PV-Induced Low Voltage and Mitigation Options

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***Abstract* — With increasingly high penetrations of PV on distribution systems, there can be many benefits and impacts to the standard operation of the grid. This paper focuses on voltages below the allowable range caused by the installation of PV on distribution systems with line-drop compensation enabled voltage regulation controls. This paper demonstrates how this type of under-voltage issue has the potential to limit the hosting capacity of PV on a feeder and have possible consequences to other feeders served off a common regulated bus. Some examples of mitigation strategies are presented, along with the shortcomings of each. An example of advanced inverter functionality to mitigate over-voltage is shown, while also illustrating the ineffectiveness of inverter voltage control as a mitigation of under-voltage.**

***Index Terms* — data analysis, distributed power generation, photovoltaic systems, power system modeling, voltage control.**

I. INTRODUCTION

Sandia National Laboratories (SNL) conducts research regarding the increasing integration of photovoltaic (PV) generation onto distribution systems. This report focuses on PV voltage impact modeling and analysis using EPRI's OpenDSS software [1]. Examples of under-voltage caused by the combination of PV and line-drop compensation (LDC) are shown, as well as mitigation options and the shortcomings of each.

The under- and over-voltage conditions are defined as steady-state voltages outside the ANSI C84.1 limits [2], sustained such that any 10-minute average is outside the applicable limits. For all examples, ANSI Range A limits of 117 V to 126 V applied for under/over-voltages on the feeder primaries, as shown in Fig. 1.

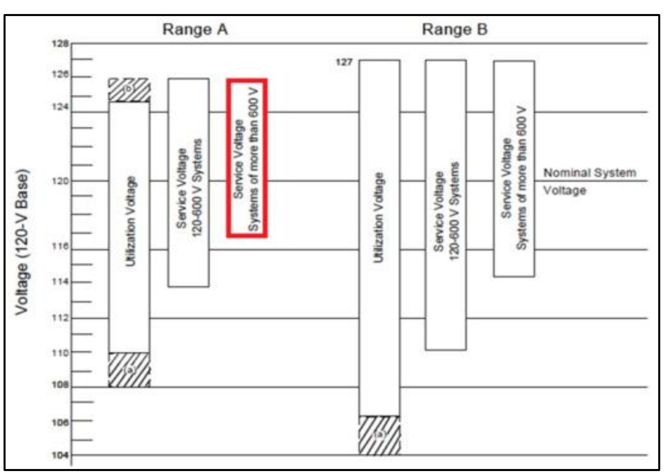

Fig. 1. ANSI C84.1 Range A and B service voltage limits [2].

SNL has found sustained under-voltage to be a PV impact under circumstances involving both PV and LDC. LDC is a load tap changer (LTC) and voltage regulator (VREG) control setting. LDC can set the voltage control point downstream of the LTC/VREG [3]. LDC settings consist of impedance characteristics, both real and reactive defined in volts at CT rated current, which are representative of the section of feeder between the LTC/VREG and the virtual control point (VCP). The control calculates line drop using the impedance settings and line current and regulates accordingly. Fig. 2 shows a line drop compensator circuit [4].

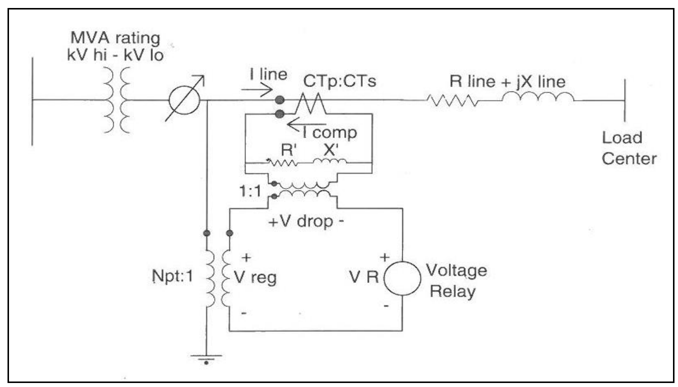

Fig. 2. Line drop compensator circuit [4].

LDC can be useful in cases where optimal VREG locations present excessive physical obstacles or for conservation voltage reduction (CVR). Because LDC results in a lower voltage setpoint when there is low or reverse current, LDC can often mitigate potential high voltages caused by PV.

The use of LDC becomes more complex when applied to a substation LTC serving more than one feeder. Despite the complexity of these applications, SNL has encountered a fairly high incidence, ~50% (12/25), of substation models studied. Analysis of these feeders revealed the characteristics of under-voltage in a variety of scenarios.

II. UNDER-VOLTAGE IMPACT OVERVIEW

Several cases of under-voltage impacts have been identified through different analysis approaches. The under-voltage cases have some commonalities: PV near an LTC or VREG with LDC causing under-voltages toward the end-of-feeder (EOF). The effectiveness of LDC relies on the measurement of line current being the actual current flowing across the line, but PV generation offsets the current, reducing line current measurement at the LTC/VREG. This results in a lower-than-actual calculation of the voltage drop across the line, resulting in under-compensation, or a lower tap position than is needed.

Fig. 3 shows snap-shot simulation results of Ckt24 (see Section III-A) at peak load (28 MW) with a 25 MW PV system to show the different voltage profiles of a feeder with LDC as the PV location varies. PV magnitude and proximity to the LTC/VREG play a role in the risk of under-voltages [5, 6]. The further the PV is from the LTC/VREG, the more likely it is to counteract the under-compensation with the natural voltage rise inherent to PV.

The distance of the VCP is approximately at the intersection of the blue and red lines (~4.5 km) in Fig. 3. PV induces EOF voltages lower than the basecase when the PV PCC is between the LTC and the VCP. Interconnections further than the VCP cause voltages higher than the basecase. An interconnection right at the VCP would result in a voltage rise to the PCC similar to the blue line up to the VCP, and an equivalent profile to the basecase downstream from there. PV-induced under-voltages on the interconnection feeder can occur only when the PCC is between the LTC and the VCP.

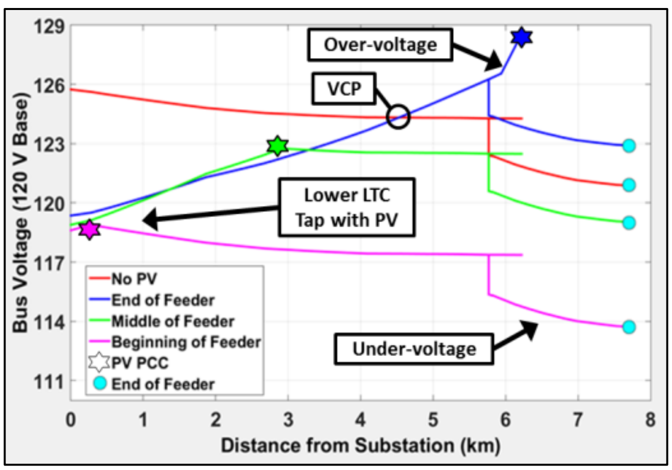

Fig. 3. Ckt24 voltage profiles for basecase and with 25 MW PV near beginning, middle, and end of feeder with LDC on the LTC.

III. Simulation Examples and Mitigations

This section uses two different feeder models simulated in OpenDSS to demonstrate examples of PV-induced under-voltage. Both feeders have LTCs with LDC settings enabled. The examples differ in analysis type and provide two different perspectives learned from each.

A. EPRI Feeder Ckt24 Example – Volt/VAr

EPRI Ckt24, provided with the OpenDSS download, was used in this example [1]. Ckt24 is a 34.5 kV feeder with a 28 MW peak load. The feeder contains several 13.2 kV step-down transformers and the longest primary path is 7.7 km (13.2 kV). The substation 230/34.5 kV transformer has an LTC setpoint of 123 V with LDC of R=7 V and X=0 V (volts at rated CT current). There are no VREGs and three fixed capacitors totaling 3.3 MVAr. Fig. 4 shows the general topography of Ckt24 with major components highlighted.

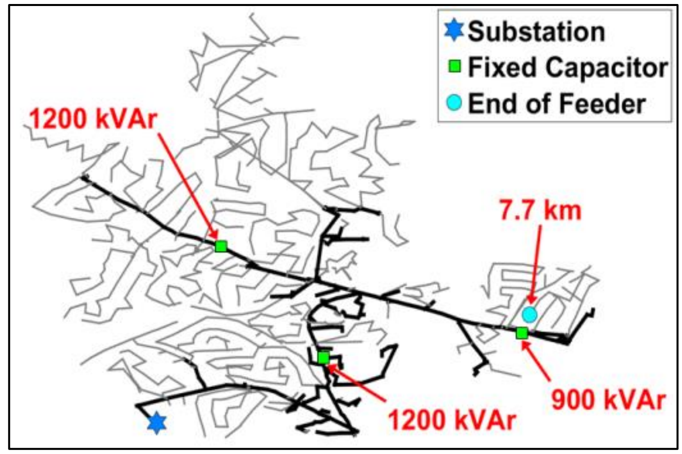

Fig. 4. Ckt24 topography and major components.

One way to investigate potential under-voltage issues caused by PV is to do a comprehensive PV hosting capacity analysis. SNL has developed an advanced feeder analysis methodology to simulate a wide range of PV deployments varying in size and location, combined with a range of load levels, capacitor states, and voltage regulation taps [7, 8]. The results indicate the maximum PV size that can be placed at each bus without causing any of a variety of violations monitored, including steady-state over/under-voltage.

Ckt24 was analyzed using the hosting capacity methodology presented in [7, 8] to determine the locational PV limits and violations associated with each. To simplify the analysis and visualization, only the PV interconnections along the 3-phase backbone (94 locations) highlighted in Fig. 5 were considered.

Fig. 5 shows the maximum PV that can be placed at each bus before a violation occurs anywhere on the feeder. The limiting factor near the substation is under-voltage (▼), thermal line loading in the middle (●), and over-voltage near the end (▲). In the cases where under-voltage is the limiting factor, the under-voltage never occurs at the PV point-of-common-coupling (PCC). The max PV at each location was determined by the PV size just before any limiting factor was exceeded anywhere on the feeder.

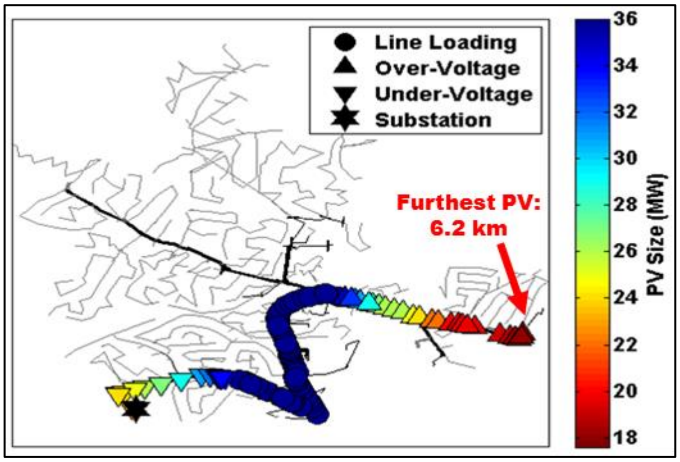

Fig. 5. Ckt24 locational hosting capacity along backbone of interest.

The limiting factors on Ckt24 could commonly be expected for feeders with LDC enabled. Fig. 6 shows the hosting capacity vs. distance on the backbone highlighted in Fig. 5 for three cases: PV with LDC (blue), PV with Volt/VAr control (red), and PV with LDC removed (green). A standard Volt/VAr curve algorithm was used assuming enough AC capacity to never curtail the real power.

The blue line in Fig. 6, which uses the same symbols to indicate the limiting factors, reflects what was observed in Fig. 5. Adding Volt/VAr (red) does eliminate all over-voltage limitations caused by PV when it is near the EOF because the over-voltage issues exist at the PV PCC where the Volt/VAr control can adjust them. Volt/VAr does not eliminate under-voltage limitations when the PV is near the substation because the under-voltage issues do not exist at the PV PCC and it cannot adjust remote voltages.

Since under-voltage issues in this case are caused by the interaction of PV with LDC, one potential mitigation strategy is to remove the LDC. Eliminating LDC and raising the LTC setpoint enough to bring all voltages within compliance (Fig. 6, green) eliminates the under-voltage limitations, but results in more over-voltage constraints on the outer half of the feeder because the LTC does not lower the setpoint with increasing PV as it does with LDC. Combining the elimination of LDC and Volt/VAr control would result in the best profile limited only by line loading.

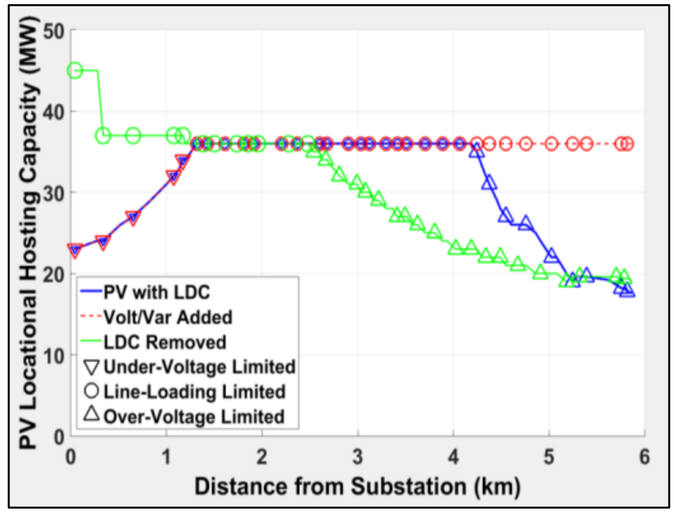

Fig. 6. Ckt24 hosting capacities for standard PV with LDC, PV with Volt/VAr control, and standard PV with LDC removed.

This example illustrates the value of performing a thorough analysis to determine the effects of mitigation techniques on overall feeder hosting capacity. There is no “one size fits all” mitigation technique, and it is likely that each one will have trade-offs. Determining if the benefits will outweigh the detriments, or which method results in the greatest overall benefit will depend on the feeder and can only be quantified with a detailed study of this caliber.

B. Feeder UQ12 Example – Other Feeders Served

Feeder UQ12 is a 12.47 kV feeder with a 6.2 MW peak load. The longest 3-phase conductor path from the substation is approximately 5.7 km. The substation 69/12.47 kV transformer has an LTC setpoint of 121 V with LDC of R=5 V and X=3 V. There are no VREGs and four fixed capacitors totaling 1.8 MVAr.

UQ12 was chosen for this example because it essentially splits into two feeders just outside the substation, which are referred to as UQ12-A and UQ12-B. As would commonly be the case, a substation transformer likely serves more than one feeder, so the LTC with LDC regulates all feeders. A 6 MW PV system was simulated at the end of UQ12-B. The general topology of the feeders with major components and simulated PV scenario highlighted are shown in Fig. 7.

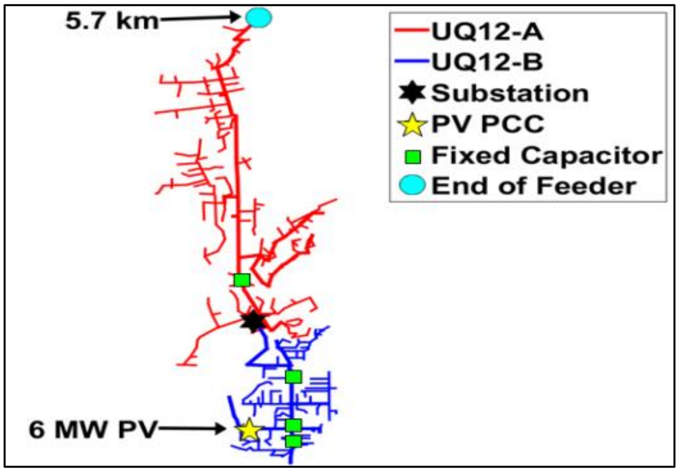

Fig. 7. UQ12-A and UQ12-B topography and PV location.

To illustrate the main focus of this example, Fig. 8 shows the voltage profiles of UQ12-A and UQ12-B for the basecase (solid lines) and the case with 6 MW of PV at the end of UQ12-B (dotted lines). This was a snapshot simulation assuming peak load and full 6 MW PV output. UQ12-B is an example where the PV deployment offsets the LDC under-compensation on the feeder with PV with the voltage rise to the PV PCC at the EOF. However, the LDC under-compensation causes under-voltages on UQ12-A, which would be unchanged regardless of the PV location on UQ12-B.

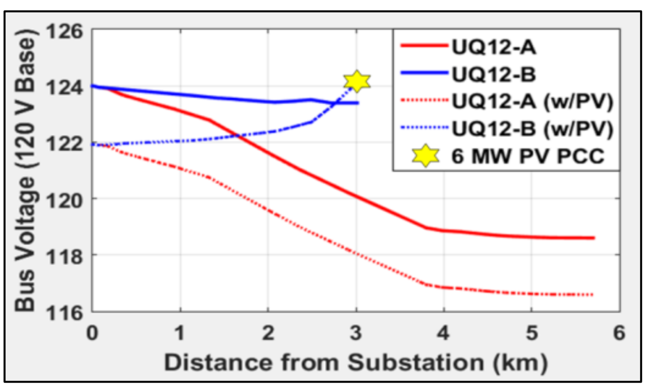

Fig. 8. UQ12-A and UQ12-B voltage profiles, with and without 6 MW PV, at peak load.

The snapshot voltage profiles in Fig. 8 highlight one challenge in mitigating this type of impact. Notice that the basecase profiles resulted in a range of voltages of approximately 5.3 V (118.7 - 124 V). The PV case profiles range is approximately 7.4 V (116.7 - 124.1 V), about 2 V greater than the basecase. The ANSI voltage range used for primary voltages in this report is defined as 117 V to 126 V, a 9 V span. Since the LTC bandwidth is 2 V, which added to the PV case span is 9.4 V, simply adjusting the LTC setpoint to mitigate voltage impacts would result in the risk of non-compliance at either of the bandwidth limits.

In order to analyze the time-dependent interactions between load and PV, and to estimate the 10-minute voltage averages, quasi-static time series (QSTS) analysis [3] simulations were performed to detect any potential over- or under-voltages caused by PV. QSTS analyses simulating the 6 MW PV scenario highlighted in Fig. 7 were performed using SNL's GridPV toolbox [9].

The following UQ12 cases were simulated during the peak load day and the daytime minimum load day (day where lowest load point from 11:00 AM to 1:00 PM was found) at 1-second resolution. A clear-day 6 MW PV profile was used in an attempt to maximize the duration of out-of-band voltages. All time-series voltages shown are the 10-minute rolling average voltages of the simulation results, but it should be noted that the combination of 15-minute linearly-interpolated load data and clear-day PV data resulted in a negligible difference between the one-second simulation voltage results and the averaged data in this case. No modifications to the default OpenDSS LTC control algorithms were implemented [10].

The focus of the example was under-/over-voltages, so all plots show the worst phase of the highest voltage point (either PCC or feeder head depending on the case) and the lowest voltage point at the north end of UQ12-A (as marked in Fig. 7). All references to "Feeder Head" pertain to the UQ12 feeder head, which is equivalent to the bus from which both feeders UQ12-A and UQ12-B split off. Any other impacts, such as thermal line limits and reverse power limitations, were not included.

Fig. 9 shows the 10-minute rolling average voltages for the basecase and the 6 MW PV case. Applicable voltage boundaries are highlighted with red horizontal gridlines. Note that all voltages on the feeder are within the allowable range for the peak and daytime minimum day without PV (solid lines), but once the 6MW PV is interconnected (dotted lines), there are under-voltage issues at the EOF during the peak load day.

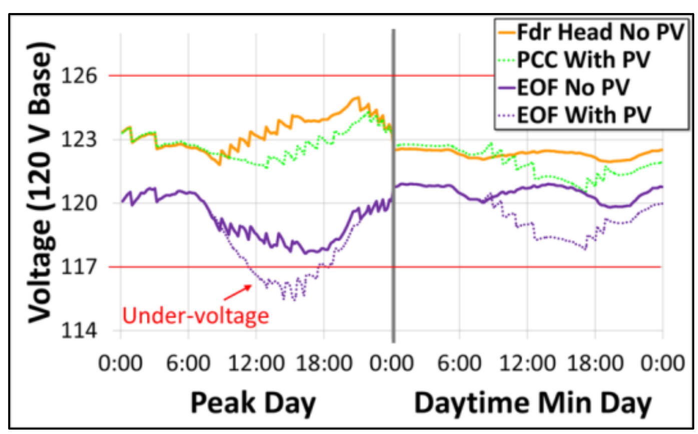

Fig. 9. UQ12, 10-minute rolling average voltage extremities, with and without 6 MW PV, peak and daytime minimum days.

Simply raising the voltage setpoint and keeping the original LDC settings to mitigate the under-voltages highlighted in Fig. 9 would result in over-voltages both with and without PV. Fig. 10 shows the results with the LTC setpoint raised to 123 V (+2 V).

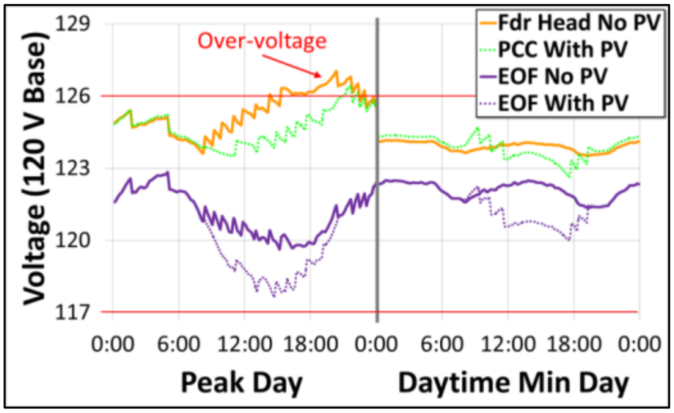

Fig. 10. UQ12, 10-minute rolling average voltage extremities, with and without 6 MW PV, LTC raised to 123 V with original LDC, peak and daytime minimum days.

Mitigation of voltage impacts in this example could be achieved with some combination of LTC/LDC setting adjustments and advanced inverter function on the PV deployment reducing the voltage rise to the PV, such as fixed power factor (PF) or Volt/VAr. To determine how much the LTC setpoint needs to be raised, Fig. 11 shows the PCC and EOF results for the 6 MW PV case with LDC settings removed. The Fig. 11 EOF peak results (solid purple) indicate that the LTC setpoint needs to be raised by more than 3 V with the LDC removed, which in turn will result in over-voltages on the PCC during the daytime minimum day (dotted green).

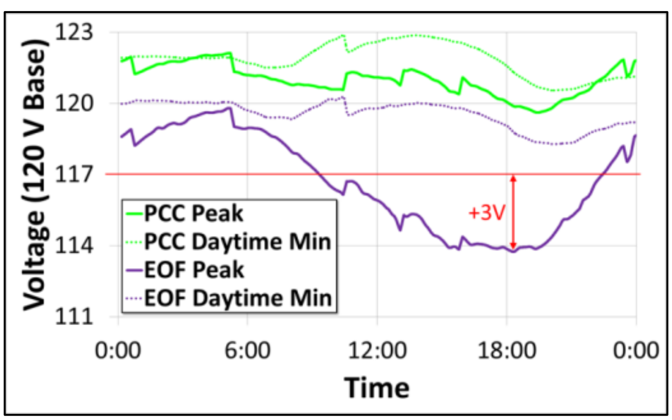

Fig. 11. UQ12, 10-minute rolling average voltage extremities, 6 MW PV, LDC removed, peak and daytime minimum days.

Fig. 12 shows the results when the LTC setpoint is raised to 124.5 V (+3.5 V) and with the PV PF fixed at 0.99 leading. The combination of LDC elimination, LTC setpoint change, and advanced inverter functionality mitigated the over- and under-voltage impacts in this example.

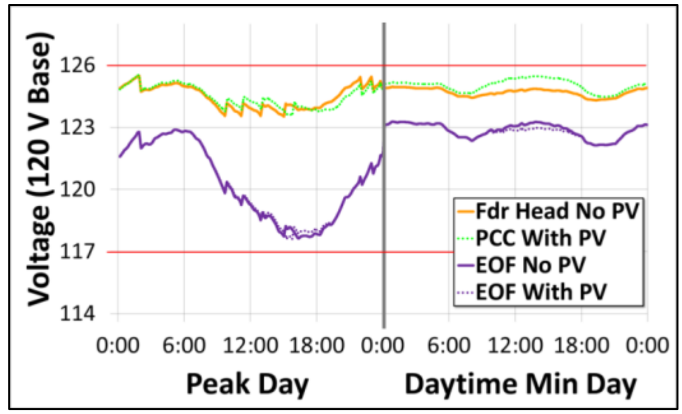

Fig. 12. UQ12, 10-minute rolling average voltage extremities, with and without 6 MW PV at -0.99 PF, No LDC, and LTC raised to 124.5 V, peak and daytime minimum days.

As with most cases, there may be several ways to mitigate voltage impacts with a PV interconnection: LTC/LDC settings, PF inverter settings, additional voltage regulation device installation and/or adjustment, etc. This example simply illustrates one possible challenge that can arise, and one way to achieve a cost-effective mitigation.

IV. Conclusions

Determining the best mitigation strategy for PV and LDC induced under-voltage will vary from feeder-to-feeder. There is also likely to be trade-offs that come with each mitigation strategy, requiring a thorough analysis to quantify the benefits and detriments of each strategy to determine the optimal course of action. It is also important to note that ANSI C84.1 voltage compliance applies to 10-minute average voltages. QSTS would be required to estimate 10-minute averages, at which point both the load and solar variability assumptions would play a critical role.

Many conventional ideas regarding PV impacts to distribution system may be case-specific and potentially incorrect for certain scenarios. For example, PV is commonly thought to cause issues of high voltages on a feeder, but this paper highlighted the opposite impact. It is also often assumed that advanced inverter functions for regulating voltage will eliminate PV-induced voltage issues, which is incorrect for cases of remote under-voltage issues.

LDC elimination can be a viable mitigation for under-voltages in some cases, but in other cases it could reduce overall feeder hosting capacity. Combining LDC elimination and advanced inverter voltage control may be an optimal solution. Any mitigation strategy must be verified during both peak and minimum load extremes, both with and without PV, for all feeders and phases affected, and for all impacts of concern before it can be considered a viable option.

ACKNOWLEDGEMENT

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