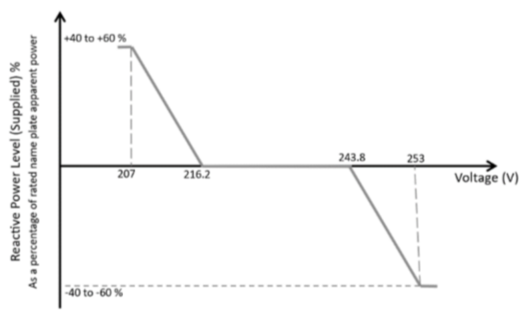
Discussion Paper

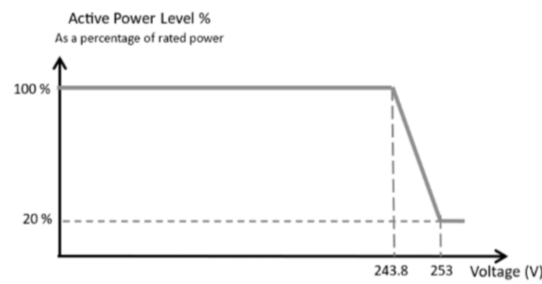
Increasing the Renewable Energy Input to the Grid from Rooftop Solar PV Systems

by

Optimizing the Inverter Voltage Response, and Revising the Statutory Voltage Limits

(to Minimize Grid Overvoltage Issues).





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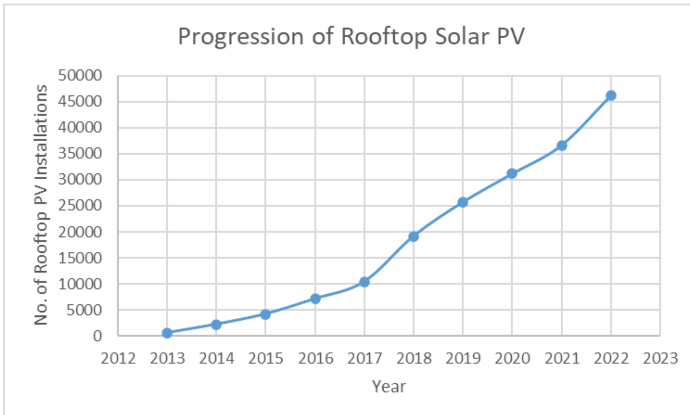
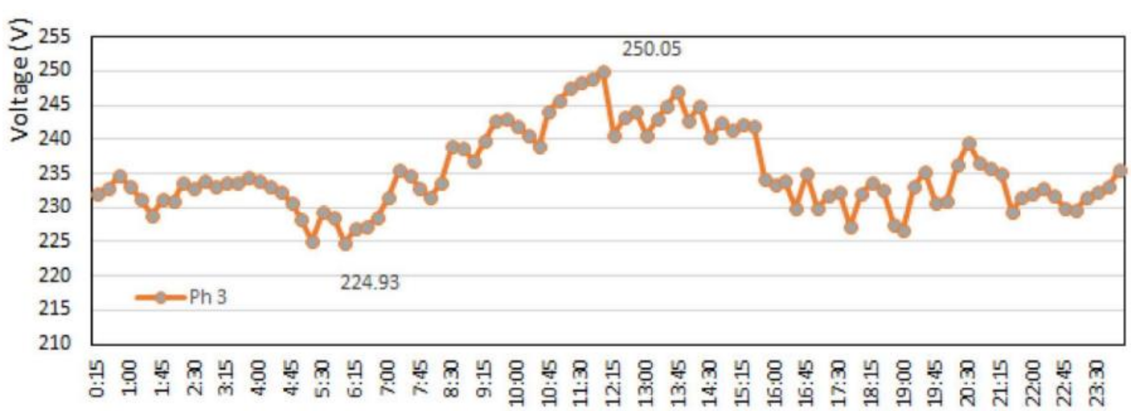
1 Introduction

The interruption of rooftop solar photovoltaic (PV) generation, resulting from inverter tripping caused by overvoltage in the distribution network's low voltage (LV) feeders, has got significant attention. This issue is of particular concern due to the loss of renewable generation, leading to lost revenue for consumers who have invested in rooftop solar PV installations. Following graph illustrates the rapid increase in rooftop solar installations. Hence actions need to be taken now to minimize the looming issue of voltage quality of distribution network.



Graph: Rapid Increase in Rooftop Solar PV Installations in Sri Lanka

In the case of low-voltage (LV) feeders, daytime load demand is generally minimal, with some exceptions. The integration of rooftop solar photovoltaic (PV) systems into these feeders can result in a gradual elevation of voltage levels. Typically, tripping of inverters occurs when the local network voltage surpasses the inverter's predetermined overvoltage set-points. This leads power output to be zero, even in the presence of behind-the-meter loads. This occurrence is particularly prevalent during mid-day hours when solar PV energy production is at its peak due to heightened irradiance. (see the figure below to understand the voltage rise during day time)



Graph : Variation of the voltage at common coupling at the end of a LV feeder on a peak PV generation day.

(Ref: *Voltage Impact of Roof-Top Solar Photo-Voltaic Systems on Low Voltage Network and Measures of Mitigation, by K. G. R. F. Comester et al., R&D Journal 2020, Ceylon Electricity Board.)*

The implementation of advanced technologies, such as inverters equipped with the capability to regulate both active and reactive power in response to grid voltage fluctuations, can effectively alleviate overvoltage concerns arising from the substantial penetration of rooftop solar PV systems during mid-day periods of heightened solar energy production.

Cost-effective strategies involve firstly incorporating voltage quality response modes within inverters, a feature readily available in most contemporary inverters. Additionally, a pragmatic approach would entail revising the statutory voltage limit from the present 230V+/-6% (between phase and neutral conductors) to a range that ensures compatibility with the existing distribution system and electrical appliances. This adjustment in the voltage limit range facilitates an elevation in the Solar PV inverter overvoltage setting, subsequently minimizing curtailments attributed to grid overvoltage.

The Public Utilities Commission of Sri Lanka (PUCSL) seeks recommendations and views from stakeholders on implementing voltage quality response modes of inverters as an initial measure to overcome grid overvoltage issue and also on considering the revision of statutory steady state voltage limits. Currently, Sri Lanka adheres to a statutory steady state voltage limit of 230V +/- 6% between phase and neutral conductors. This discussion paper aims to explore the potential benefits and drawbacks of increasing the statutory voltage limits beyond 230V +/- 6% by examining examples from other countries and international standards.

2 Analysis of Data from Rooftop Solar PV Systems

As an initial study data was obtained from 20 number of rooftop solar systems (3kW, 5kW and 6kW capacity) which are already having the issue of grid overvoltage significantly. The data set which covered the months of March and April 2023 indicated possible voltage excursions. (Areas : Alawwa, Dankotuwa, Kelaniya, Mahabage, Malambe, Marawila, Nugegoda, Rajagiriya, Thulhiriya, Wennappuwa, Boralesgamuwa, Embuldeniya, Hingurakgoda, Makola, Panadura, Polonnaruwa, Seeduwa and Thalangama)

Further, according to another set of rooftop solar PV data (from 49 systems) obtained from the respective inverters during the 2023-07-17 and 2023-07-18, revealed that 23 of those PV installations subjected to possible grid overvoltage.

(Areas: Anuradhapura, Battaramulla, Colombo, Gampaha, Hanwella, Hatton, Homagama, Horana, Kalutara, Kandana, Kandy, Katunayaka, Kotikawatta, Kurunagala, Matara, Moratuwa, Mount Lavinia, Mulleriyawa, Negombo, Panadura, Pita Kotte, Trincomalee, Wattegama, Welisara)

3 Prevailing regulations and Standards in Sri Lanka on Steady State Voltage levels

Electricity (Safety, Quality and Continuity) Regulations 2016 .

> Regulations No. 50 and no. 53 state that voltage declared in respect of low voltage shall be 230V between phase and neutral conductors at supply terminals. In case of low voltage, the variation shall not exceed 6% above or below the declared voltage. (i.e. 230V ±6%).

Electricity (Distribution) Performance Standard Regulations 2016.

The regulation no. 17 states that deviation of actual voltage level from its nominal voltage shall not exceed 400V/230V ± 6% (voltage variation at steady state).

Further the regulation no.20, describes the way to take measurements to check the voltage level. Accordingly, the voltage level at a connection point is determined by recording its voltages over a 24 hour period. The average value of the r.m.s. voltages recorded in a 15-minute interval at a sampling rate not less than one sample/minute shall be considered as the voltage of an installation.

The regulation no. 21 states that the voltage level of a location shall be considered to be within the specified levels, if the voltage so measured remains within the allowed tolerances during 90% of the time and the voltages measured during the balance 10% of the time, do not exceed 50% of the allowed tolerances.

Sri Lanka Standard 1259:2003 (IEC 60038:1983) Specification for Sri Lanka Standard voltages for electrical systems :

Under normal system conditions it is recommended that the voltage at the point of delivery of electricity from the distribution system of the electricity supply authority should not differ the nominal voltage (230/400 V) by more than ±10%.

4 Voltage Limits Specified in Prominent International Standards

BS EN 50160: The BS EN 50160 is a widely accepted international standard that recommends steady state voltage limits of 230V +/- 10%. It specifies that : Under normal operating conditions, during a period of 1 week and excluding the periods of interruptions, 95% of 10 min r.m.s. values should remain within +/-10% of the nominal voltage. Further, all 10 minute r.m.s. values of the supply voltage should be within the range of +10% to -15% of the nominal voltage.

IEC 62749: The IEC 62749 standard also recommends steady state voltage limits of 230V +/- 10%. This standard provides guidelines for power quality assessment, including voltage levels. It specifies that : Under normal operating conditions, during each period of one week (excluding the periods of interruptions), 99% of the 10-minute r.m.s. voltage values should not exceed +10% of the nominal voltage. Also, 5% of the values should not fall below -10% of nominal voltage, while 1% of the values should not fall below -15% of the nominal voltage.

It is observed that the prominent international power quality standards such as IEC, BS EN cross refer each other and also converge to very similar set of limits, hence it is recommended that the voltage quality regulations to be based on IEC and BS EN standards.

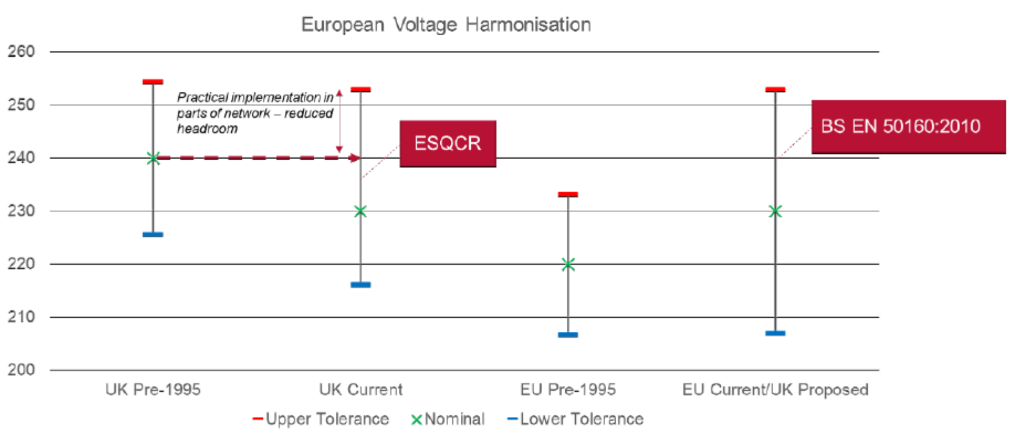
5 Regulations in other Jurisdictions with Extended Voltage Limits

Kerala - India : Kerala State Electricity Regulatory Commission (Power Quality for Distribution System) Regulations, 2019 which is in the draft stage is the regulatory tool for their power quality regulatory activities, with the scope of specifying the main characteristics of power quality of electrical supply at the supply terminals of Customers in the distribution system. The specified power quality statutory limits for Supply Voltage Variations in the LV network from declared voltage specified with reference to mean r.m.s., the 99% of values of supply voltage measured over a period of 10 minutes should be within ± 10 % of each period of one week and for 100% of time the voltage should be within ± 15 %.

Meghalaya – India : Meghalaya State Electricity Regulatory Commission (Power Quality) Regulations, 2018 governs the power quality of utility supply. The scope of these Regulations is to specify the main characteristics of power quality of electrical supply at supply terminals of Customers in distribution system. The 95% of the 10 min average r.m.s. values over periods of one week should be within ± 10 %, and 100% of the time it should be within ± 15 %.

Haryana – India : Haryana Electricity Regulatory Commission's, Standards of Performance of Distribution Licensees and Determination of Compensation Regulations, 2020 has set the limits on voltage quality. The supply voltage variations in LV networks from declared voltage should comply the limits as follows. The 95% of values of supply voltage measured over 10 minute intervals for one week should be within the limit of ±10%, and 100% of the time it should be within +10% and -15%.

United Kingdom : The Electricity Safety, Quality and Continuity Regulations 2002 (ESQCR), is the main legal document and then there is a Distribution Code which refer several engineering recommendations specifying the limits of power quality. However, the engineering recommendations are not intended to replace or override requirements in BS EN 50160 for ensuring acceptable voltage quality. According to ESQCR the supply voltage variation in the case of a low voltage supply, should not exceeding 10 per cent above or 6 percent below the declared voltage at the declared frequency. See following graph for the for past, present and future expected voltage levels.



(Ref: Electricity Engineering Standards Review, Report prepared for BEIS, Final, December 2020, by Frazer-Nash Consultancy Ltd.)

Australia : As indicated in the National Electricity Rules, Version 166, as at 3 June 2021 (South Australia), Schedule 5.1a System standard, following limits on supply has been imposed : Except as a consequence of a contingency event, the voltage of supply at a connection point should not vary by more than 10 percent above or below its normal voltage, provided that the reactive power flow and the power factor at the connection point is within the corresponding limits set out in the connection agreement. According to the Australian Standard AS 61000.3.100, (Electromagnetic compatibility (EMC) - Part 3.100: Limits-Steady state voltage limits in public electricity systems) the LV steady state voltage limits should comply with the values as shown below table.

Steady State Voltage Measure (10 minute average r.m.s)	Phase-to-neutral voltage	Phase-to-phase	1 phase 3 wire centre neutral phase-to-phase voltage
$V_{1\%}$ Limit	216 V	376 V	432 V
$V_{99\%}$ Limit	253 V	440 V	506 V
$V_{50\%}$ Preferred (min)	225 V	392 V	451 V
$V_{50\%}$ Preferred (max)	244 V	424 V	488 V

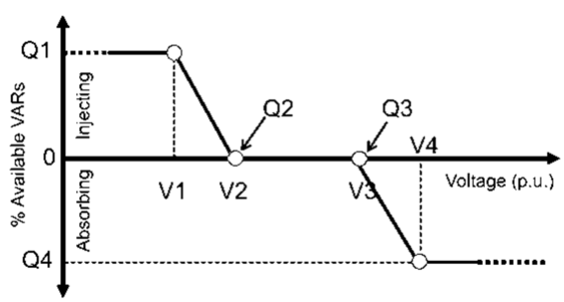
The above limits apply at the customer point of connection. The 1st, 50th and 99th percentile values are evaluated with at least one week's worth of continuous 10-minute average measurement data.

Norway : Regulations on delivery quality in the power system adopted by Norwegian Water Resources and Energy Directorate (NVE) has stated that the slow voltage variations should remain within a range of ± 10% of the nominal voltage, measured as an average over one minute, at the connection point in the low-voltage network.

6 Inverter Capabilities to Control Voltage

Modern inverters are able to control their terminal voltage by manipulating their output reactive power, and therefore can perform voltage regulation. Modern inverter the ability of configuring the volt-var capability curves, and therefore may manipulate its terminal voltage on a wide range of operational points by varying its reactive power independently from its active power production, all the way to the Volt-Var capability limits. However, note that the low reactance/resistance (X/R) ratio in LV networks forces voltage magnitudes to be more sensitive to the active power injection rather than to reactive power. This is the exact opposite of the high voltage (HV) grid situation, where the X/R ratio is high and the grid operator utilizes reactive power to regulate voltage magnitude.

The Volt-var control function, tries to maintain the voltage at the terminal of a PV system within statutory voltage limits. It allows each individual PV system to provide a unique var response.



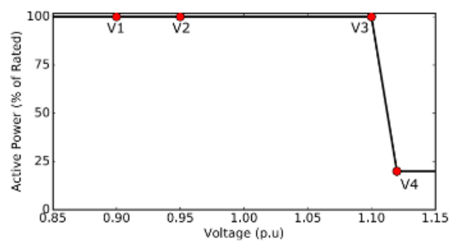
Some set points are given below as an example.

Reference	Voltage (V)	Var % Rated VA
V1	208 (0.90 p.u)	44% leading (exporting Vars)
V2	220 (0.95 p.u)	0%
V3	241 (1.04 p.u)	0%
V4	253 (1.10 p.u)	44% lagging (sinking Vars)

In contrast, Volt-Watt manages the active power output of the PV systems trying to maintain the voltage at the terminal of the PV system within statutory voltage limits.

Typical Settings – Curtailment triggered once the voltage reached 1.1p.u.

Reference	Voltage (V)	Power % Rated Power
V1	207 (0.90 p.u)	100%
V2	220 (0.95 p.u)	100%
V3	253 (1.10 p.u)	100%
V4	259 (1.12 p.u)	20%



The AS/ANS 4777.2:2020 standard suggests response commencement time of 1 second and completion time less than 10 seconds. As per the aforesaid standard the default set values for New Zealand and some areas of Australia are as follows. By reducing the output wattage up to 20% of the rated the voltage level is being kept within limits. Further the standard states that both the volt-watt and volt-var shall be enabled by default.

Volt-Watt Response

New Zealand		Some Australian Regions	
Voltage	Active Power Output (% of rated)	Voltage	Active Power Output (%)
242 V	100%	253 V	100%
250 V	20%	260 V	20%

Volt-Var Response

New Zealand		Some Australian Regions	
Voltage	Reactive Power Output (% of rated)	Voltage	Reactive Power Output (%)
207 V	60% supplying	207 V	44% supplying
220 V	0%	220 V	0%
235 V	0%	240 V	0%
244 V	60% absorbing	258 V	60% absorbing

The IEEE 1547-2018 standard also state that inverters should be capable of injecting or absorbing reactive power up to 44% of name plate apparent power (kVA) rating.

Discussions with leading companies engaged in inverter business in Sri Lanka, it was informed that all newly imported inverters are having the grid support functions such as volt-var and volt-watt controlling. Furthermore, a significant number of inverters with the aforementioned grid support functions have already been installed without activating these features.

Further, it is important to note that, establishing standardized defaults at the national level, which can be pre-programmed by inverter OEMs or conveniently chosen during commissioning, enhances overall compliance. Mandating complicated parameter sets to be configured by installers during commissioning poses a risk of non-compliance.

7 Critical Importance of Inverter Voltage Settings

7.1 Ensuring the integrity

Ensuring the integrity of the voltage settings within the inverter is of utmost importance in maintaining the safe operation of the electrical grid. During the commissioning phase of rooftop solar PV systems, the utility, often referred to as the Distribution Licensee, undertakes a critical verification process. This process involves validating the overvoltage settings of the inverter to ensure that it promptly disconnects from the grid whenever grid overvoltage limits are reached. Failure to correctly set these parameters can result in the inverter operating at elevated voltage levels, thereby exacerbating grid overvoltage issues.

In situations where multiple rooftop solar PV systems are interconnected to the same feeder, a misconfigured inverter can have cascading effects. These interconnected systems may also respond to the overvoltage condition by generating power at higher voltages than the grid, further contributing to the sustained overvoltage condition. Consequently, the integrity of the inverter's grid overvoltage setting assumes paramount significance. Properly configured settings serve to maintain grid voltage within statutory limits, safeguarding not only the appliances connected to the installation but also those within the vicinity of the same Low Voltage (LV) feeder.

Safeguarding the operational integrity of the inverter's overvoltage settings is thus pivotal in preventing damage to consumers' appliances and ensuring grid stability in compliance with regulatory standards.

7.2 Importance of Periodic Inspection

Implementing a periodic inspection scheme for rooftop solar inverters is of paramount importance to ensure the sustained efficiency and reliability of these systems. Regular inspections serve as a proactive measure to validate the correct configuration of vital settings, particularly those related to volt-var controls. By conducting routine checks, potential issues or deviations from prescribed settings can be promptly identified and rectified, preventing long-term disruptions and safeguarding the integrity of the electrical grid.

Australian Energy Market Operator (AEMO) have identified that as much as 40% of grid-connected inverters installed with rooftop solar PV systems since 2016 may not comply with some of the mandatory settings prescribed in AS/NZS 4777.2:2015 and the relevant Distribution Network Service Provider (DNSP) connection agreements. They have stated that this is causing issues for grid reliability and security that without rectification will limit consumers’ choice to invest in DER. To overcome the issues the Australian Government Clean Energy Regulator has implemented a Small-scale Renewable Energy Scheme inspections.

7.3 Solar PV System Installer Responsibilities

The responsibility for ensuring the correct configuration of inverter voltage settings lies primarily with the solar PV system installers. These professionals must adhere rigorously to established regulations and guidelines governing grid interconnections. It is imperative that they possess a comprehensive understanding of statutory voltage limits and the intricacies of inverter operation. The responsibility is on them to set and validate these parameters accurately during the commissioning phase to prevent grid overvoltage scenarios. Furthermore, ongoing monitoring and maintenance are essential to guarantee that the inverter's settings remain aligned with regulatory standards. By fulfilling these duties diligently, solar PV system installers contribute significantly to the reliability of the electrical grid and the safety of consumers' appliances.

The system designer should do the sizing of the AC cable connecting the inverter to the consumer unit to minimizing voltage drop. Ideally, the voltage drop should remain below 1%, ensuring efficient power transfer and preventing inverter nuisance tripping due to voltage excursions during peak output.

The SLS 1522:2016 standard specify the voltage drop between the inverter and point of connection of supply to be kept as small as possible (recommended <1%) to minimize voltage rise within installation.

The objective is to minimizing voltage drop to the greatest extent possible, while still adhering to a maximum acceptable threshold of 3%. When generating, the voltage at the inverter terminals is higher than the voltage at the supplier’s cut out, during periods of high-power output this voltage drop must be kept to a minimum in order to prevent the inverter nuisance tripping on overvoltage.

8 Other Benefits

Reduced Infrastructure Investment**:**

One of the primary benefits is the potential to reduce the need for extensive infrastructure upgrades or expansions. DLs might be able to avoid costly investments in substations, and distribution lines that otherwise may require for maintaining the stricter statutory voltage limits.

Energy and Demand reduction through conservative voltage reduction:

Increasing the allowance for steady state voltage variation, may help electricity distributor to use conservative voltage reduction technologies to reduce consumer demand by reducing the supply voltage level within statutory limits.

Electrical appliances are designed and tested for optimal efficiency at 230 volts. Because of this, higher supply voltages can result in higher energy consumption, which in turn increases energy bills and greenhouse gas emissions. However, the demand response of electrical appliance to voltage may differ according to the electrical characteristics of the appliance. Constant impedance loads will reduce the energy consumption in case of lower supply voltages. Consumption increase as supply voltage increases :

The energy consumption of single-phase motor appliances (fans and washing machines). Heating appliances (electric water heaters and kettles). Unlikely to increase the consumption as voltage increase : Electronics, such as computers (constant power devices).

9 Activities to be carried out by Distribution Licensees (CEB and LECO)

9.1 Analysis to identify LV feeders having issues of overvoltage

Distribution Licensees can identify the LV feeders that consistently have higher demand than local consumption throughout the year. The feeders having greatest risk in respect of overvoltage issue (and high PV curtailment) can be subjected for pilot projects that test the feasibility of expanding the voltage thresholds. For each solar PV installation, the utility issues a clearance prior to the installation of rooftop solar PV system. The clearance is based on the receiving LV terminal voltage of the Distribution transformer and will calculate the voltage impact due to the location, capacity, and connection arrangement. The information that already have in planning divisions of Distribution Licensees can be utilized on identifying LV feeders that have reached the grid overvoltage levels.

9.2 Phase balancing.

Low voltage (LV) phase load balancing is crucial for integrating additional rooftop solar without encountering grid overvoltage issues. This involves careful management of the distribution network to ensure that load and rooftop solar capacities are evenly distributed across all phases.

If higher capacity of rooftop solar is connected to a particular phase compared to other two phases, then there is a higher possibility to that particular phase may observe grid overvoltage when the solar energy production is high.

Distribution Licensees are required to periodically measure the load in LV phases and conduct Phase balancing of LV lines to avoid overloading of individual phases, resulting accommodation of more LV connected rooftop solar without violating the voltage criteria.

9.3 Cost/Benefit analysis Identify the potential cost savings:

The distribution Licensees are need to identify the potential cost savings (if any) from relaxing the voltage limits, such as reduced need for costly upgrades to the distribution network, lower energy losses, and demand reduction through voltage reduction (conservative voltage reduction)

9.4 Prescribe Voltage Quality Response Modes Settings on the Inverters

Licensees to study and propose volt-var and/or volt-watt settings that are suitable for the LV connected inverters (of roof top solar systems) to preserve the steady state voltage quality of LV distribution system. The licensee may obtain the guidance from the values stated in IEEE 1547 and AS/NZ 4777.2 standards. Then to introduce volt-var and volt-watt settings in the operational and technical codes and standards. (Ex: In Appendix 3 of Distribution Code : CEB guide for grid interconnection of embedded generators)

9.5 Pilot projects to identify the feasibility:

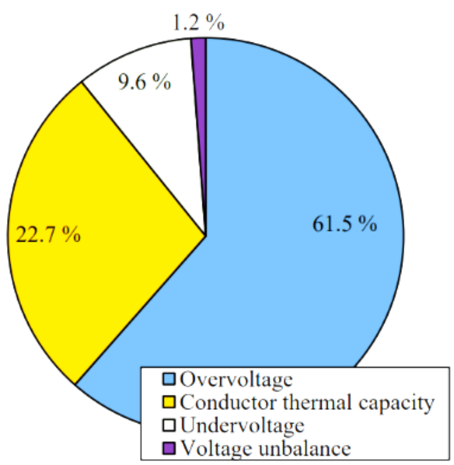
Before implementing the changes across the entire network, it is beneficial to conduct a pilot project in a limited area to assess the impact of the higher voltage limits. This will help identify any potential issues and allow for adjustments to be made before expanding the changes to the wider network.

Therefore, DLs are required to conduct pilot projects to identify the effects of relaxing the steady state voltage levels of the LV feeders with high solar PV penetration.

In a pilot project, DL may install monitors at selected LV distribution substations and feeders to collect data to:

- Find the actual demand and voltage headroom available in LV network
- Understand the distribution of LV network voltage during high solar exports (Daytime)
- Understand the Distribution of the LV network voltage during night peak (where no PV exports)
- Assess the loading of lines and transformers during hours of high rooftop Solar PV energy export.
- Assess the application of tap reductions in distribution transformers to manage the voltage where feasible.

A Study done in Brazil (for Example) : Here a comprehensive study has been carried out by analyzing 50,000 LV systems from a Brazilian distribution utility.



Incidence of the operational limit first violated by PV penetration in the 50,000 DNs

In this study, various operational indices were taken into account, encompassing concerns such as over/under voltage incidents, voltage unbalance, thermal capacity of conductors, and transformer overload. Similar to findings from comparable research, the primary factors leading to initial violations on the feeders were identified as overvoltage and conductor thermal capacity.

10 Identification of the Impact to LV connected electronic and electrical appliances

Exposing appliances to voltages above their labelled or nameplate (designed rating) rating may cause issues such as immediate failure or accelerated degradation. Sustained operation at voltages above 230 volts but still within the compliant range is expected to reduce the lifespan of appliances. However, it is worth to note that many appliances are likely to be replaced before their technical life is consumed.

On the other hand, undervoltage causes excessive current draw and associated heat increases of some appliances, there may also be a risk of appliance damage and reduced appliance life span. In undervoltage conditions the appliances may not work accordingly and the comfort of the consumers may negatively affect.

Consultation with manufactures and importers of LV electronic and electrical equipment/appliances need to be carried out to identify the immunity levels of such LV equipment when subjected to voltages of 230V±10%.

In addition, consultation with Sri Lanaka Standards Institution (SLSI) on immunity levels of LV connected appliances in the market is required.

11 Recommendations

In order to reduce the curtailment of rooftop solar PV energy, owing to the grid overvoltage, it is recommended following actions to be implemented.

I. To implement volta-var, volt-watt power quality response modes of existing inverters. A relevant directive needs to be given by Sustainable Energy Authority to rooftop solar PV system installers to implement volt-var and/or volt-watt response for voltage controlling in the inverters (if the facility available in the already installed inverters).

II. To specify the voltage controlling capability of inverters as a mandatory requirement when importing inverters to Sri Lanka. The directive is to be given by the Sri Lanka Sustainable Energy Authority (SLSEA) to the solar PV inverter industry.

III. To direct Licensees to study and propose volt-var and/or volt-watt settings that are suitable for the LV connected inverters (of roof top solar systems) to preserve the steady state voltage quality of LV distribution system. The licensee may obtain the guidance from the values stated in IEEE 1547 and AS/NZ 4777.2 standards. Then to introduce volt-var and volt-watt settings in the operational and technical codes and standards.

IV. Sri Lanka Standards Institution (SLSI) to update the relevant SL standards to incorporate the ability of the inverters to set volt-var and volt-watt power quality response modes.

V. Distribution Licensees and SLSEA to implement a mechanism such as a periodic inspection scheme to guarantee the volt-var, volt-watt configuration of inverters in alignment with prescribed settings.

VI. To change the statutory LV voltage limits beyond 230V ±6% up to 230V±10%. If the curtailment issue owing to grid overvoltage is persisting significantly even after the implementation of volt-var and volt-watt response modes of the inverters.

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