Voltage Assessment of High PV Penetration in Radial Power Distribution Network

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Abstract. The total photovoltaic (PV) installed capacity of China plans to increase above 56 GW by 2050 to realize the goals of carbon peak and carbon neutrality. As a result, the hosting capacity of PV in a power distribution system affects the operation performance such as the quality of voltage, power balance, stability, and frequency problems. To investigate impacts of different PV penetration levels on the voltage and feeder in a typical power distribution network, this work considers uncertainties of PV output, and a Monte Carlo-based method is employed to simulate the impacts for different PV penetration levels on a power distribution network to evaluate voltage deviation from the normalized level (0.9 to 1.1 p.u.). A typical IEEE 33-bus system is studied and the connected PVG is based on 10-min resolution historical data from California in America in 2006. Results of the studied power distribution network are showed under three different cases: underloaded, overloaded, and fully-loaded that the 33-bus system injected with a higher PV penetration causes more voltage problems on the buses as well as the main feeder utilization tends to increase when the distribution system is underloaded or overloaded.

1. Introduction

In recent years, attention is paid towards decarbonization and increasing demand of customers [1]. Deployment of PV into power distribution networks is increasing because of government subsidy and global energy transition [2]. Regularly, in an electrical distribution network, power is assumed to flow from high voltage networks down to low voltage networks. If the distribution system is connected with a number of photovoltaic generation (PVG) units through electronic devices, parts of loads in the system could be fully supplied by the local PVG units. In other words, integration of PVG into power distribution systems changes network operation and is likely to result in system asymmetries [3]. As power distribution systems come across high PV penetrations, it is essential to examine and identify technical issues to assist managing the integration of PVG [4]. For a large-scale PVG integration system, the complexity of the assessment process will increase significantly in terms of power capacity, PV locations and voltage profiles due to the fact that power flow direction may changes to flow from the lower voltage networks to the higher voltage networks.

In order to assess voltage profiles in the systems connected with PVG, many papers studied and characterized the impacts in regard to PV penetrations [5, 6], feeder length and impedance [7], peak load and max PV power [8] and various resolution models [9]. Reference [5] considered the fault current profile and voltage variations in a typical residential distribution system and it pointed out that high PV penetration could be accommodated assuming that proper improvements were made to the protection and voltage control schemes. Addressing on equipment assessment, [6] captured the impact
of solar variability in different time scales and found out high PV penetration could extend the life of oil-immersed distribution transformers. According to [7], a longer feeder (higher impedance) caused a higher voltage rise in the power distribution network. To cope with variable loads and determine a feeder-allowed maximum level of PV penetration, [8] presented an index-based assessment safe margin for assessing the impact of PV generation with respect to the reverse power flow and voltage rise phenomena. In [9], the impact of time averaging on high-resolution data for customer load demand and PV output and on voltages in a lower level power distribution system was investigated and results showed different time averaging had a considerable impact on the demand in individual households.

Inspired by references [5-9], the main aim of this research is to assess the impact of integration of PVG into a typical power distribution network to evaluate voltage issues and feeder utilization based on the standard voltages. A Monte Carlo-based method is used to deal with uncertainties. Instead of considering PV installation for each customer, this research focuses on PV integration for each bus in a larger system, namely, the IEEE 33-bus system fed with 10-min resolution data for domestic loads. Additionally, a 10-min resolution PV data from California in America in 2006 from the National Renewable Energy Laboratory (NREL) Resource Data Center [10] and a synthesized 56-nodal load data [11] are used for the assessment.

This work is organized as follows: section II displays structure of the power distribution system. Section III introduces characteristics of the historical PV data and load demands as well as processes of the voltage assessment and feeder utilization check. Section IV presents the analytical and numerical results for different PV penetrations. Finally, section IV concludes this paper and the future prospective is discussed.

2. System components

2.1. Beta distribution based estimation for PV power

For longer chronological PV data, fitting beta distribution based on the one year California PV data can provide a sufficient guarantee for future prediction of PV output. The beta distribution function is shown as [12]:

\[
\begin{align*}
f_{\beta}(p') = \begin{cases} 
\frac{1}{\Gamma(\alpha' + \beta')} \left( p' \right)^{\alpha' - 1} \left( 1 - p' \right)^{\beta' - 1} & \text{if } 0 \leq p' \leq 1, \\
0 & \text{otherwise}
\end{cases}
\end{align*}
\]

\[
\alpha' = \frac{\mu_p^* \beta}{(1 - \mu_p)}
\]

\[
\beta' = (1 - \mu_p) \left( \frac{1 + \frac{\mu_p}{\sigma_p^2}}{\frac{\mu_p}{\sigma_p^2}} \right)
\]

Where \( \Gamma(\cdot) \) is the Gamma distribution, \( p' \) is the normalized PV output power with respect to the maximum PV power at the \( t^{th} \) hour, \( \alpha' \) and \( \beta' \) are defined in (2), \( \mu_p \) and \( \sigma_p \) are the average PV power and the standard deviation of PV power. The expected total PV power data can be obtained by [13]:

\[
P_t = \int_0^1 P_{pv}(p') \times f_{\beta}(p') \, dp'
\]
2.2. **IEEE 33-bus power distribution system**

The typical distribution system, proposed by reference [14] in 1989, comprises 33 buses, 32 fixed and 5 switchable lines without reactive power compensation. The network structure, shown in Fig. 1, is connected in a radial form and has no generation units connected to the system. The voltage limit for each bus is in the range of 0.9 to 1.1 p.u. which is an acceptable range for practical power distribution systems. To relax these limits, the addition of RPCs is necessary.

It should be noted that in the proposed distribution system all switchable branches are removed for simplification and the power flow is assumed to flow from the slack bus 1 to the rest. These changes do not affect the network reconfiguration in the test system but reduce unnecessary complexities. To assess the growing trend of PVG integration, the IEEE 33-bus system is fed with practical synthesized load demands and connected with PVG units with practical power data. More specifications of the 33-bus system can be found in [14].

![Figure 1. A typical structure of IEEE 33-bus system](image)

### 3. Analysis Methodology

The methodology in this paper involves the stochastic process of load profile assignment for each of the buses in the 33-bus system. PVG locations and the power output are also randomly selected for the rest of the buses. After the 33-bus system is properly assigned with load demand and PVG, a MATPOWER toolbox is implemented to calculate power flow via the `runpf` function to assess the system states. A Monte Carlo method is performed 150 times for different penetration levels to analyze the assessments.

#### 3.1. Characteristics of the historical PV data and load demand.

From the perspective of performance assessment in the 33-bus system, analyzing the correlation between PV generation and load demands at each bus is important. In Fig. 2, 3 out 60 PVG units are selected to represent the PV output characteristics in California in 2006 from the National Renewable Energy Laboratory (NREL) Resource Data Center. It should be noted that the smallest PVG capacity in California is 5 MW, 44 MW is taken as the medium capacity since the average PV capacity is 42.1 MW and the local highest PV capacity is 150 MW. The load demands used in this paper are synthesized 56-nodal load profiles and an example of it is shown in Fig. 3. Both PV profiles and daily domestic load profiles used in this research are measured with a resolution of 10 minutes. For the 33-bus system, load profiles are randomly selected from the synthesized load demands, and 33 of them will be assigned to the power distribution system. Similarly, buses of a certain penetration level are selected to install PVG units.
Figure 2. Practical PV characteristics with lower, medium and high capacity in California

Figure 3. Example of load demand at bus 16 in the 54th day

3.2. Monte Carlo based simulations
Monte Carlo method (MC) is a multiple probability simulation that estimates the possible results of an uncertain scenario or event. They provide several advantages over predictive models with fixed inputs [15], which includes sensitivity analysis and data correlation investigations.

With the load and PV data assigned to the 33-bus distribution system, the assessments for the system bus voltage and feeder utilization can be obtained via the computation of power flow under different PV penetration levels. The simulation procedure is explained as follow:
1. Randomly select N samples from the synthesized 56 load profiles;
2. Assign N load profiles to N buses in the 33-bus power distribution system (N ≤ 33);
3. For a PV penetration of P %, P % of the N buses are selected to install PVG units with the PV capacity illustrated in Fig. 2;
4. With the historical PV data and the PV size, the power output is calculated using (3) and the injection is modeled with an unity power factor;
5. Calculate the power flow in the distribution system with the MATPOWER tool box in MATLAB 2019a;

6. Assess the impact of different PV penetration for voltage problems and utilization of the system feeder.

The bus voltage under normal situations should be maintained between 0.9 p.u. to 1.1 p.u. according to the voltage standard, and those outside this boundary are considered as faulty situations and require voltage and power regulations.

4. Results and analysis

In this section, the voltage assessment result for the 33-bus system is presented in terms of the percentage of buses that occur voltage overflow (above 1.1 p.u.) or underflow (below 0.9 p.u.). In other words, the buses with voltage problems are excluded and recorded for an increasing PV penetration. This research is performed on MATLAB 2019a and the Monte Carlo simulation is implemented 150 times for buses with PVG units for different PV penetration levels. Based on specifications of the typical IEEE 33-bus power distribution system [14], the base voltage and base capacity are 13 kV and 10 MVA, respectively. The active power demand of the system is 3715 kW and the reactive power is not considered in this work.

In order to study the impacts of integrating PVGs into the IEEE 33-bus system, Fig. 4(a) illustrates an underloaded case for the percentage of the buses with voltage problems under different PV penetration levels. It should be noted that the system demand is 3715 kW and the minimum capacity of PVG units from California is 5 MW, which means the distribution network is severely underloaded. To study the underloaded case, the PVG profile is scaled down to 10% of the average capacity, which becomes 4400 kW (0.1 × 44 MW). By using the Monte Carlo method, it is possible to show the average percentage of the faulty buses and their deviations. From Fig. 4(a), it is apparent that voltage problems begin to occur when PV penetration level reaches 20%. With PV penetration increasing, more and more buses of the system continue to suffer from a voltage rise or sag issue and nearly 70% of the buses have voltage problems once the PV penetration level is at 100%. Additionally, Fig. 4(b) shows the utilization rate of the distribution feeder. Generally, it tells how the state of the feeder changes according to different PV penetration levels. It can seem that the feeder utilization rate reaches over 100% at the PV penetration of 50 to 60% with the cable ampacity of 2000 A. The reason why the feeder is tremendously taken up is that the connected high-capacity PVGs are feeding power to electricity grids.

![Figure 4](image_url)

**Figure 4.** Impact assessment of different PV penetration for underloaded IEEE 33-bus system.
To further assess cases of the system that is overloaded or fully-loaded, the California PV data is scaled by two factors of 0.002 and 0.085. Since the average PV capacity in California is 44 MW, the scaled factor can be selected around 0.085 (3715 kW/44000 kW) for the fully-loaded case, and those smaller than 0.085 can be taken as the overloaded case. Fig. 5 shows feeder utilizations of both cases and no voltage issues occur for each penetration level. The average utilization of the mainline segment under overloaded fluctuates between 132.5 to 137.4 % under different PV penetrations. Feeder utilization in the overloaded system is great because the distribution system is fed by electricity grids. In Fig. 5(b), when the distribution system is almost fully-loaded, most of the PVG units are supplying the system load demand, the lowest feeder utilization is 33.3 % with a PV penetration of 20 %. It is possible that 20 % of the penetration level can provide the most economic solution for power usage since it uses the least power supplied from electricity grids. After 40 % of PV penetration, the usage of the main feeder segment becomes busy as the system is getting underloaded with more PV installations.

5. Conclusion
This paper employed a Monte Carlo method to assess the impact of different PV penetration levels on the typical IEEE 33-bus power distribution system. A 10-min resolution California PV data and a synthesized 56-nodal load data are used for assessing voltages of the buses based on the standard voltages (0.9 to 1.1 p.u.) and investigating the main feeder utilization rate under different PV penetration levels. The results are shown with three cases: underloaded, overloaded, and fully-loaded distribution systems. When the system is underloaded, voltage issues can occur at a PV penetration of 20 % and the main feeder utilization tends to increase due to the PVG units are feeding power to the grid. For the overloaded and fully-loaded distribution systems, no voltage problems occur. The lowest feeder utilization rate for the fully-loaded system is 33.3 % at a PV penetration level of 20 % and it tends to increase with greater PV penetration levels. On the contrary, feeder utilizations of the underloaded or overloaded system are high as the 33-bus system supplies/receives power to/from the grids.

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