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Energy Management Control Based on Standalone Photovoltaic Battery and Supercapacitor Hybrid Energy Storage System Using PI Controller

Soedibyo[1,*] Avian Lukman Setya Budi[1*] Sjamsjul Anam[1] Mochamad Ashari[1] Adi Soeprijanto[1]

[1]*Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Jawa Timur 60111, Indonesia*
[*]*Corresponding author. Email: dibyosoe@gmail.com, avianlukmans@gmail.com*

ABSTRACT
Standalone photovoltaic system is a system that does not connect with main grid. So, it is necessary to have a backup supply, considering day and night cycle, where there are no solar radiation at night. Backup supply is often be the grid in the on-grid system, but in an off-grid system, backup supply has to be energy storage system, as in this paper, storage system contains battery and supercapacitor. As stated, standalone photovoltaic with hybrid energy storage system must have its own energy management system. The proposed method in the paper is to use PI controller as the energy management system control. The examined aspect is the voltage and power stability in both battery and supercapacitor. The result compared with the stability characteristics from uncontrolled energy management system. From the result, the PI controlled system is proven to give the better result due to compensation of the load power surplus during the maximum irradiance and increase the battery input by 162.261 W or 69.836% more power to the battery. The load has been optimized, in both maximum irradiance by the decreasing of 178.309 W and half irradiance by the increasing of 15.166 W.

Keywords: *Battery, Photovoltaic, Supercapacitor, Stability, PID*

1. INTRODUCTION

Renewable energy is energy generated from sources that are not depleted or can be replenished in human life. The most common examples include wind, solar, geothermal, biomass, and hydropower. This is different from non-renewable sources such as fossil fuels.
Although renewable energy is often considered a new technology, harnessing the forces of nature has long been used for heating, transportation, lighting, and more. But over the last 500 years, humans have increasingly turned to cheaper and dirtier sources of energy such as coal and crushed gas.
From the related field, it is generally known that stand-alone photovoltaic systems must be equipped with energy storage systems. There are various types of energy storage today, includes using multiple energy stores with parallel connections. However, energy management systems for multiple energy storage systems in parallel should function properly for better stability and continuity.

1.1. Literature Review

There is research behind this research, including stand-alone photovoltaic systems, batteries, supercapacitors, and evaluation studies, conclusions, and recommendations for previous energy management systems.

1.1.1. Standalone Photovoltaic System

The concept of solar power generation is a simple concept to convert sunlight into electrical energy. Sunlight is a form of energy from natural resources. Solar natural resources have been widely used to supply electric power to communication satellites via solar cells. These solar cells can produce an unlimited amount of electrical energy which is drawn directly from the sun, with no rotating parts and requires no fuel. Thus, the solar system is often said to be clean and environmentally friendly [1].
A standalone photovoltaic system is a system that is not connected to the main grid. Therefore, it is necessary to have a backup supply, given the day and night cycle, where solar radiation is at 0 W / m2 at night. The backup supply is often networked in a grid system, but in an off-grid system the

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backup supply must be an energy storage system, such as a battery, hydro pump storage, heat storage, or supercapacitor. The voltages and currents for these standalone systems are not sufficient for many applications, so generally a number of solar cells are arranged in series to form a solar module. One solar module typically consists of 28-36 solar cells, and produces a total DC voltage of 12 V under standard irradiation conditions (Air Mass 1.5). Solar modules can be combined in parallel or in series to increase the total voltage and output current according to the power required for a particular application.

1.1.2. Energy Storage System

The energy storage system is essential for the operation of the power system. They ensure continuity of energy supply and increase system reliability. Energy storage systems come in all shapes and sizes. The size, cost, and scalability of energy storage systems depend largely on the form of energy stored. Energy can be stored as potential, kinetic, chemical, electromagnetic, thermal, etc. Some forms of energy storage are more suitable for small scale systems and some are used only for large scale storage systems. For example, a chemical battery is perfect for small systems ranging from watches and computers to building backup systems, but is still expensive when considering the megawatt scale. Pumped hydropower storage, on the other hand, which stores a large amount of energy in the form of water potential energy, can only be found in large power systems [3].

Examples of chemical energy storage systems include batteries, flow batteries, and fuel cells. Mechanical (kinetic and potential) energy storage systems include pumped storage hydropower, flywheel, and pressurized gas storage systems. Thermal energy can be stored as molten salt and is also mainly used for large scale systems. Magnetic energy can be stored in superconducting magnet storage systems, which is still a relatively new and expensive technology.

Using an energy storage system (ESS) is proposed and is one of the most appropriate solutions in this area. This new category allows engineers to manage the power system optimally.

Generally, the ESS operation is categorized as follows:

- The charging period: This process is applicable using the network electrical energy, during the off-peak intervals when the electrical energy is available at lower prices.
- The discharging period: In times of peak the stored energy in an ESS is used. It should be mentioned that in this period the network electrical energy has a higher price and use of distributed generators (DGs) is more economical. Accordingly, application of an ESS system is mainly explainable for reducing or even eliminating the uncertainties of renewable DG.

It is worth mentioning that the most commonly used method in ESS is based on DC type, so the use of this system is more related to power electronic devices to connect to the national power grid.

Generally, various ESSs can be provided in terms of technology, location, capacity, demand and investment costs.

1.1.2.1. Battery.

Batteries are one of the most widely used energy storage devices in the power sector, especially in stand-alone photovoltaic systems. Each battery consists of a Positive Terminal (Cathode) and a Negative Terminal (Anode), as well as an electrolyte that functions as a distributor. The electric current output from the battery is direct current (DC).

Lead Acid battery type is a type of battery suitable for solar panel systems. This can be seen clearly because by using Lead Acid type batteries, users can take advantage of the electrical energy stored in the battery (discharge) when the solar panels are not exposed to sunlight. Conversely, when there is sun, the battery will be charged (charged) by solar panels [2].

VRLA AGM or VRLA Gel Deep Cycle batteries are the most suitable and most widely used batteries for solar panel systems, both SHS (Solar Home System), SPSL (Solar Street Lighting), Solar Power Pumps, Solar Street Lights, PV (Solar Power Generation) Power.

The reason for using VRLA AGM and VRLA Gel Deep Cycle batteries is because they have charge cycle resistance, use resistance, spillage / leakage, and are maintenance free. It is the most preferred option for energy storage of stand-alone photovoltaic systems.

From previous research work, it was chosen to use Li-ion batteries because there was no need for further research on VRLA batteries because of their better performance.

1.1.2.2. Supercapacitor.

Supercapacitors are capacitors whose capacitance values far exceed other capacitors (but with a lower voltage limit), and can be thought of as an intermediary between (ordinary) electrolytic capacitors and rechargeable batteries. Supercapacitor is considered as storage of electrical system because it has two working frequencies. When the supercapacitor is given a low working frequency, it acts as an ordinary capacitor (having capacitance characteristics). However, if the supercapacitor is given a stable frequency of 50 Hz to 60 Hz, it works with resistive characteristics. Super capacitors can store 10 to 100 times more per cubic charge than electrolytic capacitors, can accept and distribute charges faster than batteries, and have better tolerance to usage cycles than rechargeable batteries.

Unlike ordinary capacitors which use solid dielectrics, supercapacitors use a double layer of electrostatic capacitance and electrochemical pseudo capacitance, both of which contribute to the total capacitance of the supercapacitor, with some differences as stated below:

- Electrostatic double-layer capacitors (EDLCs) use carbon as electrodes or the like with the amount of electrostatic double-layer capacitance greater than the amount of electrochemical pseudo-capacitance, resulting in the separation of Helmholtz double-layer charges on the surface of the conductive and electrolyte electrodes. The amount of charge separation is several ångström (0.3-0.8 nm), smaller than an ordinary capacitor.

- Electrochemical pseudo-capacitors use metal oxides or electrodes made from conductive polymers with higher amounts of electrochemical pseudo-capacitance coupled with double-layer capacitance. Pseudo-capacitance is achieved by Faradays electron traction by redox, intercalation, and absorption by the electrode surface [4].

Hybrid capacitors, such as lithium-ion capacitors, use electrodes with different characteristics: one emphasizes electrostatic capacitance while the other emphasizes electrochemical capacitance.

1.1.2.3. Energy Storage Management System.

ESMS (Energy Storage Management System) maximizes the value of energy storage by predicting and controlling the flexible capacity of any storage device, anywhere on the network. It increases ROI by taking advantage of all energy storage use cases and providing a new revenue stream. The most preferred method of dividing the input power into storage is by filtering the first sequence into the battery and the other into the supercapacitor. Previous research on first-order filters has uncontrolled scheme for the energy management system.

1.2. Our Contribution

This paper presents some improvements based on the control system in the energy management system. The aspect that acted as the parameter is the voltage and power stability. The result without control and with PI controller is compared. More noise and oscillation, high starting overshoot or undershoot will be categorized as less contribution to system stability.

1.3. Paper Structure

The rest of the paper is organized as follows. Section 2 introduces the methodology used in this paper, which include Maximum Power Point Tracker (MPPT), input model and the PI tuning. Section 3 presents a simulation results and comparison analysis. Finally, Section 4 concludes the paper and presents direction for future research.

2. METHOD AND METHODOLOGY

2.1. Maximum Power Point Tracker

MPPT is a method for determining the operating point that produces maximum power. The point that produces maximum power is called the Maximum Power Point (MPP). MPPT works by increasing or decreasing operating voltage so that maximum power is obtained [6]. The MPPT working scheme is by measuring current and voltage from photovoltaics. Currents and voltages will be processed in the MPPT algorithm and a duty cycle will be generated which can produce power at the MPP point. The Duty Cycle will control switching on the converter.

Power input is obtained through the conversion of solar and using photovoltaics. Then, the voltage and current will be read at the sensor of each photovoltaic. MPPT will operate according to its algorithm to get maximum power. In the MPPT algorithm a duty cycle will be generated which will control switching on the multi-input converter. When the power produced by and PV is greater than the load power (P_{load}), then the surplus energy will be used by the converter and does not produce power.

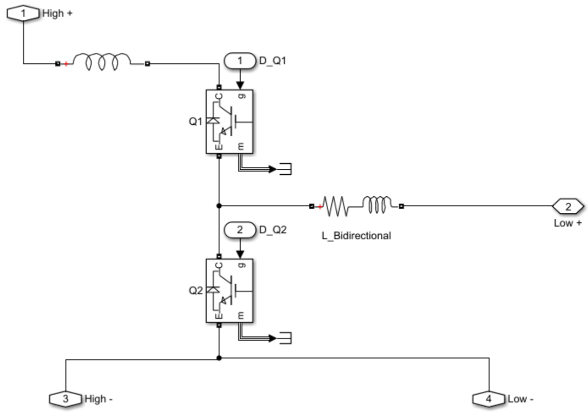

Figure 1 Bidirectional converter for the PV-connected storage system

When the power produced by PV is equal to the load power (Pload), the energy will not produce power. When the power produced by PV is less than the load power (Pload), then the lack of energy will be compensated by the supercapacitor by producing electricity. This hybrid system will still be able to operate in a state where one input voltage cannot provide voltage. Therefore, a hybrid energy storage system using the MPPT P&O algorithm is expected to improve the efficiency of the power generated so that the output power in this system becomes more optimal [7].

2.2. Perturb and Observe Algorithm

The Perturb and Observe (P&O) algorithm is often used in searching for Maximum Power Point (MPP) in PV. This method can be used for various types of characteristics of PV and does not require information about the characteristics of energy storage systems. However, the P&O method has the disadvantage that there is an oscillation in steady state conditions caused by constant duty cycle changes.

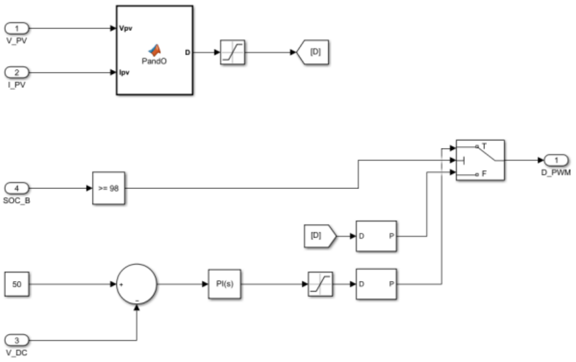

Figure 2 Perturb and Observe Algorithm based Maximum Power Point Tracker

Perturb and observe algorithm is also called hill climbing method. In this algorithm the MPPT method is based on the calculation of output power. In this algorithm the perturbation leads to change in the output power of system. If perturbation increases towards the maximum power point then voltage must be increased. And if perturbation decreases away from the maximum power point then the voltage must be decreased. With this the duty cycle is also changed and this process continues until the maximum power point has reached [6].

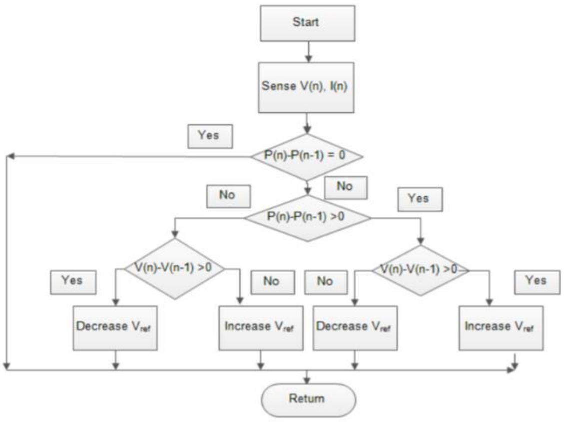

Figure 3 Flowchart of Perturb and Observe Algorithm

Figure 3 shows the flowchart of perturb and observe algorithm. First, we determine the value of V(n) and I(n). Then after finding power, we check the slope dP/dV at three different conditions.

If slope dP/dV= 0 at MPP

If slope dP/dV>0, at left of MPP

If slope dP/dV<0, at right of MPP

2.3. Input Model

Data used in this simulation is divided into 2 phases, the 0-1 s (first phase) contains the normal condition (using Surabaya, Indonesia sample at maximum (1000 W/m^2) during sunny day). The 1-2 s (second phase) contains the condition where the cloud and/or pollutant in terms of dust pollutant cover up the panel so the irradiance is half of the maximum (50% pollutant equals to 500 W/m^2 represents sudden cloud in Surabaya, Indonesia sample area). The temperature is given constant at the value of 25 °C. The simulation is only 2 seconds due to simulation computational load limit. The input also had given the model so load power input could be examined [5].

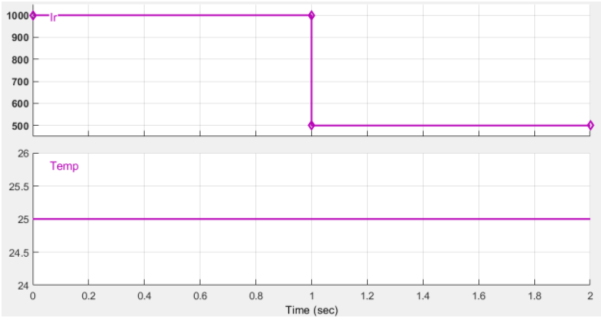

Figure 4 Input model for photovoltaic input

PV Modules used in the simulation is the model from MATLAB Simulink Waaree Energies WU-120. The load model in the system is the same for both simulation, 500 W with unity power factor, for easier simulation tracking since PV and the load is in the same direct current (DC) bus.

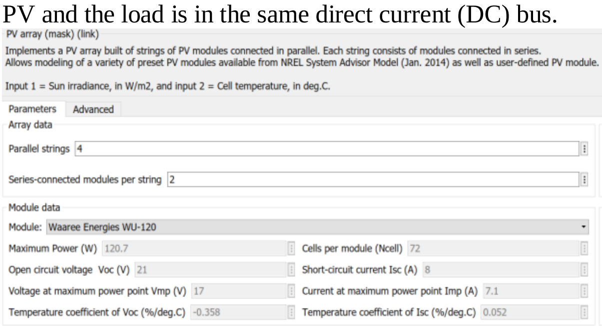

Figure 5 PV-modules parameter

The supercapacitor used is electric double layer capacitors (EDLC) type with parameter as shown in figure 6.

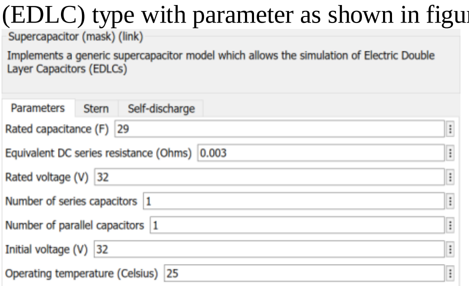

Figure 6 Supercapacitor parameter

The battery used is Lithium-ion type with parameter as shown in figure 7. Initial state of charge is set in 50%.

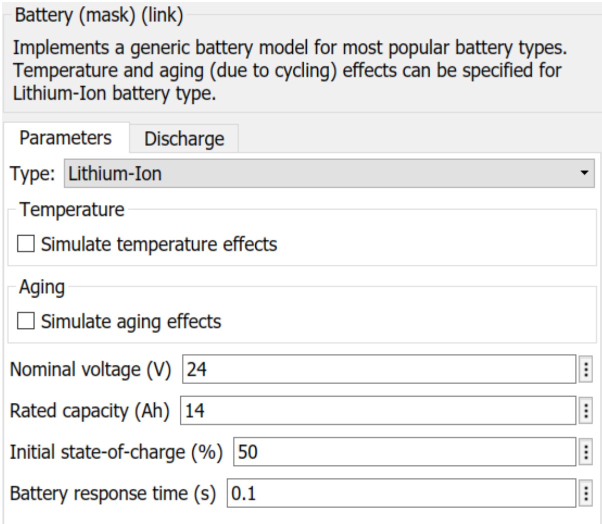

Figure 7 Battery parameter

3. SIMULATION RESULT

3.1. Uncontrolled System

This is the result from uncontrolled system, from previous research, it is known for its inability to control the power load. Simulation is run in MATLAB Simulink, including the default system simulation.

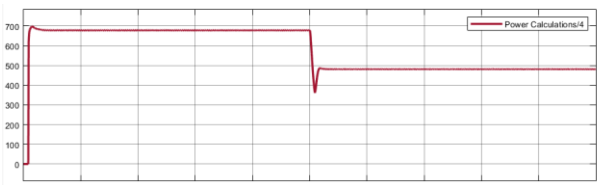

Figure 8 Load Power Stability (W)

From the simulation result, it is proven the uncontrolled system could not maintain the stability in different irradiance input due to direct input power from PV to the load in the same bus.

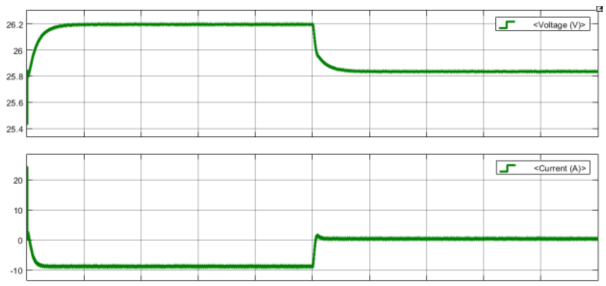

Figure 9 Battery Voltage (V) and Current (A)

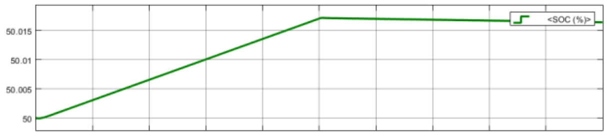

Figure 10 Battery State of Charge (%)

From the simulation result, the battery shows there is not much contribution during the 500 W/m^2.

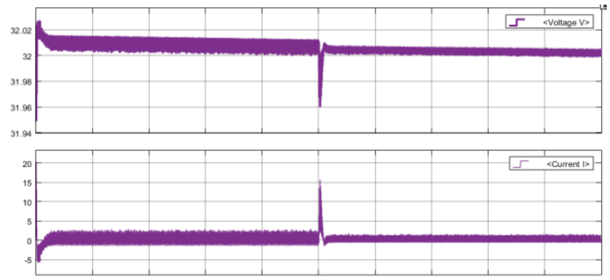

Figure 11 Supercapacitor Voltage (V) and Current (A)

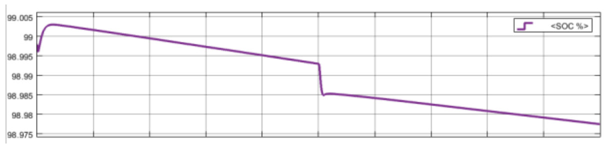

Figure 12 Supercapacitor State of Charge (%)

From the simulation result, the supercapacitor shows there is not much contribution because the slope in the irradiance change is almost the same. Besides, the supercapacitor had given non-first order input, which is very small comparing to the first order input in real power.

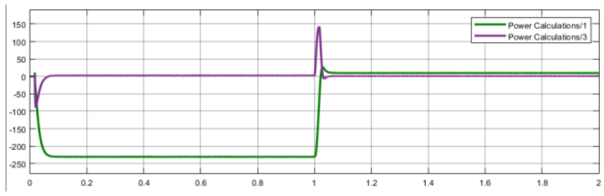

Figure 13 Battery and Supercapacitor Power Comparison (W)

From the simulation result, the supercapacitor acted as the change compensator, while the battery acted as the main energy storage supply. While at full irradiance, the battery is charging 232.344 W and the supercapacitor use 3.806 W, while at half irradiance, because the input is less than load power demand (484.239 W < 500 W). The battery is discharging 14.048 W, and supercapacitor is 3.335 W to the system. The total load power demand of 500 W is satisfied with the input of 484.239 W + 14.048 W + 3.335 W = 501.622 W. In the 1000 W/m^2 simulation, load power is 180.595 W more than the demand power.

3.2. PI-controlled System

This is the result from uncontrolled system, from previous research, it is known for its inability to control the power load. Simulation is run in MATLAB Simulink, including the default system simulation.

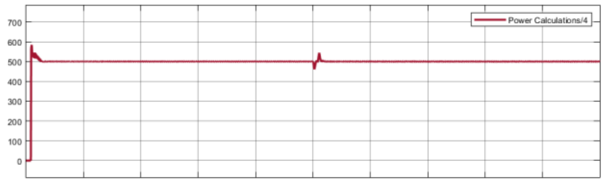

Figure 14 Load Power Stability (W)

From the simulation result, the PI-controller could maintain the stability in different irradiance input, increasing the power efficiency by decreasing 36.119% power into the load.

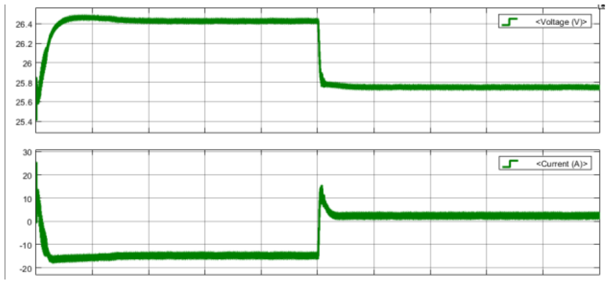

Figure 15 Battery Voltage (V) and Current (A)

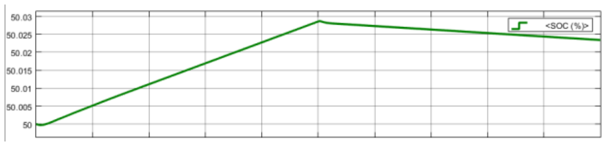

Figure 16 Battery State of Charge (%)

From the simulation result, the battery shows there is more contribution during the 500 W/m^2 than the uncontrolled system.

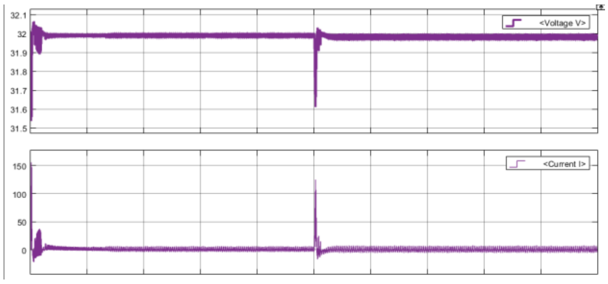

Figure 17 Supercapacitor Voltage (V) and Current (A)

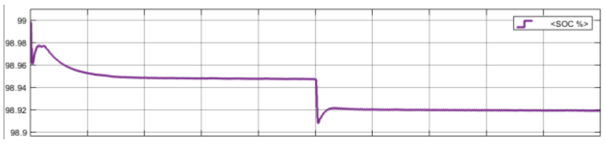

Figure 18 Supercapacitor State of Charge (%)

From the simulation result, the supercapacitor shows there is not much contribution because the slope in the irradiance change is almost the same. Besides, the supercapacitor had given non-first order input, which is very small comparing to the first order input in real power.

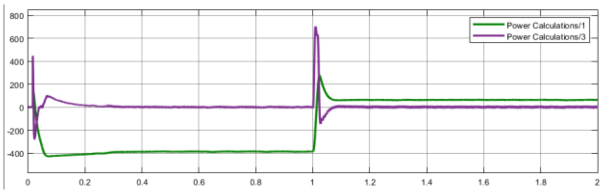

Figure 19 Battery and Supercapacitor Power Comparison (W)

From the simulation result, it is clear that PI-controlled system has the better result due to compensation of the load power surplus during the 1000 W/m^2 and increase the battery input by 162.261 W or 69.836% more power to the battery. The supercapacitor has not affected significantly due to its contribution as secondary energy storage.

Table 1 Uncontrolled and PI-controlled system power input comparison result.

Control	Load Power		Battery Power		SC Power	
	1000 W/m^2	500 W/m^2	1000 W/m^2	500 W/m^2	1000 W/m^2	500 W/m^2
No Control	680.595 W	484.239 W	-232.344 W	14.048 W	-3.806 W	3.335 W
PI Controller	502.286 W	499.073 W	-394.083 W	68.811 W	-0.628 W	1.609 W

The battery power and SC power after being 500 W/m^2 could not contribute much due to direct input from PV to the load in the same bus. Meanwhile, the load power is still could not stable in decreasing of irradiance input. PI-controller system compensate the inability of maintain the load power.

4. CONCLUSION

From the result, it is obtained that PI-controlled standalone system has the better result due to compensation of the load power surplus during the 1000 W/m^2 and increase the battery input by 162.261 W or 69.836% more power to the battery. The load has been optimized, in both 1000 W/m^2 by the decreasing of 178.309 W and 500 W/m^2 by the increasing of 15.166 W. Hopefully this research can help another research in the renewable energy and storage system fields.

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