Experimental Testbed for Solar PV-Battery Hybrid System

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Abstract

Indonesia has a high potential of solar energy due to its location on the equator and in this paper, experimental testbed for PV-Battery hybrid system is developed and discussed. The hybrid system is designed to supply electricity during the night time with on-grid inverters. Practical and inexpensive solar PV-Battery hybrid system was developed and tested in Tangerang area with flexible AC electric production during the daytime as well as the night time. Practical issues for hybrid system were discovered such as limited range of inverter output voltage, sensitivity of solar panel electric production to its position and shading, accurate DC current sensor, cable and component over-heating, lower inverter conversion efficiency than what specification states, safety on charging Lithium-Ion battery. Conclusions from this study are that wet battery seems to store more electric energy and more robust than the free maintenance battery, battery voltage is not a good indicator for battery level of charged, solar panel electric production is sensitive to its position and clearness from the shading, measurement of cable and component temperature is needed to justify enough cable size to deliver designed electric power, enough capacity of the component and quality of connections, care need to be taken when Lithium-ion batteries are used due to possible explosion for too high charging current.

Keywords

Photovoltaic, PV, solar panel, battery, hybrid system.

CCS CONCEPTS

•Hardware~Power and energy~Energy distribution~Smart grid

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1. Introduction

Most household is powered by electricity from city electric energy supplier. However, the price of the electricity keeps going higher therefore electricity use needs to be more efficient. To reduce electricity bill, other sources of energy should be considered that can be converted to electricity such as sun radiation, wind, running water, biomass, etc. see [1,2,3,4,5].

The source of energy that is availably abundant in Indonesia is sunlight. Sunlight is available almost everywhere and anytime of the year with different sun radiation intensity due to local weather, such as clouds, fogs, temperature and rains [6,7]. The weather is changing every day and every month and average sun radiation energy can be analyzed in every location to calculate available electric energy harvested from the sun radiation.

Sunlight is only available during the daytime and most household electric demand is high during the night time when the occupants come back home from their daily activity. Energy storage device is needed to store electricity generated from the sunlight during the daytime to make it available during the night time. Battery is mostly used for this purpose. However, the price for battery with enough capacity for household Solar PV system is still expensive. Application of battery for PV system has been discussed in [1,2,8] and optimization of battery capacity for Solar PV system needs to be done in order to minimize the investment cost.

2. Literature Review

2.1. PVGIS in Indonesia

Photovoltaic Geographical Information System (PVGIS) is a free online solar energy calculator for almost the whole world from America, Europe, Africa and Asia by the European Commission's science and knowledge service [9]. It can calculate annual, monthly and daily output of average power and energy and potential electric generation by solar PV panel with different tilt and orientations. PVGIS utilizes map representing yearly average of daily global solar irradiation on a horizontal and inclined surface. The weather map data is derived by data enhancement of HelioClim-1 database [10] which contains 20-years average, period of 1985-2004. PVGIS contains several calculations

- Computation of clear-sky global irradiation on a horizontal surface.
- Sky obstruction by local terrain features (hills or mountains) calculated from the digital elevation model.

- Interpolation of the clear-sky index and computation of global irradiation on a horizontal surface.

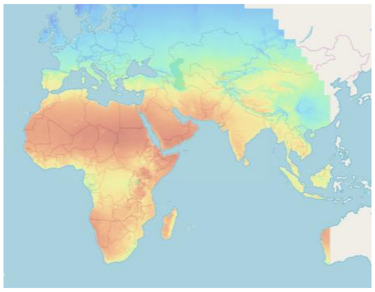

Figure 1: Map of global irradiation in Africa and Asia containing 20-years data average [9].

Fig.1 shows the global irradiation map in Africa and Asia. It shows that solar irradiation in Indonesia is not as high as in Africa due to lower solar irradiation level, however, it is still high enough to be harvested for electricity.

2.2. Poly-Crystalline Solar Panel

The most common solar panel sold in the market is Poly-Crystalline silicon based solar panel with its efficiency converting sunlight energy to electrical energy of around 17%. Recently, its price is getting lower due to advancement of technology in manufacturing process for this type of solar panel and abundantly cheap raw material. Market share of Poly-Crystalline solar panel in the year of 2010 is around 53% [11]. This type of solar panel is used for this development. Other type of solar panel is Mono-Crystalline which is slightly more efficient than Poly-Crystalline but slightly more expensive, see Fig. 2.

Figure 2: Comparison of Poly-Crystalline and Mono-Crystalline.

2.3. Battery

There are several types of battery that can be used for solar PV hybrid system, such as lead-acid, nickle-cadmium and sodium-sulfur batteries. However, automotive 12-Volt lead-acid battery is quite common to be used due to its availability and affordability. In the hybrid system, the battery voltage should be set as high as possible to reduce electric current for the same electric power. However, the battery voltage should be suitable with electric charger controller being used in the hybrid system. Typical charger controller works with multiple options of voltage: 12V, 24V, 36V, 48V, or higher.

Battery is not only used to store electric energy, it can also be used to stabilize the electric grid system. Battery storage power plant with large power capacity can be used for short-term peak power supply and ancillary services to provide frequency respond to minimize power outages.

Other type of battery, Lithium-ion batteries type 18650 was tested in this study. Its specification is 3400 mAH, 3.7 Volt and its continuous discharge current of 20 A. However, the batteries exploded due to too high charging current during the first day. We stopped using this type of battery due to safety.

2.4. On-Grid Inverter

One of important component in the Solar PV-Battery hybrid system is on-grid inverter. This device can convert DC to AC electric current. The term on-grid means that AC electric output of the inverter can be injected to an electric power grid. To inject electric power safely and efficiently into the grid, on-grid inverters must accurately match the voltage and phase of the grid sine wave AC waveform. A high-quality on-grid inverter has a fixed unity power factor and its phase angle is within 1 degree of the AC power grid.

On-grid inverter is designed to produce zero power when the utility grid goes down. This is a NEC requirement [12] to ensure that in the event of blackout, the on-grid inverter will shut off to prevent electric power transfer to the wireline harming workers fixing the grid wires.

Typical specification of the on-grid inverter can be seen in Fig. 3. This inverter has a conversion efficiency from DC to AC of around 86%.

Technical parameter GTI-D-series

Model	GTI-D1000B	GTI-D600B	GTI-D300B
Output Power	1000W	600W	300W
Solar Panel	Vmp:35-39V,Voc:42-45V		
MPPT Voltage Range	30-40V		
AC Voltage Range	190-260V		
Voltage Frequency	50HZ±1%		
Power factor	>97.5%		
MPPT Efficiency	>99%		
Total Harmonic	<5%		
Phase Shift	<2%		
Conversion Efficiency	>85%	>86%	>87%
Maximum Efficiency	>89%	>89%	>90%
Operating	-20°C-45°C		
Waterproof Rate	Interior Design		
Cooling Mode	Intelligent design of the electric fan control system		
Standby Power Loss	2-3W		
Product Size	257*195*88.5mm	210*195*88.5mm	180*195*88.5mm

Figure 3: On-grid inverter specification.

Notice that this inverter works in the range of grid voltage of 190-260 Volt. In some area, it is often that PLN voltage drops below 190 Volt and when this happens, the inverter cannot produce AC electricity until the grid voltage higher than 190 Volt.

2.5 Electric Charger Controller

The main purpose of electric charge controller is to protect the battery from over-charging and over-discharging which can reduce battery performance or lifespan. The controller can stop charging process when the voltage of battery exceeds a set high voltage level. Maximum power point tracker (MPPT) is a technology that can adjust charging rates depending on battery level to charge closer to the battery maximum capacity [13].

Charger controller may have battery temperature monitoring to prevent over-heating of the battery.

2.6 Heat on Cable and Component

A solar cable is used to interconnect solar panels and electric components in the solar PV hybrid system. Solar cable is designed to be ultra violet resistant, weather resistant and can be used in wide range of temperature.

Over-heating on a cable can take place when high electric current occurs on the cable, such as due to short-circuit, or simply because the cable is too small to deliver the required electric power. Over-heating cable can cause damage to the cable, shorten its lifespan and can cause fire and injury.

Good solar PV system should not have cable over-heating problem in its system and enough cable size is used in the system.

3. Methods

3.1. Experimental Testbed System

Table 1: Battery configurations for each group.

Group Number	Group -1	Group - 2	Group - 3	Group - 4
Battery number	3	3	3	3
Type of battery	Free Maintenance	Wet	Wet	Free Maintenance
Battery Capacity	100 Ah	60 Ah	100 Ah	100 Ah
Total Voltage	36 V	36 V	36 V	36 V
Total KWh Capacity	3.6 KWh	2.16 KWh	3.6 KWh	3.6 KWh

Testbed of Solar PV hybrid system is developed with solar panel and battery as main component in the system. This system is designed to store electric energy in the battery to be used in the night time after 18:00 where household electric demand start to go higher. Electric supply from the hybrid system will stop whenever the battery runs out of energy. Concept of hybrid system can be seen in Fig. 4. Total solar panel capacity is 4000 Watt Peak (Wp) and splitted into 4 groups with each of 1000 Wp. Each group is equipped with different group of 3 units of 12-Volt batteries in series with total of 36V connected to electric charger controller. Each group of battery is connected to on-grid inverter with a switch connector controlled by an Arduino Mega System. Each group is also equipped with power meter to measure electric energy and power deliver to the power grid. Different types of battery is used to measure their performance, see Table 1.

Capacity calculation for this system as follows. Each group uses 1000 Wp solar panel. Based on PVGIS result on the site from previous work [14], annual electrical energy using 1kWp solar panel is 1260 kWh, or average 3.45 kWh per day. Ideally, total battery capacity should be able to store 3.45 kWh generated during daytime to be used in the night time.

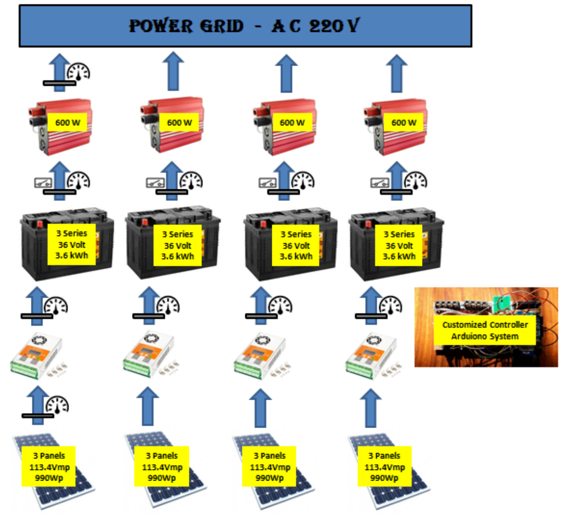

Figure 4: Four (4) groups of Solar PV-Battery hybrid system each consists of 1000 Wp solar panel, electric charger controller, 3 units of 12V battery and 600W on-grid inverter.

With the energy of 3.45 kWh per day, 600 Watt On-Grid inverter can run for 3.45 kWh / 0.6 kW = 5.75 hours. When the inverter is ON at 18:00, it should run until 23:45.

Ideally, four of the hybrid systems can save total electric energy of 3.45 kWh x 4 = 13.8 kWh and with the PLN price of 1 kWh to be Rp. 1,500 the total saving is 13.8 x 1,500 = Rp. 20,700 per day or Rp. 621,000 per month.

3.2. Setting Parameter

An Arduino Mega is used in the hybrid system as an electronic controller to control and turn ON/OFF the on-grid inverters and electric fan. The inverter activation depends on current time, battery voltage, and rule for electric delivering process.

Electric fan is used to cool the electric panel box and it turned ON based on inverter activation and current time. Source of heats inside the panel box are inverters and electric chargers. The electric chargers are usually on peak of demand during the middle of the day when sun is on the peak.

3.3. Prototype

Prototype of four (4) groups of solar PV-Battery hybrid systems was constructed in an electric panel box with the size of 1.2m x 0.8m x 0.25m for electric components and wirings as shown in Fig. 5.

In the electric panel box, 4 units of electric charger controller and 4 units of on-grid inverters are installed. In the middle, 4 units of MCB for DC electric lines along with 4 units of Surge Protection Device (SPD) are installed to protect from electric surge of possible lighting. 2 units of MCB for AC electric lines are also added. 8 units of DC power meters are installed on the door panel. To measure electric energy from and to the batteries.

The batteries are stored in a rack outside of the panel box and connected by large wirings.

Figure 5: Electric panel box containing electric components of four groups of solar PV-Battery hybrid systems.

When the hybrid systems are running and the box door is closed, the air inside the box is hot. So, the air inside the box is hot during the daytime when the charger controllers are running and during the night time when the inverters are running. To cool the box, small fan is installed on the door to pull fresh air entering the box and the rules for the fan:

Fan is ON if

- Current time between 12:00 to 18:00
- Or when any of inverter is ON

When the prototype was tested, the inverters were not running for around 6 hours as estimated based on amount of kWh and they were running only for around 1 hour. It seems that the battery capacity is significantly less than what stated in its specifications. Because of this situation, condition of inverter ON is set to only let them run with maximum of two units simultaneously.

Night time: Inverter ON if

- Current time between 18:00 to 06:00
- Battery voltage > 31 Volt
- Maximum of 2 units running simultaneously

The last condition is applied to extend the electric power supply from the hybrid system.

On the other hand, since the battery capacity is low, there will be excess electricity from solar panel that cannot be stored in the battery during the daytime. To utilize this excess electricity, inverters can be ON during the daytime when the battery is considered full. Inverter rule during daytime:

Daytime: Inverter ON if

- Battery voltage > 42 Volt

Daytime: Inverter OFF if

- Battery voltage < 37.5 Volt

4. Results and Analysis

4.1. System Performance Measurement

There are several practical problems in running the prototype:

- One of the inverters failed only after 2 weeks testing. Mosfet components inside the inverter were failed and burned.
- One of solar cable failed after only 4 weeks testing. One of the connectors was failed and burned.
- Cables to the battery were hot even though the cable size requirement is satisfied. This might due to low quality of cables.
- Power meter from the solar panel to the electric charger controller is not working well.
- Lithium-ion batteries type 18650 exploded due to too high charging current.
- All current sensors were not working properly. So, electric power and energy cannot be calculated. Only voltage sensors are working although sometimes giving incorrect value.

Fig. 6 shows the history of battery voltage of each group for one-day data.

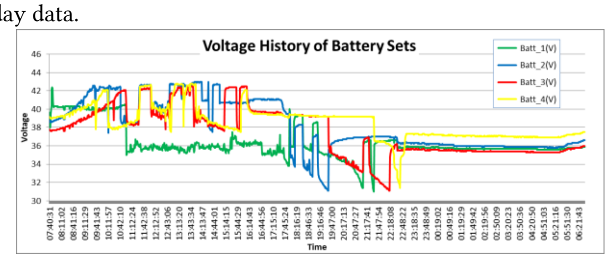

Figure 6: One-day data for the history of each group battery voltage.

The graphs shows that battery 2, 3 and 4 were charging started from around 6:00 in the morning indicated by the rise of voltages. Voltage sensor for battery 1 seemed to be failed at the beginning. When the battery voltage reached 42V, starting with battery 2, then 4, and 3, the corresponding inverters were ON indicated by the drop of voltage due to power drawing by the inverters. When the battery voltage reached 42V at the first time around 10:00 in the morning, the corresponding inverter was ON only for few minutes. This indicates that the battery was not really full. Around 11:00, battery voltage 2, 3, and 4 are dropping for longer time, indicating longer inverter runs. Short inverters run happened again at around 13:15. Battery voltage 3 and 4 are dropping from14:00 to 15:15 indicating longer inverter runs for number 3 and 4.

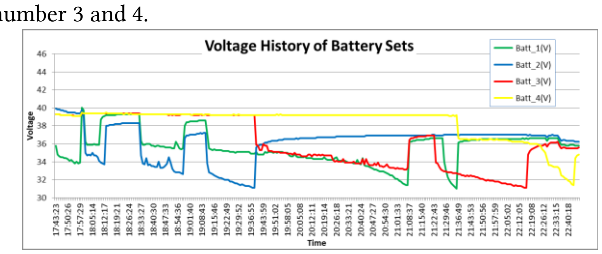

Figure 7: History of each group battery voltage after 18:00.

Fig. 7 shows the same history data but zooming at the period after 18:00 to 23:00 when all hybrid systems produce their energy out to supply the electricity. The graph shows that at 18:00, battery 1 and 2 are working for around 10 minutes and stopping for around 20 minutes, from 18:10 to 18:33. Both are working again and stopping again around 18:58. Again, both are working at around 19:11. Battery 2 runs out of energy at around 19:38 indicated by its voltage drops to lower limit of 31V. At the same time, battery 3 starts to work together with battery 1 and both are stopping at 21:08. Then both are running again at 21:24 and battery 1 runs out of energy at 21:36. At the same time, battery 4 starts to work together with battery 3. Battery 3 runs out of energy at around 22:16 and battery 4 runs out of energy around 22:44. From this history, it shows that Battery 1 runs the longest and battery 3 runs the second longest.

To complete the data, Fig. 8 shows graph of inverter flag ON/OFF. Note that even though the inverter flag is ON, sometimes the actual inverter is OFF, indicated by battery voltage to remain high. This could be due to PLN voltage to be less than 190 Volt which prevents the inverter to be running.

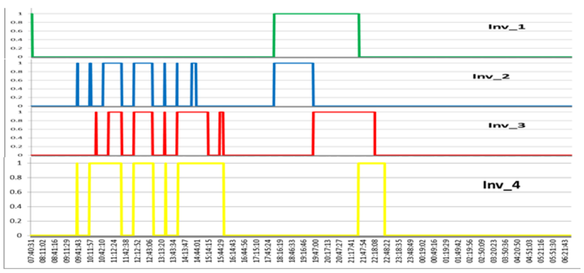

Figure 8: History of each group inverter flags (1=ON, 0=Off)

Based on this one-day data, we can conclude:

- battery 1 is completely not working during the daytime and gives the longest power during the night time.
- battery 4 is the most active power generation during the daytime and short during the night time.
- Battery 3 (wet type) seems to store more electric energy than battery 4 (free maintenance type) indicated by battery 3 running longer during the night time.
- Battery voltage is not a good indicator for battery level of charged. Battery charging current should do better.
- Voltage sensor for battery 1 is not reliable.

4.2. Energy Analysis of kWh Measurements

The solar PV-Battery hybrid system is equiped with 4 DC power meters and 1 AC power meter as shown in Fig. 9.

Manual data taking from these power meters has been done for several days and the data is shown in a table Fig. 10. Note that the energy measurements will cover both daytime and night time inverter activities.

The table in Fig. 10 shows that for 9 days of testing, battery 1, 2, 3, and 4 produced 16, 15, 26 and 26 kWh and all the DC energy combined is 83 kWh. Notice that hybrid system group of 3 and 4 produces 60% more than group 1 and 2. This could be due to solar panel position for group 3 and 4 to be higher and more open to the sunshine than group 1 and 2.

Figure 9: AC and DC power meters.

No	Day	Date	Hour	KWh AC	KWh Batt_1	KWh Batt_2	KWh Batt_3	KWh Batt_4
1	Sunday	03-11-19	7:31	148.2	77	58	53	59
2	Monday	04-11-19	6:26	154.7	79	59	55	62
3	Tuesday	05-11-19	7:14	160.9	81	60	57	64
4	Wednesday	06-11-19	7:55	168.5	84	62	60	67
5	Thursday	07-11-19	6:43	172.7	86	63	62	68
6	Monday	11-11-19	7:13	204.9	91	72	76	82
7	Tuesday	12-11-19	6:35	212.4	93	73	79	85
9 day enegy generation (7-1):				**64.2**	**16**	**15**	**26**	**26**
					Total DC energy generation:			**83**

Figure 10: AC and DC power meter manual collection data for several days and total AC and DC energy calculations.

Notice also that energy measurement from AC power meter is less than from total DC power meters, with ratio of 64.2/83 = 77%. This is due to conversion efficiency for DC to AC electric current change in the inverters which is 86% based on their specification. The possibility is that the actual inverter conversion efficiency is lower than what is stated, or inverter standby electric consumption which is around 2-3 watt that increase DC electric consumption without producing AC current, or DC power meter is not very accurate.

4.3. Thermal Measurements

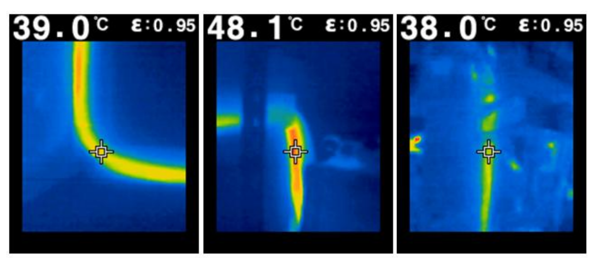

Figure 11: Thermal image of cables connecting to the batteries.

When electric current in the cable is too high, over-heating can happen. This effect is investigated in the prototype at time of 19:00 when we expect large current to the inverter and to the output of the hybrid system. Heat measurements on the cables are done using thermal imaging camera FLIR TG165. The results for cables connected to the battery are shown in Fig. 11. It shows that cable temperature can be as high as 48C which is quite hot.

This indicates that the cable needs to be improved with larger cable.

Fig. 12 shows the thermal image results of the cable connecting to the DC power meter on the box door. It shows that the DC power meter temperature can go up to 56C which indicates that the current flowing to the component larger than its capacity.

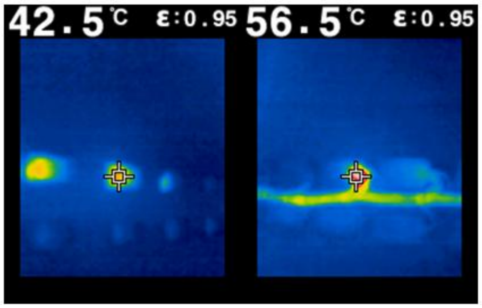

Figure 12: Thermal image of cables connecting to the DC power meters on the box door.

Fig.13 shows thermal image for batteries. The surface temperature of batteries are less than 33C, which is low temperature. However, battery cable connectors are quite hot.

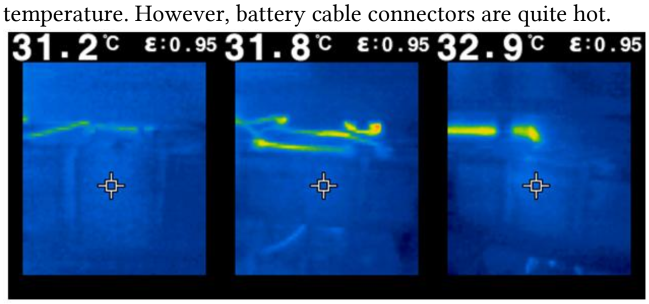

Figure 13: Thermal image of batteries.

5. Conclusions

When the hybrid system actively produces AC electricity during the daytime, electric energy left in the battery is low and the battery cannot produce AC electricity optimally during the night time. Optimization needs to be done to maximize AC electric production during the night time.

Wet battery seems to store more electric energy and more robust than the free maintenance battery. It might due to some leakage of the free maintenance battery and the cell becomes dry.

Battery voltage is not a good indicator for battery level of charged. Battery charging current should do better.

Solar panel electric production is sensitive to its position and clearness from the shading.

Inverter conversion efficiency can be lower than what the specification states which might due to inverter standby electric consumption.

Measurement of cable and component temperature is needed to justify enough cable size to deliver designed electric power, enough capacity of the component and quality of connections.

Care need to be taken when Lithium-ion batteries are used due to possible explosion for too high charging current.

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