

Using the yearly load and PV output profiles, a year quasi-static time-series (QSTS) simulation is run, which takes slightly less than 1-hour to run on a desktop computer. Each control type requires parameter tuning, which is time consuming if done over the entire year simulation. Thus, a one-week period with the single highest number of over-voltage violations in the no-control case is used as a test period. Of all the over-voltage violations that occur during the year, most occur during the middle of the year when the load and irradiance are at their peaks, as shown in Figure 5. The worst week for over-voltage violations in the base case starts on the 132nd day of the year, which is the time period used for tuning the controls as described next. Only the tuning of the real-power controls is presented since a standard Volt/Var curve is used and the ZCI control has no parameters to tune.

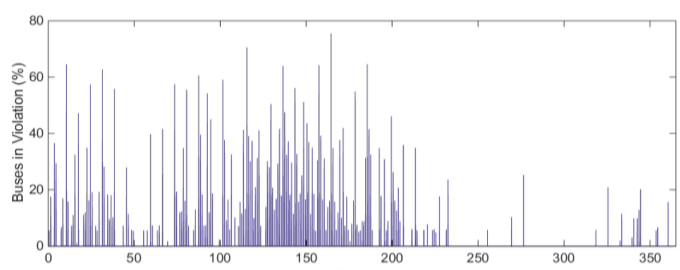

Figure 5. Percent of feeder buses that experience an over-voltage violation for each day in a one-year simulation.

Local Voltage-Based PV Curtailment: The parameter set $\boldsymbol{v} = [v_1, v_2]$ that defines the controller Volt/Watt curve in Figure 1 is tuned using the worst week of data in the year. Ten parameter sets are tested using $v_2 = 1.05$ and linearly varying $v_1 = [1.040 \ldots 1.049]$. The performance of each parameter set is summarized in Figure 6. The top plot of Figure 6 shows the percent of the week the network spent in an over-voltage violation, which should be zero for a successful control performance. The bottom plot shows the percent by which the total PV power generation is curtailed due to each control. As expected, a lower v_1 parameter corresponds to more curtailment but an increase in over-voltages due to a steeper Volt/Watt slope. Further investigations show a tendency for power to oscillate at low v_1 so the control is set conservatively at $\boldsymbol{v} = [1.045, 1.05]$ for the full year simulation.

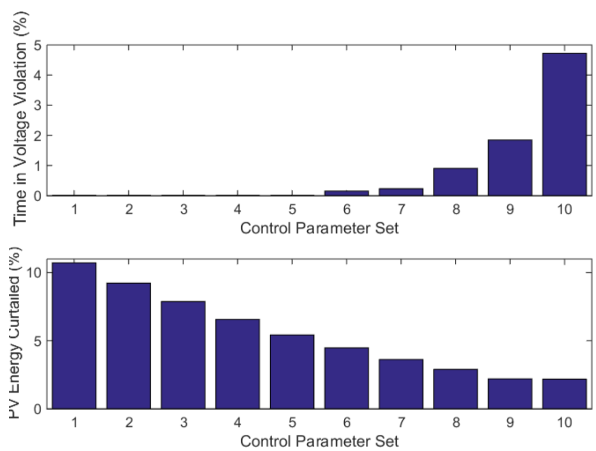

Figure 6. Comparison of performance of different Volt/Watt control parameter sets during a one-week tuning period.

Centralized Fair Curtailment Dispatch: Tuning this control took several iterations due there being more parameters in (1). After a few attempts, the inertia gain is kept set to $K_\Phi = 1.0$ with $V_{lim} = 1.049$ and only the regulator gain is adjusted. The tuning results are shown in Figure 7.

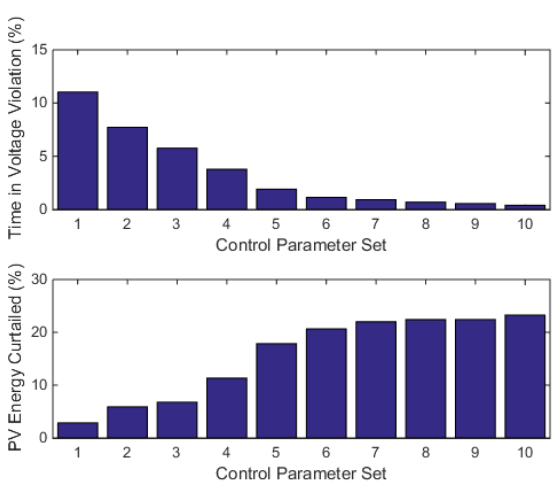

Figure 7. Comparison of different centralized fair control parameter sets during a one-week tuning period.

The different parameter sets in Figure 7 correspond to the set K = $[1, 5, 10, 20, 30, 50, 60, 70, 80, 90]$. To test the effect of communication limitations, both centralized controls are simulated at 1-minute and 5-minute dispatch windows, which need to be tuned for separately. The fair control 1-minute dispatch uses a regulator gain of $K = 30$ and the 5-minute dispatch uses a gain of $K = 5$. These were both selected conservatively after investigating the time-domain responses.

Curtailment Dispatch via PV Voltage Sensitivities: A similar approach as the previous controls is used to tune the sensitivity-based control. The control parameters in (5) are tuned to be $K_A = 1.1$ and $\Delta P_{lim} = 0.5$ for the 1-minute dispatch and $K_A = 0.9$ and $\Delta P_{lim} = 0.1$ for the 5-minute dispatch. Even with several attempts at tuning, though, it was found that the 5-minute dispatch window was too slow and resulted in power oscillations to achieve comparable results. These oscillations between 5-minute dispatch times can be seen in Figure 8.

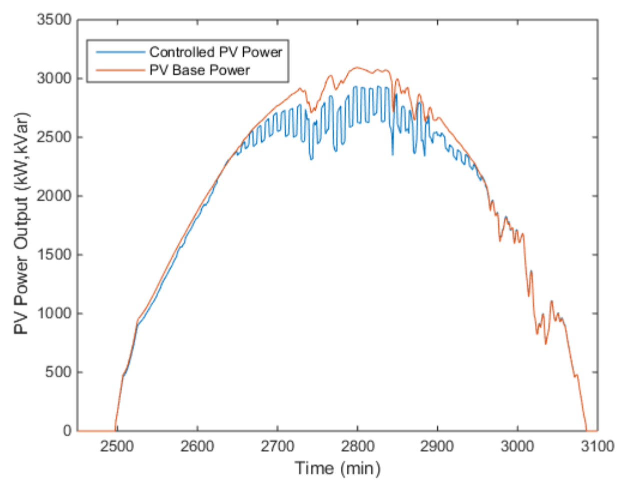

Figure 8. Daytime inverter power output under 5-minute dispatch of sensitivity-based curtailment compared to the base power output.

V. Simulation Results

The results of the real power curtailment controls are briefly covered in this section, followed by a summary comparison of all control types considered.

Local Voltage-Based PV Curtailment: The overall curtailment of each PV system during the simulation is shown in Figure 9 based on its location in the feeder. This map demonstrates the PV systems facing the highest control costs due to their location. The worst-week data is displayed since it has a larger disparity that will be more visible, but the full year results are similar. Each point represents how much energy the PV system at that location had to proportionally curtail over the week due to the Volt/Watt control. The highest curtailments occur in a cluster of loads on a lateral branching off near the substation. The next highest curtailments occur towards the end of the feeder, as is to be expected due to the voltage rise effect along the entire feeder. The distribution of the probability of how much a single inverter curtails with this control type is shown in Figure 10 for both the one week and one year simulations. Although this control was capable of mitigating all over-voltage violations, from these two figures, it is clear that several customers curtail a disproportionate amount with this control.

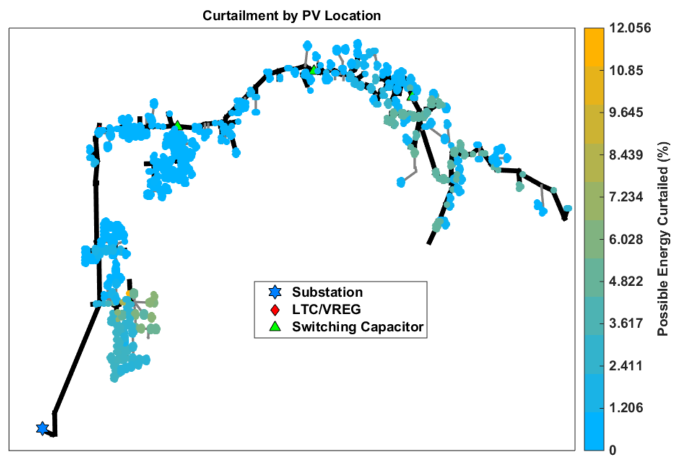

Figure 9. Geographic distribution of PV system curtailment in the feeder due to Volt/Watt control.

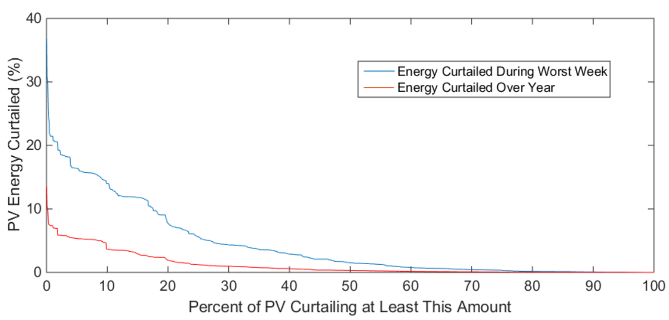

Figure 10. Cumulative distribution of PV power curtailment using Volt/Watt control during one week and over one year.

Centralized Fair Curtailment Dispatch: Using a centralized approach that dispatches an equal, proportional curtailment signal to all inverters, the geographic distribution of power curtailment is shown in Figure 11. The scale of the curtailment should be noted here, since all inverters curtail power roughly the same. This is clearer in looking at the cumulative distribution of the curtailment among all inverters in Figure 12. The reason for the slight east/west geographic difference in curtailments is due to the east/west bias in changes in irradiance. In other words, this control would be completely fair to all customers except for the variability of cloud coverage that provides some customers with more power than others at different times. That said, this control is slightly less effective at mitigating over-voltages and curtails more power overall than the local Volt/Watt control. The numerical comparison of the performance of all controls is given in the summary tables at the end of this section.

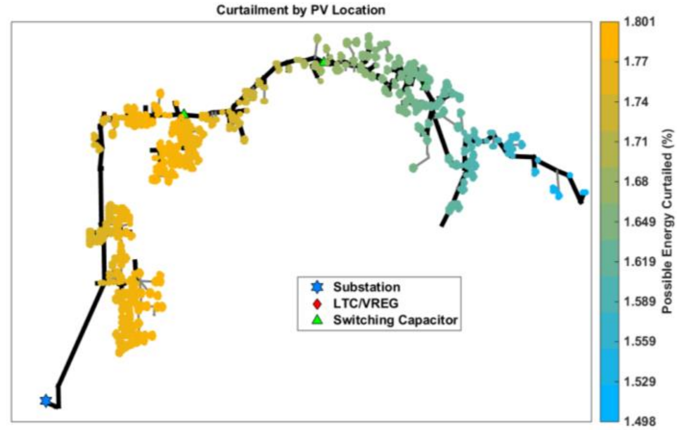

Figure 11. Geographic distribution of PV system curtailment in the feeder due to centralized fair curtailment.

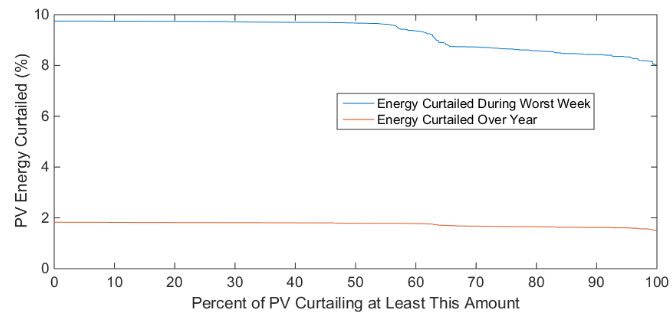

Figure 12. Cumulative distribution of PV power curtailment using centralized fair curtailment during one week and over one year.

Curtailment Dispatch via PV Voltage Sensitivities: The last curtailment strategy examined in detail uses knowledge of voltage sensitivities to control each PV inverter to regulate all voltages within ANSI limits. The distribution of percent energy curtailed over all PV inverters is shown in Figure 13. This control type was the most efficient at mitigating all voltage violations at the least energy curtailed, but it was also the least fair approach. In Figure 13, it can be seen that some customers curtail several times more energy than their neighbors. While this control was the most effective for the one week period on which it was tuned, it actually performed worse than the local and centralized fair curtailment controls over the full year. This suggests this control's parameters are more sensitive to the time period on which they are tuned. This can be seen in the summary table and also explains why the two curves cross in Figure 13.

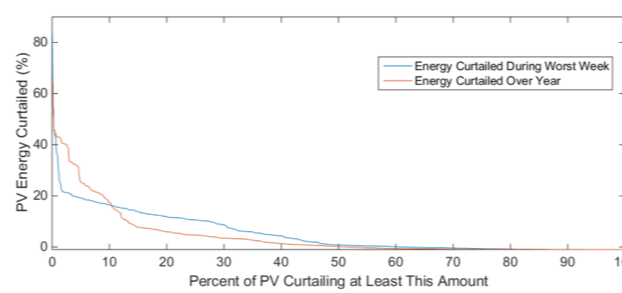

Figure 13. Cumulative distribution of PV power curtailment using sensitivity-based central control during one week and over one year.

Summary of All Controls: The results for a 1-week period for which the controls are tuned are shown in Table I. The Volt/Watt control did a comparable job of mitigating over-voltage violations as the simple method of preventing reverse current injection into the feeder through curtailment, ZCI, while also curtailing significantly less energy than SCI. Additionally, the application of Volt/Var control was able to mitigate most voltage violations with no curtailment at all. The combination of Volt/Var with curtailment only when necessary should be able to prevent 100% of voltage violations at a minimal level of PV real power curtailment.

TABLE I. COMPARISON OF INVERTER CONTROL TYPES DURING THE WORST ONE-WEEK PERIOD OF VOLTAGE VIOLATIONS.

Control Type	ZCI	Volt/ Watt	Volt/ Var	Central Fair (1m)	Central Fair (5m)	Sensitivity -based (1m)	Sensitivity -based (5m)
Violations Mitigated (%)	100.0	100.0	98.7	99.0	91.7	100.0	99.7
Power Curtailed (%)	21.6	4.35	0	9.30	5.89	3.99	4.58
Curtailment Deviation (%)	0.75	5.69	0	0.57	0.16	8.21	8.23

TABLE II. COMPARISON OF INVERTER CONTROL TYPES OVER A ONE YEAR SIMULATION PERIOD.

Control Type	ZCI	Volt/ Watt	Volt/ Var	Central Fair (1m)	Central Fair (5m)	Sensitivity -based (1m)	Sensitivity -based (5m)
Violations Mitigated (%)	100.0	100.0	98.2	100.0	97.6	100.0	99.7
Power Curtailed (%)	10.7	0.85	0	1.75	2.00	2.46	2.82
Curtailment Deviation (%)	0.46	1.81	0	0.09	0.05	9.78	9.89

Compared with the local controls, the centralized control types had global network knowledge that allowed them to achieve specialized tasks. Specifically, the fair dispatch was able to prevent a large number of over-voltage violations while evenly distributing the burden of curtailment relative to the size of each PV system. Contrarily, the centralized control method that made use of the knowledge of each PV system's impact on the overall network voltage was able to mitigate essentially all over-voltage violations using the least amount of curtailment during the time it was tuned to improve.

VI. CONCLUSIONS

Five different advanced inverter control strategies were developed with differing objectives to run in a timely manner in a 1-year, 1-minute time step quasi-static time-series simulation. The two centralized control strategies that were developed were able to leverage data from thousands of PV systems and quickly calculate simulated control actions in a fraction of a second. Reactive power control of PV inverters, without the need for an increase in the rating of the inverter, was investigated to determine that real-power curtailment could be avoided over 97% of the time. The legacy control action of curtailing PV power output based on reverse power flow was compared to more advanced voltage-based curtailment methods. Four of the five methods investigated using the 1-year long simulation achieved curtailment of less than a net 3% of kWh produced by PV on the feeder while maintaining feeder voltages within ANSI voltage standards >98% of the time.

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