Mitigating Voltage Violations Caused by Rooftop Solar PV Systems in LV Distribution Networks: A Case Study

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Abstract

Distributed generation (DG) in power systems have become financially attractive. The number of grid-connected roof-top solar photovoltaic (PV) systems in Sri Lanka has exceeded 30,000 units by the end of 2021. Voltage violations attributed to PV systems have been reported in urban areas, requiring detailed analyses of impacts on the operation of these networks. This paper presents the case of a LV distribution network in Wennappuwa in north-western Sri Lanka. The study evaluates solutions to manage the voltage rise in the LV distribution network caused by roof-top solar PV systems under different scenarios.

Keywords

Solar PV system, voltage violation, hosting capacity, inverter power factor

Introduction

With subsidies and incentives provided by governments worldwide [1][2], installation of rooftop solar PV systems accelerated faster than any other renewable energy technology. Most countries allow the use of electricity generated and to export the excess to the national grid [1].

Distributed generation in low voltage (LV) distribution networks may lead to undesirable levels of reliability, power quality and stability issues [3]. Distribution networks have been traditionally designed assuming unidirectional power flow with no consideration of possible bi-directional power flow owing to renewable energy-based generation. Planning and operating guidelines of LV networks should be revised to match increasing penetration levels of grid-connected renewable energy sources such as wind and solar PV systems.

Power flow in a LV network occurs across a voltage gradient from the transformer secondary to load ends, in proportion to the ratio between resistance R and reactance X (ie R/X) in each network [4]. At higher levels of solar PV penetration, the voltage along a line would be different to its designed values when it is used for power delivery. When the generation from solar PV surpasses customer loads on a LV line, power flow occurs in the reverse direction. Variations in network voltage profile and the reverse power flows are the major power quality issues in integrating distributed generation into LV distribution networks.

Design and Modelling

The LV distribution network considered in this study is located in Wennappuwa, Sri Lanka and it is managed by Ceylon Electricity Board (CEB). The network consists of five main LV feeders served by an 11 kV/0.415 kV, 160 kVA 3-phase distribution transformer. The network serves 376 customers, of which 353 are single-phase customers and 23 are three-phase customers. Figure 1 shows the geographic layout of the LV distribution network. Customers served by each feeder is shown in Table 1.

Some three-phase customers have digital meters, and their load profiles were built-up using actual data obtained from their digital meters. Load profiles of customers who do not have digital metering facility were assigned load profiles [6] according to their tariff category and monthly electricity consumption. Similarly, single-phase customer profiles were developed. Figures 2 and 3 show these load profiles.

Figure 1: Geographic Layout of LV Network

Note: There are four active LV lines (feeders) in this network. Each LV feeder and its spur lines are shown in a different colour. Customer locations are indicated by a shaded square. Feeder 4 had no customers connected.

Table 1: Feeder Data Summary

	Feeder 01	Feeder 02	Feeder 03	Feeder 05
Total length (m)	1,640	1,869	2,580	264
Number of single-phase customers	104	144	98	7
Number of three-phase customers	4	4	15	0
Total number of customers	108	148	113	7
Line type	AAC & ABC	AAC	AAC & ABC	AAC

AAC: all aluminium conductor, ABC: aerial bundled conductor

Figure 2: Load Profiles of Three-phase Customers

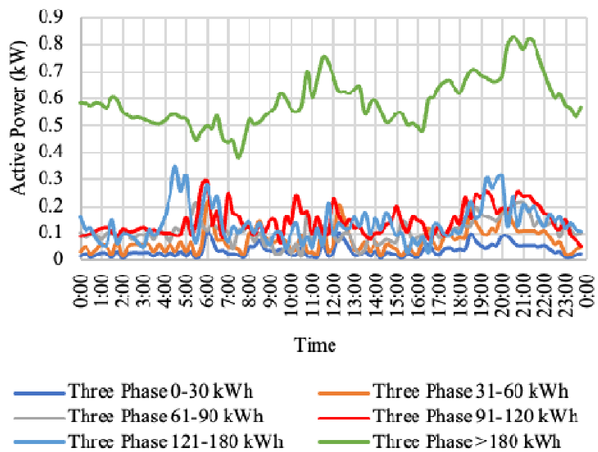


Figure 3: Load Profiles of Single-phase Customers

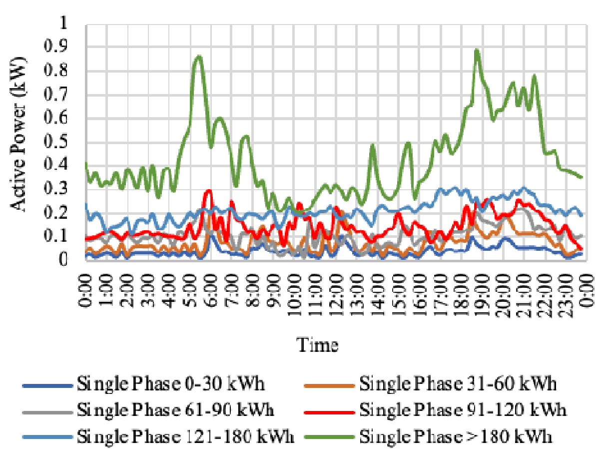


Table 2 shows the line technical information. To analyse the impacts of solar PV systems, each LV feeder was separately modelled to calculate the voltage profile under three test cases, and then results for all four feeders were combined to obtain the results for the network.

Table 2: Summary of Line Data

	Type	AC-Resistance (R) (20⁰C) (Ohm/km)	Reactance (X) (20⁰C) (mH/km)
All Aluminium Conductor (AAC)	Single-phase 60 mm^2 × 1 + 60 mm^2	0.433	0.082
	Three-phase 60 mm^2 × 3 + 60 mm^2		
Arial Bundle Conductor (ABC)	Single-phase 70 mm^2 × 1 +70 mm^2	0.460	0.333
	Three-phase 70 mm^2 × 3 +54 mm^2		
Service Conductor	Single-phase	1.766	1.665
	Three-phase		

Methodology

This study considered policies adopted by utilities in several countries to overcome the voltage rise caused by rooftop solar PV systems in LV distribution networks. It analysed the most effective policy for the Wennappuwa distribution network to overcome the voltage rise issue due to rooftop solar PV systems. The following test cases were analyzed.

Testing the difference in impacts of single-phase solar PV systems and three-phase solar PV systems on voltage rise in LV distribution networks

Customers in each feeder were arranged in descending order of their average monthly consumption. A solar PV system was introduced at each customer node in this order. Its capacity was assigned to be the average of the capacity required to generate their monthly consumption and the contract demand.

Maximum contract capacities for LV customers were the following- single-phase 30 A: 7 kW, three-phase 30 A: 21 kW.

Scenario 1

Solar PV systems were introduced according to the descending order of monthly consumption until at least one of the phases showed a voltage violation (>1.06 pu).

Scenario 2

All possible single-phase solar PV systems in scenario 2 were converted to three-phase systems

Scenario 3

Solar PV systems were introduced according to the descending order of the monthly consumption until all phases showed voltage violations (>1.06 p.u.)

Scenario 4

All possible single-phase solar PV systems in scenario 3 were converted to three-phase systems.

Testing the impact of inverter power factor on voltage rise in LV distribution networks

Generally, grid-tied solar PV inverters are set to deliver power at unity power factor. Power factor of the inverters can be changed within a certain range of values to absorb or inject reactive power, and this could provide voltage support to the distribution network [3]. In this analysis, the effects of inverter power factor setting on the distribution line voltages were studied. Simulations were carried out for 2 test scenarios where the power factor of the inverters were varied from 0.8 lagging to 0.8 leading in 0.1 increments.

Scenario 1 - All customer loads connected to the grid operate at unity power factor.

Scenario 2 - All customer loads connected to the grid operate at 0.8 lagging power factor.

Testing the impact on maximum solar PV hosting capacity of the LV distribution network under different regulartory limits on rooftop solar PV system capacities.

Scenario 1

Under this scenario, it was assumed that the maximum allowed capacity of the solar PV system is the capacity that is sufficient to generate the monthly consumption of the customer. Capacities were calculated considering the customers' average monthly consumption.

Scenario 2

Under this scenario, the maximum allowed capacity is the contract demand. It was assumed that a typical customer will choose a PV system whose capacity would be the average of the capacity required to generate the customer's monthly electricity consumption and the contract demand.

First, customers in each feeder were arranged in descending order of their average monthly consumption. Solar PV systems were connected starting from the customer with the highest average monthly consumption. Once a phase was about to show voltage violation, no further solar PV systems were added to that phase (including three-phase solar PV systems) but the procedure was continued for the rest of the phases until all the phases were about to show voltage violations (>1.06 p.u.). Hence the maximum solar PV hosting capacity of each feeder without voltage violation was obtained by adding the installed capacities of all solar PV systems in the feeder.

Results

A. *Testing the difference in impacts of single-phase solar PV systems and three-phase solar PV systems on voltage rise in LV distribution networks*

Under this test condition it was observed that, this could act as a solution only if one phase experiences a voltage violation and the other two phases are well below the voltage limit.

As seen in Figures 4 and 5, by using three-phase inverters instead of singe-phase inverters.voltage levels in the Y phase will reduce and balance out with the other two phases.

Figure 4: Voltage Variation at f3.1.22.5 Pole (Scenario 1)

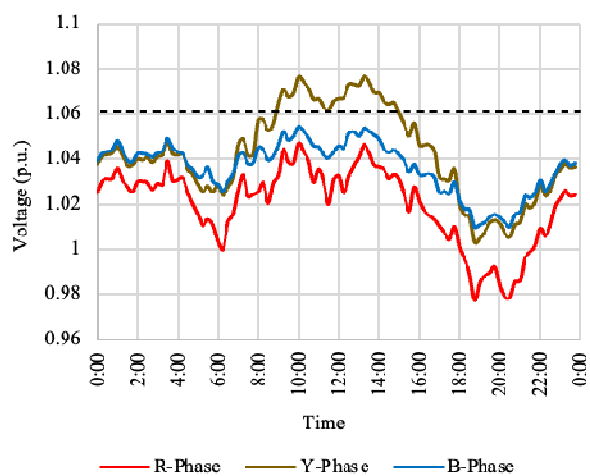


Figure 5: Voltage Variation at f3.1.22.5 Pole (Scenario 2)

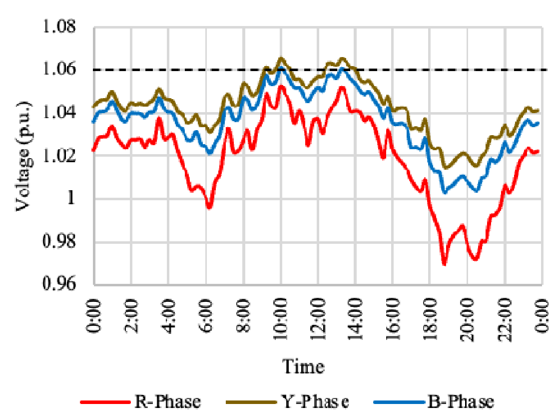


Figure 6: Voltage Variation at f3.1.22.5 Pole (Scenario 3)

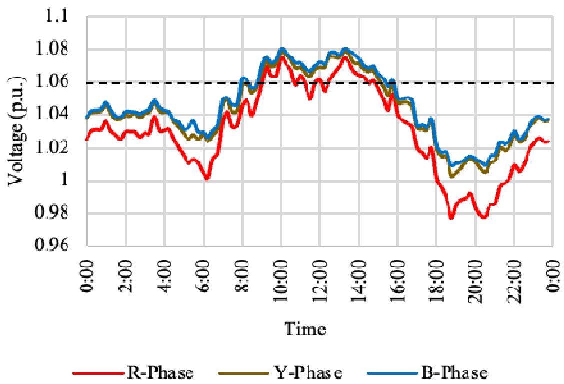
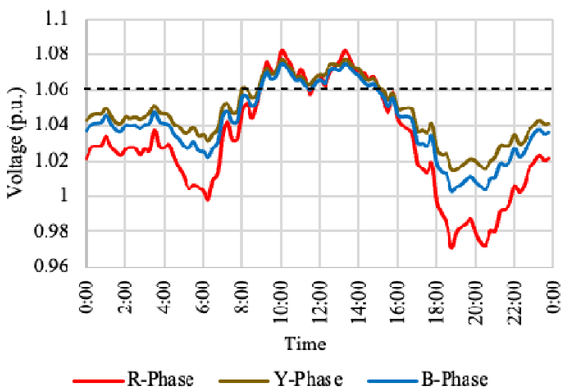


Figure 7: Voltage Variation at f3.1.22.5 Pole (Scenario 4)



As seen in Figures 6 and 7, when all phases show voltage violations, the conversion of single-phase inverters to three-phase inverters do not yield much benefit to reduce voltage levels.

This solution has many constraints. The distribution network layout itself hinders the conversion of single-phase inverters to three-phase, as most spur lines are single-phase.

Commercially available capacities of inverters also limit the number of customers that could convert their single-phase solar inverter to three-phase, without oversizing the inverter.

(Note – The dotted line in each figure shows the regulatory voltage limit)

Figure 8: Voltage Variation at Different Inverter PF (Scenario 1)

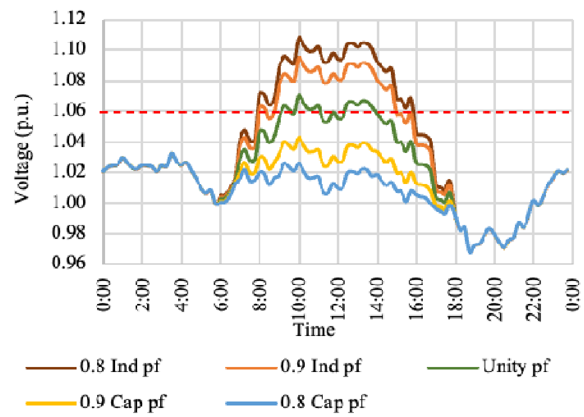
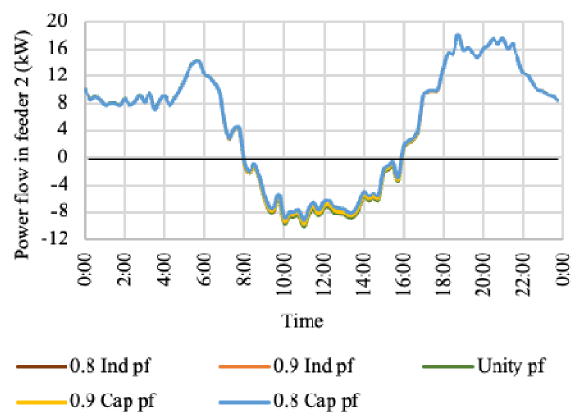


Figure 9: Active Power Flow with respect to Inverter PF (Scenario 1)



Under a capacitive power factor, generators absorb reactive power from the network, and under an inductive power factor reactive power is injected to the network. The results for scenario 1 are shown in Figures 8 and 9. When the inverter power factor was set to 0.8 or 0.9 capacitive, a significant change in the voltage levels during solar PV generation could be noticed. In Figure 9, the power flow in feeder 2 is shown at different levels of inverter power factor.

When the inverter operates at 0.8 or 0.9 capacitive power factor, the active power injected by the inverter is slightly reduced compared with operating at unity power factor. This may be one disadvantage of changing the inverter power factor from unity.

Results for scenario 2 are depicted in Figures 10 and 11. These results are similar to those of scenario 1.

(Note – red dotted line in figures shows the threshold voltage limits)

Figure 10: Variation of Voltage at different Inverter PF (Scenario 2)

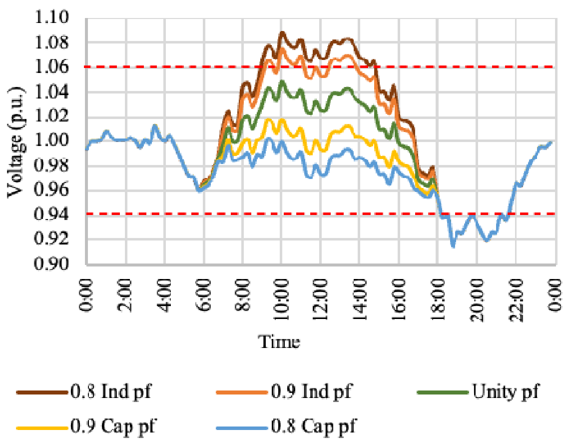
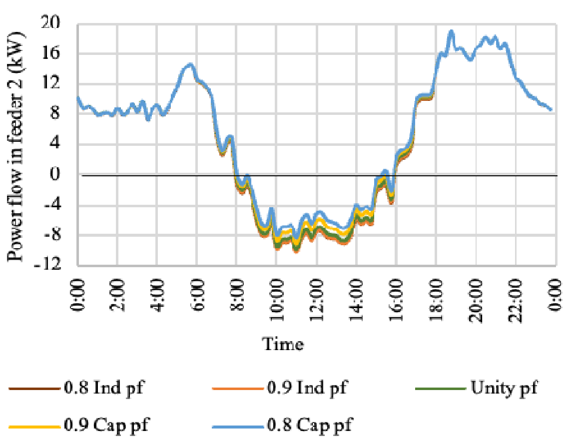


Figure 11: Active Power Flow with respect to Inverter PF (Scenario 2)



Testing the impact on maximum solar PV hosting capacity of the LV distribution network under different regulatory limits on rooftop solar PV system capacities.

Results obtained under this test condition are summarized in Table 3.

Table 3: Summary Results when Regulatory Limits are Imposed on PV Installed Capacity

Feeder	Total Installed Capacity (kW)	
	Scenario 1 *PV capacity adequate for customer's monthly consumption only*	***Scenario 2*** *PV capacity up to the customer's contract demand is allowed*
Feeder 1	68	73
Feeder 2	80	73
Feeder 3	30	27
Full Network	178	173

In scenario 1, total installed capacity of solar PV systems without voltage violations is comparatively higher than that in scenario 2. There is an increase of 5 kW (around 2.89%) of total installed solar PV capacity in scenario 1, compared with scenario 2.

Conclusions

In this study, a distribution network in Wennappuwa, in the north-western Sri Lanka was modelled to examine possible solutions for the voltage rise issues that may be caused by high levels of power injection from rooftop solar PV. The main objective of this study was to provide methods to mitigate the voltage rise issues when inverters are delivering power to the network, without modifying or introducing any sophisticated control mechanisms to the network. Several options were analysed through simulations. In one of the options, converting single-phase inverters into three-phase inverters provides a solution, when one phase shows voltage violations while the other two remain well within the voltage limits. In the case when all three phase voltages are violated, this option does not make a significant impact. Furthermore, there are some practical complications in implementing this option which was discussed briefly in the paper. Hence converting single-phase inverters to three-phase inverters is the least favourable option.

The next option of changing inverter operating power factor showed promising results. A significant level of voltage reduction was observed when the power factor of the inverter was changed from unity to 0.8 or 0.9 capacitive. However, it also resulted in reducing the active power. It showed that the voltage levels of the distribution network having rooftop solar PV systems could be maintained within the allowed limits by varying inverter operating power factor. Despite its limitations, varying the inverter operating power factor will be the feasible and economical option to mitigate the voltage rise issue.

From the analyses of the third option, it could be concluded that the solar PV hosting capacity of a distribution network could be increased by a small margin, if the installed solar PV capacity is distributed than being concentrated.

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References

[1] Cox, S., Walters, T., Esterly, S. and Booth, S., 2015. Solar Power. Policy Overview and Good Practices. Washington, D.C.: United States. Dept. of Energy.

[2] H. Fayaz, N. A. Rahim, R. Saidur, K. H. Solangi, H. Niaz, and M. S. Hossain, "Solar energy policy: Malaysia vs developed countries," in 2011 IEEE Conference on Clean Energy and Technology (CET), 2011.

[3] T. Alquthami, R. Sreerama Kumar, and A. A. Shaikh, "Mitigation of voltage rise due to high solar PV penetration in Saudi distribution network," Electr. eng. (Berl., Print), vol. 102, no. 2, pp. 881–890, 2020.

[4] S. F. Kagadi and P. M. Joshi, "Impacts of High rooftop PV Penetration in distribution network and its mitigation using DSTATCOM," in 2021 7th International Conference on Electrical Energy Systems (ICEES), 2021.

[5] Alam MJE, Muttaqi KM, Sutanto D. "A comprehensive assessment tool for solar PV impacts on low voltage three-phase distribution networks" In: Proceedings of the 2nd International Conference on the Developments in Renewable Energy Technology (ICDRET);2012.p.1-5.

[6] D. Chathurangi, U. Jayatunga, M. Rathnayake, A. Wickramasinghe, A. Agalgaonkar, and S. Perera, "Potential power quality impacts on LV distribution networks with high penetration levels of solar PV," in 2018 18th International Conference on Harmonics and Quality of Power (ICHQP), 2018.