SINERGI Vol. 26, No. 1, February 2022: 37-46
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2022.1.006

Distributed Generation installed by the Phasor Measurement Unit to improve voltage

Azriyenni Azhari Zakri[1*], Rangga Eka Saputra[1], Makmur Saini[2], Hidayat[3]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Riau, Indonesia
[2]Power Plant Engineering, Politeknik Negeri Ujung Pandang, Indonesia
[3]Department of Electrical Engineering, Faculty of Industrial Engineering, Universitas Bung Hatta, Indonesia

Abstract
This study is intended to design a system connected to the Distributed Generation (DG) sourced from solar cells, using Matlab/Simulink. A Phasor Measurement Unit (PMU) is installed in the DG system to monitor the phasor voltage and current. Furthermore, the system comprises four buses with two 20 kV load voltages, two amplifying transformers, and four transmission lines. The DG's role is to keep the power supply to the load stable and improve power efficiency by reducing power losses on the network. However, in this network, the DG increases the current on each bus. Thus, affecting voltage increase on each bus, consequently increasing the stress experienced by both loads. The DG-connected system simulation on PMU-3 & PMU-4 has a minute error value of 0.02% and is slightly higher than the unconnected simulation. This comparison also shows the positive sequence values of the phasor currents as well as phasor voltages before and after the DG connection. The DG system connected to the PMU has monitored voltage and current for PLN and DG systems based on the simulation results. Therefore, installing the DG can increase the line voltage, especially on the load.

Keywords:
Distributed Generation;
Phasor;
Phasor Measurement Unit;
Solar Cells;
Voltage;

Article History:
Received: March 17, 2021
Revised: July 25, 2021
Accepted: August 4, 2021
Published: February 1, 2022

Corresponding Author:
Azriyenni Azhari Zakri
Electrical Engineering Department, Universitas Riau, Indonesia
Email: azriyenni@eng.unri.ac.id

INTRODUCTION

Distributed Generation (DG) or distributed power generation consists of small-scale electric power plants installed directly in a system close to the load centre, with a low voltage level. Meanwhile, the Phasor Measurement Unit (PMU) is useful for obtaining time-synchronised phasor values for improving distribution network characteristics and developing monitoring tools to evaluate as well as reduce the impact of intermittent DG. However, PMU application in the distribution system is currently largely under-explored (especially at the implementation stage), which is primarily due to economic factors. Therefore, this study designed a DG-connected system to use PMU with a solar cell supply for monitoring the voltage and current on each bus in the distribution system. This study used four buses, each with PMU, enabling each bus's voltage and phasor current to be monitored.

A study by Haddad described a classification technique for the DG system. The proposed classification technique can detect and classify local events, with a major impact on the system's safety and operation. This technique is implemented using the Artificial Neural Network (ANN) pattern recognition feature, designed optimally to classify parameters. A total of four parallel ANN classifiers were used for classification, and each artificial neural network's output was arranged in vector form. Furthermore, 310 samples connected to the network were generated to test the system's performance. The application of this classification to the DG system is helpful to system operators [1].

Meanwhile, Zakri et al. conducted fault diagnosis in electric power transmission systems with high sensitivity to power outages. The Phasor Measurement Unit (PMU) is a measurement for a large area related to the monitoring system's condition in a large area. This measurement system is to be carried out through monitoring, controlling, and protecting by combining the phasor measuring instrument's functions. In this study, a PMU-based 9-bus system was designed using the software. At the same time, the simulation was run under three-phase short circuit fault conditions and tested on the IEEE 9-bus system with variations of 10%, 30%, 50%, 70%, and 90% distances. Subsequently, the simulation results were used as input for fault diagnosis to determine the location of fault points on the IEEE 9-bus system [2].

Taufani also investigated the power flow analysis for optimal DG locations and capacities using the K-means clustering technique. This technique is based on the Loss Sensitivity Factor (LSF), and the voltage of each bus is used to find a candidate location for DG installation. In this study, the IEEE 33-bus and 69-bus systems technique used was tested. According to the simulation results and data analysis, in the IEEE 33-bus and 69-bus systems, power losses are reducible by 87.5% to 25.3272 kW, and 69.84% to 67.4816kW, respectively. Furthermore, the method can also determine the amount of DG with a more optimal penetration level to reduce system power losses. For example, the K-means clustering method can determine the amount of DG with a more optimal penetration level to reduce power losses to a minimum of five DG units in the IEEE 33-bus system [3].

Meanwhile, Revandy researched PMU data with parameters of frequency, voltage, and current and voltage and current phase angles [4]. The Suralaya Extra High Voltage (EHV) and Cilegon 500kV Java-Bali TET electrical systems were used to evaluate the power stability conditions in two approaches: steady-state and Thevenin Equivalent, as well as dynamic stability with the concept of Frequency Domain Analysis (FDA). Based on the evaluation results, the TET Suralaya and Cilegon's stable conditions within the range of 0.8442 - 0.9993 was concluded to be the steady-state system. Furthermore, the dynamic stability approach seen from the amplitude trend at the three phasors dominant frequency shows the Suralaya and Cilegon systems are also dynamically stable [4].

A study by Iswadi et al. were conducted on Prony analysis to identify small-signal oscillation mode parameters from the actual PMU ringdown data. The well-known two-area four-engine power system was considered a case study. At the same time, the PMU ringdown data was the latest, derived from the Irish power system's 275kV dual circuit main interconnection system. Thus, the Prony analysis for parameter identification was based on the actual PMU simulation, and the study results show the PMU's optimal spread. In addition, various frequency modes have been observed in the Irish power system depending on the operating conditions. However, this system is stable because the oscillations have adequate system attenuation [5].

In this study, the DG system was designed based on literature reviews from previous research. However, the system added DG sourced from solar cells in the existing distribution network and was developed with the help of Matlab/Simulink software. Zakri et al. studied the development of PMU-based research for monitoring voltage and current parameters for system stability as applied to research, monitoring fault diagnosis based on PMU on Wide Area Systems (WAP) [2]. Meanwhile, Iswadi et al. analysed Prony parameters for identification based on PMU simulated using the existing system [5]. In this study, a four-bus system has also been built, and this comprises one DG, one more generator, and two load types, each connected to the PMU, to monitor the phasor magnitude and phase angle for each.

METHOD

DG is a small-scale power plant that can generate power between 1kW - 10MW connected to a distribution network and connected to buses directly supplying load centres or distribution substations [6]. Conversely, DG is a power plant serving customers directly or connected to a low voltage system or a small generator with a capacity of up to 50kW [7]. According to the IEEE 1547 standard, this is a directly connected power plant on the customer side, with a maximum capacity of 10MVA. Solar cells are an environmentally friendly renewable energy source that converts solar energy into electrical energy. Therefore, solar cells are widely used semiconductor-based technologies that convert sunlight into electrical energy. The solar panel array uses the Sun Power SPR-315E-WHT-D type with a 100kWp capacity and a 315,072W maximum power output. In this simulation, data input from the solar panels uses actual data from testing and direct observation [8].

Figure 1 is a DG system connected to a solar cell module to convert solar energy into electrical energy. The Maximum Power Point Tracking (MPPT) algorithm provides the maximum power point for the operation of the solar system, achieved using the P&O algorithm [9][10]. Also, the dc-dc [11] converter can ensure the output voltage is greater than the network's peak voltage. The main elements included in a conversion system are solar cell modules, converters, utility grids, dc and ac loads, as well as inverters [12][13].

Phasor Measurement Unit (PMU)

A PMU is the equipment used for monitoring purposes, capable of real-time monitoring and synchronisation between two PMUs while installed in the electrical system. This installation shows two parameters, voltage and angle on the bus and current and angle of the transmission line [14][15]. Figure 2 shows a schematic of the PMU using Global Positioning System (GPS) [16][17] satellite signals to equalise the sampling time between PMU, thus, enabling voltage and current phasors to be measured continuously. Other benefits of this equipment include protection system measurement, the combination of the local frequency with harmonic measurement, zero sequence current, and negative sequences, for instance, voltage and current measurement in general [7][18]. This research method was carried out in stages, including designing system models with Matlab/Simulink software, retrieving data after system simulations, and analysing simulation data [8]. Figure 3 shows a model built on the Matlab/Simulink equivalent, where the system consists of four buses, two loads at 20kV, two power transformers, and four transmission lines. The parameters used in designing a DG-connected system are Matlab/Simulink. Figure 4 shows a series of boost converter topologies used as a converter to be integrated with Maximum Power Point Tracking (MPPT).

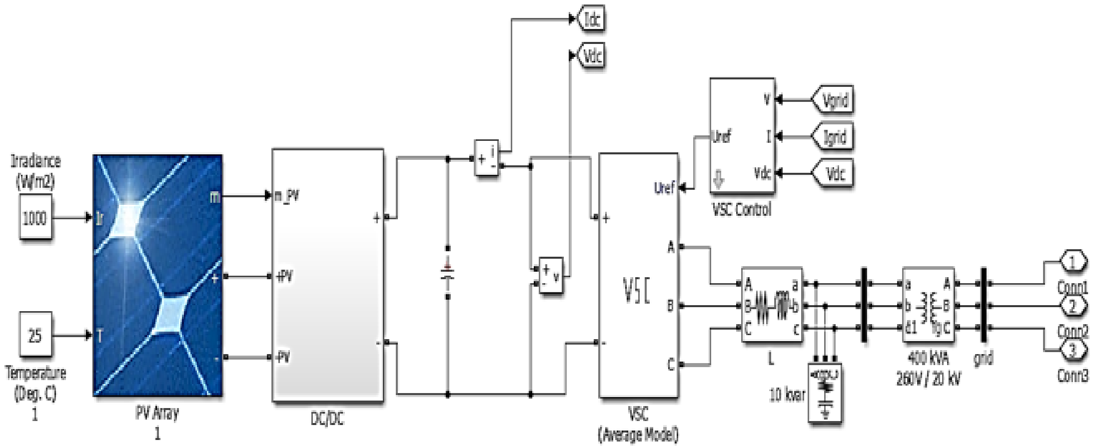

Figure 1. DG solar cell equalised by Matlab/Simulink

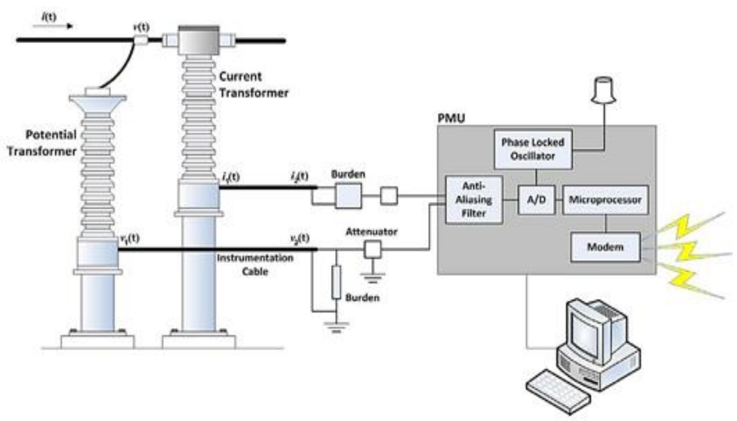

Figure 2. Schematic of a PMU connected to the power grid [19]

The MPPT P&O algorithm uses voltage and current, where the voltage and current detected is able to increase or decrease the duty-cycle the boost converter circuit is provided. Also, the three-phase inverter used to supply dc voltage is obtained from a large capacitor connected to the input terminal to reduce the harmonic feedback and dc input to the source and a constant, respectively. Figure 5 is a model design of a DG-connected system with four buses, using PMU via Matlab/Simulink. Subsequently, this system simulation is run to monitor the phasor voltage and current and collect data.

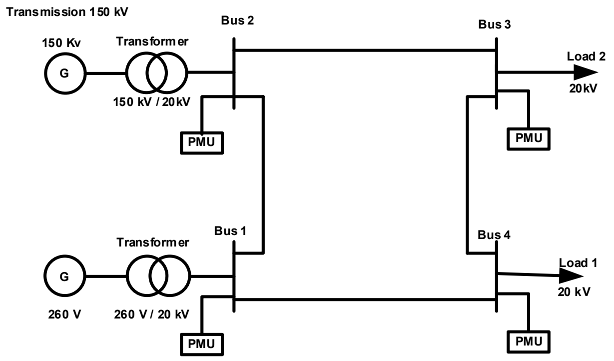

Figure 3. Single Line connected DG.

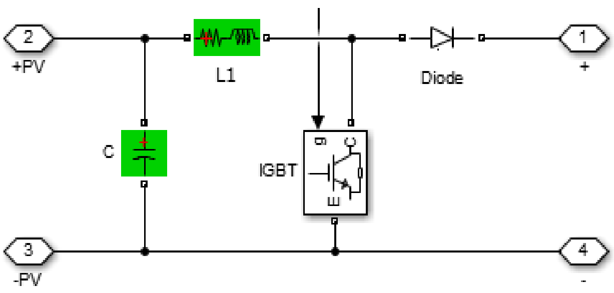

Figure 4. Boost Converter Topology

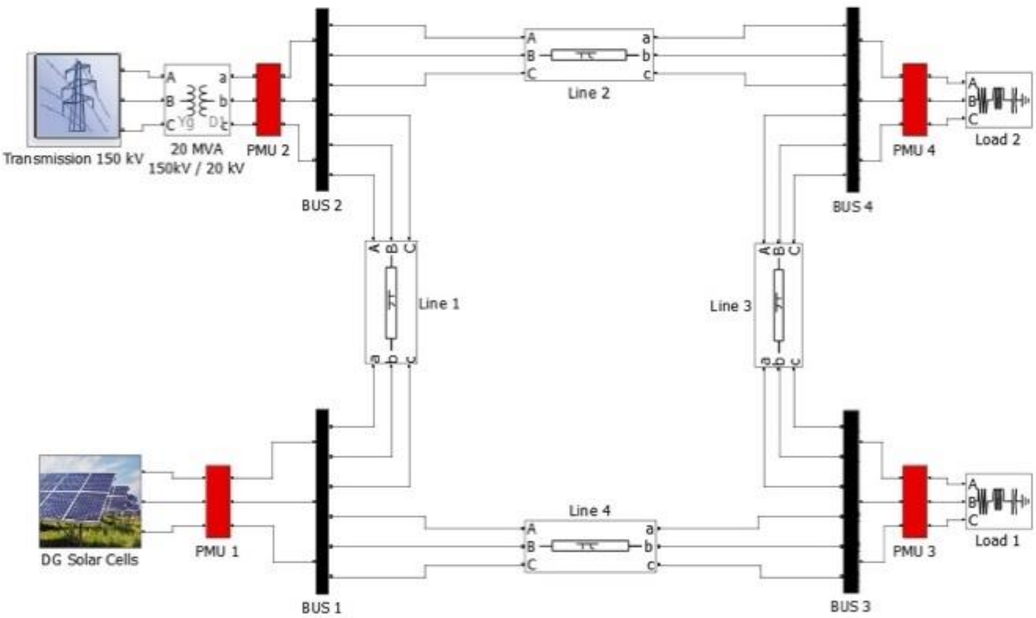

Figure 5. The four bus in the Matlab/Simulink equivalent DG

This formula is outlined [20],

$$V_o = \frac{V_s}{(1-D)} \quad (1)$$

The formula to determine a step-up transformer's output voltage based on a formula with an unknown winding value is given [21],

$$\frac{I_s}{I_p} = \frac{N_p}{N_s} \quad (2)$$

Based on (2), the transformer's output voltage is obtainable using (3),

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \quad (3)$$

RESULTS AND DISCUSSION

The DG modelling design is obtained from solar cells connected to a four-bus system, while the simulation data results from testing without DG. This chapter discusses the comparative analysis before and after connecting DG, and the calculation of data parameters on the boost converter to produce a duty-cycle value is calculated [9],

$$D = 1 - \frac{320}{500} = 0.36$$

The resistor value used in the simulation is calculated as shown [22],

$$R = \frac{500}{210} = 2.38\ \Omega$$

Subsequently, the minimum inductor value was calculated [22],

$$L_{min} = \frac{0.36*(1-0.36)^2}{(2)*(20000)} = 8.77 * 10^{-6} H$$

A capacitor is possibly found using the following method [22] to reduce the voltage ripple effect caused by switching,

$$C = \frac{(500)*(0.36)}{(2.38)*(0.01)*(20000)} = 0.378151F$$

Figure 6 is a PMU module reading display via Matlab/Simulink to monitor the current phasor value for each phase. Also, the module can display the voltage phasor value readings on each phase based on the way of the measurement for a large area. Based on the simulation results, an increase occurred in the magnitude of the voltage and current at the load. The respective voltage and current magnitudes at the load are 15.8kV and 114.2A, respectively. After connecting with DG, the voltage value was 16.73kV, while the magnitude of the current at the load was 120.1A and 120.6A, respectively. Thus, the DG system using PMU has improved the quality of power generated from the 150kV and DG networks, two power sources. Table 1 shows DG plays a role in keeping power stable and increasing energy efficiency by reducing power losses in DG-connected systems.

Meanwhile, Table 2 shows the magnitude of the voltage at the load, and the current at each PMU's load is stable, as seen in phases A, B, and C. Table 1 shows the simulation results without connecting to DG, and the value of each PMU supplied from the 150kV network. PMU-2 data is the result of monitoring the magnitude, voltage angle, as well as current angle. Furthermore, the 150kV transmission line is supplied to the load at the source.

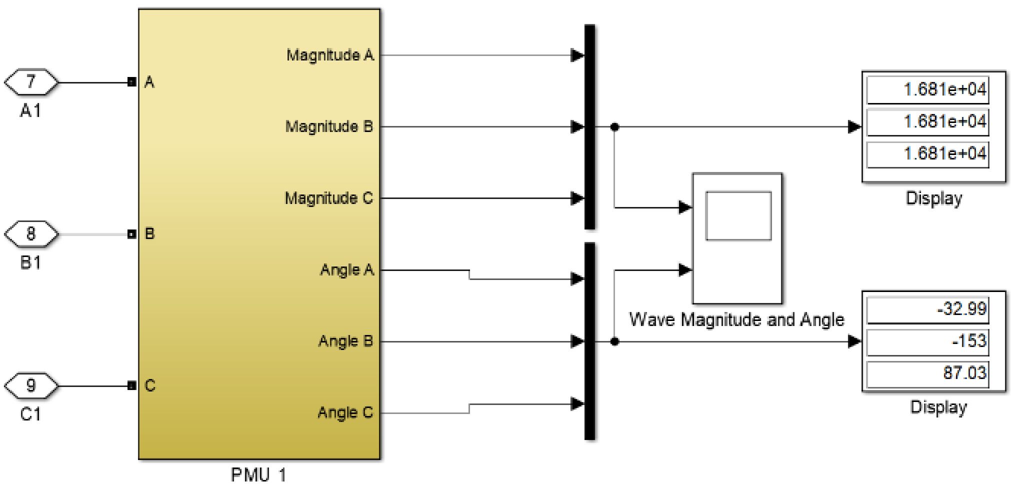

Figure 6. PMU module via Matlab/Simulink

Table 1. Simulation results without DG

PMU	Bus	Phase	Current (A)	Voltage (V)
		A	227,9 ∠114˚	15.990 ∠-31,62˚
PMU-2	2	B	227,9 ∠-6,03˚	15.990 ∠-151,6˚
		C	227,9 ∠-126˚	15.990 ∠88,38˚
		A	114,2 ∠114˚	15.840 ∠-32,35˚
PMU-3	3	B	114,2 ∠-6,03˚	15.840 ∠-152,3˚
		C	114,2 ∠-126˚	15.840 ∠87,65˚
		A	114,2 ∠114,1˚	15.860 ∠-32,23˚
PMU-4	4	B	114,2 ∠-5,91˚	15.860 ∠-152˚
		C	114,2 ∠-126˚	15.860 ∠87,77˚

Table 2. Simulation results with DG

PMU	Bus	Phase	Current (A)	Voltage (V)
		A	53,52 ∠45,53˚	16.090 ∠-32,01˚
PMU-1	1	B	53,09 ∠-75,22˚	16.110 ∠-152˚
		C	52,7 ∠165,6˚	16.100 ∠87,91˚
		A	216,1 ∠113,8˚	16.100 ∠-31,77˚
PMU-2	2	B	217,2 ∠-6,08˚	16.120 ∠-151,8˚
		C	216,5 ∠-126,2˚	16.110 ∠88,17˚
		A	115,2 ∠113,8˚	16.000 ∠-32,42˚
PMU-3	3	B	115,4 ∠-6,08˚	16.020 ∠-152,4˚
		C	115,4 ∠-126,2˚	16.000 ∠87,51˚
PMU-4	4	A	115,2 ∠113,9˚	16.000 ∠-32,34˚
		B	115,3 ∠-6,01˚	16.020 ∠-152,4˚
		C	115,4 ∠-126,1˚	16.000 ∠87,59˚

Meanwhile, PMU-3 and PMU-4 data monitor the voltage and current magnitude and angles on both loads. The voltage magnitude on the stable load is seen in the three phases, at 15.84 kV for PMU-3, while the load voltage on PMU-4's magnitude is seen in the three phases at 15, 86kV. Also, the load current in PMU-3 is also stable, as seen in the three phases at 114.2A. Figure 7 shows the current in PMU-4 is the same as PMU-3. However, voltage and current from the system simulation results need to be increased by connection to DG. Also, the PMU measurement results are in the form of current and voltage phasor values in each phase and in the form of current and voltage phasor values in positive order. Positive sequence current and voltage phasors are used for comprehensive system monitoring, which is possible at the control centre.

The three unbalanced phasor values are possibly broken down into a balanced three-phasor system in a three-phase system. A positive sequence phasor value consists of three separate phasors of the same magnitude and a phase difference of 120 degrees. Table 2 shows the simulation results connected to DG obtained PMU-1 data, the result of monitoring the voltage and current magnitude as well as angle, for the DG source. Similarly, PMU-2 data is the result of monitoring these parameters on the 150kV transmission line against the load, while PMU-3 and PMU-4 data monitor these parameters on the load side. According to the simulation data results, there is an increase in voltage and current at the load. Initially, the voltages for each load were 15.84kV and 15.86kV, and the current magnitudes of each load were 114.2A and 114.2A. However, after connecting to DG, the voltage became 16kV, and the load currents were 115.4A and 115.3A. Thus, using this PMU, the DG system has increased the power generated from the two sources, 150kV and DG networks supplied to the load. Furthermore, distributed generation has a role in maintaining power stability in the load and increasing energy efficiency by reducing power losses in DG-connected systems.

The estimated percentage error of the PMU output voltage is used to the ideal working counterpart. The working voltage tolerance issued by PLN is in the range of 5% to 10% of the 20kV distribution network's nominal voltage. Therefore, the PMU output voltage used by the distribution network is 16.33kV and has been converted into an equal value. Table 3 shows the percentage error in the DG-connected test conditions. The percentage of simulation error associated with DG on PMU-3 and PMU-4 in phases A, B, and C, has a smaller value of 0.02%. Meanwhile, without DG contact for PMU-3 and PMU-4, the three phases had error percentages of 0.03% and 0.02878%, respectively.

Table 3. The percentage results error of PMU voltage to the effective voltage

PMU	Phase	Target of effective Voltage (V)	with DG		without DG	
			Output Voltage of PMU (V)	Error (%)	Output Voltage of PMU (V)	Error (%)
PMU-1	A	16.330	16.090	0,01469	-	-
	B	16.330	16.110	0,01347	-	-
	C	16.330	16.100	0,01408	-	-
PMU-2	A	16.330	16.100	0,01408	15.990	0,02082
	B	16.330	16.120	0,01286	15.990	0,02082
	C	16.330	16.110	0,01347	15.990	0,02082
PMU-3	A	16.330	16.000	0,02020	15.840	0,03000
	B	16.330	16.020	0,01898	15.840	0,03000
	C	16.330	16.000	0,02020	15.840	0,03000
PMU-4	A	16.330	16.000	0,02020	15.860	0,02878
	B	16.330	16.020	0,01898	15.860	0,02878
	C	16.330	16.000	0,02020	15.860	0,02878

Analysis of the conditions before and connection to DG has been conducted. The results of the data from the simulations carried out are shown above. In addition, Figure 7 compares the phasor voltage in the conditions before and after the DG connection. This comparison shows the system increased the voltage on each bus and displays the positive sequence values of the phasor currents and the phasor voltages before and after DG connection.

Figure 8 compares the positive and negative sequence values for phasor voltage to distinguish between the conditions before and after DG connection. In addition, the chart shows voltage rises while DG is connected to this four-bus system. For example, before connecting the DG on the load side, the PMU-3 and PMU-4 displayed positive sequence values for the voltages of 15.84kV and 15.86kV, respectively. Meanwhile, after DG connection to the load side, the PMU-3 and PMU-4 display a higher value of 16kV.

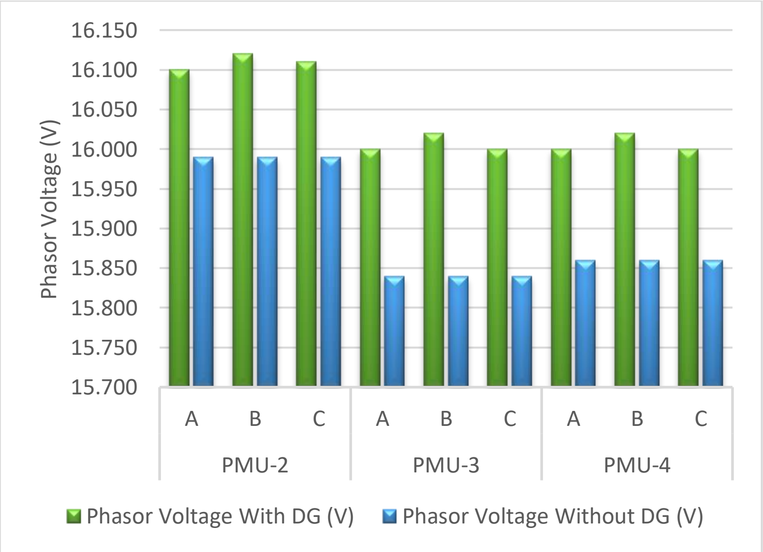

Figure 7. Comparison of phasor voltages before and after DG

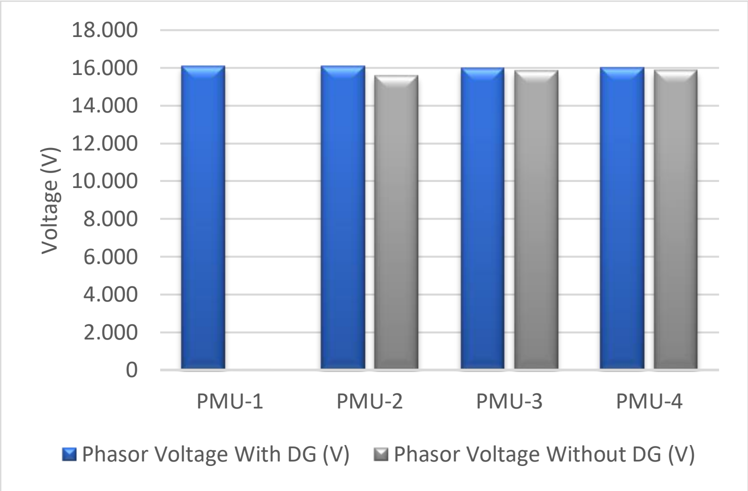

Figure 8. Comparison of the phasor voltages' positive sequence before and after DG

Voltage Validation

In the modelling system built and simulated using Matlab/Simulink, the voltage is read in the measurement phase to neutral. The simulation result voltage reading is validated using (1) in the phase-to-phase voltage measurement. According to (1), the switch in the converter is always open, the value of D becomes zero, and the output and input voltages are equal. However, as the duty ratio increases, the denominator becomes smaller, resulting in a larger output voltage. For example, in the simulation results with 1000W/m^2 irradiation, the resulting output voltage is 500.18Vdc.

$$V_o = \frac{273.5}{(1-0.453)} = 500Vdc$$

The converter generates this output voltage and is forwarded to the inverter circuit to be converted into ac voltage. Meanwhile, the voltage generated by the inverter is 207Vac, and this is read as the phase-to-phase voltage. Compared with the calculation results and simulation results applied to (2), the results obtained are not very different from the simulation results. This shows the converter and controller work well in producing the output voltage. In this case, the LC inverter and filter convert the dc voltage to ac, and the LC filter filters the PWM signal as well as improves the quality of power to be supplied to the grid utility. The equation below shows a 207Vac voltage is needed to the step-up transformer to generate a voltage on the network.

$$\frac{N_p}{N_s} = \frac{4.3}{330}$$

The following equation was obtained by comparing the number of turns in the primary and secondary coils.

$$\frac{207}{V_s} = \frac{4.3}{330}$$

$$\frac{207}{V_s} = \frac{4.3}{330}$$

$$V_s = \frac{330 * 207}{4.3}$$

$$V_s = 15{,}886.0465\ V = 1.58kV$$

The transformer's output voltage supplied is 1.6*10^4 Vac, and this voltage is generated in cases where the simulation is phase-to-neutral. Subsequently, this is converted into a phase-to-phase voltage, as shown.

$$V_{p-p}(bus\ 1) = \frac{16{,}100 * \sqrt{3}}{\sqrt{2}} = 19{,}718.39Vac$$

$$V_{p-p}(bus\ 3) = \frac{16{,}000 * \sqrt{3}}{\sqrt{2}} = 19{,}595.92Vac$$

$$V_{p-p}(bus\ 4) = \frac{16{,}010 * \sqrt{3}}{\sqrt{2}} = 19{,}608.17Vac$$

CONCLUSION

Based on the DG system modelling design and simulation results in this study, in the distribution network before DG is installed, the voltage supplied to the load side is 15.84kV and 15.86kV. Furthermore, the ideal working voltage value on the distribution network is 20kV, which has been converted to 16.33kV due to the PMU's output voltage. Therefore, in designing a distribution network connected to a Solar Power Plant with a solar cell source, this system is able to increase the voltage supplied to the load side, up to 16kV. The value of the load side voltage during DG connection was 16.33 kV. Thus, using a PMU makes voltage and current data collection and monitoring the magnitude and angle of the phasor on each bus much easier. The DG-connected test has a very small error value, especially at PMU-3 and PMU-4, with a value of 0.02%, respectively, compared to the DG-connected test error of 0.03% and 0.02878%, respectively. Therefore, the installation of DG in this system was concluded to increase the network's voltage, especially the stress on the load side. The success parameter in this study was bringing the stress on the load side close to the ideal working stress target value, and this has been successfully met.

ACKNOWLEDGMENT

This research was supported by the Ministry of Research and Technology/National Research and Innovation Agency (RISTEK-BRIN), the Republic of Indonesia. We also thank LPPM-UNRI, who provided insight and expertise that greatly assisted the research.

REFERENCES

[1] R. J. Haddad, B. Guha, Y. Kalaani and A. El-Shahat, "Smart Distributed Generation Systems Using Artificial Neural Network-Based Event Classification," in *IEEE Power and Energy Technology Systems Journal*, vol. 5, no. 2, pp. 18-26, June 2018, doi: 10.1109/JPETS.2018.2805894.

[2] A. A. Zakri, M. W. Mustafa, H. Syaibi and I. Sofimieari, "Monitoring Fault Diagnosis Based on Phasor Measurement Unit at Wide Area Systems," *2019 IEEE Conference on Energy Conversion (CENCON)*, 2019, pp. 245-249, doi: 10.1109/CENCON47160. 2019.8974748.

[3] T. Kurniawan, "Study of 3 Phase Active Power Flow in Radial Distribution System With Determination of Optimal DG Location and Capacity Using K-Means Clustering Method," *Thesis*, Institut Teknologi Sepuluh Nopember, Indonesia, 2017.

[4] R. Revandy, "Power System Stability Evaluation Using Synchronised Phasor Measurement At Gitet Suralaya And Gitet Cilegon," *Thesis*, Institut Teknologi Sepuluh Nopember, Indonesia, 2015.

[5] H. Iswadi, R. J. Best and D. John Morrow, "Identification of small signal oscillation mode parameters from simulated and actual PMU ringdown data," *2015 IEEE Eindhoven PowerTech*, 2015, pp. 1-6, doi: 10.1109/PTC.2015.7232327.

[6] X. Wang et al., "Micro-PMU for distribution power lines," *CIRED - Open Access Proceedings Journal*, vol. 2017, no. 1, pp. 333–337, 2017, doi: 10.1049/oap-cired.2017.0137.

[7] A. A. G. Mabaning, J. R. C. Orillaza and A. von Meier, "Optimal pmu placement for distribution networks," *2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, 2017, pp. 1-6, doi: 10.1109/ISGT-Asia.2017.8378415.

[8] T. T. Tesfay, J. -Y. Le Boudec and O. Svensson, "Optimal Software Patching Plan for PMUs," in *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6500-6510, Nov. 2018, doi: 10.1109/TSG.2017.2714204.

[9] K. Rawy, F. Kalathiparambil, D. Maurath and T. T. Kim, "A Self-Adaptive Time-Based MPPT With 96.2% Tracking Efficiency and a Wide Tracking Range of 10 μ A to 1 mA for IoT Applications," in *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 64, no. 9, pp. 2334-2345, Sept. 2017, doi: 10.1109/TCSI.2017.2693405.

[10] K. Mizuki, H. Yajima, S. Mineta, S. Sugita, N. Yamashita and T. Babasaki, "Maximizing power-supply time of DC power system with photovoltaics and fuel cells," *2014 IEEE 36th International Telecommunications Energy Conference (INTELEC)*, 2014, pp. 1-4, doi: 10.1109/INTLEC.2014.6972191.

[11] D. K. Chy, M. Khaliluzzaman and R. Karim, "Analysing efficiency of DC-DC converters joined to PV system run by intelligent controller," *2017 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, 2017, pp. 457-462, doi: 10.1109/ECACE.2017.7912948.

[12] I. Buyung and K. Azizi, "Portable Power Plan Solar Cell," *Prosiding Seminar Nasional Aplikasi & Teknologi*, Yogyakarta, Indonesia, 2016, pp. 332–342.

[13] A. A. Zakri, A. Syahza, D. Hanafi, and H. Syahadad, "Design and Modelling and to Improve Battery Charging Efficiency using Photovoltaics," *Technology Reports of Kansai University*, vol. 62, no. 08, pp. 4667–4677, 2020.

[14] V. Murugesan, Y. Chakhchoukh, V. Vittal, G. T. Heydt, N. Logic and S. Sturgill, "PMU Data Buffering for Power System State Estimators," in *IEEE Power and Energy Technology Systems Journal*, vol. 2, no. 3, pp. 94-102, Sept. 2015, doi: 10.1109/JPETS.2015.2448115.

[15] A. Waqar, Z. Khurshid, J. Ahmad, M. Aamir, M. Yaqoob and I. Alam, "Modeling and simulation of phasor measurement unit (PMU) for early fault detection in interconnected two-area network," *2018 1st International Conference on Power, Energy and Smart Grid (ICPESG)*, 2018, pp. 1-6, doi: 10.1109/ICPESG.2018.8384491.

[16] F. Zhu, A. Youssef and W. Hamouda, "Detection techniques for data-level spoofing in GPS-based phasor measurement units," *2016 International Conference on Selected Topics in Mobile & Wireless Networking (MoWNeT)*, 2016, pp. 1-8, doi: 10.1109/MoWNet.2016.7496634.
[17] T. Y. Mina, S. Bhamidipati, and G. X. Gao, "GPS Spoofing Detection for PMUs Using a Hybrid Network Goals for Power Grid Modernization," 2018.
[18] T. Becejac and P. Dehghanian, "PMU Multilevel End-to-End Testing to Assess Synchrophasor Measurements During Faults," in *IEEE Power and Energy Technology Systems Journal*, vol. 6, no. 1, pp. 71-80, March 2019, doi: 10.1109/JPETS.2019.2900064.
[19] J. Sexauer, P. Javanbakht and S. Mohagheghi, "Phasor measurement units for the distribution grid: Necessity and benefits," *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT)*, 2013, pp. 1-6, doi: 10.1109/ ISGT.2013.6497828.
[20] D. W. Hart, "Commonly used ower and Converter Equations," in *Power Electronics*, McGraw-Hill, NY, US, 2011.
[21] J. D. Glover, M. S. Sarma, and T. Overbye, *Power System Analysis and Design,* 4th Edition, CL Engineering, Thailand, 2012.
[22] P. Choudhary and S. N. Mahendra, "Feedback control and simulation of DC-DC Cuk converter for solar photovoltaic array," *2016 IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics Engineering (UPCON)*, 2016, pp. 591-596, doi: 10.1109/UPCON.2016.7894721.