

Monte Carlo analysis for solar PV impact assessment in MV distribution networks

Dilini Almeida¹, Jagadeesh Pasupuleti², Shangari K. Raveendran³, M. Reyasudin Basir Khan⁴

^{1,2,3}College of Engineering, Universiti Tenaga Nasional (UNITEN), Putrajaya, Malaysia

⁴Manipal International University, Nilai, Negeri Sembilan, Malaysia

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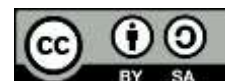
System power loss

Voltage rise

ABSTRACT

The rapid penetration of solar photovoltaic (PV) systems in distribution networks has imposed various implications on network operations. Therefore, it is imperative to consider the stochastic nature of PV generation and load demand to address the operational challenges in future PV-rich distribution networks. This paper proposes a Monte Carlo based probabilistic framework for assessing the impact of PV penetration on medium voltage (MV) distribution networks. The uncertainties associated with PV installation capacity and its location, as well as the time-varying nature of PV generation and load demand were considered for the implementation of the probabilistic framework. A case study was performed for a typical MV distribution network in Malaysia, demonstrating the effectiveness of Monte Carlo analysis in evaluating the potential PV impacts in the future. A total of 1000 Monte Carlo simulations were conducted to accurately identify the influence of PV penetration on voltage profiles and network losses. Besides, several key metrics were used to quantify the technical performance of the distribution network. The results revealed that the worst repercussion of high solar PV penetration on typical Malaysian MV distribution networks is the violation of the upper voltage statutory limit, which is likely to occur beyond 70% penetration level.

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Corresponding Author:

Dilini Almeida

College of Engineering

Universiti Tenaga Nasional (UNITEN)

Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia

Email: dilinialmeida2@gmail.com

1. INTRODUCTION

Over the last decade, many countries have initiated the process of setting up access to transmission and distribution networks to liberalize their electrical systems [1]. This has been associated with substantial growth in the participation of distributed generators of various technologies. Owing to the proposed developments in the reduction of carbon footprints and rising temperatures, a major share of distributed generators is expected to be focused on renewable energy [2]. Recently, the large-scale integration of solar PV systems has shown a remarkable expansion due to the enhanced module performance, economies of scale, and research and development relative to the other renewable energy sources. During the period of 2010 to 2019, the compound annual growth rate of solar PV has crossed over 40% and its global installed capacity is projected to reach 8519 GW by 2050 [3]. In Malaysia, the government has intended to add an annual solar capacity of 200 MW in Peninsula Malaysia and 50MW in Sabah through the implementation of the large-scale solar (LSS) program [4].

Typically, traditional power systems are configured as passive networks that consider a unidirectional power flow feed: from centralized generation to consumers. Thus, the rapid proliferation of PV systems poses new technical challenges on the operation and performance of these networks, since they have not been designed to facilitate dispersed generation [5]. In particular, MV distribution networks to which large-scale solar plants are integrated directly or by aggregation of low voltage installations are already experiencing technical challenges in areas where high PV concentrations exist [6]. Among these technical challenges, the voltage rise has been identified as the most critical challenge as its implications directly affect the performance of the distribution network [7], [8].

Owing to the stochastic nature of the output, PV units are considered uncontrollable. As a result, the varying generation and load demand could cause overvoltage problems in MV distribution networks. During periods when low demand and high generation coincides, excess generation flows towards the substation forming reverse power flows [9]. Consequently, the ordinary behaviour of the distribution network varies, leading to increased voltage levels. Besides, voltage violations could occur with a further elevation in the PV penetration level in the network. Nonetheless, the severity of these impacts depends on several factors, including network topology, geographic location and size of installed PV systems, and weather conditions [10]. The increased active power loss of the network, accompanied by high solar PV integration, is another challenge that could affect the performance of the distribution network [11]. Usually, the network loss represents a U-shape trajectory against the PV penetration level [12]. It is expected to decrease under moderate PV penetration, as the integration of PV systems reduces the net power flow within the network [13]. However, at high PV penetration levels, the increased reverse power flow could result in high network losses [14].

Recently, a considerable number of research efforts have been undertaken to investigate the potential technical challenges associated with high penetrations of PV in distribution networks. Most of these PV impact assessments have been focused on assessing the effect of grid-connected solar PV on the system and quantifying the anticipated impacts as a function of the penetration level, considering the statutes and standards. The methods utilized in previous studies to analyze, and quantify the solar PV impacts could be mainly categorized as deterministic and probabilistic types. In the deterministic approach, the uncertainties linked to PV generation are identified and evaluated using scenario-based analysis. The worst-case scenario analysis is one of the frequently adopted decision-making techniques in the event of uncertainties. Besides, this method does not contemplate the probabilistic aspect of the system, as all the input data and the events are known in advance. One of the key limitations of this method is the overestimated results which could drive unnecessary grid reinforcements. However, in the probabilistic approach, the random probability of an event is considered to assist the system uncertainties. Monte Carlo is one of the widely employed probabilistic techniques that generates repeated random sampling to address the uncertainties in the system.

Many deterministic type studies have been reported in the literature to assess the PV penetration impacts on MV distribution networks. In [15], a deterministic type impact assessment has been performed to examine the network losses and voltage issues related to PV penetration in MV distribution networks under different solar variability conditions. A similar study has been conducted in [16]-[18] to evaluate the impact of PV penetration on distribution networks' voltage profile and power losses. In [19], the authors have studied the effect of PV self-consumption on the voltage levels and system losses of a Spanish MV distribution network, considering six geographic distributions; random, dispersed, low, moderate, strong, and extreme. In [20], the impact of PV generation on the voltage profiles and power losses in distribution networks has been assessed, considering different PV inverter capacities, installed at different locations. References [21]-[25] have proposed Monte Carlo based probabilistic impact assessments to determine the influence of PV/DG penetration on MV distribution networks. In most of these publications, the authors have taken into account the number of PV systems, the installed capacity, and the location within the distribution network as uncertainties associated with solar PV generation. In [26], a study has been performed to assess the impact of PV systems on a rural MV distribution network by utilizing a Monte Carlo based technique to represent the intermittency of PV production and loads.

While a few studies have proposed Monte Carlo analysis for solar PV impact assessment in MV distribution networks, the studies that consider detailed and realistic network models with high resolution, time-series representations are limited. Therefore, this paper proposes and adopts a Monte Carlo based probabilistic framework to investigate the potential technical impacts of solar PV penetration on MV distribution networks while catering to the uncertainties related to solar PV generation.

The remainder of the paper is organized as follows: Section 2 outlines the research method including the proposed Monte Carlo-based probabilistic framework, the impact metrics, and the case study. The simulation results obtained from the application of the proposed methodology are presented and discussed in Sections 3. Finally, the conclusions are drawn in Section 4.

2. RESEARCH METHOD

This section presents the proposed impact assessment framework and the impact metrics used to analyze and quantify the impact of solar PV penetration on MV distribution networks.

2.1. Overview of the impact assessment framework

The proposed Monte Carlo based probabilistic impact assessment framework is capable of investigating the potential technical impacts of solar PV penetration on MV distribution networks while addressing the uncertainties and intermittent nature of solar PV generation. The flowchart of the impact assessment framework is shown in Figure 1. For a given MV distribution network, this framework evaluates the possible impacts of solar PV penetration in terms of several metrics.

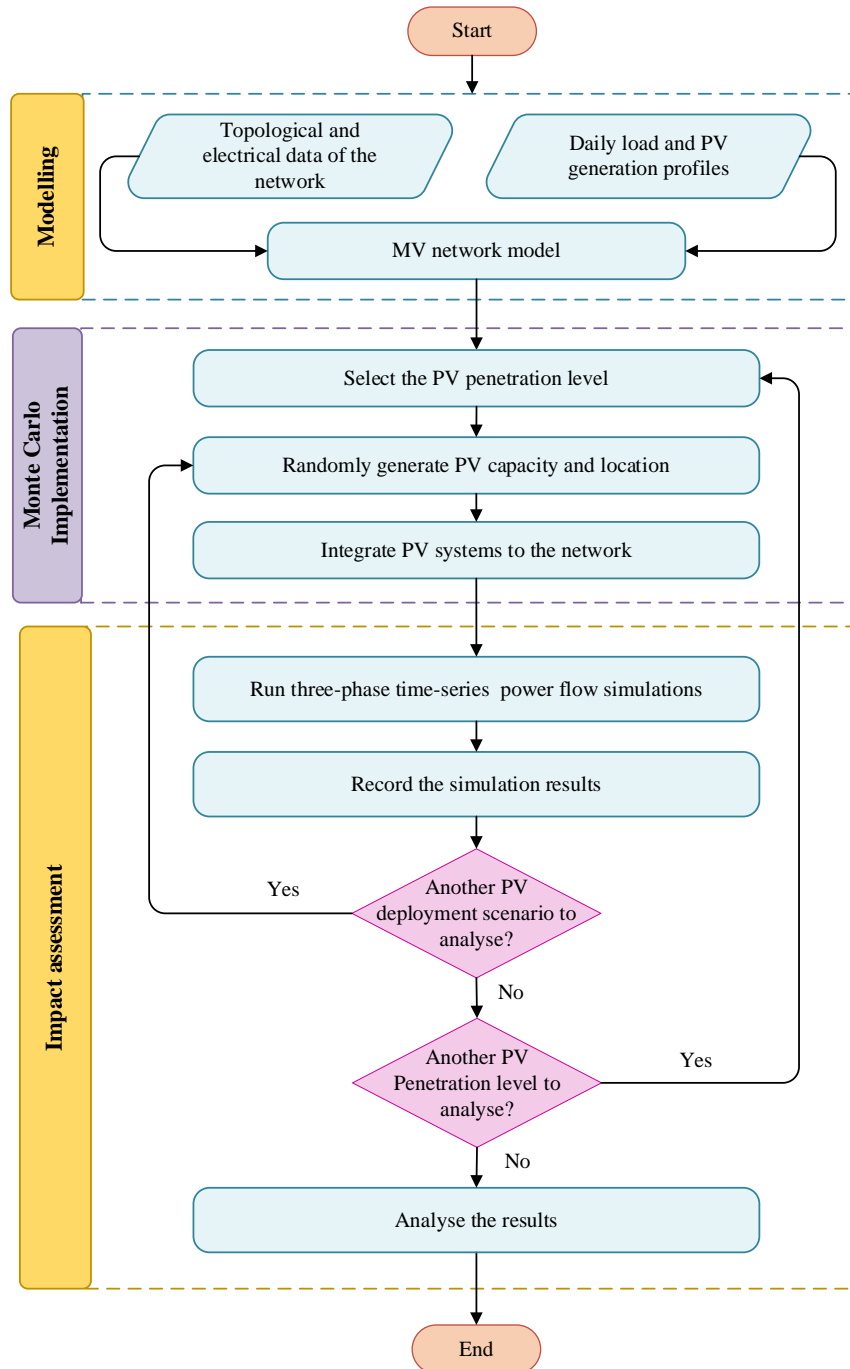


Figure 1. Flowchart of the proposed Monte Carlo solar PV impact assessment framework

Firstly, the topological and electrical data of the selected MV distribution network is used to develop a detailed network model connected with solar PV systems. In order to conduct a realistic analysis, different load profiles and irradiance profiles are employed to incorporate real-time variations in PV generation and load demand. As the first step towards the Monte Carlo implementation, a large number of PV deployment scenarios are considered by randomly allocating different PV capacities across the network. Thereafter, three-phase, time-series, minute-by-minute, daily power flow simulations are performed to investigate the possible solar PV impacts under different penetration levels. The main steps of a single simulation under a particular penetration level are summarized below.

- Allocation of load consumption profiles for residential, commercial, and industrial loads connected to the network.
- Random allocation of PV capacities across the network until the defined level of penetration is reached (randomly generated PV capacities are assigned to randomly generated nodes). The PV generation profiles are allocated to each PV system randomly connected to the network.
- Power flow simulations are performed and the required results (voltages, currents, and power flows) are extracted and recorded for later processing under the impact assessment.

The above process is repeated until a defined number of scenarios are simulated under each PV penetration level. Finally, the results of all power flow simulations are analyzed and quantified using several impact metrics to assess the potential solar PV impacts on the distribution network.

2.2. Impact metrics

The following metrics are adopted to analyze and quantify the key technical impacts of different solar PV penetration levels on MV distribution networks.

2.2.1. Maximum nodal voltage

This metric assesses the influence of solar PV penetration on the voltage profiles of the network. For each power flow simulation, the maximum nodal voltage recorded in the network is extracted to examine the variation of the maximum voltage under different PV penetration levels.

2.2.2. Voltage violations

This metric assesses the potential voltage rise problems of the network due to high solar PV penetration in the future. For each power flow simulation, the daily voltage profiles of all nodes connected to the network are analyzed for adherence to the local standards. According to the statutory limits specified by the Malaysian electric utility, Tenaga Nasional Berhad (TNB) for voltages in MV networks, the maximum and minimum voltage levels are 1.05 and 0.95pu, respectively. Subsequently, the percentage of nodes that do not comply with permissible voltage limits is extracted to examine the possible voltage rise issues under different PV penetration levels.

2.2.3. System power losses

This metric assesses the impact of solar PV penetration on the total active power loss of the network. For each power flow simulation, the daily average active power loss of the entire network is obtained to determine the variation of the system power loss at different solar PV penetration levels. The equation used to calculate the system power loss is expressed in (1)

$$\text{Average power loss} = \frac{1}{T} \int_0^T P_{loss}(t) dt \quad (1)$$

where, P_{loss} is the total active power loss of the network.

2.3. Case study

The proposed Monte Carlo impact assessment framework was applied to a typical Malaysian MV distribution network to examine the future risk of solar PV integration. Figure 2 presents the one-line diagram of the test network. The network is a three-phase radial system with two distribution feeders serving a range of residential, commercial, and industrial loads as depicted in Figure 2. The feeders are supplied by a 30MVA distribution transformer with nominal voltage ratings of 33/11kV. Feeders 1 and 2 of the network comprise fifteen and fourteen nodes, respectively. It was presumed that the maximum load demand of the network to be 6MW. The basic network parameters of the test system are summarized in Table 1.

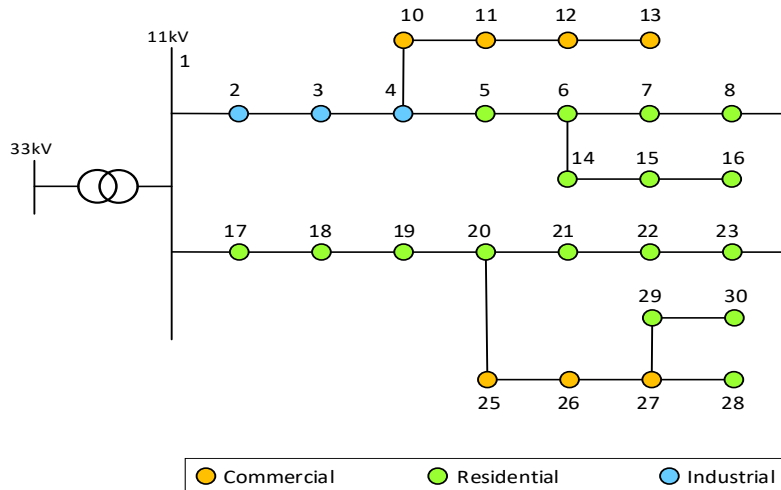


Figure 2. One-line diagram of the test network

Table 1. Basic network parameters of the test system

Variable		Value
Capacity		30MVA
Voltage		33/11kV
Number of feeders		2
Number of nodes		30
Load connected	Feeder 1	3.47MW
	Feeder 2	2.53MW

The network parameters related to the impedances and the lengths of each line segment were acquired from typical Malaysian MV distribution networks. The normalized PV generation and load consumption profiles adopted in this study are presented in Figure 3. As shown in the figure, residential consumers usually reflect a low consumption during the daytime, where PV generation is at its peak. Industrial consumers present a high consumption during the daytime and anchored at a lower consumption during the night. In contrast, commercial consumers depict a stable consumption during the daytime. Moreover, a PV generation profile concerning a sunny climatic condition was adopted to investigate the maximum possible impact due to high solar PV penetration.

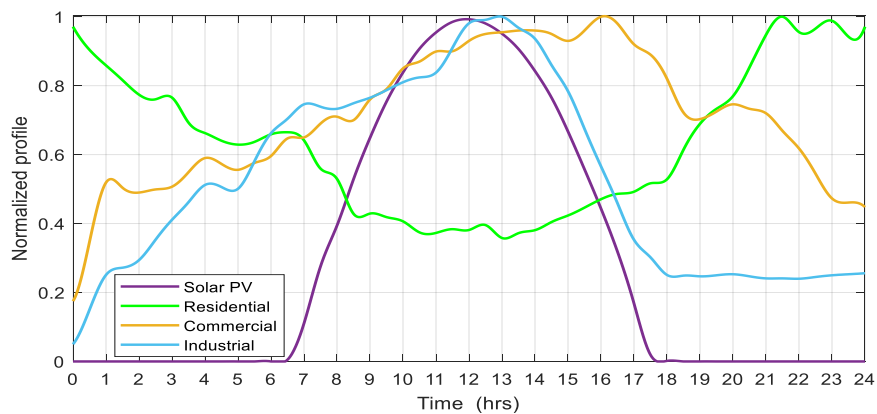


Figure 3. Normalized PV generation and load consumption profiles

Firstly, a detailed network model of the test system was developed in the open distribution system simulator (OpenDSS) simulation platform interfaced with MATLAB software. In order to examine the influence of solar PV penetration on the network, multiple PV deployment scenarios were considered by

integrating ten randomly generated PV capacities at randomly generated locations under different PV penetration levels. In the realization of PV installation capacity for each penetration level, the randomly generated PV capacities were assigned until the corresponding total PV capacity in each penetration level was reached. The maximum installed solar PV capacity was limited to 12MW at a 100% PV penetration level. The below selections were counted prior to the power flow simulations.

- Selection of the PV penetration level (0-100% in steps of 10%).
- Random selection of PV installation capacity (0.1-2MW, three-phase PV systems).
- Random selection of PV location.

Thereafter, three-phase, time-series, minute-by-minute, daily power flow simulations were performed considering the sunny day PV generation profile and the load consumption profiles covering residential, commercial, and industrial loads presented in Figure 3. The level of penetration was elevated from 0% to 100% in steps of 10%, and a total of 1000 Monte Carlo simulations (100 simulations per penetration level) were conducted for unique PV deployment scenarios. The simulation results were analyzed and quantified using the defined impact metrics to assess two key technical challenges of solar PV penetration; voltage rise and system power losses on MV distribution networks.

3. RESULTS AND DISCUSSION

For each power flow simulation, the maximum voltage, the percentage of nodes with voltage violations, and the daily average power loss values were computed. Thereafter, the mean and the \pm one standard deviation of each 100 simulations per penetration level were calculated. Figures 4, 5, and 6 graphically illustrate the variation of the maximum voltage, the percentage of nodes with voltage violations, and the daily average power loss against the PV penetration level, respectively. In each graph, the distributions of computed values were reflected by scattered points under each penetration level. Besides, the minimum and the maximum values of the distribution were presented using a square mark.

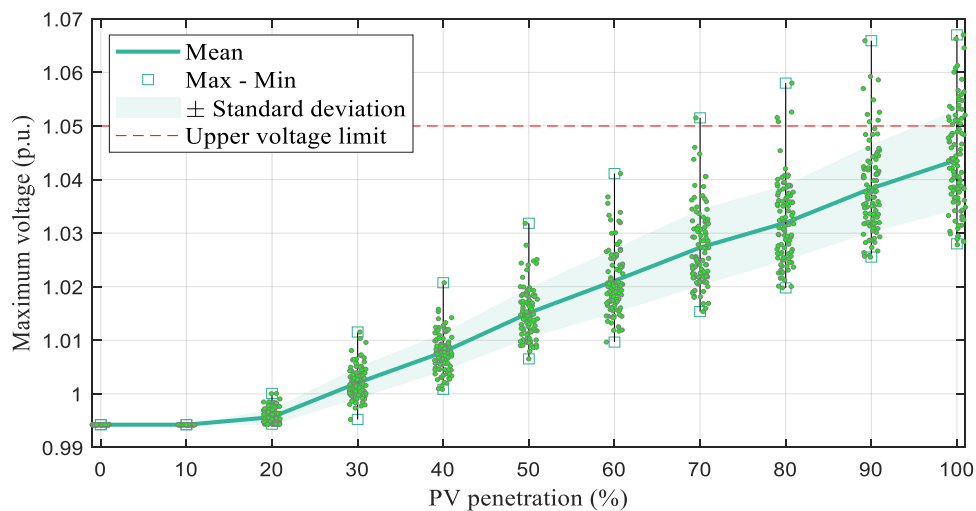


Figure 4. Variation of the maximum voltage against the PV penetration level

As shown in Figure 4, the maximum nodal voltage recorded for each power flow simulation was gradually raised with the increased penetration level. However, similar to the scenario without PV integration, the maximum nodal voltage was reported near the substation at the 10% penetration level. This is mainly due to the fact that the low PV generation at a 10% penetration level was not sufficient enough to compensate for the voltage drop due to the higher load consumption. The upper voltage limit (i.e., 1.05pu) violations were started at a 70% PV penetration level and continued until the maximum level considered in the study. According to the simulation results, there were no voltage limit violations until the PV penetration level was reached 60%. Even though a few nodes were observed with an upper voltage limit violation at a level of 70% PV penetration, the number of violations has surged with a further increase in penetration level. Consequently, the percentage of nodes with voltage violations was increased at a significant rate after 70% as depicted in Figure 5.

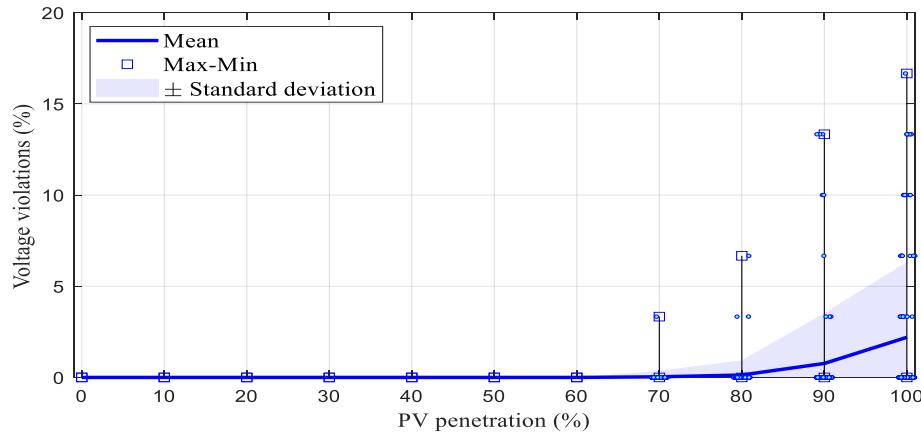


Figure 5. Variation of the percentage of nodes with voltage violations against the PV penetration level

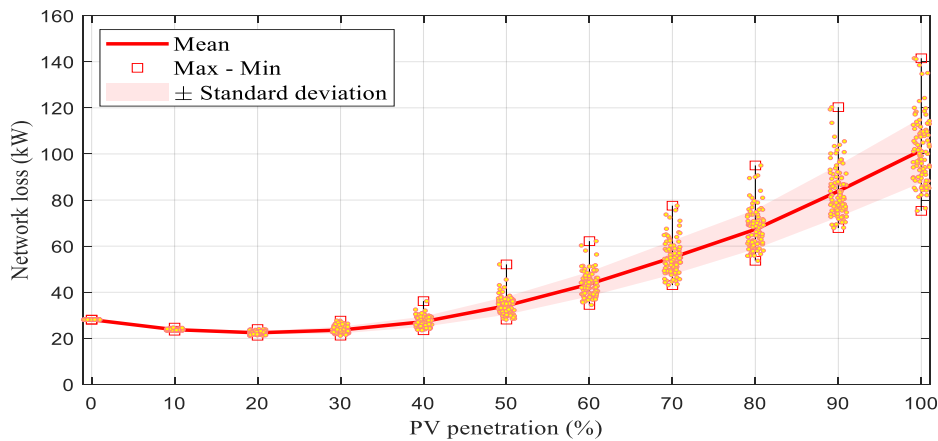


Figure 6. Variation of the daily average power loss against the PV penetration level

As it could be seen in Figure 6, a U-trajectory was depicted for the variation of the daily average power loss against the PV penetration level. The mean network loss was decreased up to 20% penetration level as the influx of PV reduced the net power flow within the network. However, it was raised above the base case network loss at a 50% penetration level owing to the increased reverse power flow.

By examining the simulation results, it was revealed that voltage rise is the worst repercussion of high solar PV penetration on the network. Besides, it was remarked that the occurrence of voltage violations does not solely rely on the total installed PV capacity of the network as the results obtained from the Monte Carlo analysis have shown a noticeable distribution at higher PV penetration levels (for each simulation at a certain penetration level, the installed capacity was retained as a constant). Therefore, it could be concluded that the size and location of PV systems connected to the network play important roles in assessing the impact of PV penetration on distribution networks. Further, the stochastic nature of solar PV generation and load consumption could have a substantial impact on the occurrence of these voltage violations. In particular, the occurrence of voltage violations could increase when most PV systems are located at residential nodes, where consumption is low during high PV generation periods. Conversely, the load consumption of both commercial and industrial nodes reflects a good correlation with PV generation, which could tend to minimize the occurrence and the magnitude of voltage violations.

4. CONCLUSIONS

In this paper, a Monte Carlo based probabilistic framework was proposed to assess the solar PV impacts on MV distribution networks while catering to the uncertainties related to solar PV generation. The case study presented has illustrated the effectiveness of Monte Carlo analysis in evaluating the potential technical challenges on a typical Malaysian MV distribution network. The maximum nodal voltage, voltage

violations, and system power losses were used as key metrics to quantify the technical performance of the distribution network. The simulation results revealed that the worst repercussion of high solar PV penetration on typical Malaysian MV distribution networks is the violation of the upper voltage statutory limit, which is likely to occur beyond 70% penetration level. Moreover, it was identified that the size and location of PV systems connected to the network play crucial roles in assessing the impact of PV penetration on distribution networks. Furthermore, it was observed that the stochastic nature of solar PV generation and load consumption could have a substantial impact on the occurrence of voltage violations. Thus, it is imperative to consider the stochastic behaviour of PV output and load demand, together with the feeder characteristics in the planning stage, to define the limits for PV installations in order to prevent future overvoltage problems.

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