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RESEARCH ARTICLE

Analysis of Rooftop Solar Impacts on Distribution Networks

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Abstract: Recently, many countries have focused on generating greener energy. As a result, the number of solar photovoltaic (PV) systems connected to the low voltage network has shown a rapid increase around the world. Many studies are being carried out to analyze the potential impact of high penetration of solar PV on the operation and performance of electricity distribution systems. This study proposes a Monte Carlo based approach to evaluate the impacts of rooftop solar PV on low voltage networks and a case study is presented for a typical unbalanced residential network in Sri Lanka using a three phase, four wire model. The model has been validated by comparing the load flow simulation results with actual measurements and the validated model has been used to investigate the impact of solar PV on distribution networks. The impacts were analyzed using parameters such as voltage unbalances, neutral currents, voltage and thermal limits. Results illustrate that PV penetration is limited under certain penetration levels due to the violation of some of the parameters. Further how phase balancing could be used to minimize high neutral currents and voltage unbalances is also illustrated.

***Keywords*:** rooftop solar PV, low voltage networks, PV impacts.

INTRODUCTION

In Sri Lanka, almost all the hydro power resources have been tapped and planned new generation is mainly by thermal. The Nationally Determined Contributions (NDCs) in accordance with Decision 1/CP.21 of the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change is to reduce the GHG emissions against 2010 values by 20% in energy sector by 2030. In order to achieve this target, Sri Lanka is intending to generate a higher share of electricity from greener energy. Recently, the government has launched a new community-based power generation project titled "Soorya Bala Sangramaya - Battle for Solar Energy"(Sri Lanka Sustainable Energy Authority, 2016) to promote the setting up of small solar power plants on the rooftops of households, religious places, hotels, schools, government institutions, commercial establishments and industries. It is expected to add 200 MW of solar power generating capacity to the national grid by 2020 and 1000 MW by 2025 through this intervention. As a result of this project, the integration of solar photovoltaic (PV) systems is gaining attention in Sri Lanka.

Traditionally, power systems have been designed considering a unidirectional power flow, from generation to consumer. Due to high integration of PV systems, bi-directional power flows can be seen on the distribution networks, thus causing adverse impacts. Many studies are being carried out globally to investigate the impact of residential rooftop solar PV systems on distribution networks. Previous researchers have evaluated these impacts on voltage rise (Begovic, *et al*., 2012, Tonkoski, *et al*., 2012, Ali, *et al*., 2012), voltage fluctuations, voltage unbalance (Begovic, *et al*. 2012, Chandra, *et al*. 2013) and higher levels of harmonics (Torquato, *et al*., 2014, Chidurala, *et al*., 2016).

According to the literature review, most of the PV impact studies are of deterministic and probabilistic types. In the case of deterministic studies, which are based on one or a few case study networks, all the input data for the analysis is known beforehand and the events are completely predetermined. In research work of Chin Ho, T. and Chin Kim, G. (2013), a deterministic study has been carried out to investigate the impact of residential grid connected PV system on Malaysian low voltage network. Thomson, and Infield, (2007) presented a detailed simulation of a very high penetration of PV within a typical UK urban distribution network using a deterministic approach. A model has been developed by Ali, S. *etal*. (2012) to investigate the impact of high penetration levels of grid connected PV systems on the voltage quality of the UK residential distribution network. The impact of voltage variation and power loss of the distribution system by PV systems have been investigated by Hsieh, W. H.*etal*. (2011) using a real distribution network in Taiwan (Main Stadium of 2009 World Games in Kaohsiung, Taiwan).

In probabilistic/stochastic studies, the random probabilities of the occurrence of an event are recognized to support uncertainties in distribution systems. According to the literature review, most of these studies are based on the case study networks. A stochastic methodology for simulation of PV impacts on LV distribution systems is demonstrated by Widen, J. (2010) using three examples

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of existing residential LV grids in Sweden. The potential impact of distributed PV generation on a LV network in New Zealand has been investigated by Watson, J. D. (2016) for a large number of realistic LV distribution networks of different types (rural, urban) using a stochastic approach. However, this study was limited to a three-phase unbalanced power flow algorithm.

Monte Carlo is a probabilistic technique which develops repeated random sampling to get statistical results and is commonly used to address uncertainties in power systems. Navarro, A. *etal.* (2013) presented a Monte Carlo technique to assess the impact of small-scale PV generation on two real LV networks in North West of England. However, the voltage related impacts have been evaluated using the European Standard EN50160. The necessity of using a Monte Carlo simulation method to estimate PV impacts on low voltage electrical network has been identified in Diop, F. *etal.* (2017).

The studies reported above have not appropriately addressed in the context of countries such as Sri Lanka in which three phase, four wire LV networks with a TT earthing system are utilized. Since most of the PV impact studies are based on European and US networks that use TN-S or TN-C or TN-C-S systems or IEEE test cases, it is not possible to apply the conclusions made in such studies to TT networks. Therefore, it is imperative to select appropriate simulation and modelling technique for TT networks.

Considering the aforementioned limitations, this paper presents a PV impact study for a typical residential network in Sri Lanka. In this research a Monte Carlo based approach has been selected to investigate the impact of solar PV on distribution networks. Results and conclusions are presented based on voltage unbalances, neutral currents, voltage and thermal limits.

METHODOLOGY

The electrical behavior (currents and voltages) of a distribution system depends on load profiles, location and the size of PV installations. To capture this vague nature of the electrical systems, it is necessary to perform a probabilistic impact assessment. As a result, a Monte Carlo based stochastic analysis framework is used in this study.

The methodology of the study is illustrated in Figure 1. A pre-defined number of PV panels with randomly generated PV capacity were connected to randomly generated nodes and phases of the selected distribution system. Snap shot power flow simulations were performed and several critical parameters were extracted from the load flow results. Then the impacts were evaluated using voltage and thermal limits, voltage unbalances and neutral currents.

The procedure is described in detail below.

A generic three phase, four wire LV network with a TT earthing system shown in Figure 2 was used to evaluate

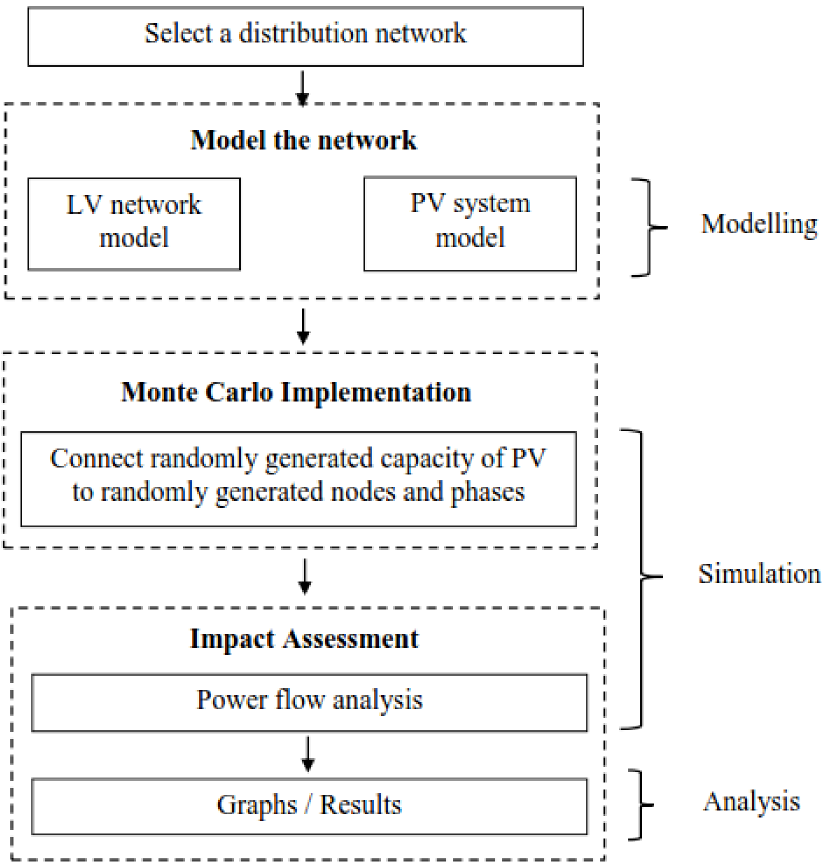

Figure 1: Methodology of the study.

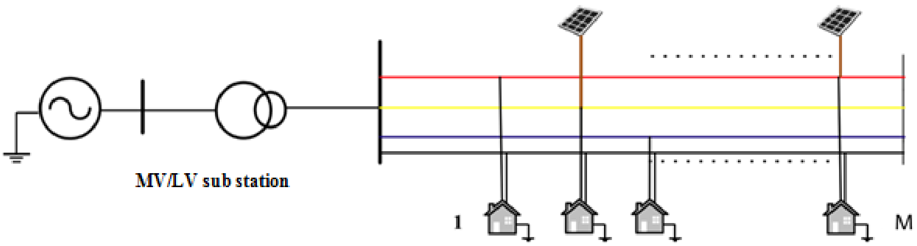

Figure 2: A generic distribution network.

the potential impacts of high penetration of solar PV. Generally, electricity distribution networks have a radial or weakly meshed configuration with several outgoing feeders from the substation transformer. The physical and electrical parameters of the network selected for the analysis may be varied. Therefore, it is important to consider these variations when modelling the network to perform the impact assessment.

Analysis tools

The open source software, Open Distribution System Simulator (OpenDSS), and MATLAB were used as the main analysis tools to model, simulate, and analyze the impact of high penetration of solar PV on distribution networks.

OpenDSS is a simulation tool for electric utility distribution systems, which is developed and distributed by Electric Power Research Institute (EPRI), USA (Electric Power Research Institute, 2011). OpenDSS can be used as both a stand-alone executable program and a COM DLL that can be driven from some software platforms. In this study, PV impacts were simulated and investigated by externally interfacing MATLAB with OpenDSS. The network model for the analysis was modelled in OpenDSS and MATLAB was used to simulate multiple PV deployment scenarios required for the Monte Carlo implementation.

LV Network Model

A detailed network model for a three phase, four wire (including the neutral), radial LV distribution system, starting from the MV/LV substation down to individual customer locations was developed in OpenDSS. Physical and geographical data of the selected network including topological parameters, conductor characteristics, customer locations, and phase connectivity were used to model the network for a realistic analysis. Electrical components of the network such as the transformer, overhead lines, loads and PV systems were modelled by providing the actual parameter values of each component as input to OpenDSS. Line geometry of the original network and conductor configurations were considered to obtain the sequence impedances which were required to model the conductors. Consumer loads were modelled as constant power loads with 0.95 power factor.

PV System Model

An in-built, combined PV model (including the PV array and the PV inverter) available in OpenDSS was used to model the PV systems in the study. The schematic diagram of the model implemented is shown in Figure 3. PV units were modelled as power delivering objects where the active power generated is a function of rated power at the maximum power point (P_{mpp}), solar irradiance, and surface temperature of the PV panel.

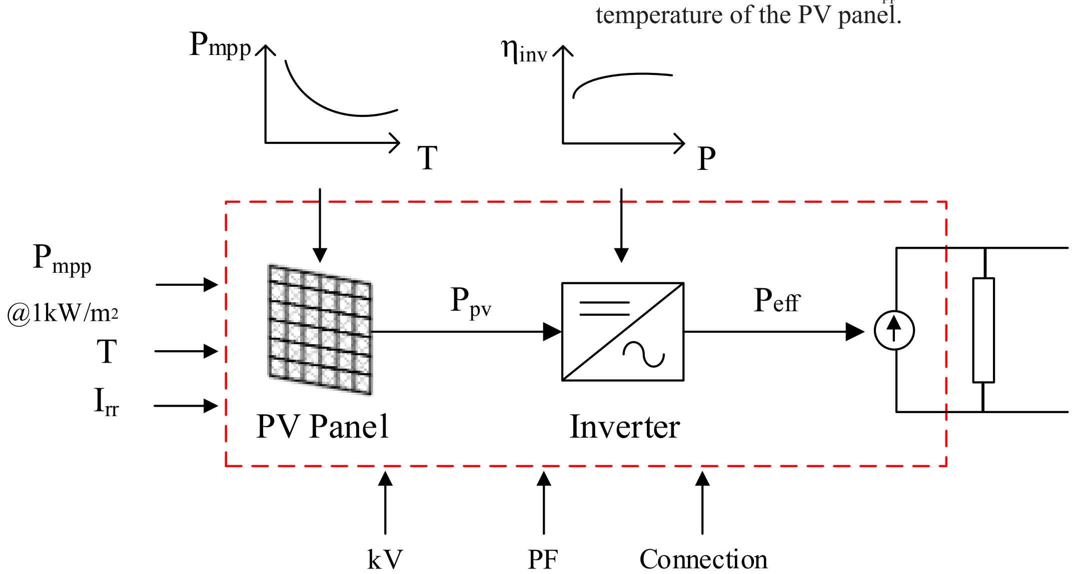

Figure 3: PV system element model

Average P_{mpp} of the PV panel at 1000W/m^2 irradiance and 25°C, per unit variation of P_{mpp} vs temperature at 1000W/m^2 irradiance and efficiency curve of the inverter (per unit efficiency vs per unit power) were provided as input to OpenDSS.

Monte Carlo Implementation

In this study, the number of PV installations connecting to the distribution grid was selected by considering the number of customers and feeders of the network. Customer unit loading and PV system data were provided as the input variables for the simulation. In order to investigate the impact of PV penetration in future, a large number of PV deployment scenarios were obtained by varying the capacity and the location of PV installations using a Monte Carlo based stochastic framework. It is a nondeterministic numerical method of approximately solving problems using sequence of random numbers. The computation procedure of the Monte Carlo approach is as follows,

1. Select the distribution type of the random variable.
2. Generate a sampling set from the distribution.
3. Conduct simulations using the sampling set.

For the implementation of Monte Carlo approach, random numbers were generated corresponding to PV capacity, nodes to which in PV plant will be connected and phases to which the panels will be connected. To carry out this step, the 'rand' function in MATLAB was employed and the numbers were sampled from the uniform distribution with a range of [0,1]. Power flow simulations were executed for unique PV deployment scenarios by varying PV capacity and location.

Impact Assessment

The following parameters were extracted and stored after each snap shot power flow simulation.

- Maximum voltage
- Maximum neutral current
- Maximum power flow
- Maximum unbalance factor

An impact study was conducted for voltage and thermal limits, voltage unbalances and neutral currents by evaluating the extracted data.

Case Study

To adequately investigate the impacts of solar PV on a last mile distribution network, it is convenient to consider a real distribution network instead of a hypothetical network where the impacts are measurable through proper instrumentation. The proposed methodology presented in the previous section was applied to the residential network shown in Figure 4 which is situated in Dehiwala area and called Lotus Grove Housing Scheme. All required data of the distribution network was collected from the main Sri Lankan electricity provider, Ceylon Electricity Board (CEB).

Domestic Loads

In Sri Lanka, the annual demand profile varies where the maximum demand is approximately four times the minimum demand (Public Utilities Commission of Sri Lanka, 2017). This pattern was utilized to scale domestic loads in simulation. The average power consumption of a house (unit consumption) was taken as 0.5kW and a factor of 0.4 was used to reduce the peak load to minimal load. Thus, the maximum and the minimum unit loads were assumed as 1.0kW and 0.25kW respectively. Single phase loads were distributed among the three phases in order to ensure that the overall network is balanced or approximately balanced.

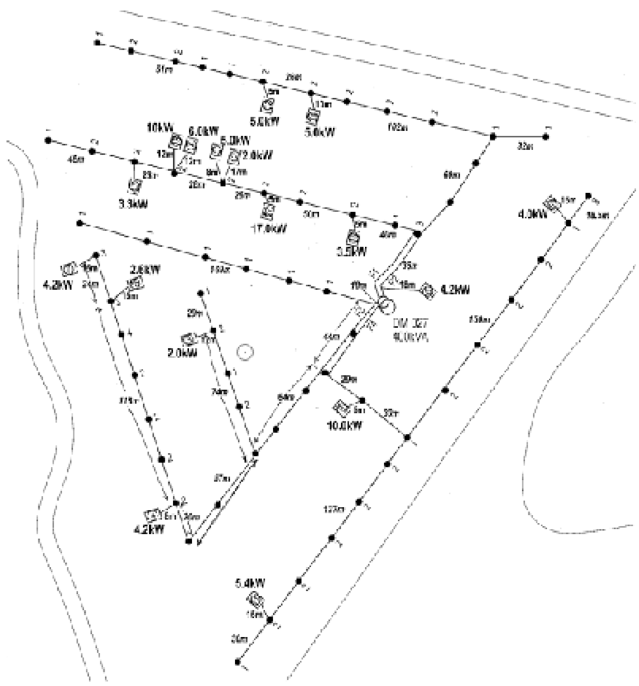

Figure 4: Single line diagram of Lotus Grove Housing Scheme.

PV Systems

The solar PV systems were distributed randomly throughout the distribution network. Typically, the capacities of the residential rooftop solar PV are less than 7kW. In order to conduct a realistic analysis, the capacity of the PV panels was varied in the range 2 to 7kW in multiples of 0.25kW. PV panels with single phase inverters were used to create an unbalance condition in the system (to obtain the critical condition).

LV Network

The network consisted of a 11kV/415V transformer of 400kVA, which has been geometrically located in the middle of the network. The transformer is a Dyn11 with a solidly earthed neutral point. The network has four distribution feeders, serving 94 customers via a three-phase connection. There are 18 residential roof top PV systems distributed throughout the network with a total installed capacity of 93.4kW. The total length of the network is 1.65km and Aluminum Aerial Bundle Cable (ABC-Al/XLPE of 3x70 + N 54.6 + 1x16) is used as the medium of electricity distribution all over the network.

Model Validation

The network was modelled in OpenDSS with all four wires of distribution lines. A model validation was performed before using the modelled network to investigate the impact of solar PV on the distribution network. It was mainly focused on one feeder out of four feeders of the selected LV network (Lotus Grove), shown in Figure 5. Two data loggers were placed at feeder starting point and feeder midpoint to measure the actual feeder parameters and the measurements were recorded in every 10 minutes, consecutively for eight days. In addition, generation data of PV panels connected to the same feeder was acquired. The data gathered was used to model the network in OpenDSS. Since the customer loading record was not available at each customer point, it was assumed that the customer loading was equally distributed between feeder starting point to feeder midpoint and feeder midpoint to feeder end point. Then the load flow simulation results of currents, voltages, active and reactive powers at feeder starting and mid points were compared with actual measurements for the validation.

The comparison of the simulation results with the actual measurements from the two data loggers were shown in Figure 6. As can be seen a substantial agreement of actual and simulated results could be seen thus validating the modelled network.

Analysis of PV impacts

The Monte Carlo based stochastic analysis presented in methodology section was applied to the validated network model to investigate the potential impact of solar PV on 'Lotus Grove' distribution network. The following selections were made prior to the power flow simulations.

- Selection of the number of PV panels connected to the distribution network.
- Selection of the unit customer loading (0.25kW, 0.5kW, 1kW).
- Random selection of the PV capacity (2 to 7kW).
- Random selection of PV location (Node and Phase).

Six cases included in Table 1 were considered and one hundred power flow simulations were executed for each case by varying the PV capacity and location.

For the impact study extracted parameters were examined to see whether the voltage unbalances, voltage and thermal limits and neutral currents are within the statutory limitations. According to CEB standards and planning criteria for LV networks, the limitations are as follows,

Under normal conditions,

- Per unit voltage should be between 0.94 p.u – 1.06 p.u
- Economical loading should be 70% of the thermal rating
- Emergency loading should be 125% of the thermal rating
- Voltage unbalance should be less than 1%

While integrating solar PV to the distribution grid, it is imperative to ensure that the voltage increment and power flow along the feeder and voltage unbalance factor do not exceed their statutory limitations.

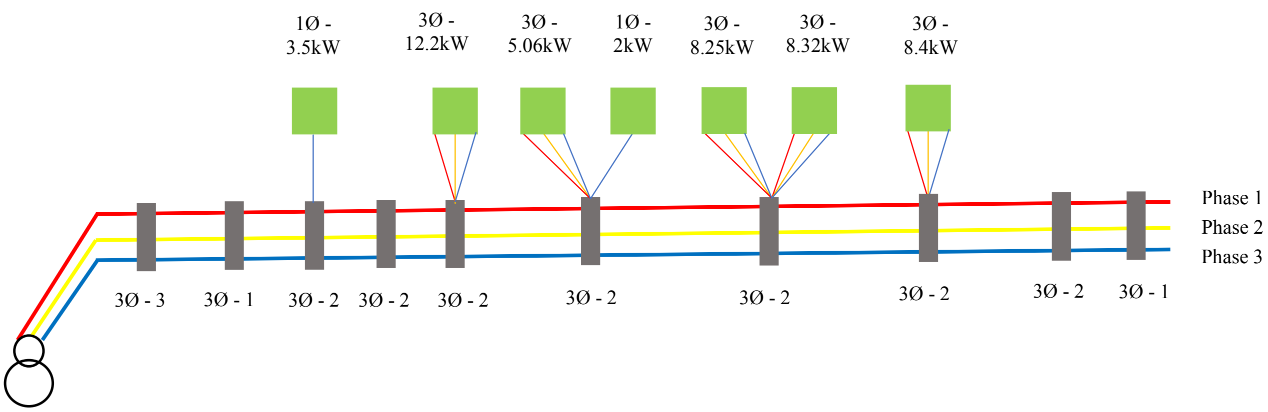

Figure 5: Schematic diagram of feeder 1.

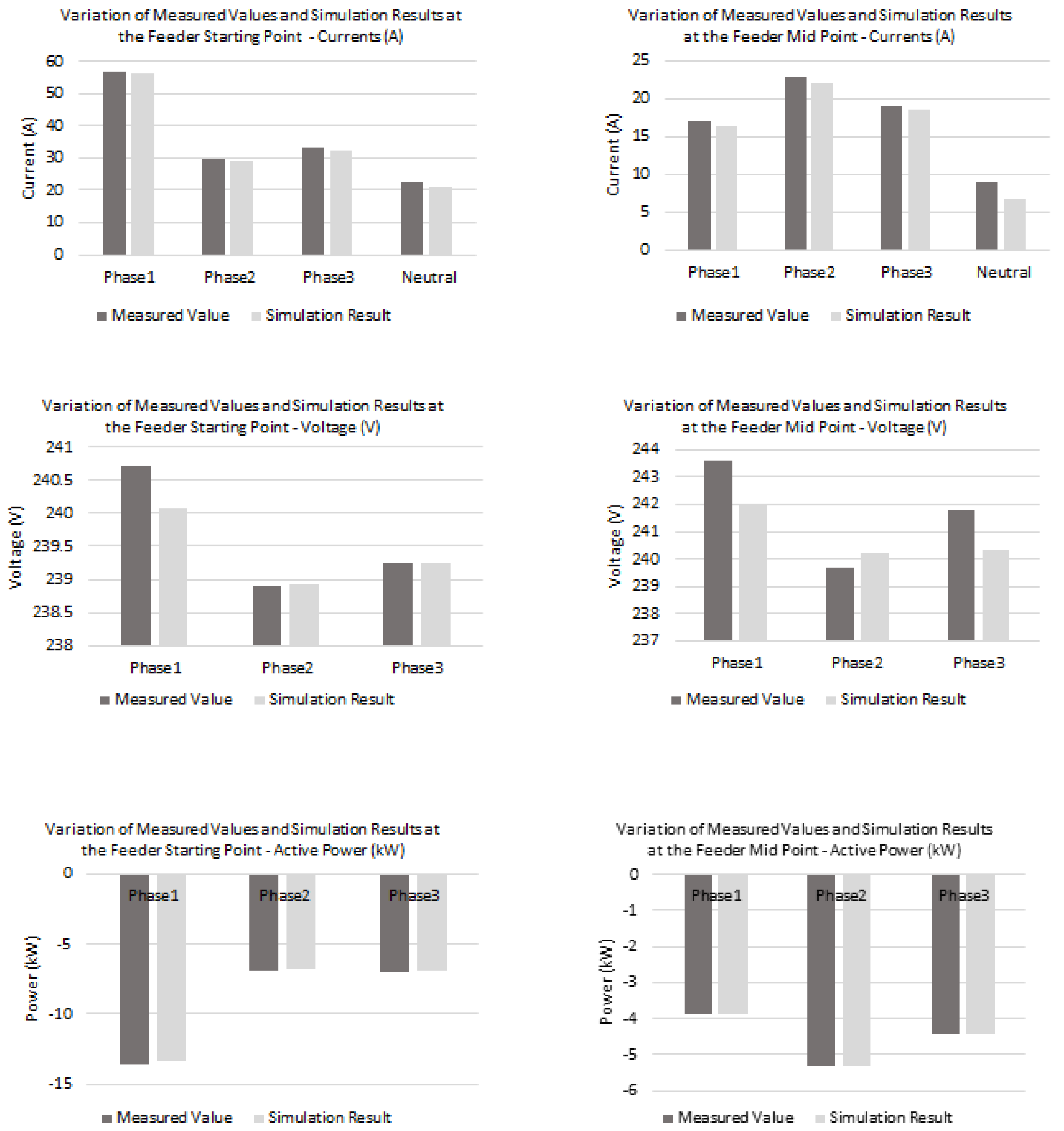

Figure 6: Comparison of simulation results with actual measurements.

Table 1: Cases considered.

Case	Unit Load (kW)	No. of PV units connected
Case 1	0.25	15
Case 2	0.25	30
Case 3	0.50	15
Case 4	0.50	30
Case 5	0.10	15
Case 6	0.10	30

RESULTS

For all the cases illustrated in Table 1 graphs and histograms were obtained after conducting one hundred power flow simulations for each case. The maximum parameter value of each simulation was extracted and stored. Then they were arranged in ascending order and graphs were plotted for each parameter considered. The graphs shown in Figure 7 and Figure 8 represent the maximum value variation and distribution of one hundred simulations for voltage, power, neutral current and voltage unbalance factor of case 2. Similarly, graphs were obtained for other remaining cases.

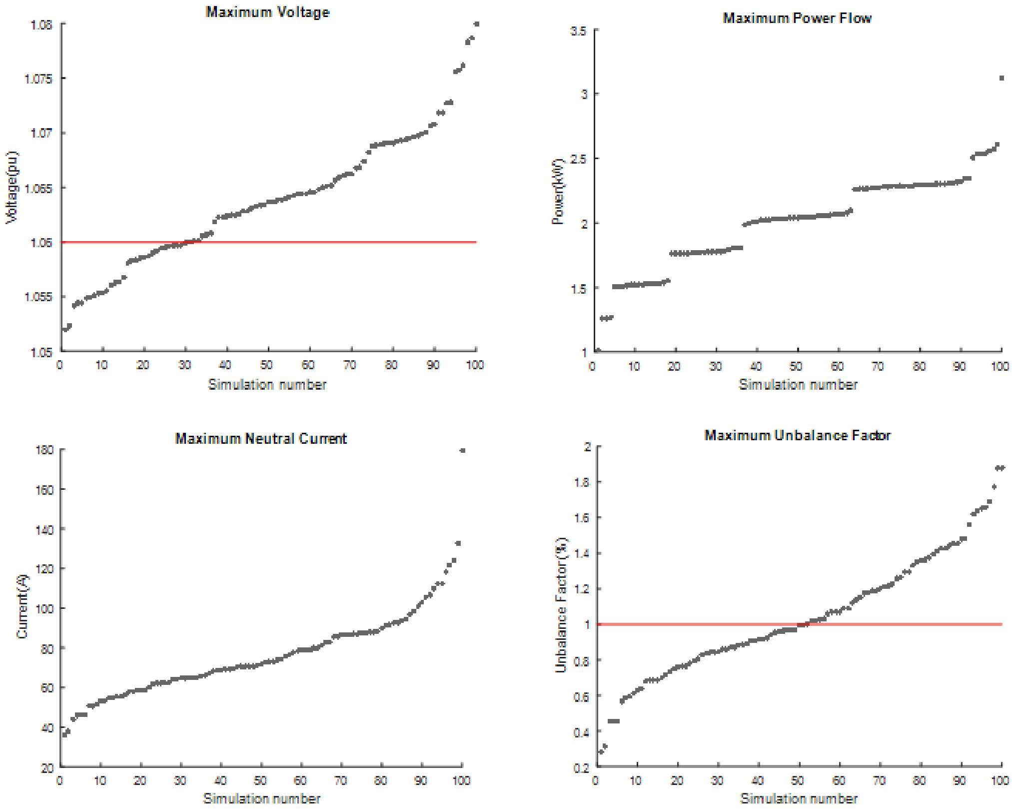

Figure 7: Variation of maximum voltage, maximum power flow, maximum voltage Unbalance factor and neutral current for hundred simulations (Case 2).

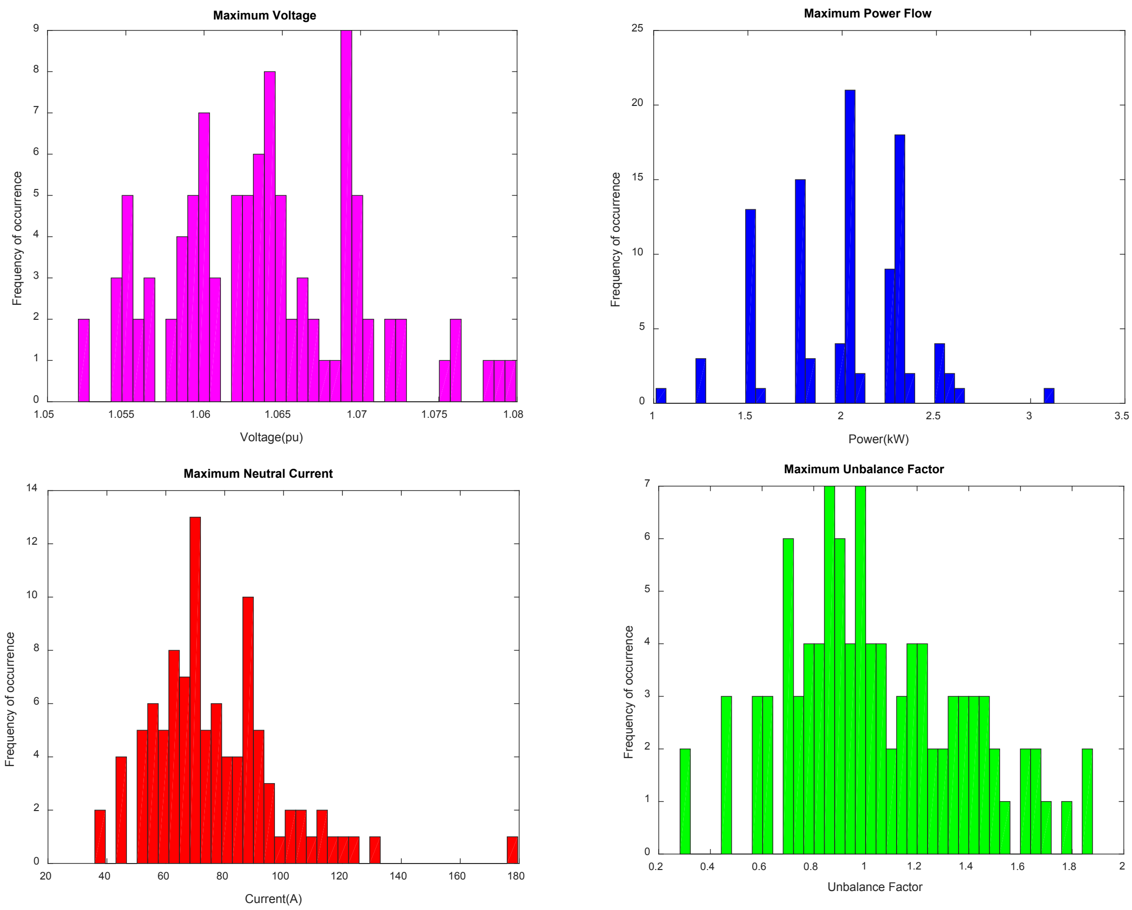

Figure 8: Distribution of extracted parameters (Case 2).

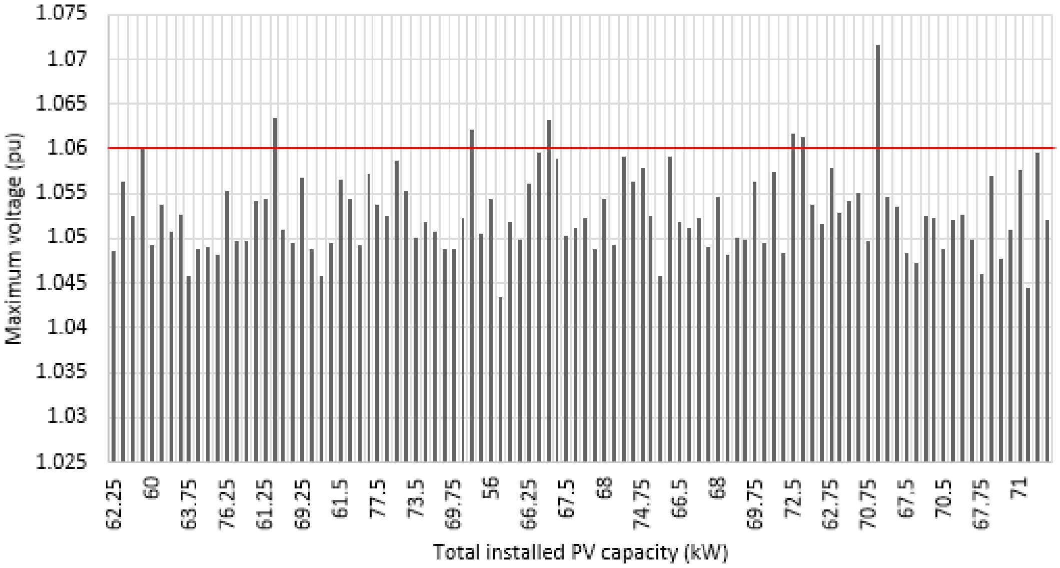

Figure 9: Variation of maximum voltage with the total installed PV capacity (15 PV units).

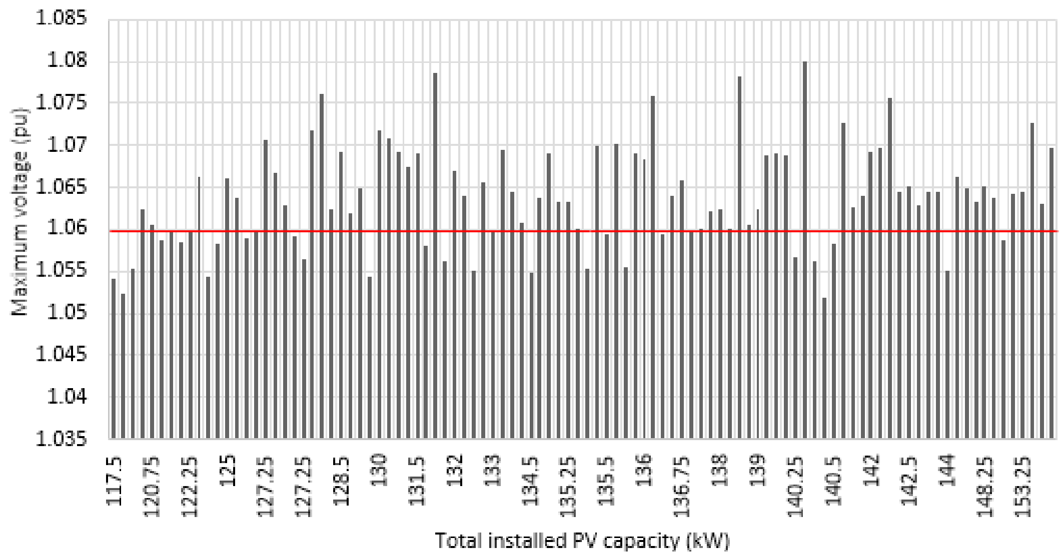

Figure 10: Variation of maximum voltage with the total installed PV capacity (30 PV units).

In addition, the variation of maximum parameter values with the total installed PV capacity was obtained by increasing the PV penetration. Figures 9 and 10 illustrate the maximum voltage variation for 15 and 30 PV units.

DISCUSSION

By examining the results obtained for all six cases/combinations, it was found that, most of the time maximum voltage and voltage unbalances were remained within the statutory limitations. However, for certain high penetration levels, the maximum voltage and unbalance factor violate the limits. These violations are not directly related to the capacity of the PV panel connected, but depend on the location and the phase to which they are connected. It was also revealed that when the customer unit loading was changed from1kW to 0.25kW, the maximum voltages obtained for each simulation showed an increment. Therefore, it is clear that the impact on voltage becomes more significant in low demand conditions.

Under none of the cases, phase current through the conductor overloads the lines. However, random allocation of PV units generated high neutral currents and voltage unbalances. As shown in Table 2, the neutral current and voltage unbalances could be minimized by a significant amount using phase balancing technique rather than randomly selecting the phase to which the PV panels are to be connected.

Table 2: Comparison of maximum neutral current and voltage unbalance factor obtained by randomly generating and after phase balancing.

		Maximum Neutral Current (A)	Maximum Unbalance Factor (%)
Case I	When randomly generated	67.96	1.018
	After phase balancing	28.45	0.190
Case II	When randomly generated	71.04	0.936
	After phase balancing	36.14	0.408
Case III	When randomly generated	98.84	1.320
	After phase balancing	48.83	0.365

CONCLUSIONS

This paper proposes a Monte Carlo based stochastic approach to investigate the impact of rooftop solar PV on electricity distribution systems. A detailed network model for a three phase four wire, unbalanced distribution network was developed and validated. The model was used to investigate the impact of PV on voltage and thermal limits, neutral current and voltage unbalance factor of distribution networks. The case study presented, demonstrates how this framework could be used to evaluate the impacts on a typical Sri Lankan residential network. Results from the impact assessment showed that under high penetration of solar PV and depending on their location and phase, some of the critical parameters such as voltage and unbalance factor violated the statutory limitations. Since, the location of the PV has a significant influence on voltage unbalance and neutral current, a phase balancing technique was adopted to select the phases to which the panels to be connected thus significantly reduces their magnitudes.

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