Probabilistic Static Voltage Stability of Power System with Integration of PV Generation

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Research Article

Probabilistic Static Voltage Stability of Power System with Integration of PV Generators using Monte Carlo Simulations

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Abstract: As a renewable source, the uncertainties and intermittencies of solar irradiance have become the main concern in developing and integrating such power generation into an electricity network. In power system operation, it is important to maintain a reliable voltage profile under random power injection from renewable power generations. The effect of photovoltaic (PV) power plants on the static voltage stability of the interconnected power system is presented in this paper. The probabilistic study was conducted through Monte Carlo Simulation (MCS) to investigate the fluctuation of voltage profiles under uncertain power injection from PV power plants. The standard test system of IEEE 14 bus and practical test system of Lombok, West Nusa Tenggara electricity network are investigated. It was noticed that the installation of a photovoltaic power plant affected the voltage profiles. The fluctuated condition of power injection from PV power plant resulted in more fluctuation of voltage profiles as indicated by higher standard deviation values. Moreover, distributed location of the PV power plant also influenced the circumstances of voltage fluctuation, providing less fluctuated condition of voltage profiles. Eventually, it can be observed that the voltage fluctuation would influence the static voltage stability of the interconnected power system.

Keywords: Photovoltaic Generator, Probability Distribution, Renewable Energy, Solar Energy, Voltage Fluctuation, Voltage Profiles.

1. INTRODUCTION

Massive development of technologies drastically changes the necessity of society. In few decades, electricity has become an essential thing for human life since most of the appliances and facilities need electrical energy to operate. Therefore, the dependences of humans live on electricity has been increasing enormously. With the fast growth of electricity demand, the invention and development of novel energy resources to ensure sufficient electricity supplies are critical. On the other hand, the deposits of fossil fuels are continuously decreasing due to extensive exploration and consumption [1, 2]. Moreover, the usage of fossil fuels introduces detrimental effects on the environment. With the limitations and drawbacks of fossil fuel, renewable energy is the promising option to overcome the energy concern. One of the most developing renewable energy resources is solar energy. By 2020, around 500 GW solar PV facilities are installed throughout the world. It is expected that in 2050, 15 % of world energy demand are fulfilled by solar energy [3].

The implementation of PV-based power plants brings economic beneficial effects due to the abundant amount and cheap energy resources. Moreover, it is also environmentally friendly as a result of the non-emission operation and the usage of non-polluting materials [4]. Despite those advantages, the integration of PV-based power plants also alters the power system operation and control. Recently, the increased penetration rate of PV generation has raised concerns over stability due to the possible negative impact on the stability of the power system [5]. The generation of electricity from the sun has a challenge because

the availability of the sun on the earth's surface depends on the sun's position which varies due to differences in latitude [5, 6]. Furthermore, the dependency of solar power on environmental and weather circumstances increases the uncertainty and unpredictable operating condition of the power system. It potentially affects the stable operating point of the power system [6, 7].

Fluctuating power injection from PV-based power plants may change the power flow direction, transmission line congestion, and hence the power losses. Eventually, it potentially influences the system voltage. The bus voltage is considered an important parameter in the power system since it significantly influences system stability and safety. The variations in P and Q affect the voltages across all the buses in the system as well. Therefore, a voltage stability analysis can be applied to decide whether the voltage levels across the buses are at an acceptable level or not [8, 9].

Power system voltage stability refers to all buses in the system that can maintain a steady voltage after a fault. However, from a system planning and operating point of view, the stress stability analysis is to find the distance of the system to the voltage drop in normal operation and to identify areas where the stress is weak when the voltage drops. This is called static voltage stability [10]. With the increasing trend of PV integration in power systems, it is important to investigate the effects of having of such renewable power generation on static voltage stability. Researchers monitored that PV location and size have a profound impact on system voltage stability [3]. It might have either adverse or advantage impacts on voltage stability. The effect of the partially solar-PV system on long-term voltage stability was investigated in [11, 2]. It was observed that the integration of PV power plants might improve the system voltage stability.

Even though many kinds of research have been conducted to investigate PV effects on voltage stability, however, it was only using the deterministic approach. The main drawback of the deterministic approach is the limited number of cases [1, 13]. Therefore it would not reflect the actual condition of system voltage profiles under random power injection from PV power generation. With the limitation of the deterministic

approach, it is important to conduct a probability analysis approach. This paper concentrates on the analysis of PV plant installations in interconnected power systems using a probabilistic approach. A probabilistic study using the Monte Carlo simulation method is implemented to provide a realistic scenario of uncertain conditions of power injection from a PV power plant.

2. MATERIALS AND METHODS

2.1 Monte Carlo Simulation

Voltage stability is concerned with the ability of the power system to maintain acceptable voltages across all buses in the system under normal conditions and after failure. The system enters a state of voltage instability when a disturbance occurs, an increase in load demand, or a change in system condition causes a aggressive and uncontrolled voltage drop. A major factor causing instability is the inability of the power system to meet reactive power demands [9].

As power injection from the renewable power plant is continuously fluctuating due to unpredictable weather conditions, it would introduce the uncertain operation of the power system. Under uncertain power injection from a PV power plant, a deterministic power flow analysis is not sufficient to represent the actual power system condition. Therefore, a probabilistic analysis approach is required to capture the behavior of the power system in particular voltage stability circumstances under random power injection from the PV power plant.

Probabilistic power flow (PLF) based on numerical methods (such as Monte Carlo simulations) or analytical methods (such as convolutional techniques) was developed in the 1970s to deal with power system uncertainty due to variations in grid variables [13].

The active bus load is an independent random variable and the transmission system is represented by a DC network model (so that the reactive power flow is negligible). The generation delivery procedure is modeled by allocating the variation of the total electric charge for the generation bus. Since the active electric load variable on each bus is

sumed to be independent, the probability density function of the circuit current can be calculated by a series of convolutions. Later, this basic method was extended and also applied to the AC network model [14].

The probabilistic distribution function is estimated from the solar irradiation data collected respectively using the Gaussian mixture distribution function [15] The Gaussian mixture model is useful for modeling data that comes from one of several groups that may differ from one another, but data points in the same group can be modeled well by the Gaussian distribution. [13] The formula for determining the Gaussian value in Equation (1):

$$PX^{(x)} = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \tag{1}$$

The variable x represents the value of the random variable and for the variable μ represents the expectation of an experiment, for the variables σ^2 or σ represents the standard deviation. For some of the different formulas, here it is written in Equation (2):

$$Px^{(x)} = N(x; \mu, \sigma^2) \tag{2}$$

which the variable N describes the normal value.

Once a statistical model is defined in terms of a probability density function, a Monte Carlo simulation is performed which involves repeating the simulation process using in each simulation a set of specific values of the random variable [16]. Various methods have been proposed to study the effect of uncertainty on stress stability. Among the proposed probabilistic analytical methods, the Monte Carlo simulation has become a popular method due to its ability to handle a large number of samples with great accuracy and flexibility. As the power output of the generation unit varies due to the uncertainty of the renewable energy system, the power-sharing scheme in the microgrid changes accordingly which might disrupt the power generation and load demand balance [15].

Load Flow results based on Monte Carlo Simulation in terms of power flow in various parts of the system and voltage profiles in all network buses can be treated statistically, and statistical estimation and inference methods can be applied [15].

In uncertainty analysis, the relationship between the dependent and independent variables can be expressed in Equation (3):

$$v = h(z) \tag{3}$$

h represents a function describing the correlation between the dynamic behavior of the output variables and the uncertain values of the input variables. The input and output vector variables can be represented as

$v = [v\_1, v\_2 \ldots]^\wedge t$ and $z = [z\_1, z\_2 \ldots]^\wedge t$ of their respective values [15].

The purpose of Monte Carlo analysis is to estimate the uncertainty of the output or the dependent variable resulting from the uncertainty of the input or the independent variable through certain complex functions [12].

For modeling the power generation in PV, there are several models of system problems that do not need to be considered, such as not considering the system configuration and line impedance values. The purpose of modeling the power distribution function in PV is to schedule the generator by considering the solar energy system by determining the optimal amount of generating power for the solar energy system units during the study period so that the total cost can be minimized by the power balance equation, requirements for power reserves, and other constraints [17].

Calculation of changes in the duration of radiation can be converted to power using Equation (4):

$$P_{PV}(G_t) = \begin{cases} P_{sn} \dfrac{(G_t)^2}{G_{std}R_c} \\ P_{sn} \dfrac{G_t}{G_{std}} \end{cases} \tag{4}$$

G_t = Forecast radiation per hour
G_{std} = Solar radiation in a standard environment is set with a value of 1 000 W m^{-2}
R_c = The point of radiation is defined as 150 W m^{-2}
P_{sn} = Average PV power output

These values can only be known through short-term forecasting. Because the demand for system load and solar radiation depends on the social behavior of the customer and weather variables [18].

2.2 Photovoltaic Model

In this manuscript, probabilistic analysis of system voltage profiles under PV power uncertainty is conducted using DigSILENT Power Factory analytical software. Therefore, the default PV model provided in Power Factory software is considered in this study. The template model of PV with additional features and control is comprising of multiple control blocks and functionalities.

The PV-based power plant is modeled as a static generator with MPPT control system, and DC link capacitor as depicted in Figure 1. The inverter system of the PV model employs Udc-Q which maintains the voltage of DC capacitor constant to ensure stable operation of the PV system by suppressing power and voltage fluctuations. The voltage controller is providing direct (Id_ref) and quadrature (Iq_ref) current reference values to control switching stages of the inverter. While PLL model ensures synchronized operation between the PV system and the other generator units during grid-tied operation.

For the static voltage stability study, the dynamic model of the PV power plant is simplified as follows [19, 20]: The dynamic of the MPPT controller is neglected and it is assumed that the PV array model

provided reference values for the Udc-Q controller. Due to the high-frequency switching features of the inverter system, the fast response of the inverter inner control loop is neglected.

3. RESULTS AND DISCUSSION

Two test systems are considered in this paper to investigate the impact of uncertain power injection from PV systems. The first investigated test system is IEEE 14 as depicted in Figure 2. To investigate the effects of PV power uncertainty on system voltage profiles, the PV power plants are connected in bus 4, 5, and 10.

The second study case considers the electrical system of Lombok, West Nusa Tenggara, Indonesia as depicted in Figure 3. the Lombok electricity system consists of seven generating units, which operate at a voltage of 150 kV, and consists of 17 buses and 19 channels connected to load centers. Multiple PV-based power plants are connected in three buses which are located in Sengkol, Pringgabaya, and Paokmotong with a capacity of 3×5 MW. By integrating PV sequentially, it will be done by randomizing the PV radiation capacity to analyze the voltage profile of the transmission system.

The Lombok network was selected in this research due to the high solar potential energy in the island while most of the conventional power generations were powered by diesel engines. The penetration of PV generation in Lombok island has been significantly increasing, replacing a certain
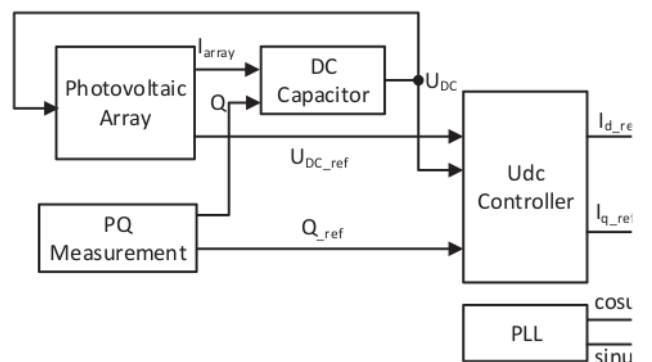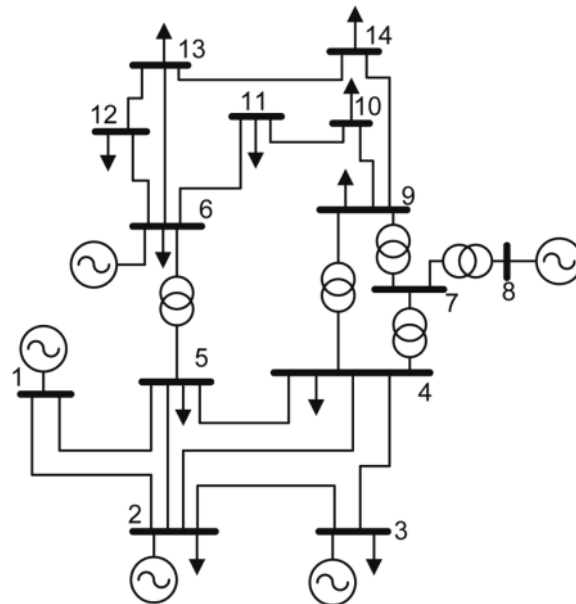

Fig.1. PV system model in DigSILENT power factory
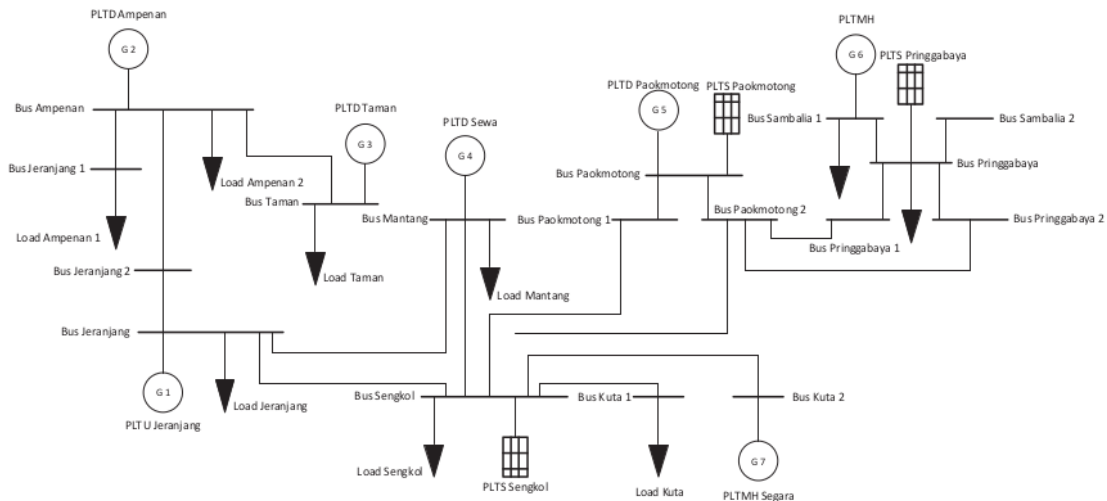
Fig 2. Single line diagram of IEEE 14 Bus

Fig. 3. Single line diagram of Lombok 150 kV

tion of diesel engine-based power generation. Therefore, it is necessary to investigate the impacts of PV integration on static voltage stability in this island electricity network.

To realize the uncertain condition of PV power plant power injection in the investigated test systems, 1 000 data of PV power are randomly generated and sampled through the Monte Carlo simulation method. The 1 000 random scenarios of PV power injections from different regions are then implemented in DigSILENT power factory analytical software. Fluctuation of voltage profiles of the selected bus is statistically investigated through average and deviations values of the selected buses.

The dynamic model of PV generation developed in DigSILENT power factory is considered to provide more realistic system dynamic behavior

under the different generations of PV generations.

3.1 Analysis of Voltage Profiles in IEEE 14 bus

In the first study case, two scenarios were considered. The first scenario investigates the effects of integrating one PV power plant to bus 4 of the IEEE 14 bus system. The 1 000 data of random power injection from the PV power plant are considered, resulting in 1 000 values of bus voltage fluctuations.

Figure 4 shows the fluctuation of bus 5, 8, and 9 in the IEEE 14 bus system after the integration of the PV power plant on bus 4. It was monitored that when one PV power plant is integrated, bus 5 V fluctuated moderately as depicted in Figure 4a. The bus voltage of bus 5 has an average value of 0.967 5, a maximum value of 0.968 02, a minimum value of 0.966 97, and the standard deviation value on bus 5 is 0.000 74. The less fluctuating condition was observed in bus 8 as shown in Figure 4b.

It was monitored that the voltage of bus 8 has

an average value of 0.958 03, a maximum value of 0.958 30, a minimum value of 0.957 76, and the standard deviation value on bus 8 is 0.000 37. More stable bus voltage under different power injections from one PV power plant is monitored in bus 9 as presented in Figure 4c. It was observed that the voltage of the corresponding bus has an average value of 0.947 02, a maximum value of 0.947 13, a minimum value of 0.946 91, and with lower standard deviation value on bus 9 is 0.000 15.

The second scenario considers the integration of three PV power plants on bus 12, 14, and 15 in the IEEE 14 bus system. Integration of three PV power plants in the existing power system network would inject more power into the system. Therefore more voltage enhancements were expected. On the other hand, the distributed energy sources would provide a more stable power flow in the network, resulting in less fluctuation of system voltage profiles.

The investigated result from the IEEE 14 bus system with the integration of PV generators is depicted in Figure 5. The voltage of bus 5 has an
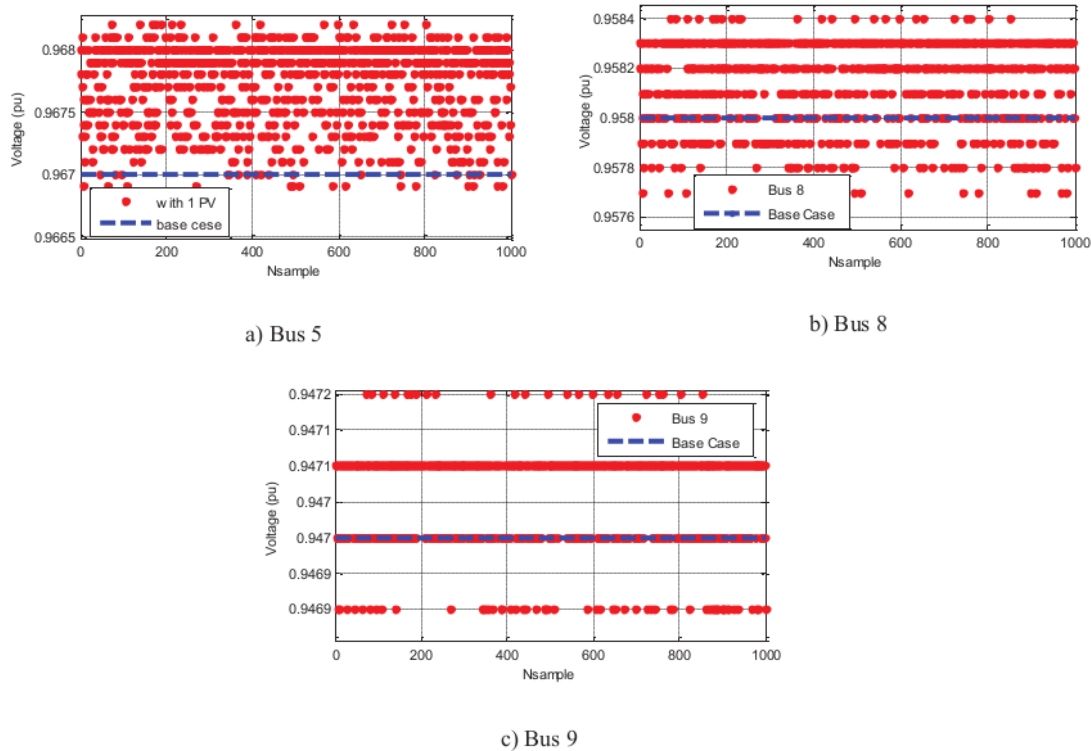

a) Bus 5

b) Bus 8

c) Bus 9

Fig. 4. Bus Voltage of selected bus of IEEE 14 bus with the integration of 1 PV power plant.
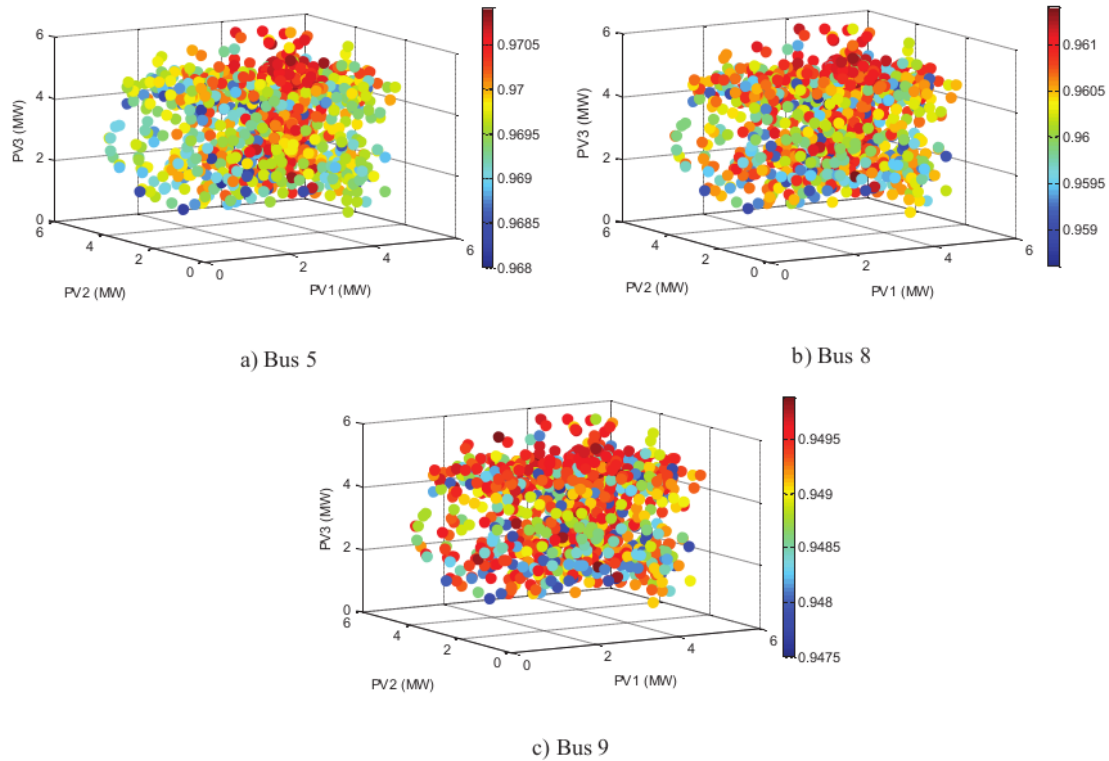
a) Bus 5

b) Bus 8

c) Bus 9

Fig. 5. Bus Voltage of selected bus of IEEE 14 bus with the integration of 3 PV power plants.

average value of 0.969 66, a maximum value of 0.969 90, a minimum value of 0.969 42, and the standard deviation value on bus 5 is 0.000 34. Enhancement of voltage profile is also monitored in bus 8 and 9. After integration of three PV power plants, the voltage of bus 8 has an average value of 0.960 4, a maximum value of 0.960 58, a minimum value of 0.960 40, and the standard deviation value on bus 8 is 0.000 12. While the voltage of bus 9 has an average value of 0.949 27, a maximum value of 0.949 28, a minimum value of 0.949 27, and the standard deviation value on bus 9 is 0.000 13.

From the two scenarios, it can be noticed that integration of one PV system results in a slight change of voltage profile and hence a small fluctuation in voltage values. In the second scenario of integrating three PV power plants, the voltage profiles of the investigated buses are less fluctuating than in the first scenario with one PV power plant. The placement of PV power plants close to each other results in the less fluctuating condition of power flow and hence enhanced the voltage stability. Additional power injection from

three locations of PV power plants results in more stable voltage profiles of the investigated bus.

3.2 Lombok Network Power Flow Analysis

Similar scenarios were implemented in the second practical test system of the Lombok interconnected power system. In the first scenario, one PV power plant is integrated. The rated capacity of a 5 MW PV system is considered.

Figure 6 represents the fluctuation of bus Ampenan, Jeranjang, and Mantang in the Lombok system after the integration of one PV power plant. It was monitored that when one PV power plant is integrated, the bus voltage of Ampenan fluctuated significantly. The bus voltage of bus Ampenan has an average value of 0.987 9, a maximum value of 0.988 1, a minimum value of 0.987 8, and the standard deviation value on the Ampenan bus is 6.045 1. Similarly, the fluctuating condition was observed in bus Jeranjang. It was monitored that the voltage of bus Jeranjang has an average value of 0.991 9, a maximum value of 0.992 1, a minimum
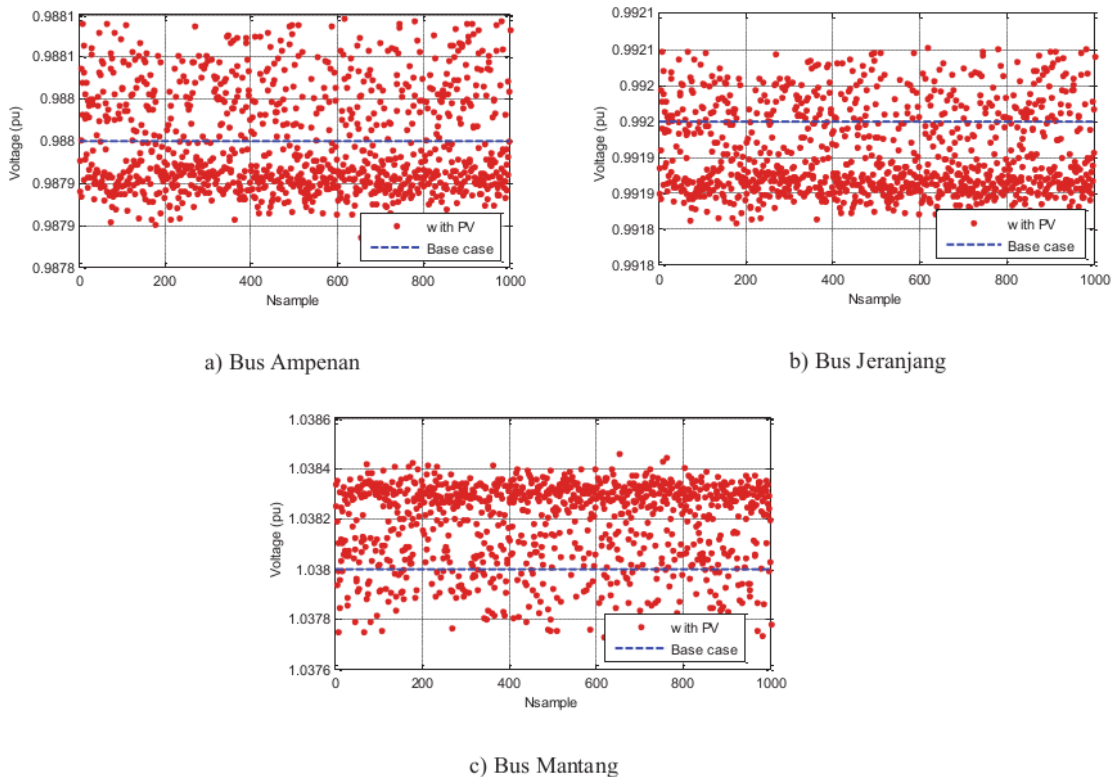
a) Bus Ampenan

b) Bus Jeranjang

c) Bus Mantang

Fig. 6. Bus Voltage of selected bus of Lombok system with integration of one PV power plant.

value of 0.991 8, and the standard deviation value on the Jeranjang bus is 6.015 4.

More stable bus voltage under different power injections from one PV power plant is shown in bus Mantang. It was observed that the voltage of the corresponding bus has an average value of 1.038 1, a maximum value of 1.038 4, a minimum value of 1.038 4, and the standard deviation value on the Mantang bus is 0.000 1.

Fig. 6. Bus Voltage of selected bus of Lombok system with integration of one PV power plant. The second scenario considers the integration of three PV power plants in Sengkol, Pringgabaya, and Paokmotong with a capacity of 3 × 5 MW. Figure 7 shows the fluctuation of bus 5, 8, and 9 voltages under uncertain power injection from three PV power plants.

Additional power injection from three locations of PV power plants results in more stable voltage profiles of the investigated bus. More power

injection from three distributed PV power plants enhanced the voltage profiles of the system and also reduced the voltage fluctuation.

The bus voltage of Ampenan is indicated by an average value of 0.987 6, a maximum value of 0.9879, a minimum value of 0.987 3, and the standard deviation value on the Ampenan bus is 0.000 122. The average value of the voltage profile is higher and the standard deviation is lower than the scenario with one PV system. These conditions indicate the improvement of static voltage stability. Similar results are observed in bus Jeranjang and Mantang. In detail, the voltage profile of bus Jeranjang has an average value of 0.986 7, a maximum value of 0.987 1, a minimum value of 0.986 5, and the standard deviation value on the Jeranjang bus is 0.000 123. While bus voltage of Mantang has an average value of 1.039 113 a maximum value of 1.03 96, a minimum value of 1.038 3, and the standard deviation value on the Mantang bus is 0.000 256.
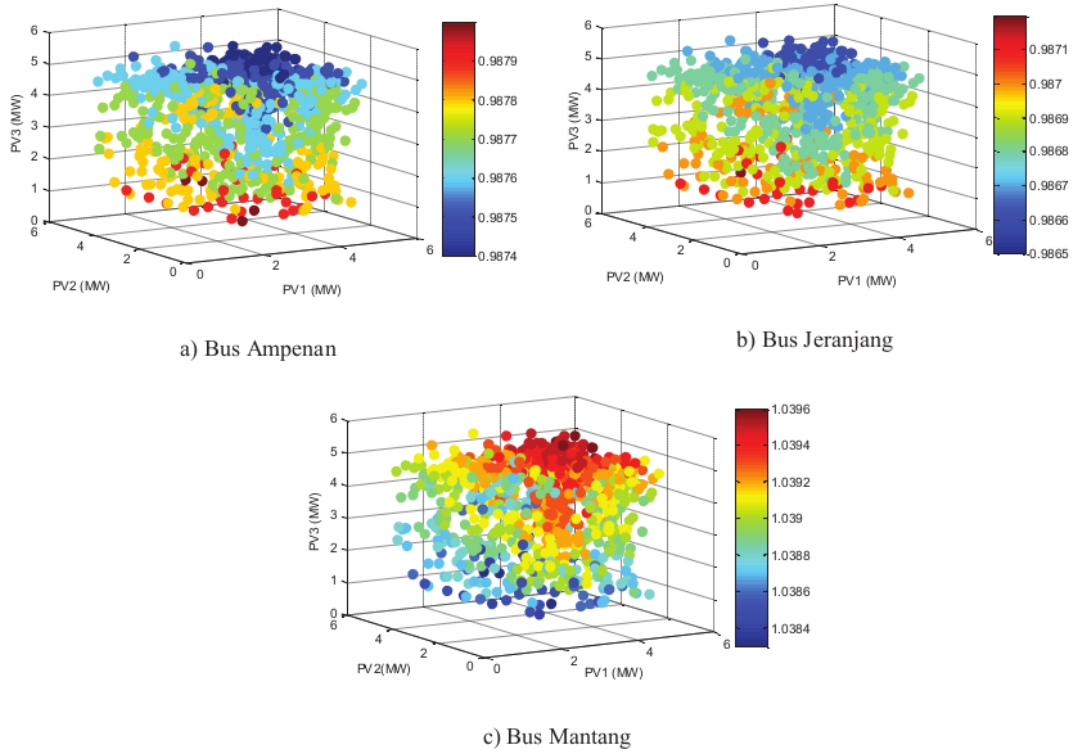
a) Bus Ampenan

b) Bus Jeranjang

c) Bus Mantang

Fig. 7. Bus voltage of selected bus of Lombok system with integration of three PV power plants.

From the presented results, integrating more PV power plants in some locations provides beneficial effects on power system operation. Since the function of the PV power plant is to support the power demand without reducing existing power generation from conventional power generation. Eventually, it would improve the voltage profiles of the system. The static voltage stability of the power system is enhanced with the increase of PV power plant penetrations. It can be observed from the presented research that most of the voltage profiles had higher values than in the base case scenario without penetration of the PV power plant. Moreover, distributed location of the power system would reduce congestions of transmission lines and power losses. It would provide a more stable voltage profile as indicated by lower values of standard voltage deviation. With these results, it can be suggested that more distributed PV power plant installation would provide a more stable situation of voltage profiles. The obtained results can be implemented to planning the PV allocation and transmission line expansion. Hence, the effect of uncertainties of solar irradiance can be minimized and more stable system voltage profiles can be maintained.

In this research, Monte Carlo Simulation is considered to provide the probabilistic study of system voltage variations under random power injection from PV generations. To obtain more realistic results, the number of data can be increased. However, it should be considered the computational time when a large number of data were considered in the studies. In the future, more detailed data resolution can be considered to perform the probabilistic analysis and more renewable energy sources such as wind power generation can be involved in the study.

4. CONSLUSION

A probabilistic study of voltage profiles of the interconnected power system has been addressed in this paper. It was clearly shown from standard test systems and practical test systems that the integration

of PV power plants and additional power injection from those renewable power sources enhanced the system voltage profiles. It was also observed that more distributed power sources would maintain the static voltage stability conditions even though the power system was operated under uncertain circumstances of power injection from PV.
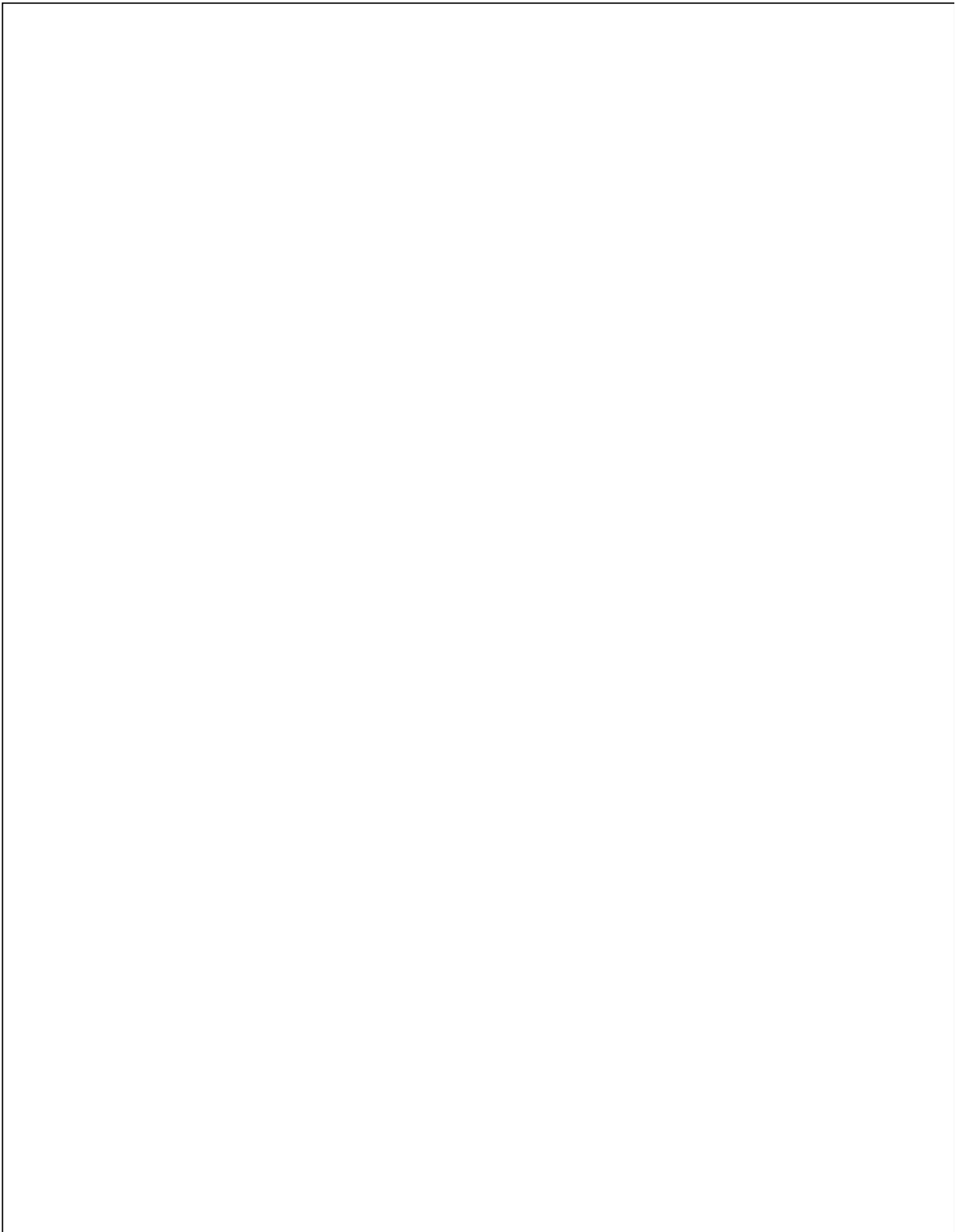
5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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