

Design the Balance of System of Photovoltaic for Low Load Application

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Abstract

This paper presents an alternative method to reduce the monthly electricity bill at Centre of Excellence for Renewable Energy (CERE) which is by installing a stand-alone photovoltaic (PV) system. In the stand-alone PV system, apart from the PV module and loads, other components in the system such as battery, charge controller, inverter and protection device are categorized under Balance of System (BOS) component. In order for the loads to receive adequate energy to operate, the overall system must be sized through calculations due to find the optimum combination. This sizing will determine the amount of each component that needed in the system. The hardware is setup in front of CERE building which located at Kangar, Perlis, Malaysia. As the results from the calculation, the system required 6 units of PV module, 5 units of battery and a 0.23 kW inverter. The cable and protection devices are from the calculation. The entire system was successfully installed and was able to support the load demand.

Keywords: stand-alone photovoltaic (PV) system, balance of system, inverter, battery storage, solar radiation

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1. Introduction

The BOS term is referred to the balancing of power generated by PV array with the power using by the loads. BOS system covered all components in the complete system, except PV array [1]. It can be said that a complete stand-alone PV system consists of 2 main parts, which are the PV array and BOS component [2]. An example of BOS components are inverter, battery, charge controller and load. Mounting structure and the wiring within each component also included as BOS component as well as the protection devices [3]. Meanwhile, a stand-alone system is where the power is generated and consume in the same place and which does not interact with the main grid (in Malaysia the main grid is TNB) [4].

Before the system is being installed, it is important to perform an early investigation due to ensure that the system does not undersize or oversize [5]. Thus, a system sizing is needed as to ensure that the proposed system can operate in optimum condition and efficiently. This paper presents a mathematical formula for PV system sizing as well as the experiment setup. The proposed system configuration consist of 11 units of LED bulb (load), PV array as the main generator, a charge controller to protect the battery from over charging, battery bank as energy storage and a inverter, as to convert the direct current (DC) from PV array to alternating current (AC). This is because the load demands consume AC.

2. Description of Data and Load Demand

2.1. Solar Radiation Resources

The peak sun hour (PSH) can be obtained by dividing the amount of solar radiation Wh/m² for 1 year with solar irradiance level of 1000 W/m². The PSH of Kangar, Perlis were obtained from [6], which is 5.27 h. The value shows that Kangar has a big potential in developing PV system.

2.2. Load Demand

In order to identify BOS component for standalone system, the requirement load demand needs to be determined. For this project, the load consists of 11 units of LED bulbs (AC) with 8 hours of consumption per day, which start at 9.00 am until 5.00 pm. Therefore, the energy needed per day is 1320 Wh/day.

3. System Sizing

3.1. PV Array

Before the PV array is being sized, the main parameters of the PV module must be determined. The main parameters consists of power (W), open circuit voltage (V_{oc}), short circuit current (I_{sc}), etc. Meanwhile, the losses must be considered as to avoid an under sizing or oversizing [7]. There were several component efficiencies that must be determined because not all equipment was expected to produce 100 % (efficiently). To obtain the configuration of PV array, the daily energy demand is divided with all the components efficiency. The components included were battery bank, charge controller and inverter.

$$\text{Required energy, } E_r = \frac{\text{Daily energy consumption (E)}}{\text{Components efficiency}} \quad (1)$$

By dividing the daily energy requirement that were needed in the system with the Peak Sun Hour (PSH) of Kangar, the peak power of the PV array need to be generated per day were obtained.

$$\text{Peak power, } P_p = \frac{\text{Daily energy requirement (E}_r\text{)}}{\text{PSH (h)}} \quad (2)$$

In order to find the total current produced from the PV array per day, the peak power that has been generated from PV array per day, can be divided with the system voltage (V_{dc}).

$$I_{dc} = \frac{\text{Peak power (P}_p\text{)}}{\text{System DC voltage (V}_{dc}\text{)}} \quad (3)$$

In order to generate the voltage and current desired, the PV module must be connected in parallel and series. Due to the voltage is added when in series connection, thus the V_{dc} is divided with the PV module rated voltage in order to determine the number of series PV module.

$$\text{No. of series module} = \frac{\text{System DC voltage}}{\text{Module rated voltage}} \quad (4)$$

As for the string module, the module current must be divided with the rated current for one module since the current is added when in parallel connection.

$$\text{No. of Parallel module} = \frac{\text{Overall current}}{\text{Rated current of 1 module}} \quad (5)$$

$$\text{Tot. no. of module} = \text{No. of string module} \times \text{No. of series module} \quad (6)$$

3.2. BOS component sizing

3.2.1. Charge controller

By using the formula, the input current from the PV module can be obtained. Because the module is in parallel, thus the current increases and to be safe, it is then multiplied by a safety factor of 125 % [8]. To implement the charge controller in the system, the rated current of the charge controller must be choose higher than the calculated as safety.

$$\text{Max. controller input} = \text{Module } I_{sc} \times N_{\text{parallel}} \times \text{Safety factor} \quad (7)$$

3.2.2. Battery Bank Storage

Before calculating the required number of batteries, the Depth of Discharge (DOD) and autonomy days has to be estimated. DOD is the deeply the battery is discharged. The DOD

needs to be estimated due to if the battery bank is discharge too deeply, it will causing a permanent damage, that will affects the performance of battery and lastly reduce the life of the batteries [9].

Meanwhile, the autonomy days is the number of days for the batteries can provide the load without being recharged by the PV array? As for the battery's nominal voltage and nominal capacity, it can be obtain from the manufacturer. Nominal capacity is the total charged that can be stored by a battery.

In order to obtain the amount of rough energy storage for the battery bank, the total power demand of the load is multiply with the autonomy days.

$$\text{Amount rough energy storage} = \text{Tot. power demand} \times \text{Autonomy days} \quad (8)$$

To ensure that the battery will not discharge more than the required energy, the energy storage that required was divided with the DOD. Therefore, the energy for safety will be higher than the amount of energy needed per day.

$$\text{For safety, } E_{\text{safe}} = \frac{\text{Energy storage required}}{\text{DOD}} \quad (9)$$

The safe energy storage was divided with the battery voltage of 1 unit of battery due to find the total capacity that needed to be form as battery bank storage. Therefore, by dividing the capacity of the battery bank with the capacity of a battery, it will determine the total number of batteries that were needed in the system.

$$\text{Capacity of battery bank} = \frac{\text{Safe energy storage}}{\text{Battery voltage per battery}} \quad (10)$$

$$\text{Tot. number of batteries} = \frac{\text{Capacity of battery bank}}{\text{Capacity of one battery}} \quad (11)$$

The battery bank is also similarly as the PV module, composed of parallel and series connection to form battery storage. By dividing the V_{dc} with the voltage of 1 battery, the total number of batteries can be obtained. To configure the total number of batteries that were in parallel, the total number of battery needed to form battery bank storage is divided with the number of battery that were in series connection.

$$\text{Num. of battery in series} = \frac{\text{System DC voltage}}{\text{Voltage per battery}} \quad (12)$$

$$\text{Num. of battery in parallel} = \frac{\text{Tot. num. of batteries}}{\text{Num.of battery in series}} \quad (13)$$

3.2.3. Inverter

Typically the input voltage ranges from 12 V to 72 V and the current from 1 A to about several 10 A. The power ratings of an inverter should be specified in the PV system design. It can be estimated based on the total load connected to the inverter. The total loads need to be multiplied with 125 % as a safety factor [8].

$$P_{\text{inverter}} = P_{\text{load}} \times 1.25 \quad (14)$$

3.2.4. Determination Cable Size for Each Component

Determining the correct cable size is also important in order to increase the system performances. Apart from increase the system performance, it is also to avoid an excessive voltage drop. Moreover, if selecting too large of cable size, it will increase the cost, as well as the losses. The selection of a suitable cable size is depending on the continuous current carrying capacity. The cable between PV panel and battery bank through a charge controller must withstand the maximum current flow produced by a PV panel. The rated currents are as follows.

$$I_{\text{rated}} = N_{\text{parallel}} \times I_{\text{sc}} \times f_{\text{safety}} \quad (15)$$

By referring to table of current carrying for each size of cables [10], thus the cable size can be selected based on the calculated current. According to [9], to determine the current flowing out from battery to inverter, the total power consumption must be divided with the system voltage, V_{dc} . Then, increase 20 % as a protection [4].

$$\text{Max. current from battery} = \frac{\text{Load demand}}{\text{System voltage, } V_{dc}} \quad (16)$$

In order to obtain the current flowing to the loads, the power consumption of total loads were divided with the voltage of the load. The current obtained need to be increased by 125 % as a safety protection [8].

$$I = \frac{\text{Power of loads}}{\text{Voltage of loads}} \quad (17)$$

3.2.6. Protection Devices

Apart from the cables, the protection devices also included in the BOS components. A Miniature Circuit Breaker (MCB) was used as the protective device in this system. The function of MCB is to protect an overcurrent in the system. The MCBs need to be installed at both DC and AC compartment, which is at PV modules, charge controller, battery and also loads.

$$I_{\max} = 1.25 \times I_{sc} \times N_{\text{parallel}} \quad (18)$$

According to [11], due to abnormal temperature condition, de-rating of fuse nominal rating must be considered. The temperature correction factor should be applied when the temperature more than 40 °C. Eventually, temperature in Malaysia never exceeded 40 °C (according to the Ministry of Science, Technology and Innovation, MOSTI [12]). Thus, the correction factor does not need to be applied. By referring to [9], to determine the current flowing out of batteries to inverter, the power consumption of the load is divided by the system voltage, V_{dc} . Then, increase it by 20 % as a safety protection [4].

$$\text{Max output current from bat} = \frac{\text{Power of loads}}{\text{System voltage, } V_{dc}} \quad (19)$$

4. Experiment Apparatus

From Table 1, it shows the specification of each component via calculations. The result indicates how many PV modules required forming a PV array, units of batteries to form a battery bank as well as the suitable rated current for inverter and charge controller. While Table 2 shows the selected size of cable and protection devices. The selection for each cable size was based on the maximum current flowing throughout each component. Selecting the correct cable size will enhance the performance of the system. The cable that was selected in this system was in the form of cross-sectional area (mm^2).

Table 1. Specification of Components

Component	Unit	Specification
LED Bulb	11	15 W each
PV Modules	6	70W each
Charge Controller	1	36.83 A
Battery Storage	5	100 Ah, 12V
Inverter	1	206.25 W

The MCB needs to be installed at both DC and AC compartment. The DC compartment is from PV modules until the inverter, while the AC compartment it only consists of loads. Each MCB differed in size since the maximum expected current from each component also differs. The MCB size selected must higher or close to the maximum expected current that has been calculated.

Table 2. Selected Size of Cables and Protection Devices

Position	Current Max. [A]	Size of cables [mm ²]	Size of MCB [A]
PV module to battery	34.28	4.00	63
Charge controller to battery	34.28	4.00	63
Battery to inverter	16.50	2.50	32
Inverter to load	0.73	2.50	6

By using the results from the calculations, then hardware can be set up accordingly. Figure 1 shows the overall experiment apparatus setup. The system starts with the main generator, which are 6 units of Yingli PV modules which located in front of CERE building. Each PV module is a poly crystalline type with maximum output of 70 W. By connecting in parallel, it can produce higher output power and current. Each PV module was protected with MCB that were located inside the combiner box. Each MCB represents each terminal (positive and negative) from a PV module. Hence, there will be 12 MCBs inside the combiner box which connected in parallel. In between the PV array and charge controller, a MCB need to be placed as an overall PV array protection. On top of that, it acts as main DC protection for PV array.

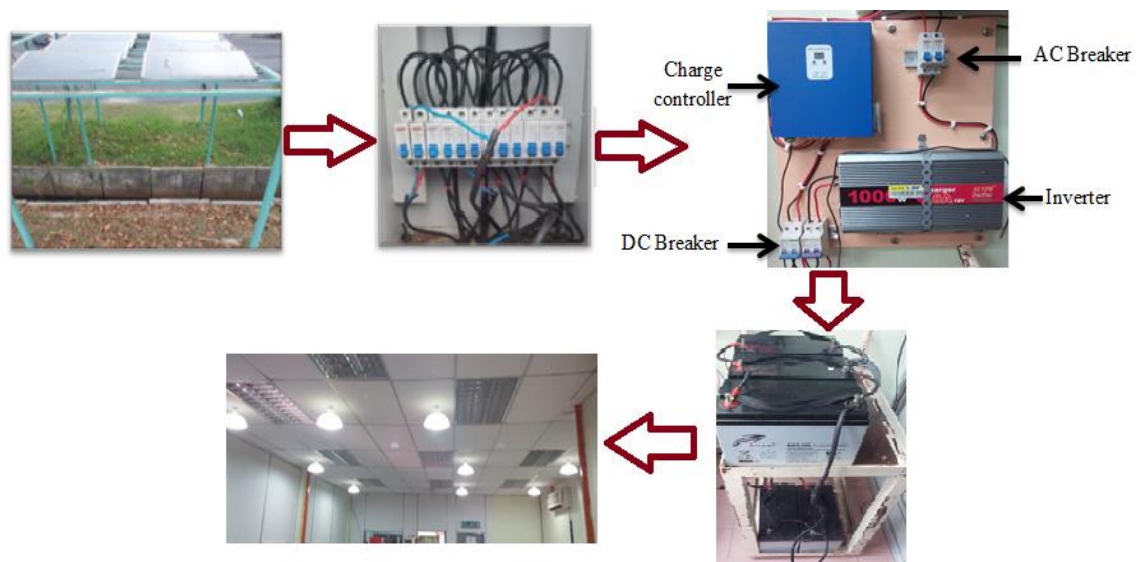


Figure 1. Overall Experimental Setup

As for charge controller and inverter, it can be assembled together in a board. All the cable size and size of MCB were according to equation 15-19. Meanwhile, the system needs 5 units of batteries due to form a battery bank and was connected in parallel connection. Lastly, the system was completed with the present of 11 units of LED bulbs as load demand.

5. Result and Discussion

The experiment was conducted after testing and troubleshooting. The data were taken from 9.00 am until 5.00 pm. The power produced from PV modules is highly affected by solar radiation. As the solar radiation increases, the power produced will also increase, as shown in Figure 2. At 9.00 am, the solar radiation is the lowest, which is 319.00 W/m². While the highest solar radiation that has been recorded is at 1.00 pm, which is 1039.00 W/m² and the power produced by PV modules is 398.09 W. The level of solar radiation is affected by the position of the sun. Generally, the power produced should be higher than recorded since it consists of 6 parallel PV modules. But, due to environmental factors such as shading and dust, the performance of the PV array is decreased.

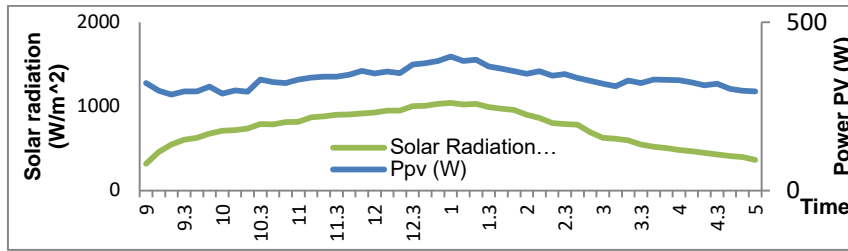


Figure 2. Relationship between Solar Radiation and Power Produced by PV Modules

The function of the charge controller is to protect the battery from overcharging by limiting the charging voltage. Thus, as can be seen from Figure 3, the average output voltage of PV module is from 16 V to 18 V. While the range of charging input battery voltage for battery bank is 12 V. This is because the system voltage for battery bank is 12 V. The voltage of input battery indicates the voltage of the charge controller. The charge controller will automatically sense the system voltage from battery system and will step down the voltage from PV array to the required system voltage.

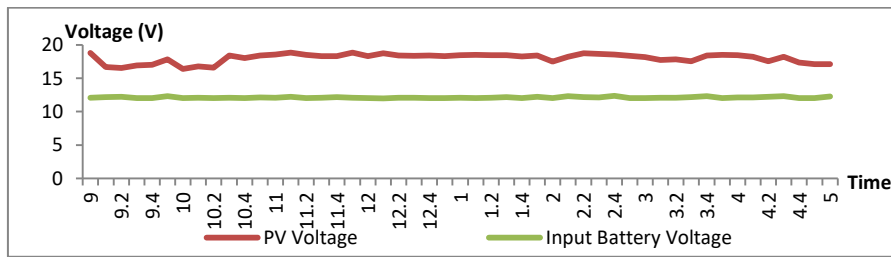


Figure 3. PV Voltage and Battery Input Voltage

As can be seen from the Figure 4, the power production from PV array is higher than the power input of battery, power output of battery and power consumption of the load. The power input battery is lower than power generated by PV array is due to limited voltage of charge controller. Meanwhile, the average power of input battery is around 200W to 230W whereas the average output battery power is around 170W to 190W. The output battery power is depending on the power demand from the load, which is 165W to 169W. Therefore, the excess power can be stored in the battery bank and can be used when cloudy or rainy days. Totally, the power generated by the PV array meets the power demand for this system.

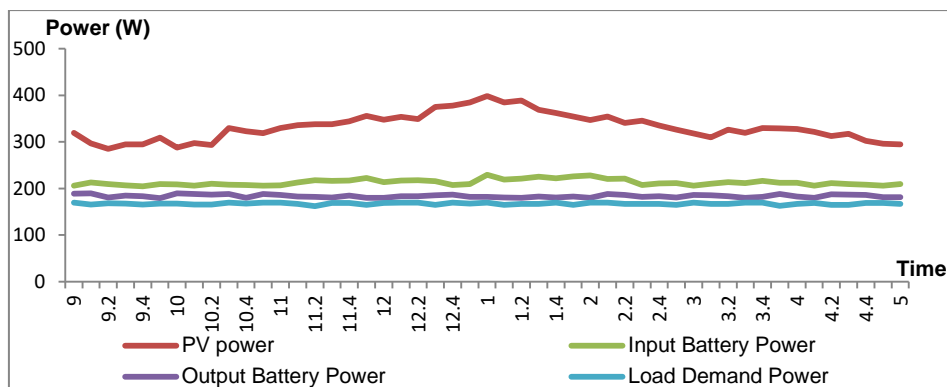


Figure 4. Overall Power Production throughout the System

6. Conclusion

The study of BOS component sizing has been conducted through the calculations and hardware implementation. The BOS encompasses all components of an off-grid system, excluding the PV array and the loads. The systems were able to support the loads during rainy days, due to the calculation method that has included the autonomy days. Eventhough the entire system was successfully installed and were able to support the load demand, but the energy production from the PV array is not high as expected, due to the shading from the dust, low solar radiation and the effect of temperature.

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