Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Voltage Unbalance Assessment of Solar PV Integrated Low Voltage Distribution System in Sri Lanka Using Monte Carlo Simulation

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Received: 03-11-2022
Accepted: 22-01-2023

Abstract

Rooftop solar PV integration into the distribution systems brings benefits to both consumers and utility organizations. These ever-increasing, unplanned generating points in the form of rooftop solar PVs can have undesirable effects on the performance of the system. From the technical point of view, maximum rooftop solar PV hosting capacity mainly depends on whether the parameters such as power loss, overvoltage, and voltage unbalance are kept within the permissible level while increasing the rooftop solar PVs' capacities. Rooftop solar PVs are owned by individual households and their locations in the distribution system are unpredictable. The locations and capacities of rooftop solar PVs are the two parameters that influence the above parameters. This paper proposes a stochastic approach to allocate rooftop solar PVs in a distribution system using the Monte Carlo method. An algorithm is developed to allocate rooftop solar PVs in a distribution system and assess the overvoltage and voltage unbalance of the distribution system. Practical data of possible rooftop solar PV capacities are used for the determination of probabilities of occurrence of rooftop solar PV with the given rating. The proposed method is tested using a Low Voltage distribution system in a sub-urban area. The results show that the voltage unbalance and overvoltage at feeder endpoints are mostly affected due to the increase in solar PV integration. The results also show an increase in the solar PV penetration level by more than 40%.

Keywords: Rooftop solar PV, Voltage unbalance, LV distribution system

DOI: 10.22059/jser.2023.350730.1262 DOR: 20.1001.1.25883097.2023.8.2.1.9

1. Introduction

Over the last few years, the use of rooftop solar photovoltaics (solar PV) by domestic consumers has been rapidly increasing. This trend becomes more significant with the present shortage of grid electricity and the unprecedented increase of electric tariffs for domestic consumers. From the system point of view, the integration of solar PV reduces the deficit of power and increases the share of energy generation from renewables [1]. Traditionally, LV distribution systems are radial systems and sometimes voltage towards the end of the feeders drops below the permissible level. Generally, voltage unbalance between the phases is frequently observed in low voltage distribution systems. But, in many cases, these phase unbalances are not severe and do not have a significant impact on the normal operation of the LV distribution systems [2]. However, this condition has been significantly changing with the integration of solar PVs into the LV distribution networks. Daytime injection of active power to the distribution network by the solar PVs from various

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load points improves the voltage along the distribution feeder.

In the meantime, solar PV integration can bring undesirable effects to LV distribution systems. These include overvoltage, voltage unbalance, voltage flickers, etc.[3]. Maximum solar PV generation during an off-peak time and haphazard allocations of solar PVs with different capacities are the two main reasons for such undesirable effects. Uniform distribution of solar PV with the same capacity in all three phases across the network is not achievable. This is because solar PV installation on the rooftop is decided by the individual consumers depending on the consumer's energy requirement, financial viability, wealth, and desire. Therefore, utilities are compelled to limit the solar PV capacity in LV distribution systems to ensure the network parameters are kept at the permissible ranges. Since the locations of solar PVs in each network are unique and unpredictable, the maximum permissible solar PV capacity in each network is different. Several studies have been carried out to investigate the effects of solar PV integration on voltage unbalance and overvoltages[4], [5], [6]. Some of these works were focused on the overall assessment of the impact of solar PV, while others focused on the impact of single-phase solar PV on a particular capacity. But real low voltage (LV) distribution systems consist of both single-phase and three-phase solar PVs with various ratings. This paper presented the impact of rooftop solar PVs on voltage unbalance and over voltage issues giving due consideration to the actual ratings of single-phase and three-phase rooftop solar PVs and the number of such solar PVs in the system.

Busra Uzum et al.[7] discussed various impacts of rooftop solar PV penetration on the distribution network. The authors showed that uncertain current and impedance caused by the net generation and demand, irregular placement of rooftop solar PV, and current imbalance due to single-phase solar PVs at the consumer side are the main reasons for the growing voltage unbalance in distribution networks.

Charoenwattana et al.[8] analyzed the impact of solar PV on both voltage unbalance and energy loss in distribution systems by simulating single-phase and three-phase rooftop solar PVs and installing them in phases with different load densities. The paper analyzed voltage unbalance due to the installation of rooftop solar PV at the end, middle, and closer to the distribution transformer of a higher load density feeder. The analysis is limited to a particular scenario and all the possible combinations of rooftop solar PV installations and their impacts have not been discussed.

Kamel L Albow et al. [9] also discussed the problems caused by solar PV penetration into the distribution systems. The paper has shown that node voltage is one of the affected parameters due to solar PV penetration. The nodes experience over voltage and voltage unbalance issues. The authors pointed out that inbuilt solar PV inverters can be used to mitigate some of these issues caused by higher solar PV penetration.

JR Jintaka et al. [10] analyzed the impact of solar PV on the distribution system using four models. These models differ from each other based on the number of phases in which the solar PVs are concentrated. The research was carried out for a practical distribution system and the solar penetration level has varied from 60% to 200%. The results showed that when a higher number of solar PVs are distributed among the three phases the impact is low. However, when the solar PVs are installed in a single phase, keeping the voltage unbalance within the allowable limits is a difficult task. This research is also limited to a practical distribution system and all the possible scenarios of solar PV integration have not been considered.

Tomislav Antic et al. [11] also analyzed the impact of solar PV on voltage unbalance in the network considering a large set of possible scenarios of solar PV integration into the distribution network. Further, the paper suggested the use of battery energy storage devices to mitigate voltage unbalance. The research was carried out for both single-phase and three-phase rooftop solar PV connections to the distribution system. In the case of single-phase solar PV connections, the random allocation was considered in one of the phases out of three. However, the research has not considered the randomization of both single-phase and three-phase solar PV connections for various solar PV penetration levels. It was shown that out of all the scenarios, the worst-case scenario is when rooftop solar PVs have connected to all single-phase consumers.

Mohamad et al. [12] have proposed to minimize the voltage unbalance due to the high penetration of rooftop solar PV in residential distribution systems using the time series Power Flow optimizing method. The paper analyzed a real LV distribution system with high penetration of solar PV by representing the domestic loads as a time series voltage-dependent model. The paper did not analyze all possible scenarios of the distribution of rooftop solar PV in the LV distribution system and the possibilities of mitigating voltage unbalance in all the scenarios with the help of the proposed method.

Alexander Lucas [13]carried out a real-time simulation of an urban reference network to investigate single-phase solar PV power injection limits due to a voltage unbalanced problem. A real-time digital simulator has been used to analyze the impact of different levels of solar PV injection on the voltage unbalanced of the LV distribution network. The maximum solar PV hosting capacity without violating the voltage unbalance limit for both balanced and unbalanced distribution of solar PVs has been presented. However, this analysis has been limited to the network of the urban area where groups of consumers have been connected to a single bus. Unlike in urban areas, in rural areas, individual houses are distributed in LV networks, and not all houses are equipped with solar PVs.

Yuju Ma and et al.[14] have published a paper on the study of the impact of the Photovoltaic – Battery system on the LV distribution system using a probabilistic approach. In this study, the Monte Carlo method has been used to create different scenarios of the combination of loads and photovoltaic-battery systems. The research was carried out for the LV distribution system loads having smart energy meters and incorporated the home energy management system. Voltage issues, phase unbalance, and transformer loading due to different solar PV – battery penetration levels have been presented. However, in many developing countries integration of batteries into solar PVs is not popular due to high capital investment by the consumers. Instead, the excess solar energy is fed to the distribution network and the consumers are rewarded under different schemes: net metering, net accounting, and Net Plus. Therefore the outcome of this research does not exactly reflect the conditions of the LV distribution network where solar PV without energy storage devices are in operation. On the other hand, energy consumption patterns in developing countries have a large diversity depending on the income level of the households.

Yushan Hou et al. [15]proposed a method to increase the solar PV hosting capacity of LV distribution systems using a phase switch device to mitigate voltage unbalance due to the high penetration of single-phase solar PVs. The Monte Carlo method was applied to investigate the different combinations of single-phase solar PV allocated to the buses of the network. The research is focused only on the voltage unbalance issues due to the allocation of single-phase consumers and the over-voltage issue due to three-phase solar PV has not been taken into the consideration. The research was carried out with the assumption that only two capacities of solar PVs are distributed in the LV system. However, in real distribution systems, the capacity of solar PVs is based on the consumer's need and wealth, and therefore, the real distribution systems consist of solar PVs of various capacities.

Nur Zolkifiri etc el. [16] have analyzed the effect of distributed solar PV on voltage unbalance and network losses under various solar variability days. Five different solar variability scenarios and their impact on the voltage unbalanced and the power and energy losses have been presented. The effect of these solar variability days has been analyzed for random allocations of solar PV in distribution feeders. Random allocations of solar PV of different capacities were carried out using a normal distribution function.

Since the locations of solar PVs and their capacities are random variables, the probabilistic method was applied to estimate the maximum solar PV hosting capacity that does not violate the technical limitations. Based on the total number of solar PVs, capacities, and type (single phase / three phase) probability of occurrence of solar PV in the network points has been determined. The proposed method has been tested using one of the LV distribution systems in a semi-urban area in the country. The distribution system has been modeled using OpenDSS software and hourly load flow calculations were performed to determine voltages at network points.

This work has been divided into two major sections: In the first part of the work, the analysis of voltage unbalance of the selected distribution system with the existing solar PV has been carried out. The results have been compared with the voltage unbalance of the same network without any of the solar PVs. In the second part of the work, voltage unbalance analysis with the increase of solar PV penetration level has been carried out and the maximum solar PV hosting capacity for the given distribution network has been estimated.

2. Materials and Methods

Voltage unbalance in the phases of the LV distribution network occurs due to the difference between loads and generation in phases and unsymmetrical phase geometry in the absence of transposition at low voltage level[17],[18]. Because of this reason, the current appears in the neutral conductor and phase magnitudes become unequal and the phase angle deviates from 120^0. According to the IEC standards voltage unbalance factor (VUF%) is defined as the ratio of negative sequence voltage (V-) to positive sequence voltage (V+) as given in equation (1)[19]. The zero sequence voltage has been ignored since it is canceled out by the transformer

$$VUF(\%) = \left|\frac{V^-}{V^+}\right| \times 100 = \left|\frac{V_{AB} + a^2V_{BC} + aV_{CA}}{V_{AB} + aV_{BC} + a^2V_{CA}}\right| \times 100$$

(1)

Another definition for voltage unbalance is line voltage unbalance rate (LVUR%) which is provided by the National Equipment Manufacturers Association in standard MG1-1993 as given in equation (2) [20]

$$LVUR(\%) = \frac{maximum\ deviation\ (V_{AB}, V_{BC}, V_{CA})}{avarage\ (V_{AB}, V_{BC}, V_{CA})}$$

(2)

Where

$$avarage\ (V_{AB}, V_{BC}, V_{CA}) = \frac{(V_{AB}, V_{BC}, V_{CA})}{3}$$

Both IEEE [21] and IEC [22] recommend keeping the VUF% below 2% for LV networks. In some European countries such as UK, this value is kept below 1.3%. The permissible voltage range for the LV distribution system is ±6% of the nominal voltage.

Solar penetration level, which is an indicator of the total capacity of solar PV in a network in relation to the capacity of the network. In this study, solar PV penetration level is defined as the ratio of the installed capacity of rooftop solar PV to the feeder capacity as given in equation (3) [23].

$$Solar\ PV\ penetration\ level(\%) = \frac{Total\ installed\ capacity\ of\ solar\ PV}{Distribution\ transformer\ rating} \times 100$$

(3)

The effect of solar PV depends on not only the penetration level but also how they are distributed across the feeders.

In this research, all the existing single-phase solar PV capacities in the country (2 kW, 3 kW, 4 kW, 5 kW, 6 kW, 7 kW, and 8 kW) and three-phase solar PV of 10 kW were considered. All the load points are considered potential candidates for solar PV installations of the above-given capacities. Various combinations of these rooftop solar PVs of the above ratings are allocated to the load points multiple times. This is done by assigning random numbers for all the load points per trail. These random numbers are equal to the probabilities of occurrence of rooftop solar PVs of various ratings and each random number decides the rating of rooftop solar PV allocated to that load point. The probabilities were calculated based on the real data and shown in table 2. Once the locations of solar PVs in the distribution feeder are known, the solar PV penetration level is determined and hourly load flow calculations for a day are carried out using OpenDSS software. The results of the loadflow calculations provide voltages at all the load points for 24 hours per day. Those voltages were stored against the solar PV penetration level. Large number of trials were carried out to obtain almost all the possible scenarios of solar PVs installation in the distribution system. At the end of trials, voltages at the load points for various solar penetration levels are obtained and VUF are determined. Since solar penetration levels are determined based on the random allocation of solar PV, for a given solar penetration level there are various distributions of solar PVs, a program code was developed using Python for the random allocations of solar PVs and carrying out multiple trials. OpenDSS software is used within the Python code for hourly load flow calculation.

Power generated by the rooftop solar PVs of given ratings were calculated using a solar irradiation curve during normal sunny day at the distribution feeder location. Smart energy meters have been installed in all consumers' locations and power consumption at each fifteen minutes' intervals are transmitted to the central control unit. Hourly load variations of the consumers for a normal working day were determined using these records.

The probability of having solar PV at a particular bus was calculated considering the number of rooftop solar PVs of different capacities and the number of single-phase and three-phase rooftop solar PVs in the country. These data were taken from the Sri Lanka Sustainable Energy Authority, Annual report 2018[24] and illustrated in Figure 1. The probabilities of occurring in each capacity of single-phase solar PVs among all the capacities (2-8 kW) and the probability of occurrence of three-phase 10 kW solar PVs among three-phase solar PVs were calculated and given in table 1. The results show that 80% of the rooftop solar PVs are single-phase and three-phase 20%.

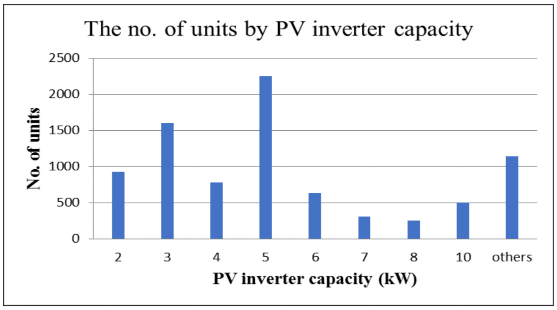


Figure 1. Number of solar ratings PVs of different

The probability of occurrence of a single-phase solar PV of a particular capacity in any of the buses in a distribution system was determined using equation (4)[25]]. This was identified as the Solar PV rating probability

$$R_S(p)=p_1 \times p_2 \times p_S \quad (4)$$

Then, the cumulative probability of occurrence of single-phase and three-phase solar PV with different ratings was calculated using equations (5) [25].

$$R_{\sum S} = p_2 + \sum p_1 p_2 p_s \quad (5)$$

The results of the calculations are given in table 2. The probability range that corresponds to the occurrence of three-phase solar PV is taken from 0.960 to 1.0.

Table 1. Probability of occurrence of solar PV of different capacities

PV Inverter Rated Capacity(kW)		Number of Solar Consumers	Probability (*p*)
Single Phase	2	931	0.1377
	3	1602	0.2370
	4	782	0.1157
	5	2248	0.3325
	6	635	0.0939
	7	308	0.0456
	8	254	0.0376
Total		6760	0.8043
3 phase	10	501	0.3046
	Others	1144	0.6954
Total three-phase		1645	0.1957
Total single & Three phases Solar Consumers		8405	

Table 2. Range of probability of occurrence of single-phase rooftop solar PV that corresponds to the different solar PV capacities

Probability range	Solar PV capacity kW
0.0000 < p ≤ 0.8	0
0.8000 < p ≤ 0.8220	2
0.8220 < p ≤ 0.8600	3
0.8600 < p ≤ 0.8785	4
0.8785 < p ≤ 0.9317	5
0.9317 < p ≤ 0.9467	6
0.9467 < p ≤ 0.9540	7
0.9540 < p ≤ 0.960	8

2.1 The Monte Carlo Method

A large number of trials (N=5000) were carried out to create different scenarios of solar PV distribution in the network. For each scenario, solar PV allocations in the distribution system were determined based on the random number between 0 and 1. After the solar PV allocations (phase-wise solar PV capacities of 0-8 kW and three-phase solar PV) unbalanced loadflow analysis were carried out to determine the bus voltages (Va, Vb, Vc) of the system. In this work, load flow calculation was carried out using OpenDSS simulation software. The Monte Carlo simulation was done using Python. The proposed algorithm is shown in Figure 2.

2.2 OpenDSS Software

Time series loadflow calculations of the LV distribution system were carried out using Open-Source Distribution System Simulator (OpnDSS) developed by Electrical Power Research Institute (EPRI), USA. It is a comprehensive electrical power system simulation package for electric utility power distribution systems. Among other features, the software is very useful for electrical distribution systems with renewable energy resources. The software package facilitates the export and import of bulk data from MS Excel. In this research, hourly load data per day of all the buses of the network has been stored in MS Excel as a CSV file and load flow calculations were performed in OpenDSS.

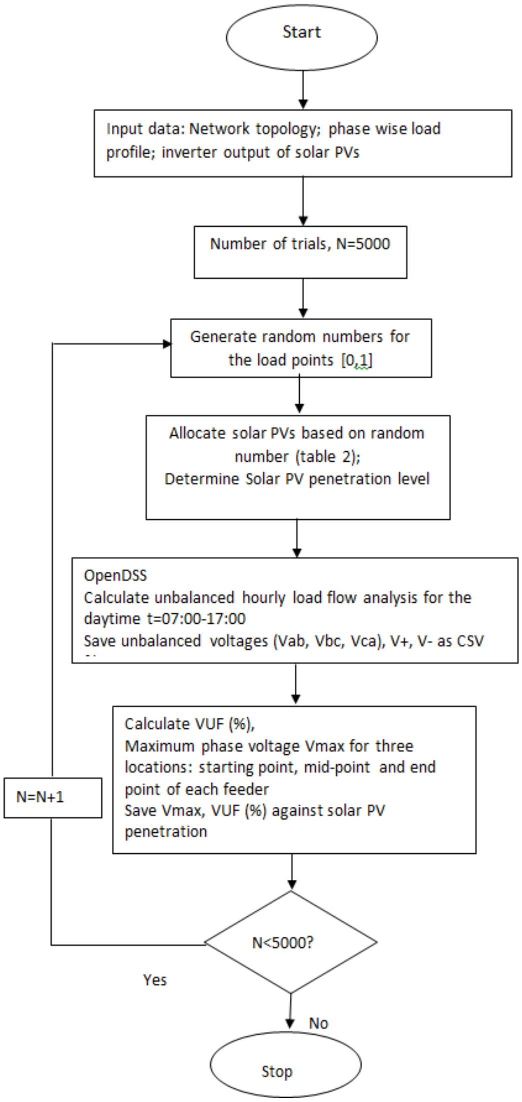


Figure 2. Flowchart for determination of voltage unbalances using Monte Carlo simulation

3. Results & Discussion

3.1 Distribution system data

The above method was applied to analyze the impact of solar PV on voltage unbalance and over voltage issues of the LV distribution network in Koswatta road Nawala (Figure 3).

The LV distribution system consisting of two feeders is fed from 160 kVA transformer. Table 3 provides details of the distribution network including the number of consumers and installed solar PV capacity in each feeder.

Table 3. Distribution system details

Total length	1.5 km	
Number of feeders	two	
Conductor type	ABC 3x50+1x16+N35 3x70+1x16+N35	
Number of consumers	231	
Consumers in feeder 1	167	Single phase =116
		Three phase =51
Consumers in feeder 2	64	Single phase =54
		Three phase =10
Total installed capacity of rooftop solar PV	92 kW	
Rooftop solar PV capacity in feeder 1	57 kW	
Rooftop solar PV capacity in feeder 2	35 kW	

Phase-wise distribution of consumers and the solar PVs are shown in table 4.

Table 4. Phase-wise distribution of consumers and rooftop solar PVs in two feeders

Feeder No:	Details	Phase A	Phase B	Phase C	Three phase
Feeder #1	Number of consumers	33	56	27	51
	Number of rooftop solar PV	0	1	3	7
	Maximum power (kW)	2.74	3.56	2.23	
Feeder #2	Number of consumers	30	15	9	10
	Number of rooftop solar PV	1	1	0	3
	Maximum power (kW)	1.24	4.72	1.52	

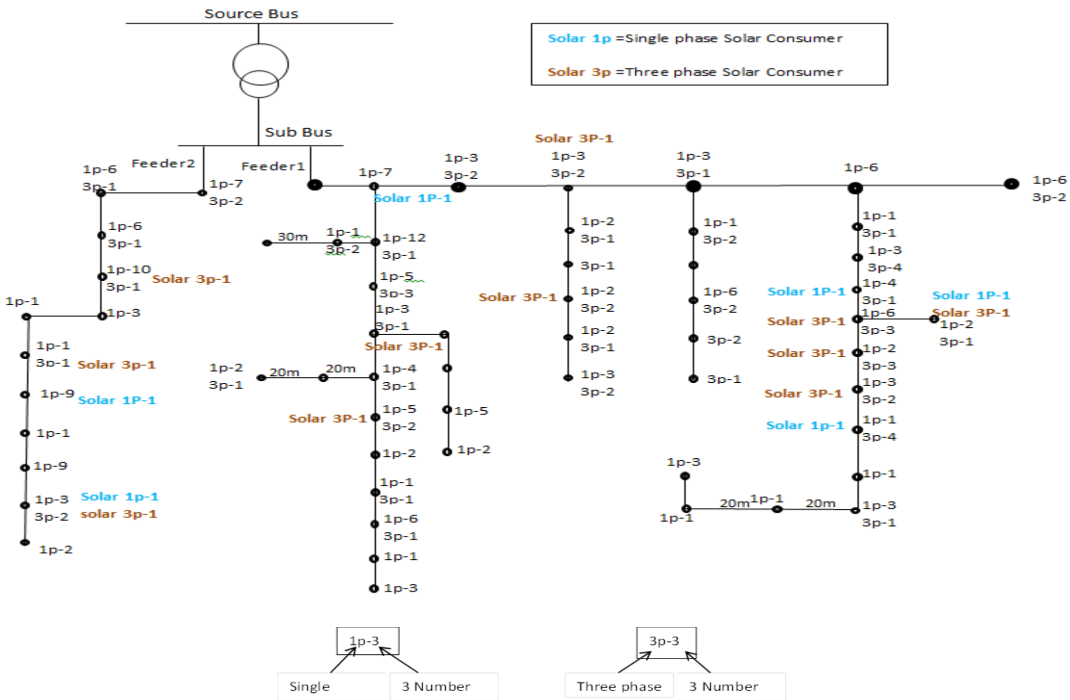


Figure 3. LV distribution network in Koswatta road Nawala

Consumers' energy consumptions are metered using smart energy meters and load profiles of the consumers are taken using energy meters. Load measurements were carried out for one month and average load variation over 24 hours' period of the day was calculated. Identification of the phase of the single-phase consumers in respective phases was done by examining the phase-wise voltage variation along the feeders. The capacities of solar PVs in the distribution system are 1.5 kW, 2.5 kW, 3.5 kW, and 4.5 kW. Hourly inverter outputs of these solar PVs were measured during 24 hours of a typical sunny day and the measured data are shown in graphical form in Figure 4.

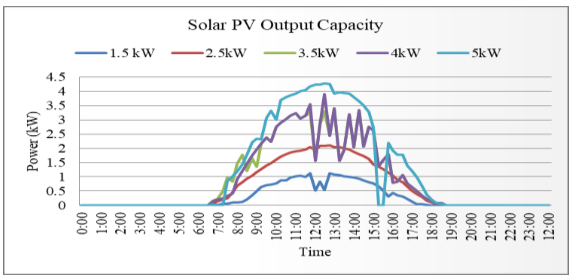
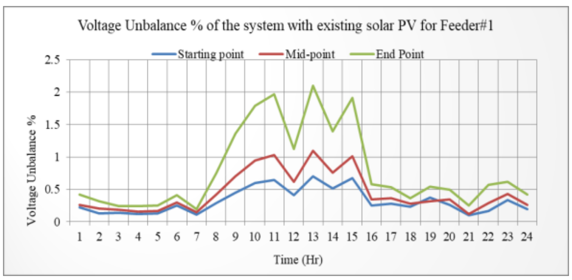


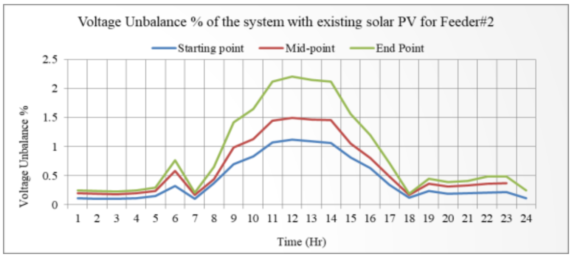
Figure 4. Solar inverter output variations

3.2 Simulation results

To examine the impact of installed solar PVs on voltage unbalance, hourly loadflow calculations were carried out for the existing system with and without solar PV. For both scenarios, VUF% at the starting, mid, and end points of each feeder were determined and the results are shown in Figures 5 (a), (b), 6 (a), and (b). Then, the Monte Carlo method was applied to investigate the variation of VUF% against solar PV penetration level. The simulation results for the three locations of each feeder are shown in Figures 7(a) and (b). VU% against the solar penetration level of the whole system is shown in Figure 8.

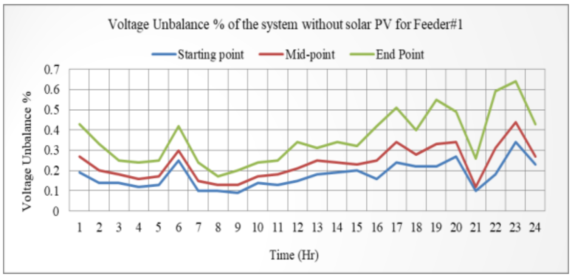


(a)

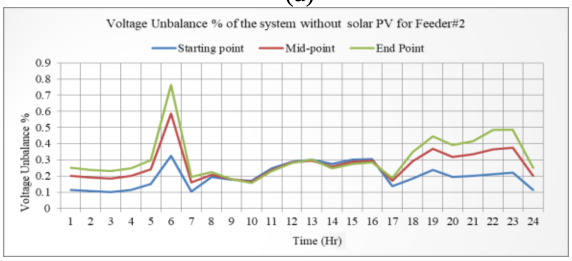


(b)

Figure 5. VU (%) at three locations of the two feeders with existing solar PV



(a)



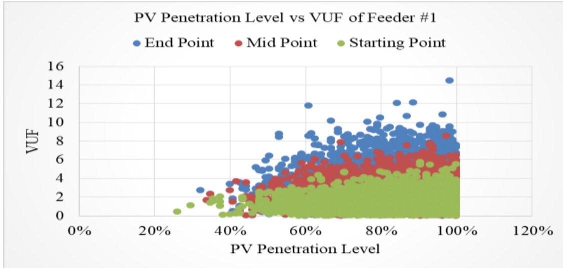
(b)

Figure 6. VU (%) at three locations of two feeders when all the solar PV are disconnected

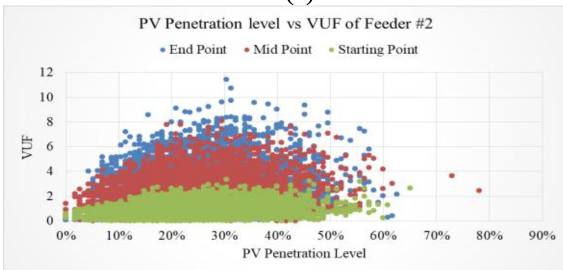
The solar PV penetration level of the distribution system is 57.5 %. As shown in Figures 5(a) and (b), VUF% has been significantly increased during the daytime when compared with the rest of the time of the day. This increase is common for all the locations across the feeders. However, VUF % has gone beyond the permissible value of 2 % only at the end points of the feeder2. VUF % of feeder 1 was within the permissible range, but there are critical moments.

Figure 6(a) and (b) show the variations of VUF% when all the solar PVs were disconnected from the network. In the absence of solar PV, VUF % is always within the permissible level. The existence of voltage unbalance in this situation can be explained by the non-uniform distribution of loads among the phases, and the diversity of operation of electrical appliances that are connected to the different phases. However, this does not have any significant effect on the system's performance.

The rise of the VU% when solar PVs are connected is due to the uneven distribution of solar PVs between the phases, their capacities, and the diversity of consumers' power consumption patterns. VUF% effect is more significant towards the end of the feeders. This is because of the culmination of different voltage drops among the phases towards the ends of the feeder.



(a)



(b)

Figure 7. VUF (%) variations at three locations of feeders 1 and 2 with the increase of solar

Figures 7 (a) and (b) show variations of VU of the feeders when solar PV penetration level varied from zero to hundred percent. The different values for the solar penetration level were obtained using Monte Carlo simulation. Since in the Monte Carlo simulation, a large number of trials were carried out many possible locations for a given solar PV penetration level were covered. The results show that the voltage unbalance factor increases with the increase of solar penetration level. However, this variation is different from feeder to feeder. For example, in feeder 1, the effect of solar PV begins when the solar PV penetration level becomes more than 35%. In the case of feeder 2, the effect of solar PV on the unbalance becomes significant at the lower values of the solar penetration levels (around 5%). feeder length and the number of consumers connected to feeder 1 is higher than that of feeder 2. This is one of the reasons for the difference in VUF of the two feeders. In all the cases the effect of solar PV on the voltage unbalance is more significant towards the end of the feeders.

The effect of the solar PV capacities on the voltage magnitude at load points is shown in Figure 8. The results show the continuous increase of the voltage while increasing the total capacity of solar PV. At the lower values of solar PV, the distribution system operates within allowable voltage limits.

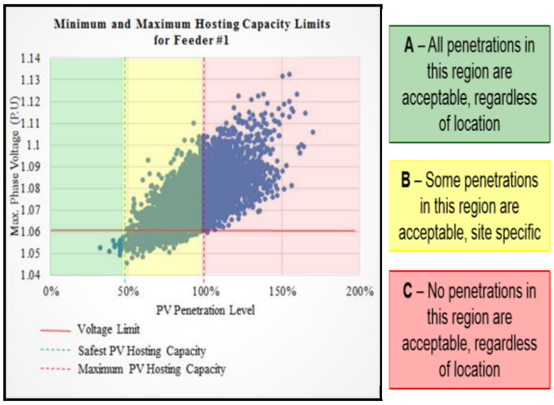


Figure 8. Maximum phase voltage variation against solar penetration level

4. Conclusions

This study shows that voltage unbalance and over voltage problems at load points are key factors in determining the upper limit of solar PV capacity. Difference feeder lengths and their electrical loads cause to have different solar penetration levels for a given distribution system. This means solar penetration level varies from feeder to feeder and having a single solar PV hosting capacity for the whole system might deny opportunities to have more solar PV consumers in a distribution system. Many of these distribution systems were designed before the distributed generators were started to utilize in distribution systems. New distribution feeders should be designed giving due consideration for distributed generators.

This work has been carried out under the assumption that the irradiation pattern remains constant all the time. However, in reality, the irradiation pattern varies due to the climate conditions of the area. For example, there can be days with higher levels of solar variability which can have different effects on the voltage unbalance. Not all consumers are ready to purchase solar PV and therefore, a group of consumers who are likely to install solar PV on their rooftops needs to be considered for obtaining a more realistic solar PV effect to the voltage unbalance. This work can be continued in the future considering the limitations discussed above.

Acknowledgments

The authors express their appreciation to Lanka Electricity Company Ltd (LECO) and the Sri Lanka Sustainable Energy Authority for providing the necessary data to carry out this study.

Nomenclature

LVUR%	Line voltage unbalance rate
p_1	probability of solar PV buses among all the busses (0.2)
p_2	probability of single-phase solar PV out of all the solar PV (0.8)
p_s	Probabilities of occurring given capacity of single-phase solar PV
R_s	Probability of occurrence of single-phase solar PV
$R_{\sum s}$	Cumulative probability of occurrence of single-phase or three-phase solar PV
V^+	Positive sequence voltage
V^-	Negative sequence voltage
V_{AB}, V_{BC},V_{CA}	Line voltages between phases AB, BC and CA respectively
VUF%	Voltage unbalance factor

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