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Research Original Article

Performance Analysis of On-Grid Rooftop Solar Power Plant with 600 Wp Capacity Based on Data Logger

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Abstract
One of the renewable energy power plants whose construction is very massive is the solar power plant (PLTS) because it can be built anywhere in Indonesia. The type of PLTS with cheap investment is the on-grid system. This study aims to analyze the performance of the 600 Wp on-grid PLTS based on data loggers. Data logger is a data recording system designed using an Arduino Nano microcontroller equipped with sensors such as a solar radiation sensor (PYR20), temperature and humidity sensor (DHT22), PV module temperature sensor (DS18B20), DC voltage sensor, DC current sensor (ACS712), real time clock (DS3231), AC digital wattmeter module (PZEM-004T 10 A) and Micro SD Card Mini to store measurement data. The data logger is set to store measurement data every 5 minutes. The results of sensor measurements after calibration have an average measurement error of 5.20%, 0.56%, and 0.68% for the PYR20 irradiance sensor, 50 V range DC voltage sensor, and DC current sensor (ACS712). Based on the results of data logger recording, the 600 Wp on-grid PLTS system has a PV module efficiency in the range of 2.45 - 19.2% with an average of 8.60%, and the inverter (smart microgrid inverter) has an average efficiency of 89.40%.
Keywords: On-Grid Solar Power Plant; Data Logger; Solar Panel Efficiency; Inverter Efficiency

Introduction
Solar Power Plant (PLTS) is one of the power plants from renewable and environmentally friendly energy. One type of PLTS system is on-grid PLTS. The electrical energy generated by on-grid PLTS is sent to the electricity grid or used by itself to increase the capacity of electrical power. The type of on-grid PLTS system has a cheaper investment cost than the off-grid PLTS system because it does not require batteries to store the power generated. However, the off-grid system is more reliable than the on-grid system when a power outage occurs. The on-grid system also goes out while the off-grid system is not affected because the electrical load is handled by the battery (VR, 2022). PLTS is a generator that has very good development prospects because the return on investment (ROI) reaches 5-10 years, so after that, the energy costs obtained are free, and PLTS owners are not worried about increasing electricity rates (SolarEmporium, 2024).

Solar power plants have many long-term advantages so that solar power plant performance is measured to obtain optimal performance. Solar power plant performance is measured using Homer simulation and from this calculation, solar power plant investment can be returned in 4 years (Makkiabadi et al., 2021). Solar power plant performance evaluation can also be used for efficiency improvement suggestions (Verma et al., 2021). Solar power plant performance evaluation can be obtained from real-time data (Bendaas et al., 2023). Solar power plant performance is measured as a source of electricity for mini greenhouses (Putri et al., 2022), a source of electricity in tropical areas (Susato et al., 2022), and a source of electricity in coastal areas (Navothna & Thotakura, 2022). Solar power plant performance that can be measured includes system efficiency, solar fraction, capacity factor, and performance ratio (Odeh, 2018). To be able to measure solar power plant performance, a data logger is needed that continuously measures system quantities. Data loggers are used to record wind energy potential data (Faisal et al., 2022), dual-fuel engine performance (Sinaga et al., 2019), diesel engine performance (Wan Mansor, 2020), and turbocharger performance for Commercial Vehicle Engines (Badal Dev Roy & Saravanan, 2017). Data loggers for PV systems only measure panel performance with 1 1k Ohm resistor load (Masarrang et al., 2021), and for off-grid solar power plant monitoring (Wikapti et al., 2023). Based on this condition, research needs to be conducted to measure and analyze on-grid PLTS to determine the performance of on-grid PLTS which has a low investment.

Arduino is widely used in system design. Arduino is an open source device that can be programmed for various purposes. Arduino is used to design smart energy meters (Nebrida et al., 2023), (Al-sehail et al., 2022), (Muljono et al., 2018) and low-cost energy meters (Ramalingam et al., 2019), create a visualization measuring device for rotation direction to determine the sequence and phase difference of a 3-phase system (Nrartha et al., 2022), and gas detection in chicken farms (Hasibuan et al., 2023). Arduino is also used for monitoring systems in electric power systems such as in (Pramudita & Ardiansyah, 2021), can be monitored via smartphone applications (Hasibuan et al., 2021), and monitoring data is stored on an SD Card (Wikapti et al., 2023).

This study designs a data logger using Arduino Nano which has a low price and small size. The data logger is used to record the performance of on-grid PLTS including variations in voltage and current (DC and AC) due to variations in solar irradiation and PV modules temperature, the relationship between solar irradiation and PV modules temperature, the relationship between power (DC and AC) to solar irradiation and PV modules temperature, PV modules efficiency, and inverter (smart microgrid inverter) efficiency. The data logger designed using Arduino Nano is equipped with sensors such as: a irradiation sensor (PYR20), a temperature and humidity sensor (DHT22), PV modules temperature sensor (DS18B20), a DC voltage sensor, a DC current sensor (ACS712), real time clock (DS3231), a digital AC wattmeter module (PZEM-004T 10 A) and a Micro SD Card Mini to store measurement data.

Literature Review

On-grid PLTS consists of the following main components: PV modules and inverter. Protection components such as: blocking diodes and fuses on each PV module, DC mini circuit breaker (MCB), DC surge protection device (SPD), AC SPD, and AC MCB. The block diagram of on-grid PLTS is shown in Figure 1 (*Mengenal Sistem PLTS Atap On-Grid*, 2021).

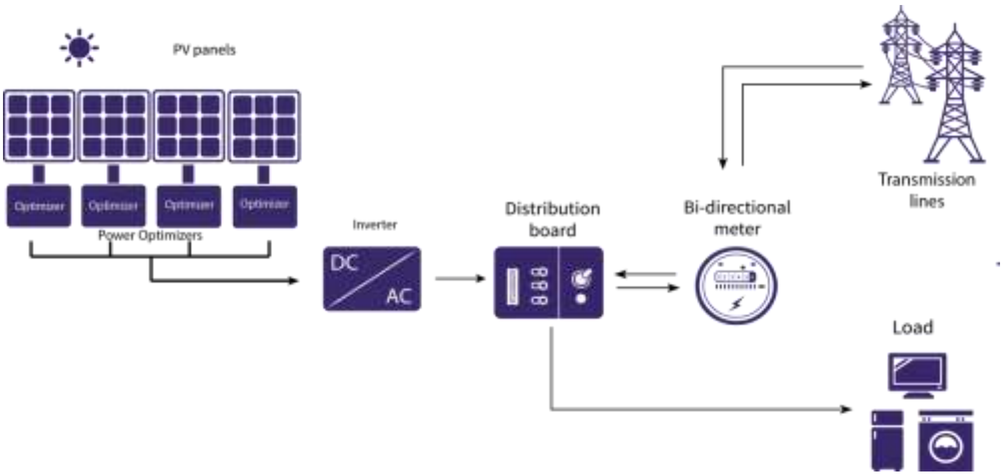


Figure 1. Block Diagram of On-Grid PLTS

Figure 1 shows the voltage on the side before the inverter is DC voltage and after the inverter is AC voltage. So it is necessary to record on both sides to get the performance of the on-grid PLTS. On the DC side, it is necessary to record such as: DC voltage, DC current and DC power, while on the AC side, it is necessary to record such as: AC voltage, AC current, AC power and power factor. Recording of environmental parameters is also required such as: solar irradiation, temperature and humidity of the environment and temperature of the PV modules.

Recording the parameters of the on-grid PLTS requires sensors such as DC voltage and current sensors shown in Figure 2.(a) and (b) ACS712 (*Datasheet ACS712*, n.d.). The DC voltage and DC current sensors can measure voltages up to 50 V DC and currents up to 30 A, respectively. Recording on the AC side uses the PZEM-004T module to measure AC voltage, AC current, AC power and power factor. Figure 3 is the PZEM-004T module (*Datasheet PZEM-004T*, n.d.). The irradiation sensor (PYR20), temperature and humidity sensor (DHT22) and PV module temperature sensor (DS18B20) are shown in Figure 4.(a) (*Datasheet PYR20*, n.d.), (b) (*Datasheet DHT22*, n.d.), and (c) (*Datasheet DS18B20*, n.d.). The measurement results of these sensors are recorded and stored on the SD Card mini via the SD Card module (MSCM). The recording time synchronization uses the DS3231 real time clock (RTC). The SD Card module (MSCM) and DS3231 RTC modules are shown in Figure 5.(a) (*Datasheet SD Card Module*, n.d.) and (b) (*Datasheet DS3231 RTC Module*, n.d.).

(a) (b)

Figure 2. Sensors on The DC Side

Figure 3. PZEM-004T Module for Measuring AC Side System Parameters

(a) (b) (c)

Figure 4. Sensors for Measuring Environmental Parameters

(a) (b)

Figure 5. SD Card Module (MSCM) and Real Time Clock (RTC) DS3231 Module

The measured performance of on-grid PLTS includes variations in voltage and current (DC and AC) due to variations in solar irradiation and PV modules temperature, the relationship between solar irradiation and PV modules temperature, the relationship between power (DC and AC) to solar irradiation and PV modules temperature, PV module efficiency, and inverter efficiency. The efficiency of PV module and inverter can be calculated using Equations 1 and 2.

$$\eta_{PV} = \frac{V \; x \; I}{G \; x \; A} \text{ x } 100 \; \% \tag{1}$$

Where V, I, G and A are the DC voltage, DC current, solar irradiance and cross-sectional area of the PV module, respectively.

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \text{ x } 100 \; \% \tag{2}$$

Where P_{AC} and P_{DC} are the output and input power of the inverter.

Materials & Methods

The specifications of the on-grid PLTS analyzed are the 600 Wp on-grid PLTS in Building B, Faculty of Engineering, University of Mataram. The on-grid PLTS is the result of the design in (Deniarahman et al., 2024). The on-grid PLTS has two electrical panels. The first electrical panel is a DC panel box and the second electrical panel is an AC panel box. Figure 6 is a block diagram of the 600 Wp on-grid PLTS.

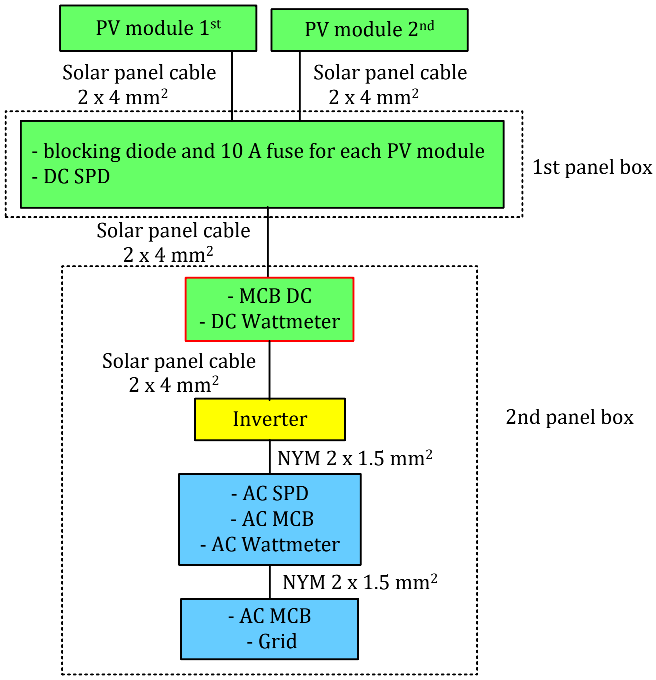


Figure 6. Block Diagram of 600 Wp PLTS

The data logger is placed on the first (DC panel box) and second (AC panel box) panel boxes. On the DC panel box, a data logger is equipped with sensors to record solar irradiation, temperature and humidity of the environment around the PV module, and the temperature of the PV module. Sensor measurement data is stored on the SD Card at the data logger. The circuit of the data logger on the DC panel box is shown in Figure 7. The second data logger is installed on the AC panel box. The sensors added to the second data logger are a DC voltage sensor, a DC current sensor, a PZEM-004T module to measure the AC side system parameters, and a temperature and humidity sensor. The second data logger also has an SD Card module to store measurement data. Data synchronization between data loggers on DC and AC panel boxes, then each data logger is equipped with RTC DS3231. The data logger circuit on the AC panel box is shown in Figure 8.

Figure 7 shows the connection of each sensor to the Arduino Nano. The solar irradiance sensor (PYR20) requires an ampere (mA) to voltage (V) interface using the HW-685. The PYR20 measurement range is 2000 W/m2 irradiance equal to 20 mA, so the HW-685 will convert 20 mA to 5 Volts according to the maximum input voltage limit on the Arduino Nano ADC (A0-A7). The PYR20 measurement results are sent to the Arduino Nano (A0) via the HW-685. The DHT22 sensor (temperature and humidity sensor) is connected to the Arduino Nano via the digital port (D4). The RTC D3231 is connected to the Arduino Nano on ports A4 and A5 (Inter-Integrated Circuit (I2C) communication). The DS18b20 sensor on each PV module is connected to ports A0 and A3 on the Arduino Nano. The SD Card module is connected to ports D7, D8, D11 and D12 (Serial Peripheral Interface (SPI) communication).

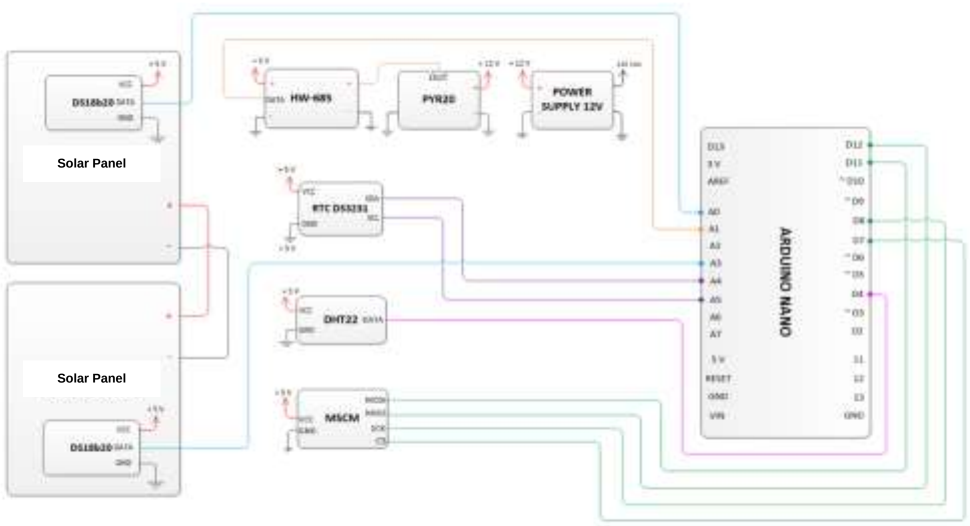


Figure 7. Data Logger System Circuit on DC Panel Box

Figure 8 shows the sensor circuit on the second data logger to the Arduino Nano. The measurement range of the DC voltage sensor is up to 50 V DC. The measurement results of the DC voltage sensor are sent to the Arduino Nano via the ADC port (A2). The measurement limit of the current sensor (ACS712) is up to 30A. The measurement results of the ACS712 sensor are sent to the Arduino Nano via port A1. The measurement results of the temperature and humidity sensors are sent to the Arduino Nano via port D2. The AC wattmeter module (PZEM-004T) is connected to the Arduino Nano via serial communication. The ports set for serial communication are A6 (Rx) and A7 (Tx). The SD Card module is connected to the Arduino Nano via SPI communication and the RTC DS3231 via I2C communication.

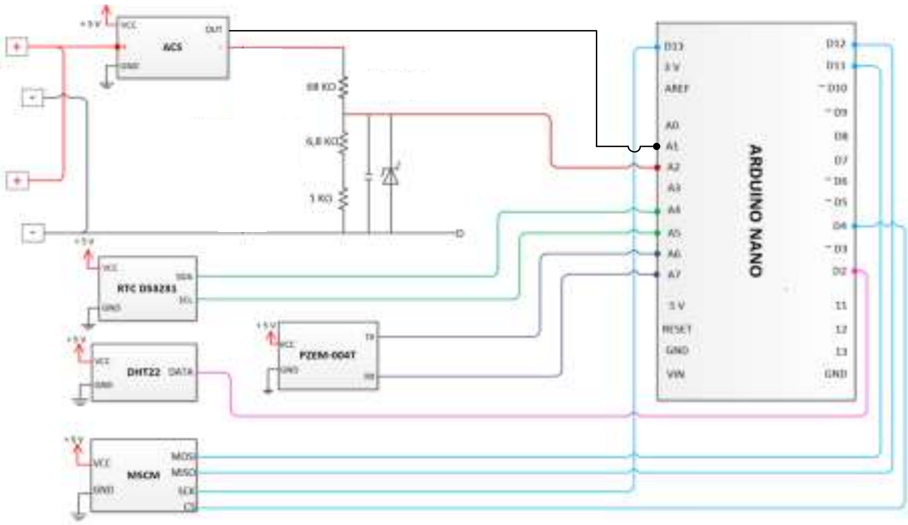


Figure 8. Data Logger System Circuit on AC Panel Box

After assembling the sensors for the first and second data loggers, continue by creating a program using Arduino IDE for the two data loggers so that the measurement results of the sensors can be stored on the SD Card. The next stage is the calibration of the DC voltage sensor, DC current sensor, and the solar irradiation sensor (PYR20). Calibrate the DC voltage sensor, DC current and PYR20 by comparing the measurement results of each with a multimeter, DC ampere clamp and pyranometer. These results are used as calibration data to create linear equations used in the program in Arduino IDE. After obtaining valid measurement results from the calibration results, the data logger is placed on each panel box to record the performance of the 600 Wp on-grid PLTS. The data logger records the performance of the on-grid PLTS for 14 days, the measurement results are stored every 5 minutes. The data stored is the measurement results averaged every 5 minutes.

Results and Discussion

The data logger on the DC and AC panel boxes are shown in Figures 9 and 10, respectively. Each part in Figure 9 can be explained as follows: A is IC 7805 for 5 V DC voltage regulator as sensor power supply, B is IC 7809 for 9 V DC voltage regulator as Arduino Nano power supply, C is IC D313 power transistor to amplify the current of the 5 V DC voltage regulator, D is DC step down circuit for PYR20 power supply, E is HW-685 for interface from mA to V, F is DC step down module for PYR20 power supply, G is SD Card Module (MSCM), H is RTC DS3231, I is DHT22 terminal, J is Arduino Nano, K is LED as an indicator data logger stores data, L is push button as a button to start recording, M is PYR20 terminal, and N is 24 V 3 A DC power supply.

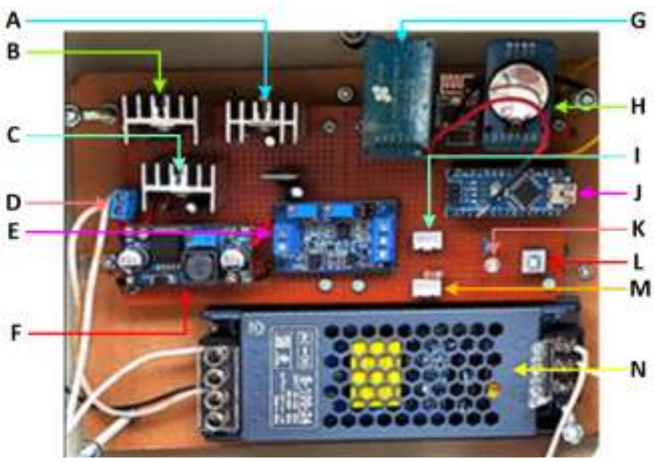


Figure 9. Data Logger on DC Panel Box

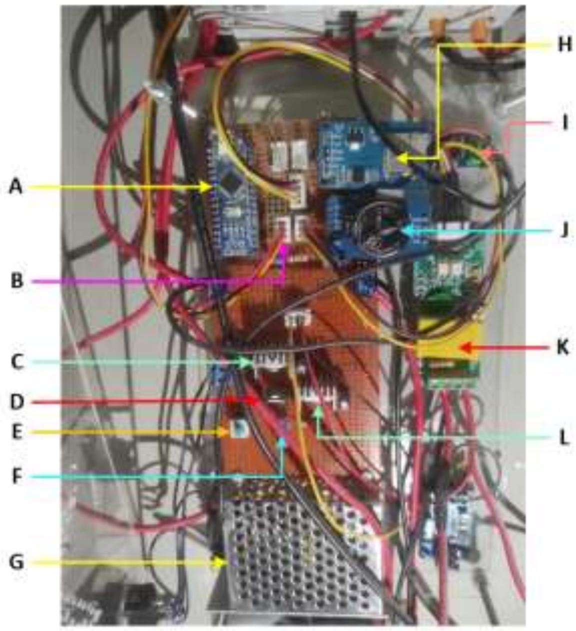


Figure 10. Data Logger on AC Panel Box

Each part in Figure 10 can be explained as follows: A is Arduino Nano, B is DHT22 terminal, C is IC 7805 for 5 V DC voltage regulator as sensor power supply, D is IC D313 power transistor to amplify the current of the 5 V DC voltage regulator, E is push button as a button to start recording, F is LED as an indicator data logger stores data, G is 12 V 3 A DC power Supply, H is SD Card module (MSCM), I is current sensor (ACS712), J is RTC DS3231, K is PZEM-004T module, and L is IC 7809 for 9 V DC voltage regulator as Arduino Nano power supply.

The measurement results of the DC voltage sensor, DC current sensor, and PYR20 sensor after calibration are shown in Tables 1, 2, and 3. Based on the measurement results, the measurement errors of the DC voltage sensor are 1.08%, 0.12%, and 0.56% for the maximum, minimum, and average measurement errors. The measurement errors of the DC current sensor (ACS712) are 1.19%, 0.40%, and 0.68% for the maximum, minimum, and average measurement errors. The measurement errors of the solar irradiance sensor (PYR20) are 8.50%, 1.80%, and 5.20% for the maximum, minimum, and average measurement errors.

Table 1. DC Voltage Sensor Measurement Results after Calibration

Measurement to	Multimeter measurement results (V)	DC voltage sensor measurement results (V)	Error (%)
1	29.96	29.71	0.83
2	31.33	30.99	1.08
3	30.96	30.92	0.12
4	31.06	30.95	0.35
5	31.29	31.03	0.83
6	31.15	31.00	0.48
7	28.92	28.84	0.27
8	30.11	29.89	0.73
9	30.44	30.26	0.59
10	31.19	31.09	0.32
Maximum error			1.08
Minimum error			0.12
Average error			0.56

Table 2. DC Current Sensor Measurement Results after Calibration

Measurement to	DC ampere clamp measurement results (A)	DC current sensor measurement results (A)	Error (%)
1	12.62	12.47	1.19
2	13.12	13.06	0.46
3	13.41	13.32	0.67
4	13.07	12.99	0.61
5	12.59	12.54	0.40
6	13.17	13.06	0.84
7	13.38	13.31	0.52
8	12.05	11.95	0.83

9	12.76	12.69	0.55
10	12.04	11.95	0.75
Maximum error			1.19
Minimum error			0.40
Average error			0.68

Table 3. PYR20 Sensor Measurement Results after Calibration

Measurement to	Solar Power Meter (W/m2)	PYR20 (Watt/m2)	Error (%)
1	909.5	866.2	4.7
2	938.2	868.5	7.4
3	962.1	880.8	8.5
4	900.2	874.3	2.8
5	910.7	894.0	1.8
6	955.4	910.9	4.6
7	985.8	923.5	6.3
8	987.9	931.6	5.6
9	1101.2	1025.2	6.9
10	1126.1	1090.5	3.1
Maximum error			8.5
Minimum error			1.8
Average error			5.2

The results of data logger recording for 14 days from February 27, 2024 to March 11, 2024 can be obtained information on temperature and humidity conditions in the environment around the AC panel box which fluctuate. During the recording, the maximum temperature was 34 ^{0}C at 15.25 WITA and a minimum of 28.3 ^{0}C at 07.10 WITA, maximum humidity was 82.7% at 06.40 WITA and a minimum of 58.9% at 16.00 WITA. DC and AC voltages also fluctuate, the maximum DC voltage is 33.21 V at 10.35 WITA and a minimum of 1.12 V at 06.00 WITA, the maximum AC voltage is 239.5 V at 07.05 WITA and a minimum of 235.3 V at 10.00 WITA. DC and AC currents fluctuate. The maximum DC current is 13.56 A at 12.25 WITA and the minimum is 0.08 A at 06.00 – 06.10 WITA. The maximum AC current is 1.29 A at 11.55 WITA and the minimum is 0.03 A at 06.00 – 06.20 WITA. The power increases along with the increase in voltage and current. The maximum DC power is 422 W at 12.25 WITA and the minimum is 0.1 W at 06.00 WITA. The maximum AC power is 289.7 W at 11.55 WITA and the minimum is 0.3 W at 06.30 WITA. The results of the data logger recording on the DC panel box show that the temperature and humidity of the environment around the DC panel box fluctuate which is influenced by solar irradiation because the DC panel box is outdoors/under the roof and outside the building. The maximum solar irradiation recording results were 1116.11 W/m2 at 13.05 WITA with a temperature inside the DC panel box of 40.5 ^{0}C, an ambient temperature of 34.76 ^{0}C, a humidity of 66.43%, a temperature of the 1st PV module of 91.12 ^{0}C and a temperature of the 2nd PV module of 90.13 ^{0}C. Minimum irradiation of 0 W/m2 at 06.00 with a temperature inside the panel box of 27.41 ^{0}C, an ambient temperature of 27.67 ^{0}C, a humidity of 87.84%, a temperature of the 1st PV module of 24.59 ^{0}C and a temperature of the 2nd PV module of 24.48 ^{0}C.

Solar irradiation for 12 hours from 06:00 to 18:00 WITA recorded every 5 minutes is shown in Figure 11. Solar irradiation increased from 06:35 to 10:55 WITA. At 11:00 to 18:00 WITA, solar irradiation fluctuated due to cloudy skies. The minimum solar irradiation at 06:00 - 06:30 WITA was 0 W/m2 and the maximum at 13:05 was 1116.11 W/m2.

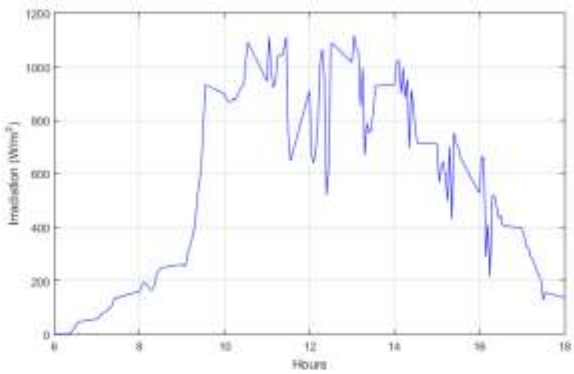
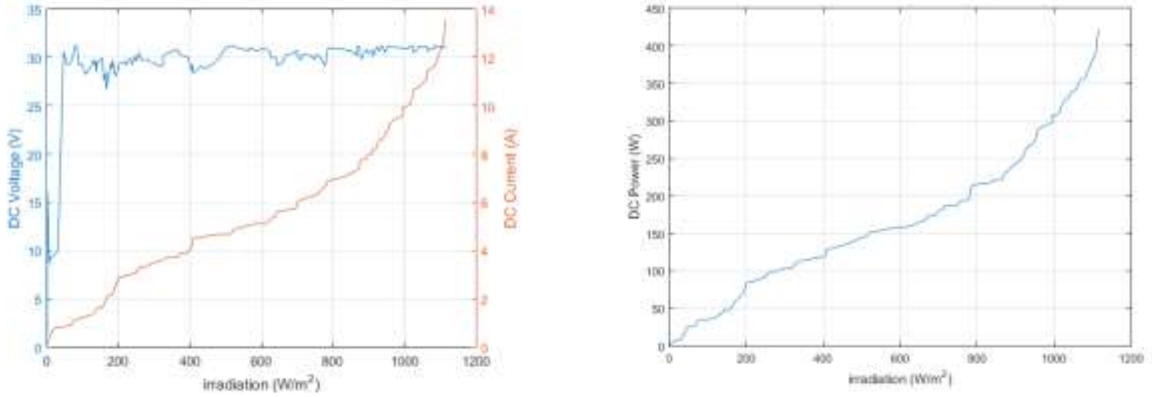


Figure 11. Solar Irradiation in One Day

Changes in solar irradiation on DC voltage, DC current, and DC power are shown in Figure 12. Changes in DC voltage and DC current due to changes in solar irradiation are shown in Figure 12.(a). Changes in DC current are directly proportional to solar irradiation. This is because the higher the solar irradiation, the higher the DC current generated by the PV module. The maximum DC current is 13.56 A at a solar irradiation of 1116.11 W/m2. The 600 Wp on-grid PLTS uses a smart microgrid inverter type inverter that already has a Maximum Power Point Tracking (MPPT) control so that the power generated is the maximum power at each solar irradiation, so that the voltage is maintained at the optimum point which tends to remain constant and fluctuate between its optimum points. Figure 12.(b) is the change in DC power sent to the inverter due to changes in solar irradiation. The maximum DC power is 422 W at a solar irradiation of 1116.11 W/m2 and the minimum is 0.1 W at a solar irradiation of 0 W/m2.

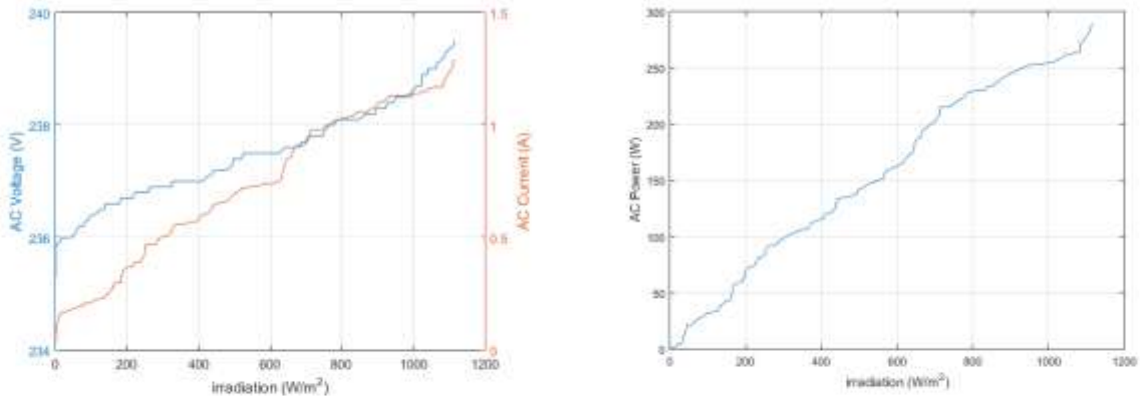


(a) (b)

Figure 12. PV Module Output for Changes in Solar Irradiance

The relationship between AC voltage, AC current and AC power to changes in solar irradiation is shown in Figure 13. DC voltage is converted to AC using a smart micro grid. Figure 13.(a) shows a DC voltage that tends to remain constant and fluctuates around its optimum voltage producing an AC voltage in the range of 235.3 – 239.5 V AC. This voltage is the same as the grid voltage. Current (Figure 13.(a)) and AC power (Figure 13.(b)) increase with increasing solar irradiation. The maximum AC current and AC power delivered to the grid are 1.29 A and 289.7 W, respectively.

The effect of solar irradiation on the temperature of the PV module is shown in Figure 14. The temperature of the PV module increases with increasing solar irradiation, the higher the solar irradiation received by the PV module, the hotter the temperature of the PV module. The maximum temperature of the PV module is 91.12 ^{0}C at irradiation of 1116.11 W/m2. The minimum temperature of the PV module is 6.56 ^{0}C at irradiation of 0 W/m2 at 06.00 WITA in the morning.



(a) (b)

Figure 13. Smart Microgrid Inverter Output Due to Changes in Solar Irradiation

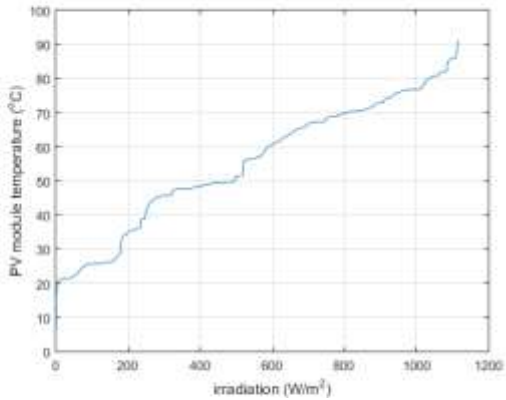
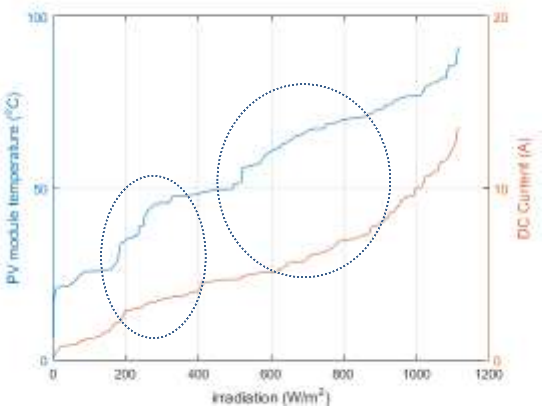
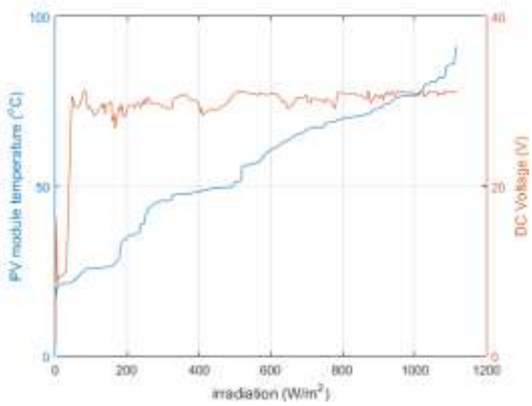


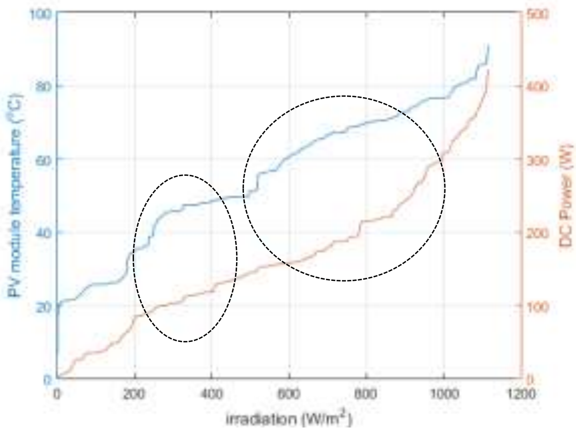
Figure 14. Changes in PV Module Temperature Due to Changes in Solar Irradiation.



(a)



(b)



(c)

Figure 15. Effect of Temperature on DC Current, DC Voltage and DC Power

The effect of PV module temperature on DC voltage, DC current and DC power generated by PV module are shown in 15.(a), (b) and (c). Figure 15.(a) shows that increasing temperature causes the DC current generated by PV module to decrease as marked in the circle with dashed line. Increasing temperature does not affect the DC voltage generated by PV module due to the influence of MPPT on smart microgrid inverter as shown in Figure 15.(b). Similar to DC current, DC power decreases with increasing PV module temperature, as marked in Figure 15.(c) with the circle with dashed line.

The effect of solar radiation and PV module temperature on PV module efficiency is shown in Figure 16. Figure 16 shows that PV module efficiency increases with increasing solar radiation, but high module temperature causes PV module efficiency to decrease as shown by the circle with a dashed line. Based on the results of data logger recording, the efficiency of the PV module is in the range of 2.45 - 19.2% with an average efficiency of 8.60%. Meanwhile, the efficiency of the smart microgrid inverter is in the range of 68.23 - 96.43% with an average efficiency of 89.40%.

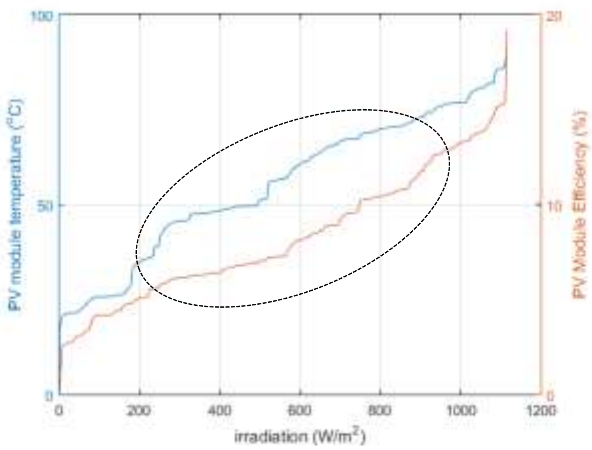


Figure 16. PV Module Efficiency Against Solar Irradiation and PV Module Temperature

Conclusions

The performance of the 600 Wp on-grid rooftop solar power plant can be recorded by two data loggers placed on the DC and AC panel boxes. Recording synchronization was successfully carried out by adding RTC DS3231 to each panel box. The results of data logger recording show that the performance of the on-grid rooftop solar power plant is affected by solar irradiation and temperature on the PV module. Increased irradiation causes an increase in DC and AC currents, and DC and AC power. But the increase in temperature causes the current and power to decrease. AC and DC voltages tend to be constant and fluctuate between the optimum voltage caused by the MPPT on the smart microgrid inverter. The efficiency of PV modules is affected by solar irradiation and PV module temperature, the module efficiency increases with increasing irradiation and tends to decrease with increasing temperature. The average efficiency of PV modules is 8.60%, while the average efficiency of smart microgrid inverters is 89.40%.

Acknowledgments

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