Potential Power Quality Impacts on LV Distribution Networks With High Penetration Levels of Solar PV

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Abstract—**Recent government policy initiatives have significantly increased the number of grid connected solar PV systems in distribution networks. Thus, it is of vital importance to understand the technical impacts of high penetration levels of solar PV systems on the operating performance of these networks. This paper presents an analysis of power quality aspects of an urban low voltage (LV) distribution network with high solar PV penetration levels in Sri Lanka. The study includes three-phase load flow analysis carried out by modeling the selected network in DIgSILENT PowerFactory simulation platform using 15 - minute load data. Effects on net power flows and voltages of the LV network, which have been verified using field measurements, are discussed. Factors influencing the hosting capacity of solar PV are investigated by analysing technical impacts at varying solar PV penetration levels.**

Index Terms—**Solar PV systems, power quality, voltage rise, hosting capacity, reverse power flow**

I. INTRODUCTION

High penetration levels of grid connected renewable energy sources such as wind power and solar photovoltaic (PV) systems have created the necessity for active management of distribution systems, since the conventional networks have not been designed to accommodate distributed generation. Bi-directional power flows possible in distribution systems with local power generation can cause operating conflicts with protection schemes, while the intermittent nature of power generation can degrade the performance of the distribution network resulting in a number of power quality related issues [1].

Solar photovoltaic systems have become the most promising renewable energy source with abundance and can be integrated in different scales [2]. However, challenges exist with their intermittency and randomness, rendering it hard to match supply and demand which itself is varying. The fluctuation of generated solar PV power output due to the variation in solar irradiance caused by the movement of clouds that could continue for minutes or hours [3] can degrade the performance of the distribution network causing power swings in lines.

Solar integration and associated operational implications have become a vital research topic during the last few years. Several studies [4] - [8] have presented active power curtailment algorithms and reactive power support methods to address the voltage and active power control issues in solar PV installations. However, as per IEEE 1547-2003 series [9], solar PV inverters are recommended to operate at unity power factor. Thus, the majority of solar PV systems cannot be upgraded to obtain reactive power support or active power control to accommodate voltage variations as well as power variations. One of the other prominent issues is the local voltage rise which is evident when solar inverters are connected to lightly loaded feeders, that could eventually lead to a violation of voltage limits. In addition, these undesirable voltage levels could far exceed the voltage limits at the inverter-grid interconnection points, often giving rise to disconnection of inverters [2], reducing total solar generation and hindering the reliability of the supply. Further, whilst single phase solar inverters are considered as a significant contributor of voltage unbalance, both single phase and three phase inverters are heavily criticised for their high harmonic injection levels. Even modern inverters, producing almost sinusoidal outputs, are also found to inject higher order harmonics (supraharmonics) into the grid, as a result of their high switching frequencies [1].

Severity of above impacts vary with the degree of penetration, location and scale and topology of the solar PV inverter systems [10]. Further, recent changes in the power grid (micro-grids/smart-grids) as well as changes in the electricity consumption with unusual types of loads (electric vehicles, LED lighting and heat pumps) have evolved, aggravating the power quality issues in distribution networks [11].

Rooftop solar PV installations have been a recent trend, addressing more of political and social aspirations than technical. Maintaining acceptable levels of power quality is likely to be a significant issue in distribution networks in the near future. Thus, it is important to decide on the maximum level of solar PV penetration level of networks without violating system stipulated limits.

This paper presents potential power quality impacts on LV distribution networks with high penetration levels of solar PV systems based on the analysis of an existing urban LV network. Further, it elaborates the necessity of hosting capacity approach for distribution system planning. The paper is organised as follows; Hosting capacity approach to connect safer levels of solar PV without violating power quality limits is discussed in Section II. Section III describes the LV network modelling in detail, while potential power quality impacts on LV networks are discussed in section IV together with field measurements for model verification. Conclusions drawn from this study are presented in Section V.

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II. HOSTING CAPACITY APPROACH FOR SOLAR INTEGRATION

Overcoming local power quality issues in distribution networks with high penetration levels of solar PV may be a challenge, unless appropriate planning strategies are applied. Solar PV systems should be integrated in such a way that the resilience of the network against local power quality disturbances is not violated [12] - [14]. Recent recommendations presented by the CIGRE working group C4/C6.29 on power quality aspects of solar power [15] elaborate a number of power quality phenomena including harmonics, supraharmonics, fast/slow voltage variations and voltage unbalance. A hosting capacity based approach was proposed and forwarded in this report as an important tool for quantifying the impact of solar PV power on the power network. Moreover, as the key finding in [15], the report highlights unresolved issues that need to be addressed with further analysis of actual solar systems.

Hosting Capacity is defined as the maximum capacity of solar PV that can be connected to a certain network/feeder without resulting in unacceptable quality and energy security [15]- [17]. This limit can help significantly in maintaining a healthy and secured electricity grid and help avoid any damages caused by violation of thermal and/or voltage limits set by standards, during times of the high PV power generation. Hosting capacity has been developed as a transparent approach (a well-defined performance index which is compared with a well-defined limit) and in essence, it does not have a unique value [17]. A single performance index cannot be used to determine the hosting capacity and the influence of different disturbances has to be investigated. Thus, evaluation of hosting capacity for solar integration will require all power quality phenomenon to be analysed in detail [15]. However, very rudimentary knowledge exists at present in assessing hosting capacity of solar integration to address all the power quality phenomena.

Accurate evaluation of solar integration based hosting capacity requires detailed network models, network measurements and stochastic assessment methodologies to address system uncertainties. However, a generalised approach for hosting capacity cannot be developed in order to address different network requirements, since a single value does not fit all networks.

III. STUDY NETWORK MODELLING

The LV distribution network under study represents an urban LV network in Sri Lanka located in Kotte area which has more than 40% of solar PV capacity (as a ratio of the distribution transformer capacity). Table I and II provide the details of the selected distribution scheme, and the reproduced single line diagram showing only PV connections is shown in Fig. 1 (The real LV system was simulated although the spur lines and individual pole locations are not shown in the single line diagram in Fig.1). The secondary per phase voltage of the distribution substation is set at 240 V (1.04pu) to ensure the voltage is within the stipulated limits under maximum demand conditions. The distribution scheme consists of three 400 V feeders and supplies a total 336 customers including 253 single phase customers and 83 three phase customers. More than 90% of the load is shared by 315 residential customers and remaining comes under commercial tariff category. This network has been reported to have some natural unbalance where measured maximum voltage unbalance factor around is 1%. Details of particular LV distribution scheme and related field measurements for this study were provided by the Lanka Electricity Company, the distribution licensee of the selected LV distribution scheme.

At present, it is reported that, the maximum rooftop solar penetration associated with a single distribution transformer in Sri Lanka is at the LV distribution scheme selected for this study. Being a tropical country where high solar radiation $(5.5 \quad to \quad 6 \quad kWh/m^2)$ is available through out the year [18], the selected distribution transformer has recorded a reverse power flow for a short period of time on certain days when the solar generation is maximum. Fig. 2 shows the reverse power flow incident recorded on a day in July 2017. Measured import and export energy (kWh) values are shown in 15 minutes time intervals.

There is a higher potential for increase in the solar penetration levels across the network, following the recent government initiatives on net metering options. Net-metered solar PV customers generally size their rooftop solar PV capacity in such a way that the electricity generation matches their monthly electricity consumption. With two newly introduced schemes, namely Net-Accounting[1] and Net Plus[2] [19], customers have the freedom to over-size their rooftop solar PV capacity up to their contract demand to generate more electricity than what they consume, if they have sufficient roof area. Thus, the study presented in the paper has focused on five scenarios of different solar PV penetration levels in order to investigate power quality aspects of solar integration. The detailed LV network was modelled in DIgSILENT PowerFactory simulation platform.

In scenario 1, the network was simulated without solar installations (0% penetration). The present network was simulated in scenario 2 (40% penetration) with existing 24 solar PV customers of cumulative solar PV capacity of 102 kWp. In scenario 3, 4 and 5, the network was simulated with increasing penetration levels of 50%, 60% and 75% of the transformer rating respectively. At increasing solar penetration levels, individual PV capacities were assumed to be connected as net metered connections. Further, customers with higher monthly energy consumption levels were assumed to install solar PVs early in the capacity built-up. Cumulative solar PV capacity for different penetration levels used for simulations are shown in Table III.

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[1] This allows customers to be paid in cash for any surplus power they generate from the solar PV system at the end of their monthly billing cycles.

[2] This allows customers to sell total electricity generated from the solar PV system to the utility while the customers pay for the electricity they consume based on the existing tariff structure.

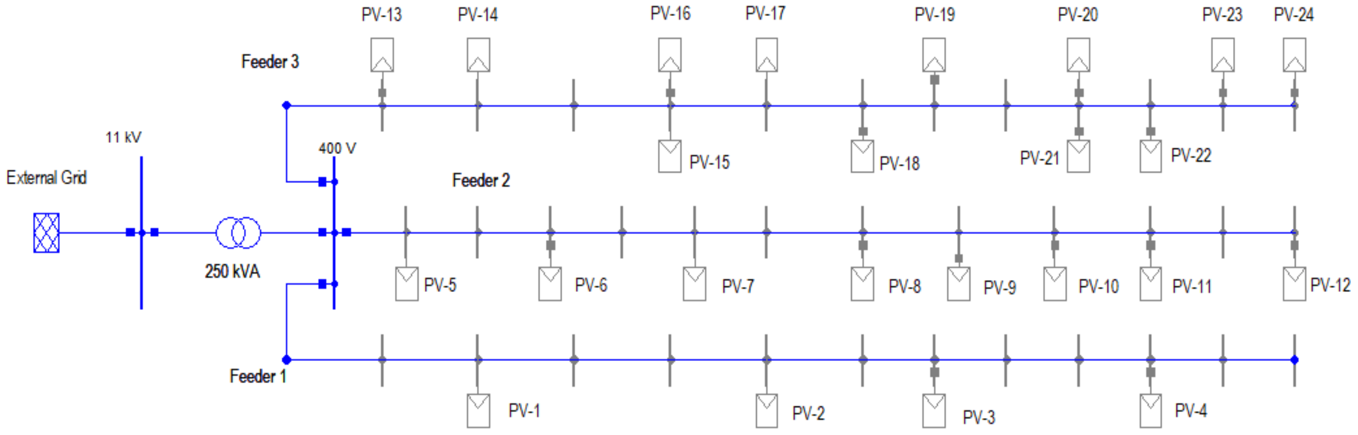


Fig. 1. Single Line Diagram of Selected LV Distribution Network.

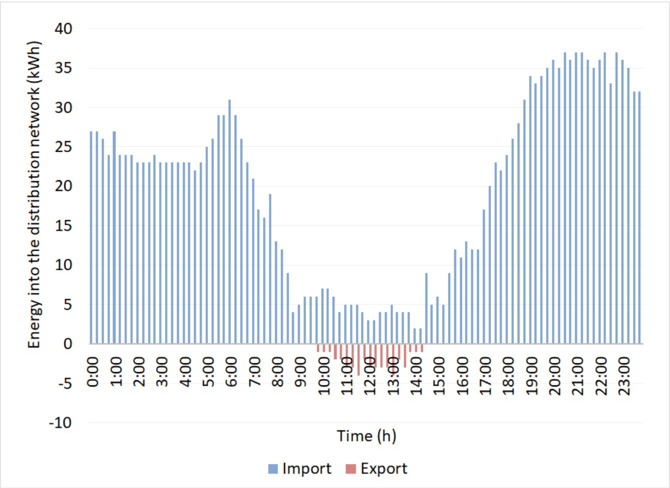


Fig. 2. Measured Import and Export Energy at the Distribution Transformer Secondary.

TABLE I
DETAILS OF THE CASE STUDY

Transformer rating	250 kVA/11kV/400V
Present maximum demand (*)	154 kW
Present maximum demand as a % of transformer capacity	77%
Number of customers served	336
Number of customers with rooftop solar PV generators (Solar capacities vary in the range from 1kWp to 15kWp eg : 1, 1.75, 3, 4, 6, 7.25, 15)	24
Number of outgoing LV feeders from the transformer)	3

* Recorded Data for July 2017.

A. Load Modelling

The selected LV network with three feeders provides electricity to a total of 336 customers. Load profiles of more than 30% of customers were derived based on the actual energy data recorded in 15 minute time intervals, obtained from the remote metering facility. The remaining load profiles were obtained by deriving an average load profile (using measured load profiles) for each tariff block in a given tariff category.

Average load profiles derived for each tariff block are given in Fig. 3. These average load profiles were used to generate load profiles of the remaining customers (those who did not have remote metering to provide actual load profiles) based on the monthly energy consumption data taken from individual customer accounts. Further, constant power factor of 0.8 lagging was assumed for all customers.

The total customer demand was assumed to be constant for different solar PV penetration levels. It is a justifiable argument to use a constant demand for all simulated scenarios since the solar penetration level was reported to reach 40% in a very short time period [20].

TABLE II
FEEDER VISE CUSTOMER DETAILS

	Feeder 1	*Feeder 2*	*Feeder 3*
Length of main feeder	510 m	400 m	610 m
No. of single phase customers	134	51	68
No. of three phase customers	20	26	37
Total no. of customers	**154**	**77**	**105**
Conductor type	3 Phase Aerial Bundle Cable (ABC) Type : 3x70mm$^2 + 54mm^2$ R = 0.443 ohm/km , X = 0.26 mH/km		

TABLE III
SOLAR INSTALLED CAPACITY UNDER VARIOUS SCENARIOS

Scenario	***Penetration***	**No. of Solar Customers**	**Cumulative Capacity (kWp)**
1	0%	0	0
2	40%	24	102
3	50%	28	127
4	60%	34	150
5	75%	45	187

B. Solar PV Modelling

All installed solar PV units are assumed to provide active power at unity power factor which is compliant with IEEE 1547-2003 [9]. Solar irradiance profiles were developed using the System Advisor Model (SAM) software considering the irradiance data applicable to Sri Lanka. In practice, solar PV

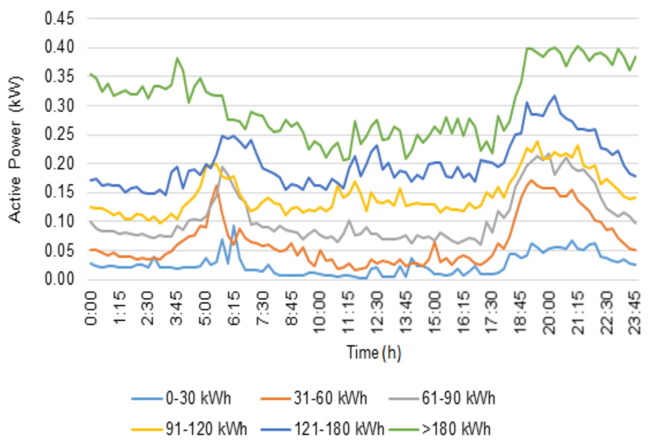


Fig. 3. Averaged Load Profiles for Customers in Different Tariff Blocks.

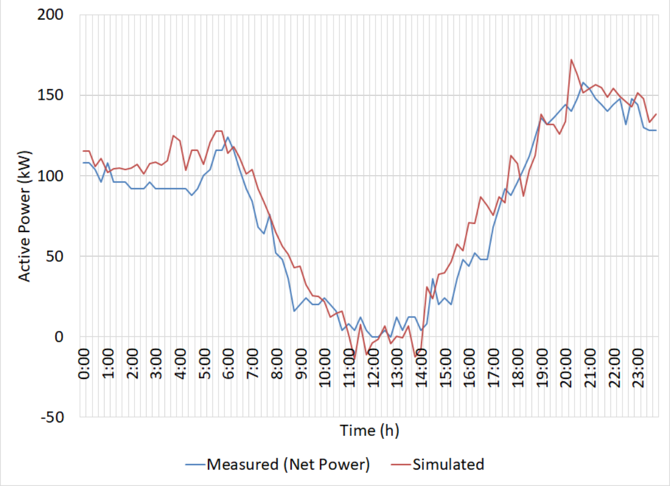


Fig. 4. Measured and Simulated Net Power Flow at the Distribution Transformer for the Present Scenario.

system's direct current (dc) power capacity does not reach its rated value even when the solar irradiance is maximum. This mismatch is typically avoided by increasing dc capacity of the system to be higher than the alternating current (ac) capacity of the inverter by introducing a dc to ac design ratio of 1.2 [21]. However, considering the local solar PV practice, dc to ac ratio of 1 was used in modelling solar PV systems.

IV. ANALYSIS ON POTENTIAL POWER QUALITY IMPACTS

The LV distribution network as discussed in Section III was modelled in DIgSILENT PowerFactory simulation platform to analyse the technical impact of different solar PV penetration levels on the distribution system performance. Following subsections discuss the simulation outcomes in terms of voltage profiles including voltage unbalance, net power flow, power factor at the secondary of the distribution transformer and network power losses for different solar penetration levels. Accuracy of network modeling can be verified by comparing the net active power flow, assessed based on the import and export energy measurements at the transformer secondary and the simulated net power flow variation as shown in Fig.4.

A. Active Power Flow

Fig. 5(a) shows the net value of active power (kW) flow at the transformer secondary side for different solar PV penetration levels. Already reported reverse power flow in the present network (40% of solar penetration) when the solar power generation is maximum during 11:00 AM to 1:00 PM can also be seen verified by the simulation outcomes. Increasing levels of PV penetration from the present network causes higher reverse power to flow towards the transformer thus affecting the 11 kV network. A reverse power flow of around 80kW which is almost equal to day time average demand load can be seen at 75% of the solar PV penetration level. In the present network, the transformer loading level has only been reduced to 22% (54kVA) as shown in Fig. 5(b) as the total reactive power is still supplied by the grid.

B. Feeder Voltage Rise

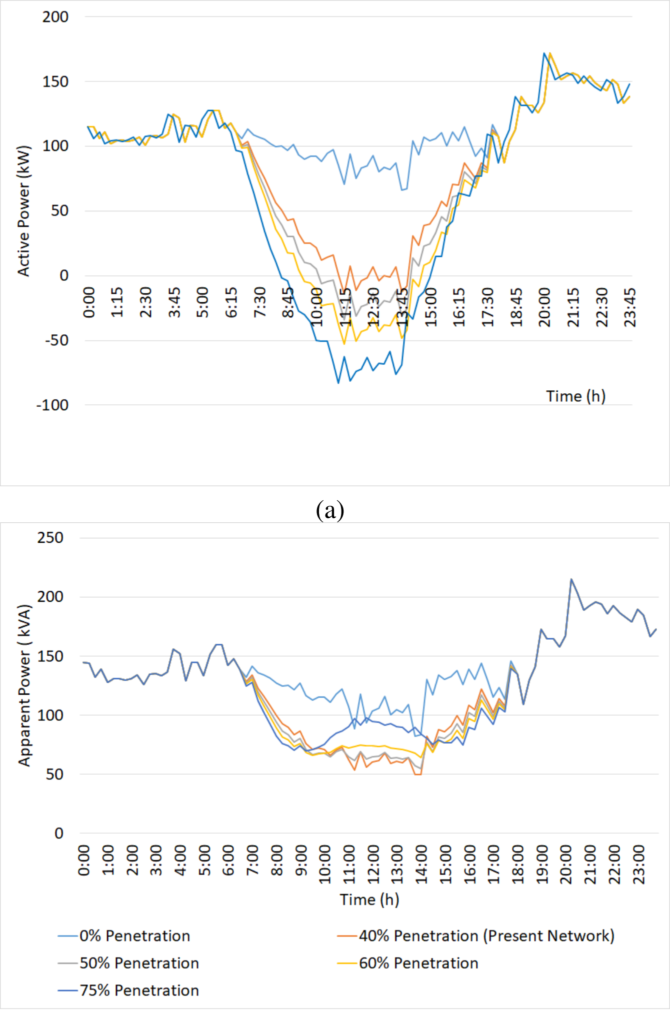
Maximum feeder voltages were observed at a time when the solar power generation is maximum and customer demand minimum. Accordingly, Fig. 6 shows the variation of phase voltages along the three feeders (the maximum voltage levels were observed in phase “c” of all three feeders). Voltages of feeder 1 and feeder 2 do not violate any stipulated limits under any solar penetration level considered. However, the longest feeder, feeder 3 (610m) has shown an over voltage situation (upper voltage limit - 1.06 pu) towards the end of the feeder at solar PV penetration level of 50%. In scenario 5, where the solar PV penetration level is 75%, 70% of the feeder-3 is in the over voltage situation. Detailed simulation studies have shown that the location of the solar PV inverter connections is influencing in the feeder voltage rise.

C. Power Factor at the Transformer Secondary

Referring Fig. 5(a) and 5(b) (reactive power and apparent power flow), net active power demand at the transformer secondary has significantly reduced during the day time where solar PV generation maximum. Since the inverter is mandated to operate at unity power factor and the total reactive power demand is being supplied by the transformer, a poor power factor is maintained at the supply side. At the present solar PV penetration level, power factor varies from 0.0 to 0.4 lagging during the time period when solar PV generation is at its maximum, whereas at the maximum solar PV penetration level (75%), leading power factor in the range of 0.6 to 0.8 can be observed.

D. Voltage Unbalance

The LV distribution system under study has been modelled in such a way that loads were unequally distributed among three phases to account for a natural unbalance (a relatively smaller voltage unbalance factor between 0.2 and 0.5). During the night peak, the same system is reported to have more than



(a)

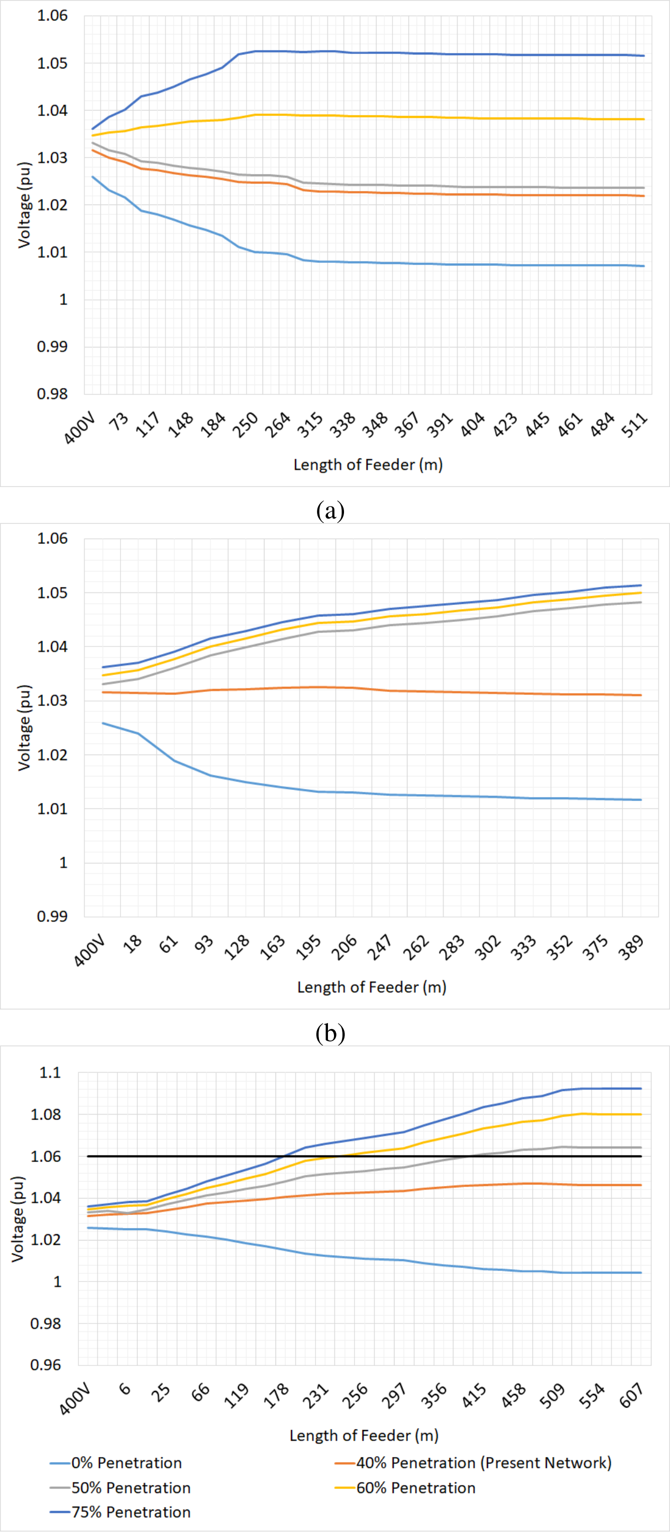
(b)

Fig. 5. Power Flow at the Distribution Transformer for Different Penetration Levels. (a) Active Power, (b) Apparent Power

1% voltage unbalance[3] based on available field measurements. The simulated model also confirms the same night peak voltage unbalance conditions. Table IV gives maximum voltage unbalance factor calculated based on the simulated voltages with resultant neutral voltages for the five different scenarios considered. At higher solar penetration levels, a tendency exists for higher voltage unbalance levels, mainly because of higher number of single phase solar PV inverter connections. Location of connections and size of the inverters can be seen to influence the resultant feeder voltage unbalance level.

E. Total Network Power Loss

Fig. 7 shows the total network power loss associated with the LV system including transformer loss for different solar PV penetration levels. Network power loss is seen to reduce with the integration of solar PV up to 50% penetration level. However, further increase in solar PV to 75% has resulted in



(a)

(b)

(c)

Fig. 6. Voltage Profiles at Different Penetration Levels.
(a) Feeder 1 - Phase c, (b) Feeder 2 - Phase c, (c) Feeder 3 - Phase c

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[3] Quantified in terms of negative sequence voltage unbalance factor

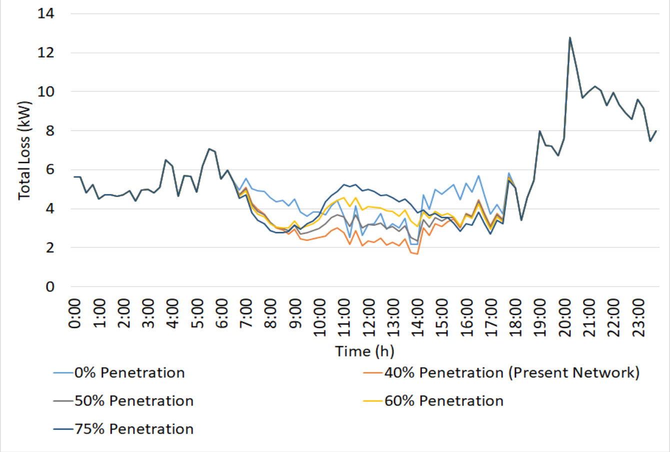

Fig. 7. Network Power Losses.

TABLE IV
VOLTAGE UNBALANCE AND NEUTRAL VOLTAGE

	Feeder 1		Feeder 2		Feeder 3	
	V2/V1 (%)	*Vn (V)*	*V2/V1 (%)*	*Vn (V)*	*V2/V1 (%)*	*Vn (V)*
Scenario 1	0.5	4.3	0.2	1.3	0.3	2.2
Scenario 2	0.7	6.2	0.1	1.7	0.6	4.2
Scenario 3	0.8	7.2	0.5	4.3	1.1	9.5
Scenario 4	1.3	9.1	0.5	2.3	1.5	13.5
Scenario 5	1.6	14.3	0.4	2.1	1.6	16.3

a higher power loss compared with scenario 1. Considering all scenarios under study, the present solar penetration level (40%) is the cause of minimum power loss during day time. Thus, 40% solar PV penetration level can be considered as an optimum level in terms of lower loss.

V. CONCLUSION

This paper has presented the technical impacts caused by higher penetration levels of roof top solar PVs on the operating performance of the LV distribution networks. The study results were based on a case study of an urban LV distribution network in Sri Lanka which has 40% solar penetration level (based on transformer capacity) at present. Effects of increasing solar connections which is realistic in near future have been analysed by modelling the detailed network in DIgSILENT PowerFactory simulation platform. Simulation results at present scenario were validated with available field measurements and voltage levels at the feeder ends were found to be marginal. Further connections of solar will cause violation of acceptable voltage limits and increase network losses due to the reverse power flow. Thus, hosting capacity of solar PVs to this network is primarily limited by the unacceptable voltage rise mainly resulting towards feeder ends.

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