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Probabilistic load flow based voltage stability assessment of solar power integration into power grids

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ABSTRACT

The interconnection of renewable energies increases the complexity of modern power systems. Hence, stability assessments should be made to ensure the system's stability after penetration. Solar power is a type of renewable energy that has become a widespread energy source among renewable energy sources. About 1 MWp of the solar power plant has been prepared to be interconnected to the IEEE 8 bus of Manokwari grid, and this paper investigates the voltage profile, power losses, and stability of the solar power plant penetration using an adaptive kernel density estimator (AKDE) and compares it to a Monte Carlo simulation (MCS)-based probabilistic load flow (PLF). About 5000 samples have been used to test the grid after the connection. Results of simulations show that the solar penetration can reduce power losses from 0.4084 MW to 0.3080 MW and 0.3045 MW by the proposed method and MCS method, respectively, and further increase the bus voltage profile. The power network has the stability to be connected to solar power, as indicated by the small stability index values of each bus. The proposed method using the AKDE method has a more accurate result in stability indices indicated by small fast voltage stability index (FVSI), line stability index (L_{mn}), and line stability factor (LQP) indices.

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1. INTRODUCTION

Renewable energy sources have attracted human attention in line with the increasing global demand for energy and the decline in fossil fuel sources [1], [2]. This condition is also supported by the urgent need for environmentally sustainable development [3]. On the other hand, the massive penetration of this renewable energy resource into the power grid will impact the security, reliability, and stability of the network due to its uncertainty [4]-[9]. In consequence, appropriate and thorough planning is needed for its operation.

Load flow study, also known as deterministic load flow (DLF), is one of the most important tools in the planning and operation of power systems. These studies are the basis for carrying out all power system applications, and they have long been carried out on conventional electric power systems [10]. With the integration of renewable energy-based power plants, the usage of this study is no longer accurate since it uses fixed values that are simply valid at certain moments.

The inaccuracies of DLF put the operation and planning of the electric power system in danger. To overcome this deficiency, the probabilistic load flow (PLF) method was introduced in 1974 [11]. The PLF method is based on the stochastic calculation of load flow, where the calculation is based on the probability distribution of network configuration, and weather data, obtained through statistical analysis of historical data. Researchers have widely used PLF to assess the safety, reliability, and stability of the penetration of renewable energy into existing power systems [12], [13].

Solar power plants have become one type of power plant that is currently very popular among other renewable energy sources [1], [14]. This popularity is due to its simplicity in installation and maintenance. In the same way, solar technology has matured, and the mass production of photovoltaic (PV) panels as a significant part of solar power generation has lowered utility costs. Every property can have a solar power utility that follows these conditions without disturbing other activities. Hence, the penetration of solar power into the grid is predicted to increase continuously; up to hundreds of MW might be present in the near future. Thus, solar power is estimated to reach 8519 GW by 2050 [15]. Some impacts of solar power penetration have been reported in previous research, i.e., frequency stability [3], [16], voltage stability [17], over-current [18], grid harmonics [6], economic and environmental [19], [20].

PLF has been considerably developed by utilizing stochastics [12], [13], [21]–[24], and machine learning [25] methods to achieve accurate random values. Recent research on PLF, i.e., Nosratabadi *et al.* [26] combined the Monte Carlo simulation (MCS) method with the Halton Quasi to get random values that vary with the same level of precision as the Latin hypercube. Yang *et al.* [25] has improved the analytical approach of DLF by occupying principal component analysis and particle swarm optimization methods in reducing the range of variation of input data. They show that their proposed method has good results compared with traditional cumulant PLF and MCS. Finally, Thasnas and Siritaratiwa [27] has proposed an adaptive kernel density estimator (AKDE) method to do the PLF on IEEE-13 and IEEE-37 buses with connected solar and wind DG. The AKDE method has faster results compared to MCS and diffusion methods.

The uncertainty in the electrical power system directly impacts the stability of the system. To determine the stability of an electric power system, several indicators have been introduced, i.e., fast voltage stability index (FVSI) [27]–[29], line stability index (LMN) [27], [29], line stability factor (LQP) [27], [29], line voltage stability index (LVSI) [27], expected stability index (ESI) and stability index (SI) [21], and VQ sensitivity analysis and QV modal analysis [30]. These indices are important when faced with uncertainty in the operation of the distributed generator from renewable energy sources.

The uncertainty generation associated with solar power and wind energy systems and the load demand should be considered to evaluate the direct impact of renewable energy penetration on the stability of the power system. Research has been working on the issues, i.e., Rawat and Vadhera [22] has done the PLF study using Hong's 2m + 1 point estimation method combined with Cornish–Fisher expansion. Then the system's stability is evaluated through a voltage stability index (VSI) assessment. The method has been tested on IEEE 33 and 69 networks in some scenarios, and the results have been compared with the MCS technique. The same concept has been proposed Farkhonde and Behnam [21] who proposed MCS-based PLF and evaluated the static voltage stability of 39-bus New England and 118-bus using the SI and ESI. Then ESI values are used to determine the critical PQ buses. Differently, Yao *et al.* [23] has done PLF using a three-point estimation method and applied it to the IEEE 14-bus and a Belgian 20-node gas system. Finally, the static system stability has been assessed through VQ sensitivity analysis and QV modulal analysis. Le *et al.* [2] has done a study on enhancing the clustering method by improving the cumulant PLF method's ability to handle input random variables with a wide range of variation. The method, which combines principal component analysis and particle swarm optimization, enables the cumulant PLF method to be applied to large power systems with a lot of random variables. The effectiveness of the study has been tested on a modified IEEE-118 bus.

The previous research mainly focused on investigating the bus voltage stability indices based on the PLF result of the point estimation method and its derivations. Then the results are compared with the MCS method. These studies become more complex and time-consuming while the stability assessment is not completely investigated.

In this paper, different ways to determine stability indices by applying different PLF methods have been proposed. First, the proposed method consists of an AKDE-based PLF to generate more particular random variables; later, the stability of lines and buses is assessed. Therefore, the research objectives of this paper are to determine the voltage profile and power losses in buses and lines by performing AKDE-based PLF and comparing the results with the MCS method, to define buses and lines stability indices using FVSI, LMN, and LQP indices, and to apply the proposed method to the IEEE-8 bus of Manokwari grid.

2. PROPOSED METHOD

This paper presents a thorough evaluation of the stability of the power system, including the VSI and line stability of both index and factor. It also offers a more straightforward way to assess the influence of uncertain renewable resources on the electrical grid. The steps to run the proposed method are given in the flowchart.

Previous research related to the proposed method has mainly focused on investigating the bus voltage stability indices [31], while ignoring the other important indices of stability assessment [32], [33]. Furthermore, the researchers are using a more complex algorithm [31]–[33]. That are time-consuming [2]. By means of the proposed method, the drawbacks of the method used in previous research are overcome by expanding the stability assessment to investigate not only the buses but also the lines. In addition, the proposed method uses a simple algorithm, and time series data is not included; therefore, the calculation and simulation times are minimized.

The flowchart of the proposed works is given in Figure 1. The proposed methods start by loading the system configuration data and continue to perform the DLF calculations. The range of both generators and load data has to be determined so that the generated data is either over or under the limit. The rates of distributed generators have to be calculated as their maximum values, and the PDF samples are generated between zero and the rate. In the same way, the PDF samples of loads are in the range of load data ± 10% of their values by the AKDE and MCS methods. Here, all the data needed to do the PLF calculations has been prepared. The next sequence is running the PLF for n samples of the data, and then the voltage profile of each bus is calculated based on (4). Next, power losses will be calculated based on the new voltage profile of PLF. Finally, the direct stability assessment is executed based on the voltage profile, and the obtained stability indices judge the distributed generator penetration.

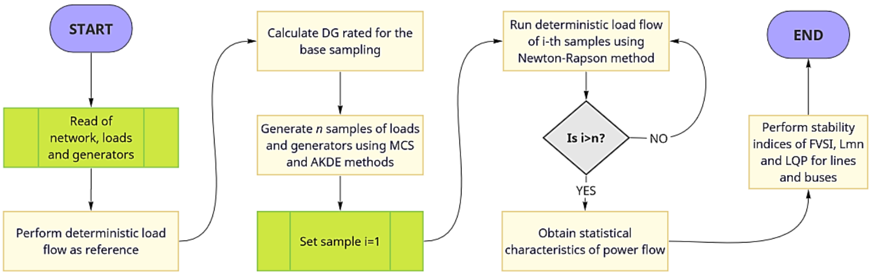


Figure 1. Proposed works

3. RESEARCH METHOD

3.1. Solar power plant modeling

A solar power plant works to convert energy from the sun into electrical energy. Energy conversion is done in solar panel modules that are typically made from silicon semiconductors. Therefore, the energy is produced in a direct current (DC) system that can be saved in battery storage or directly sent to a power grid by converting it to alternating current (AC). The battery storage is the most expensive component in this power plant. Therefore, this component is typically eliminated from the system in a large-capacity solar power plant called an on-grid solar power plant.

The essential components in a solar plant are PV panels, strings, a string monitoring box (SMB), inverters, and energy meters. A string connects each solar panel to become an array in a combiner box. The nest of strings is connected in parallel to each other. The energy generated by these strings will be approximately the same at the same level of solar irradiation. Then SMB collects data on each individual string's voltage, current, and power before giving it to an inverter [31].

The energy from a solar power plant depends on solar irradiation, while the constant parameters in calculating output power are the covered area and efficiency of the solar PV modules. A solar power plant consists of n solar PV panel(s) that cover an area of A_i $(m2)$. The output power of the power plant as the result of the solar irradiation r (W/m^2) with an efficiency of n_i is calculated by (1) [19]:

$$P_{rated} = r\sum_{i=1}^{n} A_i \frac{\sum_{i=1}^{n} A_i\eta_i}{\sum_{i=1}^{n} A_i} \quad (1)$$

Therefore, the power plant is described by a multinomial probability mass function that can be expressed as a probability distribution function (PDF) utilizing the delta of the dirac function, as in (2). The PDF of a solar PV is based on the light intensity that obeys a beta distribution on short or long time scales. The PDF model of the power plant is [13]:

$$f(P_g) = \sum_{i=1}^{m} a_i\delta(P_g = b_i) \quad (2)$$

Where P_g and a_i are the generated power and probability associated with the power value b_i.

3.2. Load modeling

Load is a most dynamic part of power system operations that makes the power system rarely reach its steady-state condition. Different types of loads have varying power characteristics and may require specific considerations in terms of electrical design and protection. The electric load can be classified into the types [32]:

a. Resistive load: these loads are electrical devices or components that convert electrical energy into heat. These loads have a linear voltage-current relationship, meaning that there is no phase shift between them, and so these loads are 100% supported by real power.
b. Inductive load: the loads are devices that rely on electromagnetic induction to operate and commonly come from equipment that uses wire coils (coils). These loads are characterized by the fact that energy is stored in a magnetic field when current flows through them. Inductive loads are known as lagging loads, where the current wave lags the voltage.
c. Capacitive load: these loads are devices that use capacitors to store and release electrical energy. Capacitive loads create a phase shift between voltage and current, typically leading voltage. Capacitors are often used in power factor correction and in electronic circuits for various purposes.

To reflect the time-varying nature of the base load, a normal distribution function is used, as in (3) [13]:

$$f(P_L) = \frac{1}{\sqrt{2\pi\sigma}} exp\left[-\frac{(P_L-\mu\ \ )^2}{2\sigma^2}\right] \tag{3}$$

Where $P_L, \mu,$ and σ are the load power, mean value, and standard deviation of the active and reactive power.

3.3. Monte Carlo simulation

Solar irradiation is very dependent on climate and weather systems that can never be precisely predicted. The uncertainty of solar irradiation and load can not be determined when mounting solar PVs to a power system network. The goal of the PLF is to obtain the PDF, or cumulative distribution function (CDF), of the system state and power flows in an electrical power network, knowing the probabilistic nature of the injected power, loads demand, and the correlation between them.

To deal with the uncertainties, several PLF methods have been proposed. The methods can be classified into analytical and approximate methods. MCS would be a basic and straightforward method to do the PLF calculation, and it would group the MCS into another classification [12]. In an MCS method, the values of uncertainty variables are randomly generated, and the values are used to solve the deterministic problem. The MCS method is the most popular method to model the probability of outcomes in a process that is difficult to predict due to the random variable. The voltage bus of the MCS-based PLF is calculated based on (4) [12]:

$$V_i = \sum_{j=1}^{m} p_j\, V_i^j \tag{4}$$

Where m, p_j, and V_{ij} show total number of MCS samples, probability of the j^{th} sample and voltage resulting of j^{th} sample for bus i^{th} in load flow.

3.4. Adaptive kernel density estimator

An AKDE is a type of estimator tool that is developed based on the density estimator method with a kernel function K. The kernel function K establishes forms of protuberances when h determines their width. The kernel density estimator (KDE) is used to set the PDF of n samples of random variable X in d dimensional space, which is in (5) [26].

The limitation of KDE is that its accuracy is not acceptable when used with long-term distribution data. To overcome this drawback, an AKDE is presented by adding local bandwith factors λ as expressed in (6). The formulation of the AKDE is given in (7) by including (6) in the KDE in (5).

$$f(x) = \frac{1}{nh^d} \sum_{i=1}^{n} K\left(\frac{x-X_i}{h}\right) \tag{5}$$

$$\lambda_i = \left[\hat{f}\left({X_i}/{g}\right)\right]^{-\alpha} \tag{6}$$

$$f(x) = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{h^d {\lambda_i}^d} K\left(\frac{x-X_i}{h\lambda_i}\right) \tag{7}$$

Where α is a sensitivity parameter between 0 and 1 that optimum in 0.5, and g is the geometric mean of $f(x)$.

3.5. Stability assessment

The interconnection of a solar power plant to a power grid can have an impact like a distributed generator [33]. The impact can be a voltage rise or drop in connection or disconnection due to weather and climate variation. Therefore, the variation becomes an unexpected event in the network.

The stability of a power system is defined as the capability of a power system to handle unexpected events successfully. This ability includes the capability to return to normal or stable conditions after being disturbed by the events. The events can be a sudden change of load, a sudden short circuit between line and ground, a line-to-line fault, and a three-phase line fault. The stability assessment is done by evaluating the SI based on the FVSI, LMN, and LQP that are in (8)-(10) [27]–[29]. The index value of less than 1 indicates that the investigated system is stable.

$$FVSI = 4\frac{Z^2 Q_j}{V_i X} \tag{8}$$

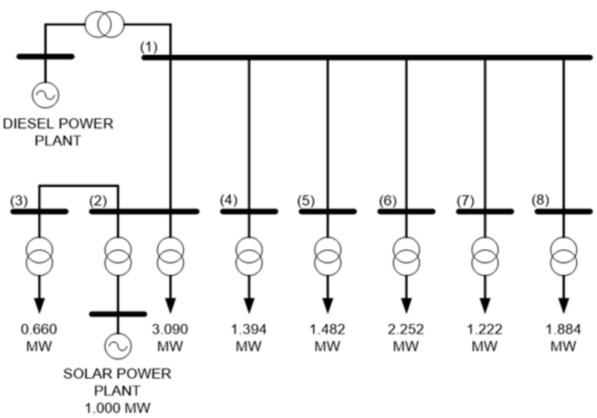
$$L_{mn} = \frac{4Q_j X}{[|V_i| \sin(\theta-\delta)]^2} \tag{9}$$

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \tag{10}$$

Where $V_i, \theta, \delta, Z, \mathrm{X}, P_i$ and Q_j are the voltage of the sending bus, the voltage angle of the sending bus, the voltage angle of the receiving bus, line impedance, line reactance, active power on the sending bus, and reactive power at the receiving bus, respectively.

3.6. System descriptions

The grid of Manokwari is used to test the proposed method, where Manokwari is the capital of West Papua Province, Indonesia. The Manokwari grid that supplies electricity in this city, consists of 8 bus feeders, namely Sanggeng, Mambruk, Nuri, Kasuari, Rajawali, Maleo, and Merpati [10]. The RSUP bus is inserted on the Rajawali bus feeder used to supply solar PV. A single-line diagram of this grid with the Sanggeng bus as the slack bus is given in Figure 2(a), while the bus data is provided in Figure 2(b) based on the 20 MVA system.



(a)

Bus No.	Bus Name	Bus Type	Voltage (pu)	Load	
				P (MW)	Q (MVar)
1	Sanggeng	Slack	1.05∠0°	-	-
2	RSUP	Load	1.00∠0°	3.0900	1.4960
3	Rajawali	Load	1.00∠0°	0.6600	0.3200
4	Mambruk	Load	1.00∠0°	1.3940	0.6740
5	Nuri	Load	1.00∠0°	1.4820	0.7180
6	Kasuari	Load	1.00∠0°	2.2520	1.0900
7	Maleo	Load	1.00∠0°	1.2220	0.5920
8	Merpati	Load	1.00∠0°	1.8840	0.9120

(b)

Figure 2. The system data, including: (a) the single-line diagram and (b) bus data

On the Sanggeng bus, there are about 20 diesel power plants and two outgoing feeders connecting a gas and oil power plant, a combined cycle power plant, and a micro-hydropower plant located more than 50 km away from the slack bus. The solar panels of the solar power plant in bus 2 consist of 3948 units of 260 Wp, which are produced by LEN Co., Ltd. The seasonal climate and weather variations will directly impact the grid's stability due to its high capacity compared to the total load of approximately 20 MW on the grid.

The bus data in Figure 2(b) shows that the biggest load on the Manokwari grid is in the Rajawali feeder at 3.75 MW, including the loads of buses 2 and 3. The addition of bus 2 can share the load on the feeder by supporting around 82.4% of the load. Furthermore, the single-line diagram of the Manokwari grid is shown in Figure 2(a), which shows that the power system in Manokwari is purely radial. The addition of a solar power plant on bus 2 slightly changes the structure of the power system.

4. RESULT AND DISCUSSION
4.1. Probabilistic power flow

Simulations are done using MatLab software under the Windows X environment on a computer with a Core i7-2600 CPU, 3.40GHz, and 4GB of RAM. The simulations run over 5000 samples of an AKDE and MCS within 73.9844s and 81.6094s.

Tipically, the PDF curve of voltage buses simulated with the MCS method is more narrow at the maximum voltage for the buses that have the highest distribution frequency at the point. This curve can have a symmetric, positive, or negative skew. The PDF curves of generated power and bus loads are symmetric on all buses in our case, as shown by the solid lines in Figure 3. The curves have the same form as the IEEE 118 bus test in reference [2] and the IEEE 39 bus test in reference [24].

In contrast, the PDF curve of the AKDE method can vary based on the system test, but it has some bend(s) in the left, right, or top of the curve, as shown by reference [26] in their simulation of the IEEE 13 and IEEE 37 bus tests. In our simulation, the bends occur at the top of the PDF curve, resulting in a flat curve, as shown by the dotted line in Figure 3. It can be seen from the figure that the proposed AKDE method has a smaller density of load from bus 2 until bus 8 in Figures 3(a)–(g). The same characteristic was also shown in the solar power curve, as shown in Figure 3(h). This lower density will result in a wider variance in the projected outcome but will lessen the bias of the load. On the other hand, the MCS method uses high density in center curves, where the high density will raise the bias of load with regard to the true density, but it will also lessen the variances between the estimates of load for different data sets.

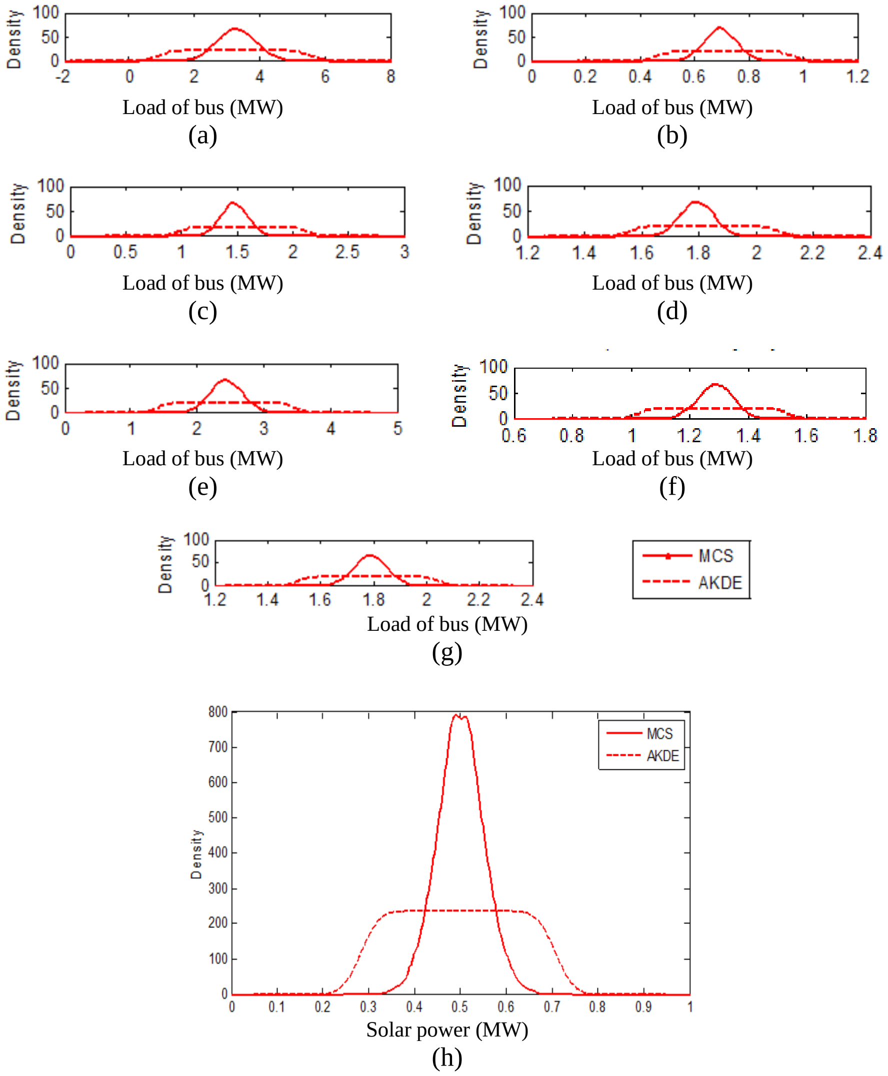


Figure 3. PDF curves: (a) load of bus 2, (b) load of bus 3, (c) load of bus 4, (d) load of bus 5, (e) load of bus 6, (f) load of bus 7, (g) load of bus 8, and (h) solar power generator

The PDF curve of the bus's voltage is given in Figures 4(a)-(g). The maximum bus voltage reached on the simulation lies between 0.87 and 1.05 p.u. for the AKDE method, and it is between 0.96 and 1.04 p.u. for the MCS method, both in Figures 4(c) and (d), which are also provided in Table 1. The maximum density is in bus 5 Figure 4(d), with over 400 samples at 1.04 p.u., where the minimum density is in bus 4 Figure 4(c), below 50 samples at 0.96 p.u. voltage.

4.2. Power flow analysis

The power flow calculation for the existing condition without solar penetration before the MCS simulation runs is based on the data in Figure 2(b). When the connection of solar PV is running, there are contingencies that happen, and so PLF has to be done along with the contingencies, as also done by reference [24]–[26]. The PLF starts by generating some samples that, in our case, are run in the AKDE method and the MCS method as a comparison. The probabilities of the contingency of PV and bus load have been generated and presented in Figure 3 and Figure 4, respectively. Based on the probability data of the PV and loads, the bus voltage is recalculated based on (4), and the result is shown in Table 1.

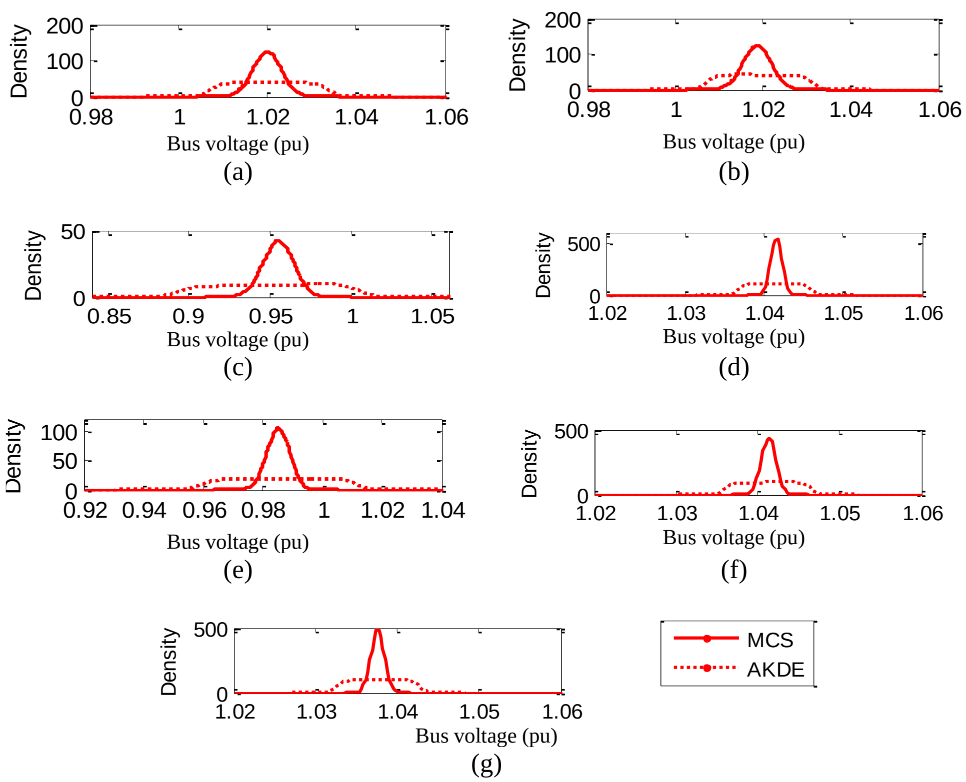


Figure 4. PDF curves of voltage bus: (a) voltage of bus 2, (b) voltage of bus 3, (c) voltage of bus 4, (d) voltage of bus 5, (e) voltage of bus 6, (f) voltage of bus 7, and (g) voltage of bus 8

In our case, the solar power plant is injected into bus 2, as also figured in the single line diagram of Figure 2(a), and this penetration has lifted the bus voltage to 1.02 p.u. This bus has high voltage drops due to the high load; hence, it increases losses, weakens the voltage profile and power quality, and escalates the congestion of distribution lines. According to Table 1, the integration of the solar power plant in bus 2 has produced flawless results in improving the power system performance of buses 2 and 3.

Power losses in the existing condition are about 0.4271 MW and 0.0167 MVar. Four of the buses have voltages below 1.0 p.u. The other three buses have arisen at 1.0 p.u., and the injected power is 12.5 MW on the slack bus. It is shown in the simulation that the injection power in the slack bus after the PLF simulation is lower than the injection power at the existing condition. Power losses in PLF simulation are about 0.1262 MW and 0.1227 MW lower than the existing conditions of both the AKDE and MCS methods. Buses 2 and 3 directly impact the penetration, which causes an improvement in the bus voltage profile over 1.0 p.u. However, only buses 4 and 6 have a voltage below 1.0 p.u.

The power injections are about 11.3518 MW compared to the existing calculation. This injection resulted in lower power losses of about 0.3080 MW, as given in Table 1. However, it is also shown in Table 1 that those power losses are higher than using the MCS method due to the lower voltage profile. This difference may be caused by the fact that the voltage profile of the PLF calculation of the AKDE method is lower than that of the MCS method.

Table 1. Voltage profile and buses power

Bus	Voltage profile			Bus power and loses					
	Existing	MCS	AKDE	Existing		MCS		AKDE	
	Voltage (p.u.)	Voltage (p.u.)	Voltage (p.u.)	P (MW)	Q (MVar)	P (MW)	Q (MVar)	P (MW)	Q (MVar)
1	1.0500∠0.00°	1.0500∠0.00°	1.0500∠0.00°	12.4999	-6.6299	11.2856	-4.6511	11.3518	-4.6029
2	0.9834∠-2.06°	1.0200∠-2.10°	1.0206∠-2.26°	-3.0764	1.5795	-2.0908	-0.1247	-2.0963	-0.2056
3	0.9821∠-2.10°	1.0187∠-2.14°	1.0192∠-2.26°	-0.6446	0.3193	-0.6588	0.3219	-0.7322	0.3083
4	0.9486∠-3.32°	0.9551∠-3.06°	0.9546∠-3.00°	-1.4886	0.7086	-1.3942	0.6759	-1.3857	0.6894
5	1.0415∠-0.26°	1.0416∠-0.27°	1.0414∠-0.27°	-1.4654	0.7527	-1.4812	0.7175	-1.4716	0.7525
6	0.9849∠-2.21°	0.9853∠-2.10°	0.9872∠-2.02°	-2.3170	1.0599	-2.2512	1.091	-2.1843	1.0642
7	1.0406∠-0.29°	1.0413∠-0.28°	1.0411∠-0.30°	-1.2816	0.6734	-1.2224	0.5925	-1.2733	0.5996
8	1.0381∠-0.39°	1.0376∠-0.41°	1.0374∠-0.41°	-1.7991	0.8833	-1.8829	0.9119	-1.9054	0.9316
		P_{Loses}		0.4084	-0.6240	0.3045	-0.4654	0.3080	-0.4708

4.3. Contingency analysis

Contingency analysis was done by simulating the injection power of solar power in variations between the minimum and maximum rated solar PV capacities on the bus of 2 and comparing the result with the existing condition before the injection. Then the consistency of the injection contingencies is calculated and ranked using (8)-(10) as proposed in [27]-[29] and the results are plotted in Figure 5.

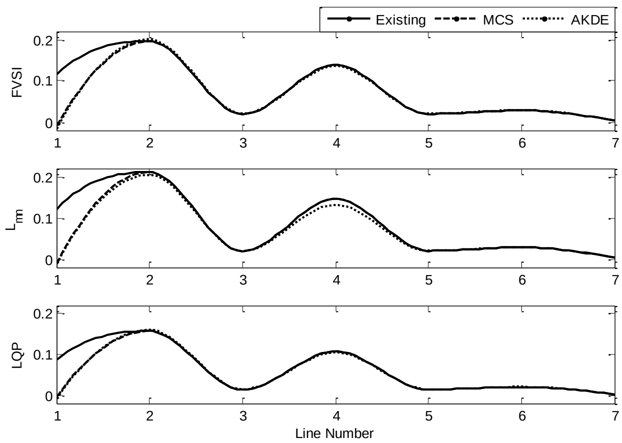


Figure 5. Stability indices

The stability assessment results are illustrated in Figure 5, where the three indices of L_{mn}, LQP, and FVSI were measured at all seven lines at the 20 kV distribution system. All indices are measured at their lowest values, indicating that the system is stable. The highest indices were recorded in line 2, which connects buses 1 and 3, and the most affected lines are in line 1, connecting buses 1 and 2. It is proof that the integration of solar power has perfect results in improving the stability of the bus, increasing the bus voltage profile, and reducing power losses. Figure 5 also shows that the proposed method gives a more accurate result in calculating the bus stability indices. The evidence is shown in the proposed method's FVSI, L_{mn}, and LQP indices, with small values in lines 2 and 4 compared to the MCS method.

The stability indices shown in Figure 5 indicated that before and after the solar power interconnection, the only indices whose values changed were in lines 1 and 7. The solar power penetration in line 2 does not influence the system's stability. In the same way, all of the index values of FVSI, L_{mn}, and LQP in each bus are less than 1. According to references [27]–[29], a system will be stable if the indices are less than one. Therefore, the results indicate that the integration of a 1 MWp solar power plant into the IEEE 8 bus of the Manokwari grid will not change the system stability for whole-day operation.

Overall simulations show that the bus voltage profile of the proposed method is a little lower in some buses than the MCS method, while it gives more accurate stability indices. Therefore, it can be summarized that 1 MWp of solar power penetration into the Manokwari grid is stable and secured, as shown by the small values in the stability indices. Therefore, the solar power penetration has little influence on the system state to handle the contingency of the solar power penetration.

5. CONCLUSION

This paper uses an AKDE-based PLF to investigate the uncertainties of solar irradiation and load demand connected to a power grid. The effectiveness of this proposed method is tested on the IEEE 8 bus of the Manokwari grid, where a 1 MWp solar power plant is prepared to be connected to the grid. The performance of this proposed method is then compared with that of the MCS method.

The simulation results show that integrating solar power into bus 2 improves the voltage profile, system losses, and the contingencies of the distribution line. The solar power plant is connected to the IEEE 8 bus of the Manokwari grid, as shown in the PDF of bus voltage between 0.87 and 1.05 p.u. and 0.96 and 1.04 p.u. using both AKDE and MCS methods. In addition, solar penetration can also improve the voltage profile while reducing power losses from 0.4084 MW to 0.3080 MW and 0.3045 MW by the proposed method and MCS method. Furthermore, the stability indices values of FVSI, L_{mn}, and LQP in each bus are less than one, which means that the solar penetration is stable. Overall, the proposed method using the AKDE method has more accurate results in stability indices, as indicated by the small FVSI, LMN, and LQP indices. On the other hand, the voltage profile of the proposed method is not as good as that of the MCS method.

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