Hybrid Energy Storage Performance Evaluation of Integrated Photovoltaic-Fuel Cell Systems

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Abstract – *In this research, some performance evaluations of battery as the main storage and supercapacitor as the supporting storage in a hybrid energy storage system were carried out to determine the recommendations of whether fuel cells could be integrated into a standalone photovoltaic system. In previous studies, the fuel cell circuit was judged to be quite different by integration with a standalone photovoltaic system, and in this study, observations were made on aspects of power quality such as voltage, current, and power for the two energy storage systems. The research method is using simulation as the medium with several self-definition aspects on photovoltaic, fuel cell, battery, and supercapacitor, also with their parameters. The result shows that on the battery, the fuel cell integration has no particular effect since the battery is the main storage, and the voltage and current had minor perturbation. While in a supercapacitor, major perturbation from the system had been absorbed due to the fuel cell integration characteristic of giving major perturbation to the system. The main recommendation is by choosing supporting storage instead of using both supercapacitors and fuel cells.*

Keywords: Battery, Fuel Cell, Standalone Photovoltaic, Supercapacitor

I. Introduction

Renewable energy electricity has a better scheme than using fossil fuel as the main source for electric generators. Problems with standalone systems, especially for new and renewable energy systems, in this case photovoltaic, are energy storage systems that are still not optimal due to power quality problems and economically still not able to accommodate most of the power generated, and many other problems related to the lifetime of energy storage, itself, in particular, the battery. Which could be solved by fuel cells [1].

Currently, the battery is still one of the primary energy storage because it has a large capacity and is proven to be more efficient in the long run, even though it is economically shifted to supercapacitors because the price is very cheap, although not cheap. has a large capacity [2].

The novelty of this research is to evaluate the characteristics of fuel cell integration in terms of hybrid energy storage power quality aspects.

II. Literature Review

In another research, hybrid batteries and supercapacitors currently, have better power quality rather than any other energy storage scheme along with the development of supercapacitor technology. In this part, it is explained the standalone photovoltaic system, hybrid battery, supercapacitor, and fuel cell as the object observed in this research.

II.1. Standalone photovoltaic system

Stand-alone photovoltaic systems are often an alternative to grid power. This usually includes a solar charging module, accumulator, and control or regulator. A floor or ceiling mount system requires a mounting structure, and if AC power is desired, an inverter is also required. Batteries are used in many stand-alone PV systems for energy storage as they can account for up to 40% of the total cost of a stand-alone PV system over their lifetime [3].

Self-contained photovoltaic systems are used in areas that are difficult to access or without access to the power grid. Autonomous systems are independent of the grid and the energy generated is mostly stored in batteries. Off-grid systems usually consist of one or more PV modules, batteries, and charge controllers [4].

The system may also include an inverter to convert the direct current generated by the photovoltaic panels into the form of alternating current required for normal devices as shown in Fig. 1.
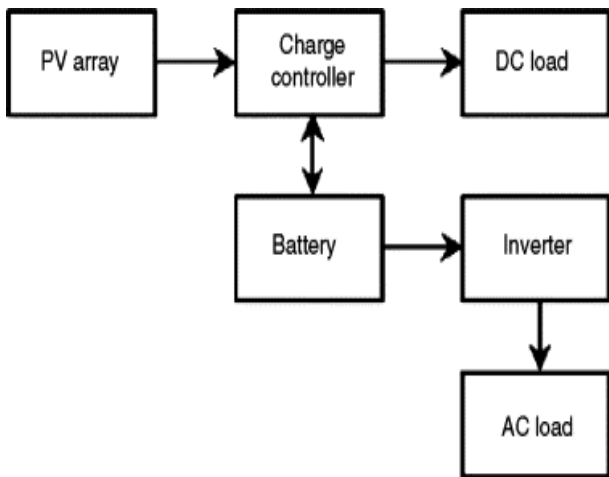

Fig. 1. Standard Standalone Photovoltaic System Scheme

II.2. Hybrid energy storage system

Hybrid Energy Storage Systems (HESS) is a storage system that consists of two or more types of energy storage technologies, and complementary features that make them superior to single-component energy storage devices, such as batteries, flywheels, supercapacitors, and fuel cells. HESS recently got wide application [5].

In this research, a hybrid battery and supercapacitor are used within the system due to their efficiency that had been proven by several types of research before, the hybrid battery and supercapacitor have their specialization by combining the capacitor's characteristics of taking and releasing (charging and discharging) the power in a huge amount within rapid time, and capacity of the battery that could fulfill the load when the power sources are in the state of intermittency. Both storages (battery and supercapacitor) have the complementary ability that fits with the standalone system's demand [6].

The commonly used scheme is as shown in Fig.

2, it is shown that the supercapacitor and battery are both in the same bus after each DC-DC converter. Its purpose is for stabilizing the output for each battery and supercapacitor with a certain duty cycle from the energy management system algorithm. In this research, Perturb and Observe are used as an algorithm.
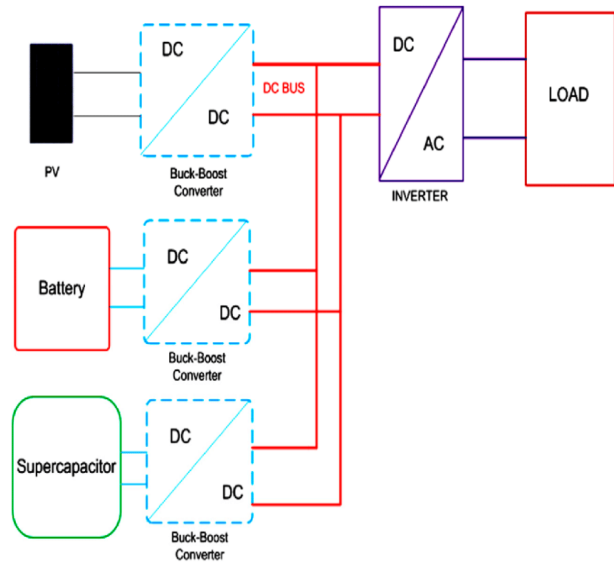

Fig. 2. Commonly Used Hybrid Storage System Scheme

II.3. Fuel cell

A fuel cell is a renewable fuel cell-type generator that produces electricity through an electrochemical process by combining the gases hydrogen (H_2) and oxygen (O_2). Developed in 1839 by William R. Groove ("gas-voltaic battery"), the fuel cell is now being developed by industry to address the increasingly critical reliance on fuel oil. There are five types of fuel cells, namely alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), liquid carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and polymer electrolyte fuel cells (PEFC). SPECs that run on hydrogen are referred to as proton exchange membrane fuel cells (PEMFC), while those that run on methanol are referred to as direct methanol fuel cells (DMFC). The working principle of a fuel cell is the opposite of the electrolysis process, in which hydrogen reacts with oxygen and generates electricity [7].

In this research, the fuel cell used for the integration is the PEMFC due to its ability to use an additional renewable source such as an electrolyzer and using hydrogen as the main source. Working principles are explained in Fig. 3.
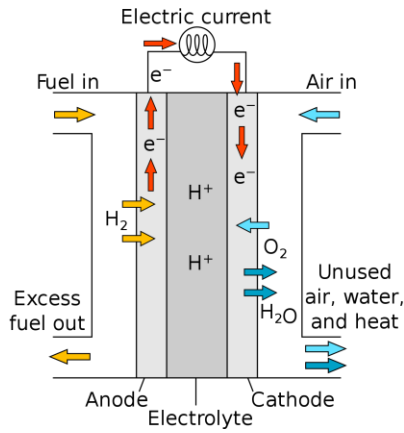
Fig. 3. Fuel Cell Working Principles

III. Method and Methodology

In this part of the paper, the method will be explained thoroughly by using research flow diagrams and research methods such as perturb and observe as the energy management system, fuel cell integration positioning, research schematic diagram, and research flowchart.

III.1. Energy management system

In the renewable energy hybrid storage system, it is known that every multi-storage system has to be controlled with an energy management system. In this research, a proven algorithm has been chosen as the main algorithm for an energy management system [8].

Perturb and Observe (P&O) is an algorithm that has been proven in several types of research for its efficiency and better power quality output due to its duty cycle-accurate determination for the DC-DC converter. It is feasible to use P&O since the algorithm has its model and simplicity rather than another complex multivariable algorithm such as neural networks. P&O usually worked as the Maximum Power Point Tracker (MPPT) for typical standalone photovoltaic systems. The flow can be shown in Fig. 4 below.

It can be seen that V(k) and I(k) are voltage and current on the probed bus, and P(k) or the power as voltage times current for a DC scheme. The main advantage of using the algorithm is that it does not need any additional input other than the voltage and the current in the probed area or the area that wants to be stabilized on a certain voltage level. In this research, perturb and observe also served as the main power tracker and the voltage level stabilizer in the load bus, which has a 50 V DC desired output voltage for the load. 50 V DC is chosen for

economically series-connected battery voltage level, which is around 48 V to 52 V [9].
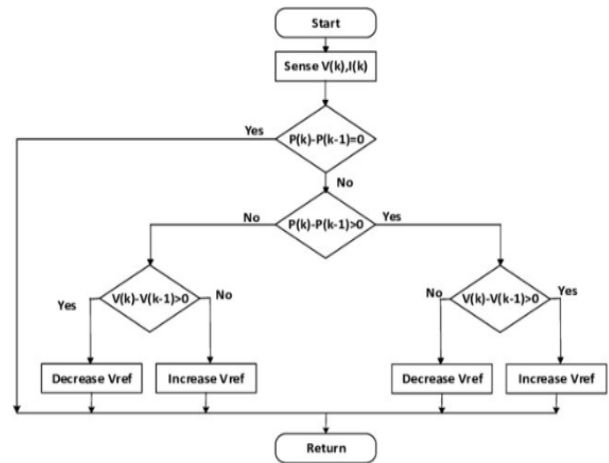

Fig. 4. Typical Perturb and Observe Algorithm Flowchart

III.2. Simulation schematic determination

For the simulation schematic determination, it had been chosen several schematics that could be the main scheme with the consideration strategy of fuel cell with the bus of storage, fuel cell with the bus of source, or fuel cell with the bus that differs from the source nor the storage [10].

The aspect that had been chosen for the evaluation is the power generated from each schematic and analyzed with every part for the power quality aspect.
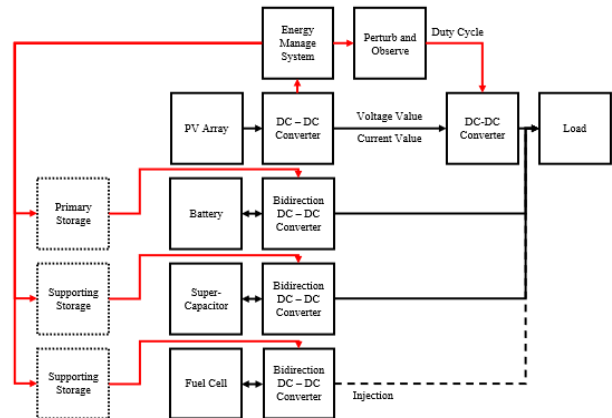

Fig. 5. Fuel Cell Storage Bus (Scheme One)

As shown in Fig. 5, the fuel cell has the bidirectional DC-DC converter for itself, has its weakness economically, and as the given additional bidirectional DC-DC converter, the losses have increased significantly, consuming slightly amount of fuel cell power generated constantly, giving the losses results on the entire power flow strategy in the system due to its position near the load.
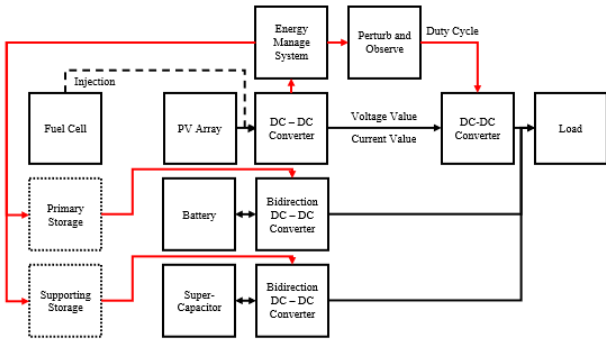
Fig. 6. Fuel Cell Source Bus (Scheme Two)

As shown in Fig. 6, the fuel cell has no bidirectional converter and in the same bus as the PV Array, this strategy theoretically, gives the best power flow on source-to-storage to the fuel cell, in the exchange, the voltage should be the same as the source bus (by modifying the stack of the cells).
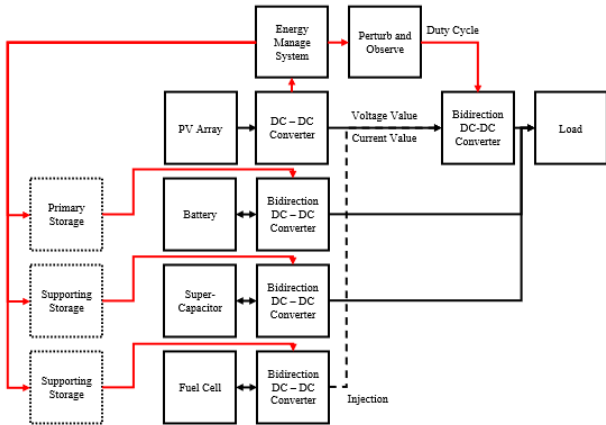

Fig. 7. Fuel Cell Stabilized DC Bus (Scheme Three)

As shown in Fig. 7, the fuel cell has a bidirectional DC-DC converter to itself and has economic disadvantages the same as the storage bus strategy. Has slightly better voltage in terms of stability due to its completely adjusted position after the PV array converter, giving better results in voltage stability theoretically, but less power generated due to its converter consumption.

From all three schemes tested, it is chosen the scheme two as the main scheme for the research due to its power-generated efficiency combined with the stability at the load and storage bus due to its position near the source.

III.3. Research flowchart

For the flowchart in Fig. 8, the research starts by defining the main problem and the novelty by choosing renewable energy (the results are photovoltaic due to the common and advancing technology).
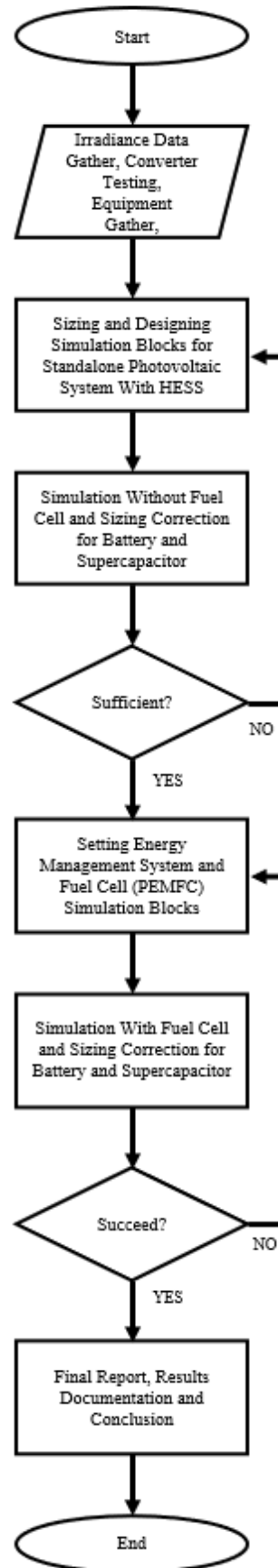

Fig. 8. Research Flowchart

Then searches for maximum irradiance data, converter simulation testing, and the equipment gathers such as the computer for the simulation. The simulation is run in MATLAB Simulink using the PEMFC projected model.

After all determination, the research starts with sizing and designing each element and diagram blocks for each plant with battery and supercapacitor as the hybrid energy storage system. Then, the simulation is tested without using a fuel cell and energy management system to see the power flow and gather sufficient data to proceed to the next step.

After the simulation succeeds, the energy management system and PEMFC are designed and then simulated totally for the analysis and performance evaluation. After all, the steps, making the final report, documentation, and conclusion.

IV. Simulation Result and Analysis

In this part, there is explained the results and performance evaluation for source output power, load power, battery (voltage, current, and power), supercapacitor (voltage, current, and power), and the analysis for each result. The simulation is run in 2 seconds due to the computational limit.

In this research, the obtained results are compared with the previous research, and it is obtained that the fuel cell that is integrated into the standalone photovoltaic system has contributed also to the perturbance increasement in terms of voltage, current, and power for the hybrid energy storage system while in the previous and recent researches stated that it is still trivial with the energy storages. The results as shown in the figure.
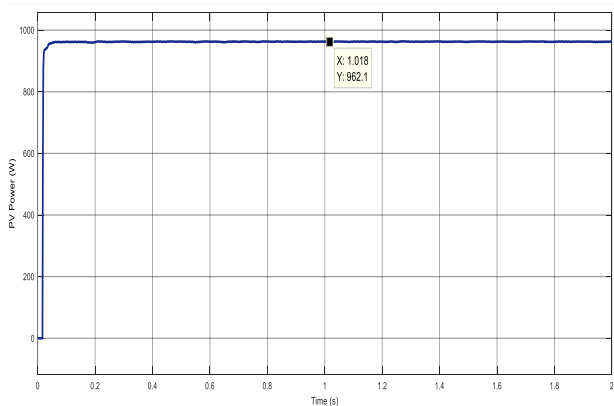

Fig. 9. Photovoltaic Power Output

As shown in Fig. 9, the photovoltaic output for the irradiance of 1000 W/m^2 is evaluated at its peak. The 1000 W/m^2 can generate up to 960 WP, and the

result is the same (from the test simulation to the final simulation) and generates up to 962.80 W. It has nothing to do with the fuel cell since the fuel cell is integrated at 1 s from the simulation.
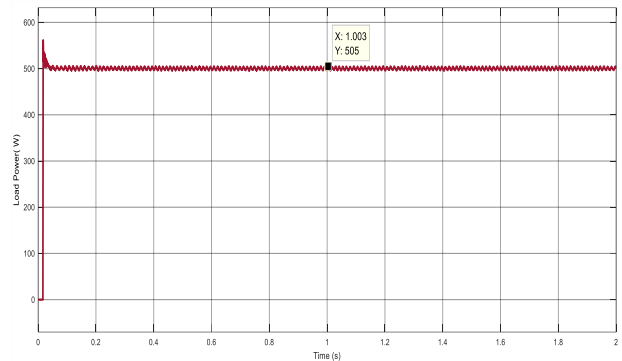

Fig. 10. Load Power Output

As shown in Fig. 10, the load power output for a nominal 500 W load is stabilized with minor oscillation during the integration of the fuel cell at its peak of 505 W or 1% perturbance right after the integration. It is proven that fuel cell usability for the standalone photovoltaic systems is feasible and the fuel cell is a proper substitution for storage.
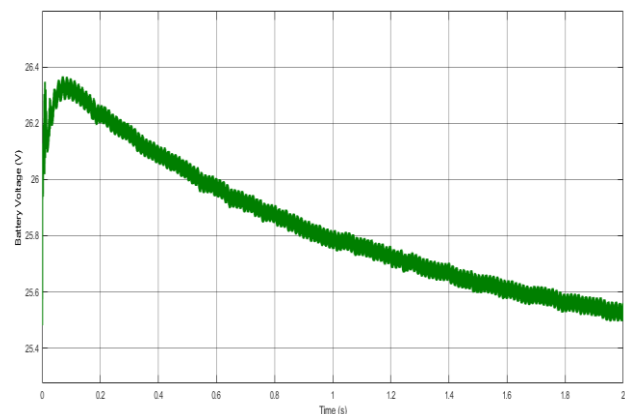

Fig. 11. Battery Voltage Output

As shown in Fig. 11, the battery voltage is increasing, then decreases, from the start. It is signified that the battery is on charge mode and then into discharge mode. It is reasonable because of the integration of the fuel cell that took place on the 1 s to 2 s of the simulation time. Also, it indicated that the perturb and observation as the energy management system works properly due to the battery mode switch from the charge to discharge after detecting the fuel cell integration on the system. The voltage is still under the upper bound (charge) of 26.4 V and had minor oscillation before the integration at 0.08 V and after the integration at 0.12 V.
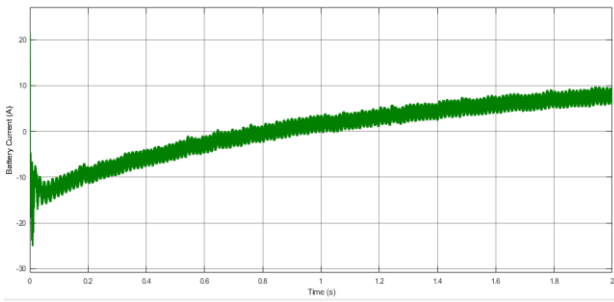
Fig. 12. Battery Current Output

As shown in Fig. 12, the battery current is decreasing, then increasing, crossing zero (detecting that below zero is absorbing power from the system, while above zero is supplying power into the system) in about 1 s when the fuel cell is integrated into the system. The current characteristics differ complementarily from the voltage. When the voltage is going up (charging) the current is decreasing below zero, and when the voltage is going down (discharging) the current is increasing above zero. The oscillation slightly increased after the fuel cell integration, while before the integration is approximately 1.24 A, and after integration is approximately 1.56 A.
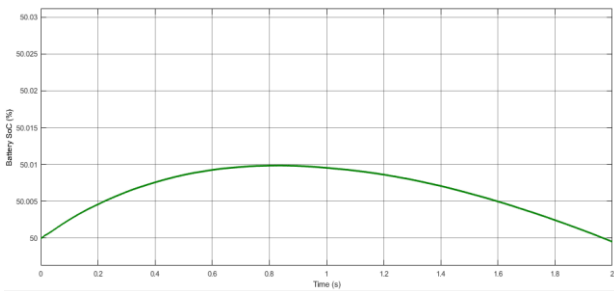

Fig. 13. Battery State-of-Charge

The state of charge of the battery, shown in Fig. 13, indicated that the battery is charging, and then start to discharge in around 1 s when the fuel cell is integrated into the system.
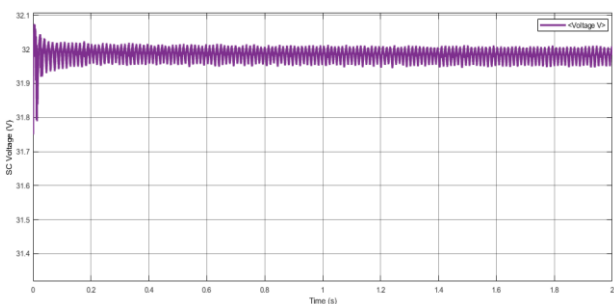

Fig. 14. Supercapacitor Voltage Output

As shown in Fig. 14, the supercapacitor voltage is stabilized during the simulation time. It is indicated that the energy management system that

determined the supercapacitor as supporting storage worked properly. During the time before fuel cell integration, the oscillation of the voltage is at 0.16 V, while after the fuel cell integration, the oscillation of the voltage is at 0.24 V. It is indicated that the fuel cell contributed also into the system in the form of voltage and current perturbance due to its high in-out characteristics while fuel cell integration itself is at the source bus.
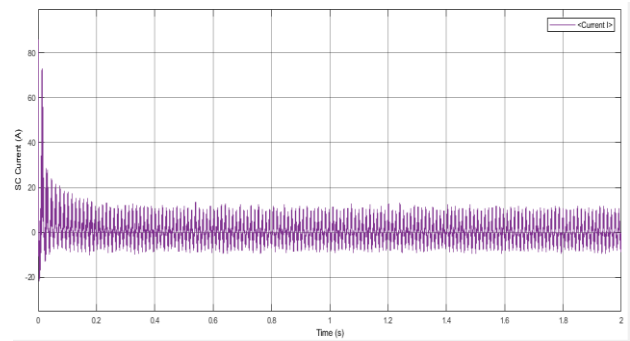

Fig. 15. Supercapacitor Current Output

As shown in Fig. 15, the visible increment in the oscillation is observed at the supercapacitor current output. While before integration, the upper oscillation bound at 10 A is crossed once, and after integration, the upper oscillation bound at 10 A is crossed multiple times. This is indicated that the most affected during the fuel cell integration is the supercapacitor. The supercapacitor characteristics that absorbed all the perturbance on the system at rapid times are going greater after the integration. This is also signified that may the supporting storage is well-chosen as the option. Either the supercapacitor is the only supporting storage or the fuel cell is the only supporting storage. Because if the system continues to have multiple supporting storages such as supercapacitors and fuel cells, the fuel cell will keep supplying meaningless power that goes right to the supercapacitor instead of giving the power into the load directly. Better choose one (SC or fuel cell) while avoiding using both storages together.
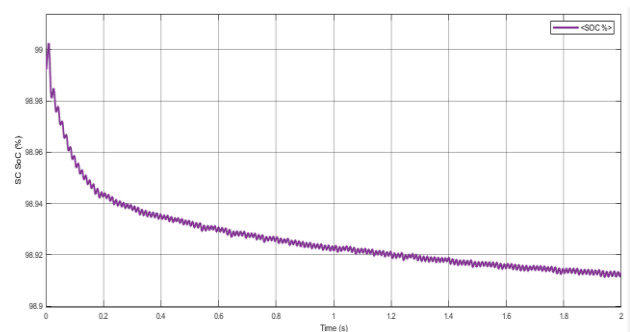

Fig. 16. Supercapacitor State-of-Charge

As shown in Fig. 16, the supercapacitor state-of-charge is indicating that the fuel cell keeps supplying meaningless power to the supercapacitor because the state of charge of the supercapacitor still decreases even after fuel cell integration regardless of the supercapacitor is set as the supporting storage in the system.
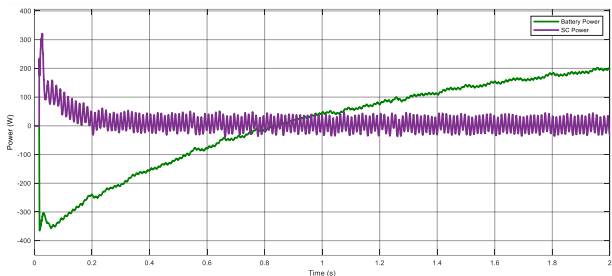

Fig. 17. Battery and Supercapacitor Power Output

As described above and shown in Fig. 17, is the power output for the hybrid energy storage system. The power in DC is calculated by voltage times current, meaning that the characteristics of the power are the same as the observed analysis above.

V.   Conclusion

In the conclusion, it is obtained that fuel cell that is integrated into standalone photovoltaic system especially at the source bus as this research simulated, has contributed also to the perturbance increasement in terms of voltage, current, and power for the hybrid energy storage system that consists of battery as the main storage and supercapacitor as the supporting storage. The effect on the PV and the load goes optimally without bothering its power output except for a reasonable 1% overshoot on load right after the integration. It is recommended to choose between supercapacitor or fuel cell as the supporting storages while avoiding using both storages together due to its bad complementary effect.

It is hoped that this research can help another researcher and give contributions to the advancement of renewable energy and storage system technology.

Acknowledgments

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