GRIDCO SYSTEMS®

Increasing PV Hosting Capacity on LV Secondary Circuits with the Gridco System emPower^{TM} Solution

APPLICATION NOTE

Executive Summary

Distributed solar photovoltaic (PV) generation connected to the low voltage (LV) distribution network can cause technical difficulties, including high voltages at customer sites. Unacceptably high voltages are most likely in areas where a high medium voltage (MV) supply is combined with high PV penetration on a long LV secondary circuit. Many techniques including transformer or conductor upgrades to lower impedance or using PV smart inverters to sink reactive power can lower customer voltages to some degree. Alternatively, customer voltages can be directly controlled using the Gridco Systems In-Line Power Regulators™ (IPRs) and Power Regulating Transformers™ (PRTs). IPR and PRT units control the LV voltage where they are connected and can prevent any customers from experiencing unacceptably high voltage, thereby increasing overall PV hosting capacity.

High PV Penetration and Voltage Rise on Secondary Circuits

Many distribution utilities are faced with the challenge of integrating increasing amounts of Distributed Energy Resources (DER). However, these DERs, especially smaller-scale (e.g. <10 kW) solar PV connected to the LV secondary network, can place stress on both medium voltage (MV) primary distribution feeders and the LV secondary circuits where they are connected. The technical challenges that high PV penetration causes at the MV feeder level include MV voltage rise; MV voltage fluctuations from variable power flow; overload of equipment from excessive reverse power flow; frequent operation of control equipment such as capacitor banks and voltage regulators; unexpected interactions with protective equipment due to altered power flow, forcing reprogramming or replacement; build up of harmonics introduced by residential PV inverters; and low power factor. In addition, residential PV can cause local disruptions by raising the voltage at the point of common coupling (PCC) due to power export, or even by overloading LV distribution equipment in extreme cases. Of these two issues, excessive voltage rise is by far the most common LV system concern and is the topic of this brief.

Residential PV Challenge

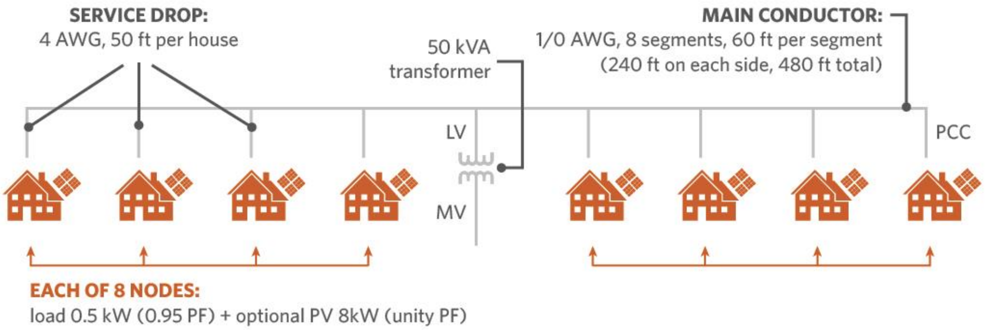
Unlike commercial and utility-scale PV, which generally undergo rigorous interconnection studies, residential PV is often permitted based on simple screens. For example, PV generation might be required to remain below 20% of feeder minimum daytime load. While these aggregate screens are useful in minimizing feeder-wide risks, they rarely consider local voltage issues, such as whether a newly added PV asset (along with all other PV) attached to a secondary line will cause any PCC voltage violation due to local voltage rise across secondary wiring and distribution transformers. This analysis is rarely performed for two reasons. First, it is rare that the construction of the secondary circuit is explicitly modeled. Second, the voltage at the residential PCC varies with feeder primary MV voltage and with loading on the secondary, and hence also with time of day and season. This can make the maximum voltage at the PCC difficult to predict from MV feeder models without solid information on loading, phasing, and LV equipment.

Fortunately, at low residential PV penetration and in relatively short secondary circuits, secondary voltage rise is rarely a concern and can safely be ignored. However, for secondary circuits that have high PV penetration and/or for longer secondary circuits, excessive voltage rise may occur and, if not addressed, will lead to high voltage violations and potential customer complaints if inverters or other equipment trip off due to high voltage. This condition limits PV hosting capacity at the secondary level. Distribution engineers can eliminate this constraint by choosing among several voltage mitigation techniques, based on technical and financial considerations, as described in the following section.

LV Secondary Hosting Capacity

To better understand secondary hosting capacity, it is best to look at an example. Figure 1 shows one typical secondary network layout consisting of two chains of four nodes each. Two other common secondary configurations are also examined in Appendix 1, with similar results.

Figure 1: Double-chain secondary network



For the purposes of this study, the hosting capacity of this secondary network is defined as the number of nodes (out of a maximum of eight nodes), which can each host 8 kW of PV. There are two constraints on the hosting capacity:

- Voltage constraint: the voltage at any PCC must not exceed 1.05 p.u. (5% above the nominal service voltage).
- Capacity constraint: the reverse power flow through the transformer must not exceed 125% of the transformer's kVA rating. Likewise, the current through each conductor must not exceed 125% of its ampacity rating. (The 125% factor has been chosen to reflect the widespread practice of allowing some overloading at peak times.)

The two constraints share the same worst-case scenario – the case of peak reverse power flow, i.e. maximum PV output (8 kW for each node with PV) and light load (defined as 0.5 kW per node in this example). For this example, a 50 kVA transformer has been used, which is a standard size that will tolerate an acceptable 125% overload during peak export. Conductors have been sized to allow all eight nodes to each host 8 kW PV at unity Power Factor (PF) without overload of more than 125%.

With respect to the voltage constraint, the PCC voltage is the sum (in p.u.) of the MV voltage at the site and the secondary voltage rise due to reverse power flow through the secondary conductors and transformer. While the secondary voltage rise can be calculated from the examples, the MV voltage is an independent variable, determined by primary-feeder-wide events and largely unaffected by what happens in the secondary network. Therefore, the hosting capacity is best described as a function of the MV voltage seen by this secondary network.

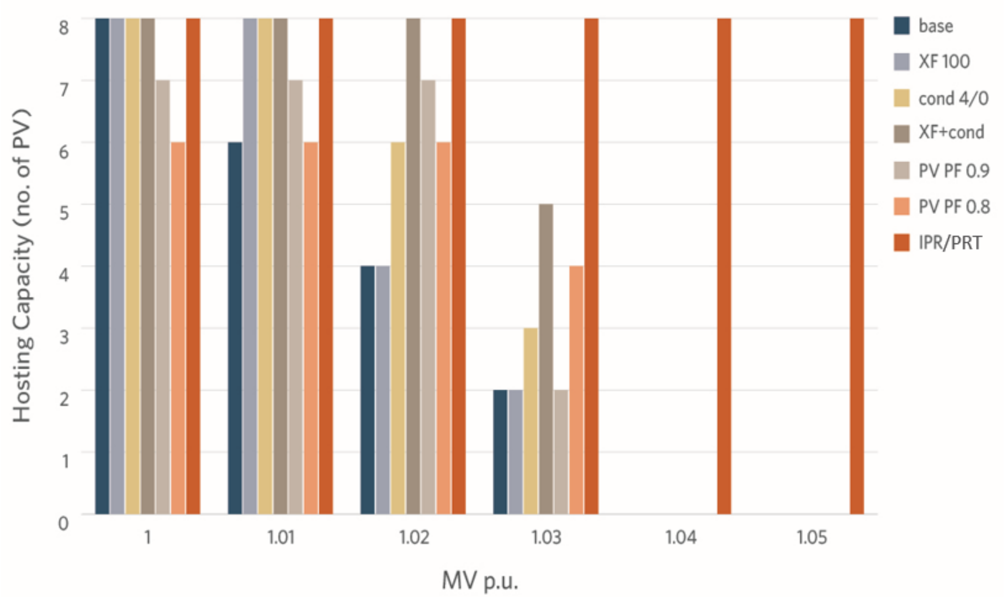
Figure 2 shows the hosting capacity of the double-chain network. The "base" case represents the network as shown in Figure 1, and as the bars for the "base" case show, hosting capacity rapidly decreases from eight nodes (at MV = 1 p.u.) to zero nodes (at MV = 1.04 p.u. or above), due to the voltage constraint. For example, if this network were situated at a point in the primary feeder with maximum MV voltage of 1.00 p.u., its hosting capacity is already at maximum (all eight nodes can host PV) without any further enhancements. However, if this network were situated at a point in the primary feeder where MV voltage is expected to be high during times of feeder-wide maximum PV and light load, then its hosting capacity will be severely limited, and various mitigation strategies must be considered before additional PV generation may be permitted.

The other bars in Figure 2 represent several sample techniques for mitigation of high voltages from PV generation:

- "XF 100" – upgrading the transformer from 50 kVA to 100 kVA
- "cond 4/0" – upgrading the main conductor from 1/0 AWG to 4/0 AWG
- "XF + cond" – upgrading both the transformer and the main conductor as above
- "PV PF 0.9 (or 0.8)" – programming each PV (smart) inverter to operate at power factor (PF) 0.9 or 0.8, i.e. sourcing real power but consuming reactive power (in an attempt to bring down voltages)
- "IPR/PRT" – deploying Gridco Systems In-line Power Regulators or Power Regulating Transformers

Each mitigation technique improves hosting capacity, but their effectiveness varies widely, with the transformer upgrade being least effective and the IPR/PRT being most effective in this example. Note that in the cases where PV is sinking reactive power at a power factor of 0.9 or 0.8, the additional reactive power causes increased current at the (50 kVA) transformer. As a result, the hosting capacity in this scenario is limited by the transformer apparent power rating to 7 or 6 nodes, respectively, even at low MV voltages.

Figure 2: Hosting capacity of the double-chain network



As shown in Figure 2, the IPR/PRT achieves maximum hosting capacity (i.e. all 8 nodes can host PV), regardless of MV voltage. This is because the IPR/PRT acts as a fast LV voltage regulator, with a +/- 10% range. In other words, as long as the MV voltage is 0.90-1.10 p.u., the IPR/PRT (installed at the LV bus or integrated with the transformer) can keep its output (load-side) LV voltage at 1 p.u. When added to the worst-case voltage rise (due to secondary conductors only since the IPR sits behind the transformer and the PRT is integrated with the transformer), this regulated voltage maintains all PCC voltages below 1.05 p.u. In essence, the IPR/PRT can decouple the MV voltage from the LV voltage, thereby removing the voltage constraint entirely.

In contrast, other mitigation techniques typically lower the PCC voltage by only ~1-2% (see Appendix 2 for details). As a result, they can only increase PV hosting capacity when the MV voltage is not too high. In the double-chain example, these other techniques are marginally useful at MV = 1.03 p.u. and completely ineffective at MV = 1.04 p.u. or above.

Similar results are obtained for a single-chain network or a star network. The details are shown in Appendix 1.

In reality, mitigation options must be selected based on both the MV voltage and the upgrade costs involved. In the case of operating PV at non-unity power factor, the source and transmission of the additional reactive power sunk by the PV inverters must also be considered, as well as the resulting additional resistive loss. In addition, operating the PV smart inverters at a PF of 0.9 or 0.8 during a time of peak real power output means the inverter apparent power rating must be oversized by 111% or 125% respectively, compared to the PV real power rating. Another consideration, depending on the control mode used by the PV inverter, is planning and managing the interaction between multiple, distributed residential inverters and the utility's capacitor bank controls to avoid an unstable voltage "hunting" situation.

Various voltage mitigation techniques can also be combined (e.g. transformer upgrade plus operating PV smart inverters at a PF of 0.9), with costs and combined effects being roughly additive. The IPR/PRT is a special case – since it already eliminates the voltage constraint (by essentially isolating LV and MV voltages), it need not be combined with other mitigation techniques except to alleviate capacity constraints.

Other Benefits of the IPR/PRT

While this brief concentrates on the most common barrier to increasing secondary PV hosting, i.e. the PCC voltage constraint during peak reverse power flow, there are other barriers that the IPR/PRT can also address. For example, the IPR/PRT's fast voltage regulation can effectively minimize downstream voltage fluctuations due to sudden changes in loads and/or solar irradiance. In addition, the IPR/PRT has various harmonic cancellation capabilities, and can increase PV hosting capacity in secondary networks where excessive harmonic content is the limiting factor. The fact that the IPR/PRT regulates secondary voltage with a series-connected component also eliminates any voltage "hunting" control interaction with the MV primary control systems.

Conclusion

There are many potential technical barriers to accepting a high penetration of distributed PV sources, and not all of them can be overcome by the IPR/PRT. However, for the most common scenario where excessive voltage rise (or fluctuation) is the main obstacle to increasing PV penetration, the IPR/PRT offers a very cost-effective solution, due to its fast, dynamic +/- 10% voltage regulation capability. In comparison, other approaches such as transformer upgrade, reconductoring, or operating PV smart inverters at 0.9 PF can only achieve ~1-2% voltage improvement, and so they are only useful against small voltage violations. The IPR/PRT effectively decouples the LV voltage from the MV voltage and eliminates any voltage concern due to high penetration of PV in a secondary network, thereby maximizing PV hosting capacity.

Appendix 1: Hosting Capacity in Single-chain and Star Networks

Aside from the double chain sample configuration discussed in the main body of this application note, two other common configurations are discussed here. The first is a single chain secondary, with customers distributed along a single LV backbone, and the second is a star secondary, with each customer connected to a dedicated service drop running from the LV bus of the distribution transformer. These configurations are illustrated in Figures 3 and 4.

Figure 3: Single-chain secondary network

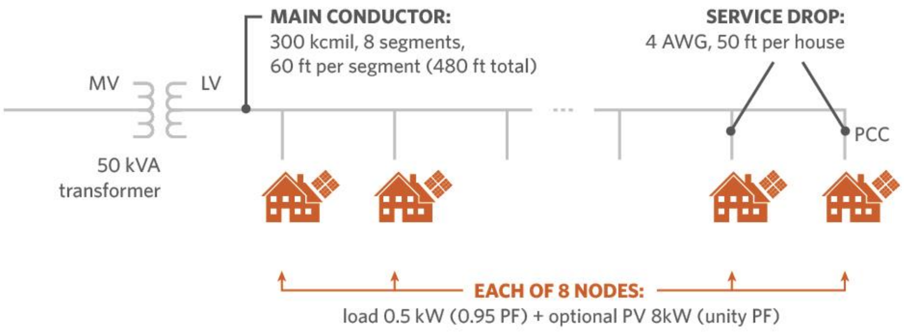
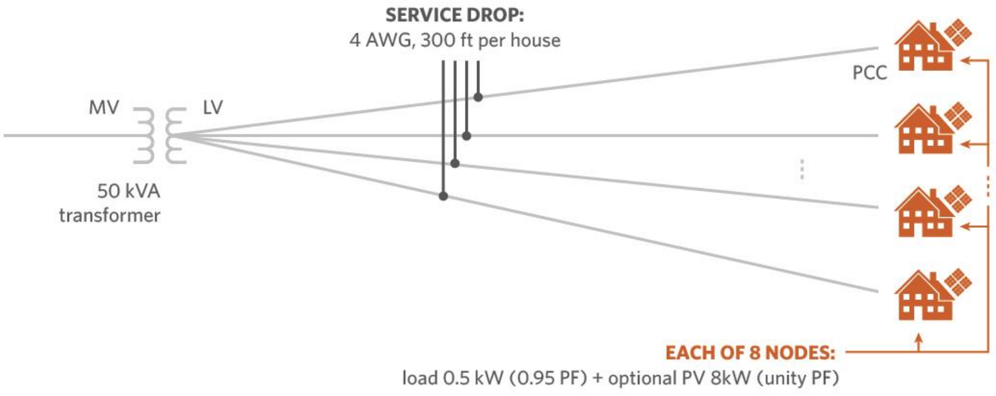


Figure 4: Star secondary network



Figures 5 and 6 show the hosting capacities of the single-chain and star networks, as functions of MV voltage and under different mitigation techniques. Note that the reconductoring being considered in each network is different:

- Double-chain network: main conductor 1/0 AWG → 4/0 AWG
- Single-chain network: main conductor 300 kcmil → 400 kcmil
- Star network: service drop 4 AWG → 1/0 AWG. Note that there is no main conductor in the star network, and so the service drop is being upgraded. This is likely to be very expensive in this example

as it entails replacing 300 feet of conductor for each of eight nodes with connected PV, for a total of 2400 feet.

Figure 5: Hosting capacity of single-chain network

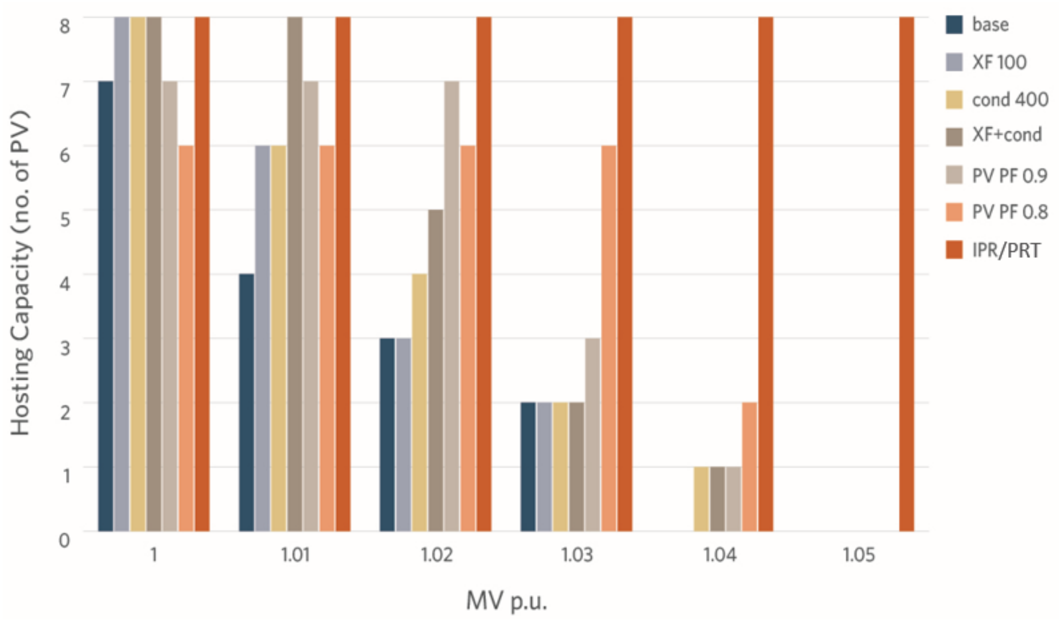
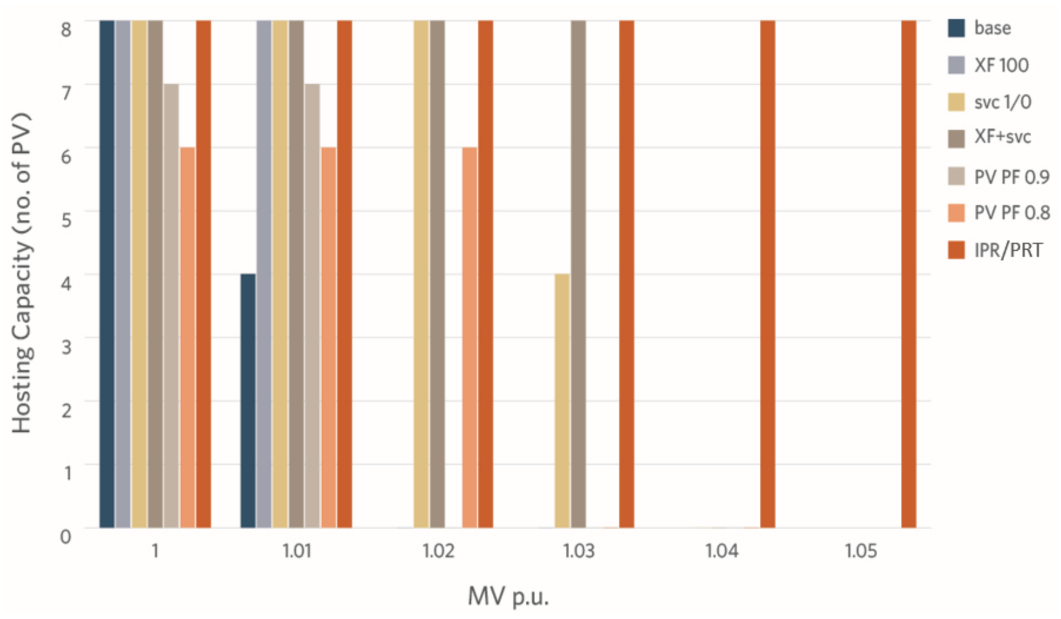


Figure 6: Hosting capacity of star network



As shown in Figures 5 and 6, the IPR/PRT once again achieves maximum hosting capacity at all MV voltage values between 0.90-1.10 p.u., because of its capability to decouple LV and MV voltages.

Another interesting observation is that, comparing all three networks, operating PV smart inverters at non-unity PF is most effective in the single-chain network and least effective in the star network. This is a direct consequence of the fact that the single-chain network has the highest aggregate (transformer + conductor) X/R ratio (reactance to resistance ratio) and the star network has the lowest aggregate X/R ratio.

Appendix 2: Comparing Mitigation Techniques by their Voltage Effects

Fundamentally, if the PCC voltage constraint is limiting PV hosting, then each mitigation technique is an attempt to decrease the secondary voltage rise, so that the secondary network can accommodate a combination of more PV and higher MV voltage. Therefore, another way to compare the different mitigation techniques is to investigate how much each technique decreases the secondary voltage rise. The secondary voltage rise caused by full PV deployment (with all eight nodes hosting 8 kW of PV each) for all three networks is shown in the following table. The figures in parentheses are the calculated improvement (i.e. decrease in voltage) achieved by various mitigation techniques compared to the base case.

Mitigation technique	**Single-chain network: secondary voltage rise**	**Double-chain network: secondary voltage rise**	**Star network: secondary voltage rise**
Base case (no mitigation)	5.2%	4.5%	4.6%
Transformer upgrade 50kVA → 100kVA	4.3% (0.9%)	3.6% (0.9%)	3.7% (0.9%)
Reconductoring (various options depending on network)	4.4% (0.8%)	3.2% (1.3%)	2.7% (1.9%)
Transformer upgrade + reconductoring	3.4% (1.8%)	2.3% (2.2%)	1.8% (2.8%)
PV smart inverter at 0.9 PF (Note: transformer overloaded at ~136% with 8 PV nodes)	2.9% (2.3%)	3.0% (1.5%)	3.3% (1.3%)
PV smart inverter at 0.8 PF (Note: transformer overloaded at ~155% with 8 PV nodes)	1.7% (3.5%)	2.1% (2.4%)	2.5% (2.1%)
Gridco IPR/PRT	**Decouples MV and LV, tolerates MV up to 1.10 p.u., essentially equivalent to (10.00%) improvement**		

Generally speaking, a transformer upgrade yields a voltage improvement of ~1% (0.01 p.u.), while reconductoring yields ~1-2% depending on the network and the specific reconductoring option being considered. Operating PV smart inverters at 0.9 PF yields ~1-2%, while a 0.8 PF yields ~2-3.5%, but the bigger voltage improvements require large amounts of reactive power. The reactive power drawn may cause unacceptable capacity overloads in the transformer or in the conductors, as well as added resistive loss. In contrast, the IPR/PRT decouples LV and MV voltages and essentially yields a 10% (0.10 p.u.) voltage improvement, which in almost all realistic cases means eliminating the voltage constraint entirely.

About Gridco Systems

Gridco Systems is a leader in agile grid infrastructure solutions, enabling utilities to more effectively integrate renewable and distributed generation, increase energy efficiency, manage peak capacity, and improve system reliability. The Gridco Systems emPower™ Solution combines modular power electronics, advanced controls, distributed networking, and power system analytics to deliver the industry's only end-to-end hardware and software platform purpose built to solve utilities' current and emerging distribution challenges in a distributed, dynamic, and decoupled fashion. To learn more, please visit www.gridcosystems.com.

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