V. Defining How To Address Inadvertent Export
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A. Introduction and Problem Statement

Distributed energy resources that are configured for non- or limited-export operation using certain export control methods may, under certain conditions, inadvertently output small amounts of power to the grid for short durations of time. This phenomenon is the result of non-instantaneous control system response times due to large swings in generation and load. While not widely considered a significant threat to grid reliability today, these unintentional injections of current onto the distribution system potentially pose power quality risks as a greater number of areas approach higher DER penetrations and as larger energy storage (and solar-plus-storage) systems with greater Export Capacity proliferate.

It is currently unclear if, or the degree to which, grid power injections from inadvertent export may cause power quality disturbances that exceed norms and standards, including ANSI C82.1 specifications. Meanwhile, no uniform specification or requirement currently exists for manufacturers to follow regarding ESS response time to limit inadvertent export. Simply put, storage systems may generate inadvertent export at different times and magnitudes, with the potential to create voltage or thermal disturbances that are not well-characterized.

Most interconnection rules do not define how utilities specify or evaluate inadvertent export that occurs while ESS controls are responding. In many cases, utilities screen and study projects with inadvertent export in the same way that they assess projects with full export. Moreover, different utilities in different jurisdictions may have varying requirements for inadvertent export, or dissimilar methods for measuring it. This variation can create challenges for equipment manufacturers, who must consequently create tailored solutions for different utilities. The lack of clarity regarding the impacts of inadvertent export and the optimal way to manage or prevent impacts is a noteworthy interconnection barrier for ESS. Projects may, as a result, be assumed to have impacts they possibly never produce. In turn, these concerns may require more in-depth review, customized equipment design, and/or grid mitigation that adds cost and time to the ESS interconnection process.

This chapter provides analytical results from modeling and simulation research that explore the potential for adverse power quality and other impacts caused by inadvertent export. Based on the results, the chapter provides key findings regarding Power Control System response time requirements to limit inadvertent export, as well as on other considerations for both recognizing and addressing the potential for disturbances caused by inadvertent export. Results can be used to modify existing interconnection procedures, applicable standards, and testing procedures.

55 The American National Standards Institute (ANSI) is a private non-profit organization that oversees the development of voluntary consensus standards for U.S. products and services. ANSI accredits standards developed by others that ensure consistency in product performance and conformance with testing protocols.

Uncertainty currently exists around the grid impacts of inadvertent export caused by export control methods, including PCS. Few study results examining the effects of inadvertent export—particularly for cases where multiple systems are connected to a feeder—have been produced. As a result, there is no industry consensus about how to evaluate interconnection of ESS with controlled import and export.

There is lack of clarity around the speed with which PCS should be required to respond to inadvertent export, and the grid impacts based on slower response times. Does the current 30-second response time requirement included in the UL CRD for PCS suffice? Or are faster response times, on the order of 10 seconds or even 2 seconds, necessary to avert voltage and thermal disturbance? Additionally, how does inadvertent export affect DER hosting capacity? Are there thresholds past which inadvertent export may impact grid reliability?

To address these and other questions, the project team conducted a series of testing, modeling, and analysis activities. Grid impacts caused by inadvertent export and thresholds were identified by studying a range of feeder scenarios, penetration levels, and inadvertent export durations. Results and observations, presented below (with additional details provided in Appendix D), aim to inform technical review of export-controlled DERs, as well as related standards, state rules, and industry design considerations.

Note: Certifications and rules for Power Control Systems are addressed in Chapter III. This chapter more narrowly addresses issues relevant to inadvertent export, including response time requirements and circumstances that may lead to adverse distribution system impacts.

C. Inadvertent Export Field Test Results

The practical speed at which PCS should be required to respond to inadvertent export remains an open question. Open loop response time (OLRT) is the metric used to convey responsiveness to inadvertent export. It measures the time it takes the PCS to recognize export beyond a limit, command a change in output, and settle back to the prescribed limit.

Ongoing debate centers around the relative benefit of faster response times for avoiding adverse grid impacts under a range of conditions. Today, the UL CRD for PCS stipulates an OLRT of up to 30 seconds for certified products. In California, however, the large investor-owned utilities are currently (as of this writing) pushing for response times as low as 2 seconds to align with the response capabilities of their non-export relays. (Tradeoffs regarding the use of controls in conjunction with, or instead of, relays are discussed in Chapter III.C and III.D)
Certified PCS, either as inverter-integrated functions or as separate control devices, are expected to meet the UL CRD’s 30-second requirement. Virtually all PCS are able to achieve response times that are faster than 30 seconds; however, independent test results are not always readily available. That said, overall response times appear to be improving for listed PCS. Most are able to respond in the range of 5-10 seconds, with some achieving less than 2-second OLRTs. For example, the California Energy Commission’s approved solar equipment list\(^5^6\) includes 59 PCS devices. As of October 2021, manufacturer-provided data indicate all but one product have OLRTs of less than 10 seconds, while 15 listed products indicate OLRTs of less than 2 seconds.

The project team conducted field testing to further characterize the performance of a few commercially available PCS. Tests were performed on a sample of residential solar-plus-storage systems sited at the Solar Technology Acceleration Center (SolarTAC) near Denver, Colorado.\(^5^7\) Of the five systems, all from different vendors, four had an available “non-export” mode. Tests were carried out on these non-export systems, with results intended to inform subsequent time series feeder modeling (described below) to determine grid impacts of inadvertent export under different grid conditions.

The non- or zero-export control mode enabled direct comparison of the four PCS. Most of the tests specified by UL CRD were conducted, though exceptions were made when the tests were not possible due to practical changes PCS manufacturers have made to better address their markets.\(^5^8\) Consequently, the tested systems were only manipulated through consumer-available use cases and by simulating rapid changes to connected load. This limitation did not prevent capture of the information needed from the tests.\(^5^9\)

Figure 2 illustrates test results. As depicted, amps are recorded at the control point where power is to be limited. All four systems show a rapid response to staged sudden load changes with some variations in the shape of the responses. In this small sample, the system with a preset power level (vendor 4) was the fastest acting. The other three samples were preset for zero export. Response times of less than 2 seconds were uniformly observed for all four of the tested systems.


\(^{58}\) For example, some manufacturers have moved away from local MODBUS control interfaces and removed ready capability to locally dispatch charge or discharge at any specific value.

\(^{59}\) Testing itself was conducted using a Fluke 1750 power recorder sampling at 256 samples/cycle and a 4.8 kW resistive load. Current sensors were placed on the phase conductors as well as on the load. The systems were operated in self-consumption mode with non-export enabled. State of charge for this testing was over 80% in all cases. The resistive load was powered on, and the systems were observed to reach equilibrium and cover the load as expected with no import or export at the PCC. Once stable operation with the load and solar was established, the load was discontinued by opening the load breaker.
D. Modeling Inadvertent Export on Urban and Rural Feeders

Modeling and analysis were undertaken to determine the typical impacts and practical limits of inadvertent export. To accomplish these aims, two real-world feeders were modeled—a short urban feeder and a long rural feeder. These two feeders were assumed to represent a reasonable range in feeder types and to produce results that can be generalized. Table 2 summarizes the circuit details (more in-depth review of the feeders’ attributes can be found in Appendix D).
Table 2. Summary Details of Modeled Feeders

<table>
<thead>
<tr>
<th>Modeled Feeder</th>
<th>Feeder Voltage</th>
<th>Feeder Load Range</th>
<th>Feeder Length</th>
<th>Feeder Voltage Regulation</th>
<th>PV Capacity Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>12.47 kV (LL)</td>
<td>0.65 MW (min.) 3.2 MW (max.)</td>
<td>7.3 mi</td>
<td>Load tap changer (LTC) at substation, 1.1 Mvar switched-capacitor bank</td>
<td>2.9 MW</td>
</tr>
<tr>
<td></td>
<td>7.2 kV (LG)‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>12.47 kV (LL)</td>
<td>5.95 MW (min.) 11.17 MW (max.)</td>
<td>11.2 mi</td>
<td>LTC at substation, 3 fixed capacitors, 8 line voltage regulators (LVRs) (delay head end 30s, tail end 37s)</td>
<td>8.9 MW</td>
</tr>
<tr>
<td></td>
<td>7.2 kV (LG)‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- Feeder voltage regulation has time delays that may interact with inadvertent export. This was most apparent in the case of the rural feeder, which contains some line voltage regulators that regulate individual phases.
- PV capacity limit is the amount of exporting solar PV that can be integrated into the circuit based on a voltage rise limit of 105% and minimum load.
- LL indicates to line-to-line.
- G indicates line-to-ground.

Time-series modeling was performed using the Open Distribution System Simulator (OpenDSS) tool. Multiple scenarios were generated for each feeder type, including variations in load, solar PV, and export-controlled energy storage systems with inadvertent export. The objective was to determine inadvertent export feeder thresholds for aggregate energy storage system contributions. Individual plant exports that overlapped in the examined time period were combined in the simulations.

Two scenarios were evaluated to study aggregate inadvertent export: 1) “simultaneous export,” in which inadvertent export from energy storage systems was simulated to occur at the same time, and 2) “period diversity export,” in which inadvertent export from energy storage systems was modeled to occur at randomized starting times over a certain time period. Both evaluation approaches involved all of the simulated energy storage plants. Simultaneous (coincident) export was examined to establish the worst, albeit improbable, scenario. Additionally, the effect of different PCS OLRT (10 and 30 seconds) was evaluated.
(Note: For the urban feeder, PCS OLRT of 2 seconds was studied. Some results are provided in Appendix D.)

Meanwhile, randomized export was simulated to study interactions with feeder-switched capacitors and regulator delay times. The randomized export was simulated to occur over 200 seconds on the urban feeder and across 60 seconds on the rural feeder, with each energy storage system inadvertently exporting at different times. Inadvertent export from export-controlled energy storage systems due to a negative step change in load was modeled by emulating the typical PCS response to a step change in load provided in UL 1741 CRD. A shorter time period was used to evaluate inadvertent export on the rural feeder in order capture the interaction with the feeder’s regulation equipment (line voltage regulators, or LVRs, The urban feeder’s regulation equipment (Load Tap Changer, or LTC, and switched The time periods (200s and 60s) were chosen to sufficiently capture the impact of inadvertent export on the feeder.

The simulation results address voltage rise concerns and power quality events, such as rapid voltage change (RVC). Continuous PV export and inadvertent energy storage export were combined to create a voltage rise along the feeders. The PV output was simulated in the steady state with the inadvertent export evaluated as a short-term Root Mean Square (RMS) voltage variation. This distinction is important because the limits are different. Steady-state compatibility limits are 105% or 106% (from ANSI C84.1, ranges A and B), while a commonly accepted short-term RMS overvoltage event threshold is 110%, as defined in IEEE 1159-2019 and in the Information Technology Industry Council (ITIC) voltage compatibility industry standards. The project assessment considers both limits.

Protection and thermal-related concerns associated with inadvertent export are not addressed by this project’s modeling and analysis effort. Protection issues are covered during the interconnection screening process. All fault current contributions of inadvertent export are considered and there is no credit given for export limiting (see Chapter IV.C.3.b.ii). An RVC screen is, however, recommended for addition to the initial screens (see Chapter IV.C.3.a.ii). Meanwhile, thermal impacts were not modeled for inadvertent export.

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62 There is no standard defining the duration of steady state. It is implied to be ≥30 seconds because variations less than 30 seconds are characterized as events (i.e., temporary overvoltage, sag, swell, transient overvoltage, or surge).
63 IEEE 1159-2019, IEEE Recommended Practice for Monitoring Electric Power Quality, defines short-term RMS variations from 0.8 milliseconds to 60 seconds. Inadvertent export falls into the momentary and temporary categories as a voltage swell.
64 ANSI C84.1 is the American National Standard for Electric Power Systems and Equipment – Voltage Ratings. It establishes the nominal voltage ratings and operating tolerances for 60-Hz electric power systems above 100 volts up to a maximum system voltage of 1200 kV. The standard divides steady-state voltages into two ranges: Range A, the optimal voltage range, and Range B, an acceptable voltage range. Range A provides the normally expected voltage tolerance on the utility supply for a given voltage class. Variations outside the range should be infrequent. Range B provides voltage tolerances above and below range A limits that necessarily result from practical design and operating conditions on supply or user systems or both. These conditions should be limited in extent, frequency, and duration. When variations occur, measures should be taken within a reasonable time frame to get back to range A.
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export because both their level (110% max) and duration (typically 2-10 seconds) were below any known thresholds for concern.

1. Simulation Scenarios and Results Summary: Urban Feeder

Table 3 relates modeling and simulation results for the urban feeder. The cases are defined by different combinations of load, exporting solar PV, and export-controlled energy storage. They are ordered in the table by increasing amounts of energy storage, with variations in other feeder characteristics. The locations of the individual solar and battery systems were fixed for the analysis, and the system sizes were scaled up and down based on the simulation scenarios. What follows are brief analyses and discussion distilled from presented results. Additional details can be found in Appendix D.

Table 3. Simulation Scenarios for Urban Feeder

<table>
<thead>
<tr>
<th>Case</th>
<th>OLRT</th>
<th>Load (MW) Min.=0.65 Max=3.2</th>
<th>Exporting Solar PV (MW)</th>
<th>Export-Controlled Storage (MW)</th>
<th>Nameplate DER (MW)</th>
<th>Steady-State Voltage Rise (pu,** RMS)</th>
<th>Steady-State Plus Short-Term Voltage in RMS***</th>
<th>Max. RMS Rise: Coincident</th>
<th>Max. RMS Rise: 200s Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td>0.65</td>
<td>0.65</td>
<td>0</td>
<td>0.65</td>
<td>103.0%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>NA</td>
<td>0.65</td>
<td>2.9</td>
<td>0</td>
<td>2.9</td>
<td>105.0%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>1.3</td>
<td>103.0%</td>
<td>103.7%</td>
<td>103.2%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>0.65</td>
<td>1.32</td>
<td>1.32</td>
<td>2.64</td>
<td>104.0%</td>
<td>105.0%</td>
<td>104%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>0.65</td>
<td>0.65</td>
<td>1.92</td>
<td>2.57</td>
<td>103.0%</td>
<td>105.0%</td>
<td>103.4%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>0.65</td>
<td>2.46</td>
<td>2.46</td>
<td>4.92</td>
<td>104.7%</td>
<td>107.0%</td>
<td>105.0%</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>3.2</td>
<td>2.9</td>
<td>2.9</td>
<td>5.8</td>
<td>101.7%</td>
<td>105.2%</td>
<td>102.7%</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>0.65</td>
<td>2.9</td>
<td>2.9</td>
<td>5.8</td>
<td>105.0%</td>
<td>107.6%</td>
<td>105.5%</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
N/A = not applicable.
*Nameplate DER is the sum of exporting solar PV and export-controlled storage.
**pu refers to “per unit,” additional detail on this term is provided in footnote 69 on the next page.
*** The Steady-State Plus Short-Term Voltage RMS category conveys the highest observed voltage rise when considering both steady-state and event-based thresholds. It reflects: 1) the maximum voltage rise observed during coincident inadvertent export, and 2) the maximum voltage rise observed during randomized inadvertent export simulated over a 200-second period.
2. Assessment of Case Results and Discussion: Urban Feeder

The cases illustrated in Table 3 illustrate potential voltage impacts caused by inadvertent export from energy storage combined with solar PV. As shown, the urban feeder was examined under minimum and maximum load conditions. Exporting PV was, meanwhile, increased from a comfortable level matching minimum load to the feeder hosting capacity limit—in this case, 2.9 MW. Export-controlled energy storage system capacity was increased from zero to 2.9 MW.

The overarching aim of this analysis was to determine the extent to which export-controlled energy storage, and related inadvertent export, could be added to exporting solar penetrations under different scenarios. Again, inadvertent export was evaluated as “coincident” and over a 200-second period of time during which the modeled energy storage systems individually export. Scenario results of interest are further illustrated below including:

- Steady-state voltage rise with no energy storage
- Maximum voltage rise with PV export and energy storage inadvertent export
- Steady-state voltage rise with maximum DER nameplate and loading
- 200-second inadvertent export diversity and RMS voltages
- Coincident inadvertent export and RMS voltages

a. Steady-State Voltage Rise With No Energy Storage

In Cases 1 and 2, the urban feeder was operated at minimum load with exporting solar PV set at 0.65 and 2.9 MW, respectively. No export-controlled energy storage was introduced. In Case 1, total DER nameplate is 100% of minimum load, while in Case 2, it is 446% of minimum load. Figure 3 shows how the steady-state voltage varies along the feeder, depicted by colors on the feeder map (left side) and by voltage level from the substation to the end of the feeder (right side). There are no voltage issues in these cases, as the 0.65 MW of exporting solar PV produces a voltage rise of 1.03 pu,69 while 2.9 MW of PV raises voltage to the hosting capacity limit of 1.05 pu (shown in Table 3).

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67 Feeder hosting capacity limit is calculated using the EPRI Distribution Resource Integration and Value Estimation (DRIVE) analysis method. The limiting factor in this case was the 105% voltage rise limit. Hosting capacity for any solar PV scenario depends on PV plant location and size distribution, as well as all other feeder and load characteristics.

68 Note that the 100% minimum load is what is presently used in penetration screens and Supplemental Reviews, as utilized in SGIP 2.4.4.1. Here the 446% of minimum load goes above and beyond what would have been used in the screen.

69 pu, for per unit, is a way to express a quantity normalized with respect to its base value. This is often used in power systems engineering when referring to voltage since nominal voltage values vary dependent on location. Therefore, the nominal voltage (such as 120 V, 12.47 kV or 34.5 kV) is represented as 1.0 pu. The percentage can be derived by simply multiplying the per unit value by 100. Here, 1.03 pu could also be expressed in percentage form as 103%.
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Figure 3. Case 1 Urban Feeder: Voltage-Level Map (Left) and Coincident RMS Maximum Voltages Along the Feeder (Right)

b. Maximum Voltage Rise With PV Export and Energy Storage Inadvertent Export

In Cases 3, 4, and 5 a nominal amount of export-controlled energy storage is added, from 0.65 MW to 1.92 MW. Again, the feeder was operated at its minimum load (0.65 MW) with exporting PV capacity set at 0.65 MW, 1.32 MW, and 0.65 MW, respectively. The storage and solar PV are sited proximate to each other; in some cases, they are co-located. For these cases, both the steady-state and the maximum coincident RMS voltages were observed.

For Case 5, export-controlled energy storage was modeled at 1.92 MW (295% of minimum load) for a total nameplate DER of 2.57 MW (0.65 MW of solar plus 1.92 MW of storage—395% of minimum load). As illustrated in Figure 4, the maximum RMS voltage rise is 1.05 pu at the end of the feeder, and there is a small amount of phase unbalance. In these cases, the inadvertent export contributes to the maximum RMS voltage but does not contribute to the steady state, even at such high penetration. There is no voltage limit violation.
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Figure 4. Case 5 Urban Feeder: Voltage-Level Map (Left) and Coincident RMS Maximum Voltages Along the Feeder

c. Steady-State Voltage Rise With Maximum DER Nameplate and Loading

Figure 5 illustrates the significant mitigation in voltage rise when the feeder load is at its maximum. As depicted in Case 7, exporting PV is at the hosting capacity maximum of 2.9 MW (446% of minimum load). On the left, Figure 5 shows the voltage profile of the urban feeder with export-controlled energy storage set at 0.29 MW, which is 10% of available inadvertent export. On the right, the export-controlled energy storage is set at 2.9 MW, which is 100% of available inadvertent export. Both outcomes indicate maximum RMS voltages that are significantly lower than the minimum load case shown in Figure 6 for Case 8.
d. 200-Second Inadvertent Export Diversity and RMS Voltages

For the urban feeder, a 200-second period was applied to determine worst-case (non-coincident) aggregate behavior of the export-controlled energy storage systems. Each energy storage system inadvertently exports to scale at random times over 200 seconds, as shown in Figure 6 (left). The aggregate of the non-coincident inadvertent export is then simulated, yielding several non-coincident max RMS voltage rises, as illustrated in Figure 6 at right. This is the basis for the maximum RMS voltage rise of 105.5% reported for Case 8 in Table 3.

Figure 6. Case 8 Urban Feeder: Inadvertent Export Profile (Left) and Time Series RMS Maximum Voltage Profiles During the Same Time Period (Right)
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e. Coincident Inadvertent Export and RMS Voltages

All of the cases with export-controlled energy storage illustrate a maximum coincident RMS voltage rise. Case 6 can be leveraged to illustrate how the maximum RMS voltage rise was determined. In this case, the feeder was at minimum load, and exporting solar PV and export-controlled energy storage were each set to 2.46 MW, or 4.92 MW total. A coincident step change with OLRT of 10 seconds was then simulated at all locations along the feeder. Figure 7 shows the highest coincident RMS voltage rise event was at the end of the feeder, and that there is no violation given that the RMS voltage rise was less than 110%.

Figure 7. Case 6 Urban Feeder: Coincident Inadvertent Export Curve (Left) and Time Series RMS Maximum Voltage Profiles (Right)

Note: The (-) in the Figure 7 title at left refers to a negative step change in load or decrease in load.

Another illustration of coincident inadvertent export and RMS voltage rise is portrayed in Figure 8. It shows the voltage profile of the circuit with coincident inadvertent export due to a step change and a PCS open loop response time of 30 seconds. At 10 seconds, the inadvertent export is at its maximum and the end of the feeder experiences an overvoltage of 1.075 pu. ANSI low voltage and medium voltage violations are observed at the end of the feeder and at the capacitor bank for a duration of 26 seconds and 30 seconds, respectively. Because the voltage at the end of the feeder remains above 1.05 pu for 30 seconds, the switched capacitor bank turns off at 40 seconds.
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Figure 8. Case 8 Urban Feeder: Coincident Inadvertent Export Curve (Left) and Time Series RMS Maximum Voltage Profiles (Right)

Note: The (-) in the Figure 8 title (at left) refers to a negative step change in load or decrease in load.

Additional simulations were run to examine the impacts of coincident and non-coincident inadvertent export. These simulations capture both time and location diversity and well as variations in the OLRT of 2, 10, and 30 seconds. As expected, observed overvoltage durations decreased with faster OLRT.

3. Simulation Scenarios and Results Summary: Rural Feeder

Table 4 presents results from six simulation scenarios performed on the rural feeder. These explore the effect of OLRT (30 and 10 seconds) on inadvertent export and voltage. In all cases, feeder minimum load was modeled. The exporting solar PV capacity was varied from around 20% to 100% of minimum load and export-controlled storage with inadvertent export was varied from 8% to 88% of minimum load on the circuit.

Table 4. Simulation of Scenarios for Rural Feeder

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30s</td>
<td>5.92</td>
<td>5.92</td>
<td>0.46</td>
<td>6.38</td>
<td>104.4%</td>
<td>106%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10s</td>
<td>5.92</td>
<td>5.92</td>
<td>0.486</td>
<td>6.41</td>
<td>104.4%</td>
<td>105%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>30s</td>
<td>5.92</td>
<td>1.37</td>
<td>1.37</td>
<td>2.74</td>
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<td>30s</td>
<td>5.92</td>
<td>5.92</td>
<td>5.22</td>
<td>11.14</td>
<td>105.0%</td>
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<td></td>
</tr>
<tr>
<td>6</td>
<td>10s</td>
<td>5.92</td>
<td>5.92</td>
<td>5.22</td>
<td>11.14</td>
<td>105.0%</td>
<td>110.8%</td>
<td></td>
</tr>
</tbody>
</table>
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Notes:
PV hosting capacity on the rural feeder is 8.9 MW based on the ANSI limit of 105%. The maximum load for the feeder is 11.17 MW. Because feeder loading tends to mitigate the effects of inadvertent export, only minimum load was used in the studied cases. The limit used for energy storage is the maximum feeder load minus the maximum PV export, which is 5.22 MW of storage and inadvertent export.

*Nameplate DER is the sum of exporting solar PV and export-controlled storage.

**pu refers to “per unit,” additional detail on this term is provided in footnote 69.

***The Steady-State Plus Short-term Voltage RMS category conveys highest observed voltage rise when considering both steady state and event-based thresholds. It reflects the maximum voltage rise observed during randomized inadvertent export simulated over a 60-second period.

To determine worst-case limits, the inadvertent export was compressed into a very short 60-second timeframe. This “rapid fire” scenario is intended to simulate distributed aggregate inadvertent export as well as movement of feeder regulating equipment. Voltage level rise caused by inadvertent export can be identified and corrected by DER export controls before voltage regulation actions (e.g., tap changing and capacitor switching) are able to occur. This is an advantage of the faster OLRTs Power Control Systems use.

What follows are brief details from a selection of analyzed cases. Note that the rural feeder was voltage challenged, as is indicated by the number of line regulators and capacitors. The modeled PV backfeed was a contributor to the observed voltage rise, while loading was a mitigator.

4. Assessment of Case Results and Discussion: Rural Feeder

Feeder impacts were evaluated by simulating inadvertent export in all the export-controlled energy storage systems at different starting times and over a short, one-minute “rapid fire” period. This aggressive approach was used to establish feeder limits and to show the value of faster response. In this way, inadvertent export was limited from around 0.5 MW to 5 MW as PV export and response times vary.

Meanwhile, a 30-second response time was found to cause tap changes in some cases, while faster response was less likely to move regulating devices. That said, even at higher levels of export-controlled energy storage capacity, none of the evaluated scenarios triggered substation LTC operations.

Results from the rural feeder analysis are consistent with findings for the urban feeder. A key difference between the two circuits, however, was the existence of LVRs on the rural feeder. For the rural feeder, a longer OLRT (30 seconds versus 10 seconds) was shown to more significantly affect regulating equipment. Faster response was, meanwhile, shown to allow for a higher level of export-controlled energy storage capacity on the circuit with minimum effect on regulation equipment. Even so only Cases 5 and 6 indicated RMS voltage rise exceeding 110%.

70 Only non-coincident inadvertent export was modeled given the low probability of coincident inadvertent export occurring in real life.
Higher OLRTs also caused increased LVR operations when compared to smaller OLRTs at the same level of export-controlled energy storage capacity on the circuit. As shown in Figure 9, with 0.9 MW of export-controlled energy storage capacity (not shown in the table), an OLRT of 10 seconds results in two LVR operations, while an OLRT of 30 seconds triggers four LVR operations.

![Figure 9. Rural Feeder: LVR Operations at 10 Seconds OLRT (Left) and 30 Seconds OLRT (Right)](image)

Higher OLRTs, meanwhile, cause higher overvoltage violations when compared to smaller OLRTs for the same level of export-controlled energy storage capacity. Per Cases 5 and 6, and as illustrated in Figure 10, at an export-controlled energy storage capacity of 5.22 MW, an OLRT of 30 seconds results in a higher overvoltage violation of 111.1%, while an OLRT of 10 seconds results in a maximum voltage of 110.8%. These results support the assertion that too much generation at the end of the rural circuit reduces the amount of inadvertent export that can be accommodated without incident.

![Figure 10. Rural Feeder: Overvoltage Violations at 30 Seconds OLRT (Case 5) at Right, and 10 Seconds OLRT (Case 6) at Left](image)
Finally, all of the cases indicate how much DER capacity can be connected to the rural circuit under minimum load conditions. In all cases, a faster OLRT (10 seconds) enables an equal or higher amount of DER capacity than does a slower OLRT (30 seconds).

E. Key Findings and Observations

Several key takeaways emerge from the completed modeling and analysis. These findings and observations, enumerated below, stem from the character of inadvertent export and from the studied urban and rural feeders. They emanate from scenarios with both exporting PV and export-controlled energy storage systems at different penetration levels, system loads, and open loop response times. Applied steady-state limits were from ANSI C84.1, while inadvertent export event limits were from IEEE 1159.

- **Testing indicates that open loop response times in a number of PCS products are significantly faster than 30 seconds.** This finding is consistent with vendor-published data and product lists published and maintained by the likes of the California Energy Commission, and others. These response times support the assertion that thermal impacts are unlikely to be a limiting factor for inadvertent export because both their level (110% maximum) and duration (typically 2-10 seconds) are below any known thresholds for concern.

- **Inadvertent export is an RMS voltage event, not a steady-state condition.** Given that inadvertent export is less than 30 seconds, it fits into an IEEE-defined event category. Therefore, it is appropriate to use the short-term RMS event limit of 110% instead of the steady-state limit of 105%. This creates more headroom for inadvertent export in most feeders.

- **Time series modeling is an effective way to evaluate RMS voltage impacts.** OpenDSS analysis enabled the assessment of coincident and time diversified inadvertent export, distributed at different locations and with varying load and PV on selected feeders.

- **Feeders can host more DER capacity if the DER is export-controlled.** This can be viewed as increasing the feeder’s available hosting capacity for nameplate DER or as a more efficient use of existing feeder capacity for DER. While both the urban and rural feeder assessments supported this finding, the extent to which hosting capacity can be increased will depend on feeder characteristics, as well as the location and size of the exporting DER.

- **DER capacity on the urban feeder could be doubled with export limiting (inadvertent export) compared to steady export.** The urban feeder was very tolerant of the simulated inadvertent export. None of the deployment cases—up to twice the feeder calculated hosting capacity—exceeded RMS voltage rise limits.

- **The rural feeder’s capacity for inadvertent export is very location dependent.** While head end capacity for inadvertent export was substantial, the capacity to support DER drops off more steeply in the longer rural feeder. This was apparent when distributed energy storage is located further from the substation. The main limiting factors were found to be coordination of regulator operations and maintaining voltage balance between phases (not seen in the urban feeder).
V. Defining How to Address Inadvertent Export

- **The value of faster control response was more apparent on the rural feeder than the urban feeder.** This observation is based on the interactions of LVRs with inadvertent export events. LVRs in series, and in some cases single-phase regulators, lead to more step changes in voltage and more voltage unbalance. This may be a limiting factor for export-controlled energy storage in long feeders (not seen in the urban feeder).

- **The impact of smart inverter functions such as volt-var\(^{71}\) and volt-watt\(^{72}\) is unclear.** These functions were not activated. There is a possibility of negative interactions between neighboring inverters during inadvertent export. Smart inverter volt-var settings may need to consider the inadvertent export as well as existing feeder line regulators. Coordination of timing will be needed to avoid oscillations. Given the high relevance of inadvertent export voltage events, this question needs further investigation in the future.

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\(^{71}\) Volt-var refers to voltage-reactive power mode. In this mode, the DER modulates its absorption or injection of reactive power in relation to the measured grid voltage; there can be a “dead band” near normal (ANSI C84.1 range A) voltage where no reactive power is absorbed or injected.

\(^{72}\) Volt-watt refers to voltage-active power mode. This mode utilizes a reduction in active power to decrease voltage (normally only once voltage is outside of the normal range).