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Recommendations for the Planning of PV-Rich Distribution Networks: An Australian Case Study

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***Abstract*— This paper consolidates the findings from the "Advanced Planning of PV-Rich Distribution Networks" project and provides a series of planning recommendations to help distribution companies in Australia, and internationally, take adequate planning actions that facilitate the widespread adoption of residential photovoltaic (PV) systems in a cost-effective and practical manner. A set of considerations are presented to perform an advanced model-based approach for solar PV hosting capacity and potential solution assessments in distribution networks. A summary of the seven investigated complete solutions and their costs for the four Australian fully-modelled high-voltage (HV) and corresponding attached low-voltage (LV) feeders, forming integrated HV-LV feeders (including urban and rural), are presented, considering PV penetrations in both the short-to-medium and long terms.**

Keywords— Distribution Networks, Hosting Capacity, Planning Recommendations, Rooftop Solar PV Systems

I. INTRODUCTION

The percentage of dwellings in Australia with solar photovoltaic (PV) varies from just over 20% in Victoria to over 40% in Queensland. This, combined with a growing number of commercial customers adopting the technology, is already posing significant technical challenges on the very infrastructure they are connected to: the low voltage (LV, 230V line-to-neutral) and high voltage (HV, up to 22kV line-to-line) distribution networks. Due to the rapid uptake of the technology, many distribution companies (aka Distribution Network Service Providers) across Australia have adopted the use of PV penetration limits based on the capacity of the distribution transformers feeding LV customers. Once this limit is reached, detailed analyses are often required to determine the need for any mitigating action due to voltage rise or asset congestion issues (e.g., use of off-load tap changers, network augmentation [aka wire alternatives], etc.).

Whilst, in principle, the use of a PV penetration limit is a sensible approach to swiftly deal with many connection requests, the lack of advanced planning approaches has led distribution companies to adopt values that might under or over-estimate their actual hosting capacity, particularly due to voltage issues in LV networks and congestion issues in HV networks. Similarly, assessing the effectiveness of non-traditional solutions, such as actively controlling smart PV inverters or deploying distribution transformers fitted with on-load tap changers, becomes a task beyond typical planning studies carried out by distribution companies. All this, in turn, becomes a barrier for the widespread adoption of solar PV as it can create delays, increase cost, and could undermine the consumer attractiveness of the technology.

To help remove the aforementioned barriers and accelerate the adoption of solar PV in distribution networks, the project "Advanced Planning of PV-Rich Distribution Networks" funded by the Australian Renewable Energy Agency (ARENA) and AusNet Services [1, 2], and led by The University of Melbourne was established in February 2019, in part, to produce planning recommendations to increase the PV hosting capacity within an existing distribution network using non-traditional solutions that exploit the capabilities of PV inverters, voltage regulation devices, and battery energy storage systems.

The modelling and analysis tasks carried out within this project have enabled the detailed quantification of the effects that different penetrations of residential PV can have on the studied urban and rural Australian HV-LV feeders, when considering a range of potential solutions. This, in turn, has made it possible to estimate not only the increase in PV hosting capacity that each solution can achieve per HV-LV feeder type, but also the associated cost.

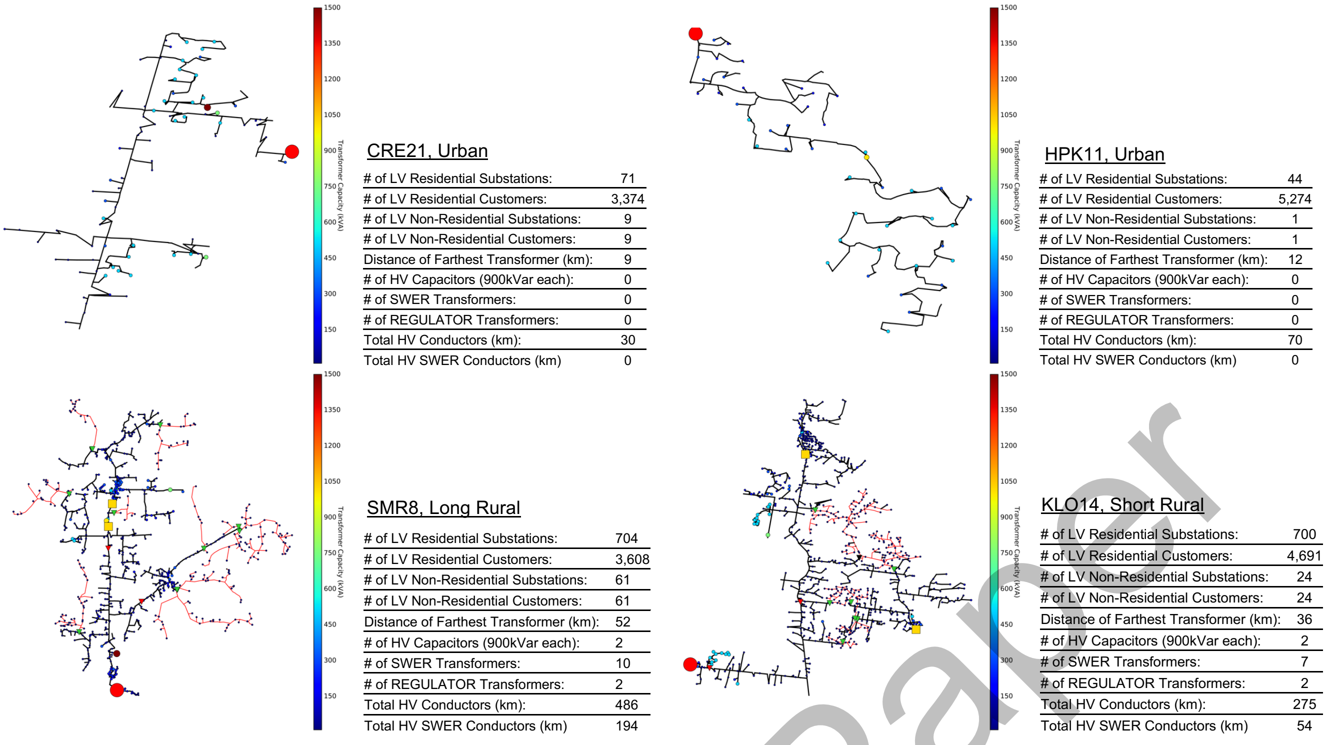
To help distribution companies in Australia, and internationally, take adequate planning actions that facilitate the adoption of residential PV in a cost-effective and practical manner, a series of recommendations are given based on the findings from Tasks 3 to 5 (reported in Deliverables 3 to 5 [3-5]). These planning recommendations are divided into two planning horizons: short-to-medium term (10-20 years from 2021) and long term (20-40 years from 2021), which are expected to reach around 40-60% of PV penetration and beyond 60%, respectively. The full summary report can be found in [6]. No such planning guidelines and recommendations are publicly available (to the extent of the authors knowledge), which concludes based on information resulting from detailed modelling assessments considering multiple solutions and realistic distribution network models.

II. ADVANCED MODEL-BASED APPROACH

In general, any model-based approach uses an explicit electrical model of the corresponding distribution network (including its topology, elements, parameters, etc.) that in turn allows to run power flow simulations (using specialised software packages) for different demand/generation scenarios. This is a well-known approach used routinely by distribution companies in Australia and around the world to design, plan and improve their networks. However, it is typically limited to HV feeders and to critical demand/generation scenarios.

The advantage of the model-based approach is that it is adaptable, network elements and participants can be added, removed or changed and control techniques can be implemented and tested through simulations. This makes the model-based approach highly effective if used to investigate the effectiveness of various solutions to various problems such as those related to the increase of PV hosting capacity. Various aspects need to be considered to move from a typical model-based approach to one that is more advanced and realistic and, hence, provide better quantifications and insights for distribution companies.

1. Explicitly Model LV Feeders. Distribution companies should consider the use of integrated HV-LV



CRE21, Urban

# of LV Residential Substations:	71
# of LV Residential Customers:	3,374
# of LV Non-Residential Substations:	9
# of LV Non-Residential Customers:	9
Distance of Farthest Transformer (km):	9
# of HV Capacitors (900kVar each):	0
# of SWER Transformers:	0
# of REGULATOR Transformers:	0
Total HV Conductors (km):	30
Total HV SWER Conductors (km)	0

HPK11, Urban

# of LV Residential Substations:	44
# of LV Residential Customers:	5,274
# of LV Non-Residential Substations:	1
# of LV Non-Residential Customers:	1
Distance of Farthest Transformer (km):	12
# of HV Capacitors (900kVar each):	0
# of SWER Transformers:	0
# of REGULATOR Transformers:	0
Total HV Conductors (km):	70
Total HV SWER Conductors (km)	0

SMR8, Long Rural

# of LV Residential Substations:	704
# of LV Residential Customers:	3,608
# of LV Non-Residential Substations:	61
# of LV Non-Residential Customers:	61
Distance of Farthest Transformer (km):	52
# of HV Capacitors (900kVar each):	2
# of SWER Transformers:	10
# of REGULATOR Transformers:	2
Total HV Conductors (km):	486
Total HV SWER Conductors (km)	194

KLO14, Short Rural

# of LV Residential Substations:	700
# of LV Residential Customers:	4,691
# of LV Non-Residential Substations:	24
# of LV Non-Residential Customers:	24
Distance of Farthest Transformer (km):	36
# of HV Capacitors (900kVar each):	2
# of SWER Transformers:	7
# of REGULATOR Transformers:	2
Total HV Conductors (km):	275
Total HV SWER Conductors (km)	54

Fig. 1. HV-LV Feeder Topologies and General Characteristics

feeder models, i.e., explicitly modelling LV feeders (or pseudo LV feeders) down to customer connection points. This is necessary to fully capture the response of voltage-related control actions from residential PV systems (e.g., Volt-Watt and/or Volt-Var) as well as network elements and, hence, correctly quantify voltage rise issues and benefits from potential solutions.

2. Perform Time-Series Simulations. Time-series simulations should be conducted by distribution companies to adequately capture time-dependent aspects of demand, PV irradiance and controllable elements in the network including those on the customer side. This enables a more accurate assessment of voltages and power flows in time and the corresponding effects on PV curtailment and asset congestion.

3. Cater for Uncertainties. Distribution companies should account, to the extent that is possible, for uncertainties related to PV location, PV size, irradiance profiles and demand profiles.

4. Other considerations. Although HV feeders can have significantly different characteristics, the investigation of potential solutions can be done on a limited number to reduce the required modelling effort and time. The selection of HV feeders should consider several characteristics such as general type (e.g., rural, urban), length, number of customers, number of PV system installations, etc. that can be used to map the corresponding population and identify the most extreme cases (as explained in Deliverable 1 [5]). Using extreme cases demonstrates the viability of a potential solution and, therefore, that solution is likely to also work (and perform even better) in milder cases. In a model-based approach, to determine hosting capacity, firstly, distribution network planning standards and guidelines should be defined (e.g., voltage limits, rated capacity of assets, etc.). Then, power flow simulations are carried out considering the demand/PV scenarios of interest. Hosting capacity and the success of any solution is determined by the ability to keep voltages (particularly customer voltages), asset utilisation and any other critical parameter within pre-specified limits.

III. REALISTIC INTEGRATED HV-LV FEEDERS

The project considered four fully-modelled HV-LV feeders, each with significantly different characteristics (i.e., urban, short rural, long rural etc.). These feeder types exhibit very different physical properties depending on their location (feeder length, substations per number of customers, etc.). This allows demonstrating that the adopted solutions can be applied, to the extent that is possible, across the wide spectrum of HV feeders in the area of AusNet Services (State of Victoria). The topology and general characteristics of each three-phase HV feeder are provided in Fig. 1. These figures only show the HV portion of the feeder that comes from real Victorian data, whilst the modelled LV feeders using modern design principles are not shown (but are modelled electrically connected).

Each of the feeders has a fully-modelled, three-phase unbalanced, LV network attached to each of the HV/LV substations (blue circles or green triangles), containing both residential and non-residential customers within. For residential demand, a pool of 30-min resolution, year-long (i.e., 17,520 points), anonymized smart meter demand data (i.e., P and Q) was used, collected from 342 individual residential customers in the year of 2014. Using this pool, the yearly demand profiles were broken down in daily profiles, resulting in a pool of ~30,000 daily demand profiles. Residential customers are modelled as single-phase loads with a separate PV system modelled depending on the PV penetration. PV penetration is defined as the percentage of residential customers with a PV system. Probabilistic uncertainty for size of PV installation was considered where the proportion of single-phase PV installations with 2.5, 3.5, 5.5, and 8kWp is 8, 24, 52 and 16%, respectively.

All the analyses in the project were carried out considering time-series three-phase (unbalanced) power flows across the selected HV-LV feeders using the software OpenDSS. The seasonal analysis within the project considers 14 consecutive days in each season as it is an adequate trade-off between capturing seasonality (the % of PV curtailment) and the corresponding computation time. Due to space limitations further details such as: non-residential demand, load and PV profiles, standards, feeder modelling, performance metrics, battery operation explanation and more can be found in [3-7].

IV. COMPLETE SOLUTIONS

The complete solutions are the combination of traditional and non-traditional solutions from [3] and [4] that ensure both voltage and asset congestion problems are mitigated to enable a given PV hosting capacity. Network augmentation is defined as the replacement of conductors or transformers with a larger current rating, which is expensive at a large scale. Augmentation can be minimized by the accompanying solution within a complete solution if it mitigates more than only voltage rise and can reduce asset congestion through lower peak exports.

The seven complete solutions investigated in this project [5] are listed below. The Victorian PV inverter requirements (VicSet) established in 2019, are considered in all complete solutions except for (3).

(1) Off-Load Tap Changers + Augmentation + VicSet

(2) Zone Sub OLTC + Off-Load Tap Changers + Augmentation + VicSet

(3) Tailored Volt-Watt and Volt-var Settings + Off-Load Tap Changers + Augmentation

(4) LV OLTC + Augmentation + Off-Load Tap Changers + VicSet

(5) Off-The-Shelf Batteries + Off-Load Tap Changers + Augmentation + VicSet

(6) Network Smart Batteries + Off-Load Tap Changers + Augmentation + VicSet

(7) Dynamic Voltage Target at Zone Sub OLTC + Off-Load Tap Changers + Augmentation + VicSet

Further information on how these solutions work individually and their performance, along with the business-as-usual analysis (and impacts of PVs) can be found in the reports of Deliverable 3 [3] and 4 [4] of the project. Complete solution performance is within Deliverable 5 [5] and 6 [6].

V. ECONOMIC ASSESMENT

The quantification of the cost of a complete solution for a given PV hosting capacity (60% or 100%) is done considering the capital and operating expenditures (CapEx and OpEx) of the assets involved (e.g., augmentation, off-load LV transformer tap adjustment, OLTC LV transformers, dynamic voltage target for primary substation, etc), as well as unserved generation due to PV curtailment. Residential batteries are considered in this project to be bought and installed by residential customers alongside (or in addition to) their PV systems to reduce their electricity bills. Consequently, from the perspective of the distribution company looking to invest, there is no cost associated with the residential batteries. The net present value (NPV) of the overall cost corresponding to a complete solution to achieve a given PV hosting capacity is the value used for all comparisons. It is important to highlight that because this study only considers the cost of solutions (and unserved PV generation), for simplicity, all NPV costs are presented as positive values. A real discount rate of 4.83% is used in calculation, based on a nominal discount rate of 6.44% and an inflation rate of 1.61%

The necessary assets of complete solutions for a given year are quantified considering superposition of the results from Task 3 [1] and Task 4 [2], i.e., any remaining asset congestion problems are solved through augmentation (e.g., replacing overloaded LV transformers). The assessment is conducted at set PV penetrations and is subsequently assigned a corresponding year based on forecasts. The cost of each complete solution considers the installation of the assets at the start of the corresponding window between PV penetrations that were simulated (e.g., for a 2031-2042 window, assets are installed in 2031). This ensures its effectiveness throughout, whilst still adequately discounted (through NPV discount rate) compared to an unnecessarily early installation. Full details of cost considerations, which is omitted due to space limitations, can be found within Deliverable 5 [5].

A. Time Frame of Analysis

Two residential PV hosting capacity scenarios were considered for cost comparisons: 60% and 100% of customers with a PV system. These timeframes are also used as two planning horizons: short-to-medium term (10-20 years from 2021) and long term (20-40 years from 2021), which are expected to reach around 40-60% of PV penetration and beyond 60%, respectively (depending on HV feeder). Because of this, 60% of PV hosting capacity can be considered as a milestone beyond which there is too much uncertainty about technologies as new solutions and challenges might emerge. The 100% PV hosting capacity scenario, despite being much further in the future (31 years for CRE21 and 49 for the others), is considered for completeness and to understand the theoretical total cost of complete solutions.

VI. COSTS OF COMPLETE SOLUTIONS

This section presents a summary of complete solution costs to achieve both 60% (i.e., short-to-medium term) and 100% (i.e., long term) hosting capacity. A full breakdown of cost results, including cost sensitivity results not presented, can be found in Deliverable 5 [5]. Because augmentation solves any remaining asset congestion issues (at a cost), the ability of a complete solution to achieve a hosting capacity is therefore limited by if the feeder and solution combination can manage customer voltage rise (from PV systems) adequately.

A. Cost of Achieving 60% Hosting Capacity

A summary of costs to achieve 60% PV hosting capacity can be seen in Fig. 2 (a) for the four HV-LV feeders, and the seven completion solutions. For urban feeders, complete solution (6) Network Smart Batteries, is the cheapest by a considerable margin. This is due to minimal augmentation costs combined with little curtailment (as voltages are kept well within limits). The only significant cost is due to off-load tap changes (applicable to all complete solutions).

The adjustment of off-load taps in LV transformers (1) and the zone (aka primary) substation OLTC's voltage target (2), combined with augmentation and VicSet inverter settings, although very cheap can only achieve 60% hosting capacity in CRE21 only. This affirms the current practice of Distribution companies as they are cost-effective solutions in the short term for urban HV feeders, particularly at lower PV penetrations.

For rural feeders, complete solution (3) Tailored Volt-Watt and Volt-var settings is the cheapest complete solution, requiring reduced asset augmentation costs compared with (6) despite higher PV curtailment. It is worth mentioning that complete solution (3) does not require off-load tap changers to work (although can result in higher curtailment due to higher voltages). For example, in SMR8 with hundreds of LV transformers, such tailored settings would reduce the cost from (AUD) $737,490 to $209,490, a significant saving. Overall, the cost of achieving 60% PV hosting capacity is more expensive in rural feeders than urban. This is because of the greater number of assets that need to be replaced in rural feeders (more LV transformers per customer).

B. 100% Hosting Capacity Cost

A summary of costs to achieve 100% PV hosting capacity can be seen in Fig. 2 (b) for the four HV-LV feeders, and the seven completion solutions. For both urban and rural feeders, complete solution (6) Network Smart Batteries is the cheapest complete solution to achieve 100% hosting capacity. In rural feeders, whilst (6) is still the cheapest, it is much closer to complete solution (3) Tailored Volt-Watt and Volt-var settings (the cheapest solution for rural feeders at 60%).

Overall, it can be observed that the cost of achieving 100% PV hosting capacities in urban feeders is lower than the cost for rural feeders (as was the case for 60%). This is due to the greater number of assets that need to be replaced per customer in rural feeders (more LV transformers per customer that will otherwise overload). KLO14 was by far the most expensive feeder due also requiring some HV reconductoring and the high number of LV transformers needing augmentation.

VII. PLANNING RECOMMENDATIONS

This section presents a series of planning recommendations that consider the complete solutions investigated in this project, their cost-effectiveness in the short-to-medium and long terms, and the practicalities surrounding their adoption by distribution companies.

A. In the Short-to-Medium Term (40-60% PV Penetration)

This considers the short term as 2030 and medium term as 2040. Although Deliverable 5 [5] showed that the adoption of advanced battery controllers (such as the Network Smart controller) combined with augmentation was one of the most cost-effective complete solutions, its usefulness depends on all PV installations to have a battery. Since in this timeframe, residential battery uptake is unlikely to match the number of PV installations, battery-based solutions may not bring significant benefits. Consequently, distribution companies need to focus on exploiting the capabilities of existing assets, from residential PV inverters (through standards or requirements) to on-load tap changers at zone substations (adapting tap positions to downstream network conditions).

1) Continue Enabling Volt-Watt & Volt-var Settings

The Victorian PV inverter requirements (VicSet) established in 2019 should be emulated so as to require Volt-Watt and Volt-Var responses simultaneously. Crucially, it was found that the VicSet curtails, in average across all customers within a HV feeder, approximately only 1% of the potential PV generation; which is a fraction of the curtailment resulting from using a standard where only Volt-Watt is enabled. By enabling both Volt-Watt and Volt-var functions, these requirements help any type of HV feeder (urban or rural) further mitigate voltage issues when compared with Volt-Watt-only standards. While the VicSet does not entirely solve voltage issues, due to the settings implemented in the standard, the number of customers affected by voltage issues and the magnitude of those voltages is much lower. Consequently, when combined with augmentation for any remaining asset congestion, this solution becomes a low-cost interim alternative for distribution companies.

2) Continue Exploiting Existing Assets

Distribution companies should adjust the off-load tap changer position of distribution transformer and/or the voltage target at zone substations to lower customer voltages and, hence, reduce voltage rise issues due to PV. When these adjustments are done in combination with VicSet and augmentation, they can increase hosting capacity to 40-60% in urban HV feeders, i.e., fully mitigating voltage and thermal issues in the medium term. Despite the cost involved in the adjustments of off-load tap adjustments of LV transformers (on top of the cost due to augmentation mainly because of congested transformers), exploiting existing assets is the lowest-cost solution. This affirms that the current practices of distribution companies are adequate and on the right track.

However, for rural feeders, these adjustments bring limited benefits and are only useful for low PV penetrations (up to 20%). Whilst for one urban feeder this method was able to achieve up to 60%. Finally, these adjustments will also provide a much better starting point for more advanced techniques, such as stricter inverter settings of dynamic voltage targets at the zone substation. This makes off-load tap adjustment an excellent short-term measure that does not hinder further techniques to increase PV hosting capacity (for the long term).

3) Adopt Stricter Volt-Watt & Volt-var Settings

Distribution companies should pursue the further improvement of the inverter settings that are stricter (than, for example, VicSet) when dealing with voltage rise. For a voltage rise limit of 1.10pu, this can be done by adopting Volt-Watt settings that start curtailing at 1.09 p.u. (250.7V) and do not allow PV generation beyond 1.10 p.u. (253V), and Volt-var settings that absorb reactive power up to 1.09 p.u. (250.7V). Whilst, in average, curtailment does increase compared to VicSet, it is only marginal; hence, bringing benefits to both networks and customers. When compared with VicSet, a much higher PV hosting capacity can be achieved due to managing voltage issues. Distribution companies and other stakeholders should not be afraid of pursing stricter Volt-Watt and Volt-var inverter settings as no investment is required to manage voltage issues. These stricter settings lead to only a 1-2% increase in the average curtailment across all customers compared to the VicSet business-as-usual case. This solution will be less effective when considering a non-homogenous implementation of inverter requirement and will lead to greater curtailment placed on customers with the stricter requirements. The earlier stricter settings are implemented, the more effective they will be. As time passes more PV systems use the updated requirements in replacements & new installs.

Overall, this is a very cost-effective method to increase PV hosting capacity, one of the cheapest to achieve 60% PV in urban feeders and the cheapest for rural feeders. Being suitable for both urban and rural makes it a very scalable solution. However, its practicality depends on the uptake of PV and a decision on inverter requirements.

4) Implement Intelligent Voltage Control at Zone Substations

Distribution companies should adopt intelligent approaches that exploit the existing flexibility provided by OLTCs at zone substations. By using intelligent voltage control that can estimate PV generation downstream (or its effects on customer voltages) and adjust the OLTC voltage target accordingly, voltage issues in LV feeders can be alleviated. Voltage regulation at zone substations (e.g., 66kV/22kV) has historically been done considering a conservative fixed voltage target at the secondary side (e.g., 22kV) that compensates for voltage drops due to peak load. By dynamically changing the voltage target based on an estimated PV generation downstream (or its effects on customer voltages), voltage rise issues during times of PV generation can be reduced. In fact, these are actions already being tested -although to different extents- by distribution companies in Australia.

B. In the Long Term (Beyond 60% PV Penetration)

This considers the long term as up to 2060 where most feeders could potentially reach very high PV penetrations (theoretically, up to 100%). However, the long-term view of this means there are significant technological uncertainties between 2021 and 2060, such as increased uptake of electric vehicles, new forms of distributed energy resources, etc. Considering the solutions investigated in this project, in the long term, distribution companies can benefit from exploiting the flexibility of PV inverters (using stricter settings), batteries (using network-friendly requirements) and zone substations (using intelligent voltage control) in combination with augmentation to achieve up to 100% PV hosting capacity in a cost-effective manner, regardless of the type of HV feeder.

1) Adopt Stricter Volt-Watt & Volt-var Settings

Distribution companies should pursue stricter Volt-Watt and Volt-var settings as they can manage voltage problems from reverse power flows for all feeder types and PV penetrations. Augmentation should be used in combination to solve asset congestion issues which, at high PV penetrations, involves not only distribution transformers but can also involve HV conductors. If stricter settings are adopted in the short-to-medium term, their benefits in eliminating voltage problems will continue to be seen at very high PV penetrations (long term). When combined with off-load tap adjustment and network augmentation, this solution can achieve 100% PV hosting capacity on all types of feeders, whilst being one of the cheapest solutions investigated due to the mitigation of augmentation through stricter inverter settings (as well as managing voltage rise).

2) Implement Intelligent Voltage Control at Zone Substations

Distribution companies should adopt intelligent voltage control at zone substations that can estimate PV effects downstream and adjust the OLTC voltage target accordingly, thus alleviating voltage issues in LV feeders. Augmentation should be used in combination for asset congestion.

3) Implement Network-Friendly Battery Connection Requirements

Distribution companies should exploit the flexibility of residential batteries by mandating network-friendly connection requirements. Whilst commercially available ‘off-the-shelf’ residential batteries today can significantly reduce electricity bills for customers with PV systems, their control strategy does not reduce grid exports. Batteries today can get full even before high PV generation times, resulting in high grid exports and the corresponding network issues. New requirements can be network-friendly whilst also providing benefits to the customer (reducing electricity bills). Network-friendly control strategies, such as the investigated ‘Network Smart’, can be cost-effective in achieving high to full PV penetrations on all HV feeder types, mitigating all issues (in combination with augmentation). If actions are taken in the short-medium term to ensure that, in the long term, enough batteries have the updated requirements, then it can be highly effective if battery uptake is high among customers. In urban feeders it can considerably reduce, or eliminate, augmentation costs.

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