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Modeling and Simulation of Hybrid System in DC Micro-Grid Based on Photovoltaic and Energy Storage

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Abstract

This paper presents hybrid system, which combines photovoltaic systems, battery and super capacitors, for energy demand and load response. Energy production of the photovoltaic system is changeable, so that energy storage for setting up energy balances, regulation and voltage protection is absolutely vital. In this article, modeling, simulation and controlling hybrid system, which consists of photovoltaic system, battery and super capacitor, also maximum power point tracer algorithm is taken. In addition, the stability of micro-grid and lifetime of the battery is shown. The simulation results show that suitable switching of power electronic converters in this system applies proper controlling over photovoltaic power and battery and super capacitor storages charge and discharge, which leads photovoltaic system acts in the high-efficiency area and to increase the battery life and reduce economic costs due to it, is that of the great achievements of this research.

Keywords: Battery, Hybrid System and DC Micro Grid, Lifetime, Photovoltaic, Super Capacitor

1. Introduction

There are two kinds of PV systems connected to the grid and stand alone. In this paper, a dc micro-grid, including solar cells, batteries, super capacitors and controllable loads has been studied. For this purpose, the stand alone performance of dc micro-grid is taken into consideration. Dc micro-grid can connected to grid or stand alone performance (Island performance). The PV systems standalone of power grid are mostly used in remote areas from the power grid. The other application of the standalone **PV** system is the usage in a remote area such as lighthouse operation, telecommunication station, and rural housing and irrigation systems. In a connected system of grid, the excess required energy of supply generation in a grid can be taken from grid and it can take back the surplus energy of micro-grid to the grid[1]. PV power generation system transforms sunlight into electricity. The main unit of the photovoltaic power generation system is PV cells where the cells are classified into panels, arrays and modules. Photovoltaic panels are grouped into photovoltaic arrays that are connected in series or parallel. Panels connected in parallel are used to increase the current and in series to provide a higher output voltage as shown in the figure bellow. PV panel, electronic converters, energy storage technologies and also load are elements used in generation of PV power. The lead-acid battery is mostly used in the photovoltaic power generation system as storage. The combination's impact of super capacitors and batteries in a hybrid power generation system for pulsed loads with high pick current is evaluated in this article.

The problems of using solar energy are uncertainty and energy storage. There are different methods for storing, increase reliability[2], costs reduction and increase lifetime in these power-generation systems[3,4]. In this paper, the hybrid method with the combination of energy storage, which includes battery and super capacitor, and solar cell, has been studied. This method is highly effective on increase battery lifetime, reduction of economic costs caused by replacement of the batteries and also the

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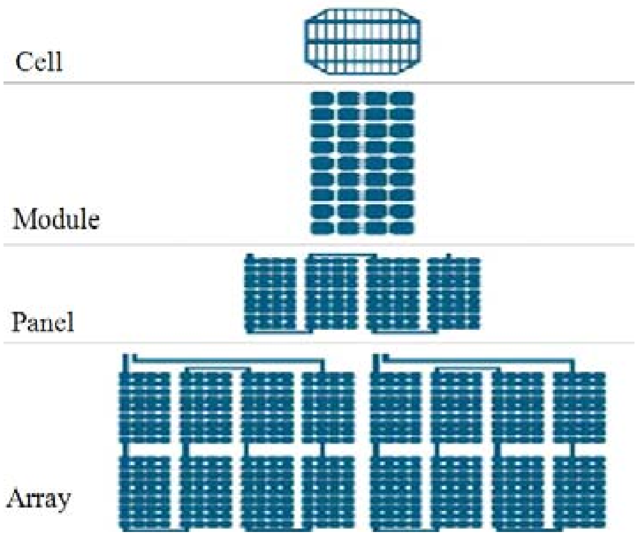

Figure 1. Panel, array, module and photovoltaic cells.

solar cell's maximum efficiency. Energy storage systems based on deference usage can be categorized and used in order to have power quality, intermediate power or energy management goals[4,5].

According to the DC output of photovoltaic panels, the consumer can be two types, whether DC or AC. Moreover, the needs for different consumer with various powers can be provided by configuration of photovoltaic panels[6].

In the simulation of photovoltaic systems various circuits and models are proposed. One hybrid system, including photovoltaic cell and battery storage and connected super capacitor to a dc micro-grid has been analyzed. Increase of battery lifetime, the performance algorithms of battery's charge and discharge and variation of step-up converter's duty cycle which is used in PV module by maximum power point tracer caused by output load variation are the strength and innovation factors of this article.

2. Fundamental Structure of the PV Hybrid System

Stand alone PV systems are made of different ingredients such as PV panel, maximum power point tracer, energy converter and storage. There is a great range of electrical energy storage to utilize in photovoltaic system, flywheel, hydrogen, battery and super-capacitor. The PV stand alone photovoltaic system with lead-acid battery storage and super-capacitor as well as maximum power tracer and electrical converter are shown in Figure 2[7].

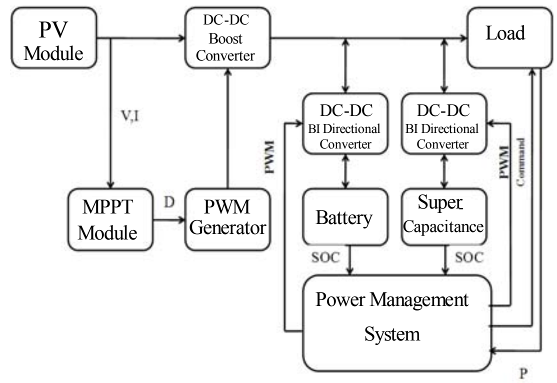

Figure 2. Stand alone PV system with lead-acid battery and super capacitor storage structures.

The photovoltaic module voltage is regulated by the step-up converter proportional to dc micro-grid voltage in this structure. The unit of maximum power point tracer is responsible for providing the maximum power produced by solar cells over the load changes and variations in solar radiation. Storage of battery and super capacitor provides the essential power in peak load and emergency time. In this structure, different states of supplied power are managed and controlled by the power management system.

2.1 Photovoltaic System Simulation

Each photovoltaic cell can be modeled by electrical equivalent circuit. Mathematical modeling method is used in this article. The advantage of this method is that we can generate this model only with information and data provided by manufacturer[8]. Figure 3 shows the typical model for photovoltaic cell.

Photovoltaic current, reverse saturation current and saturation current of the solar modules are calculated in order by equations (1), (2), (3):

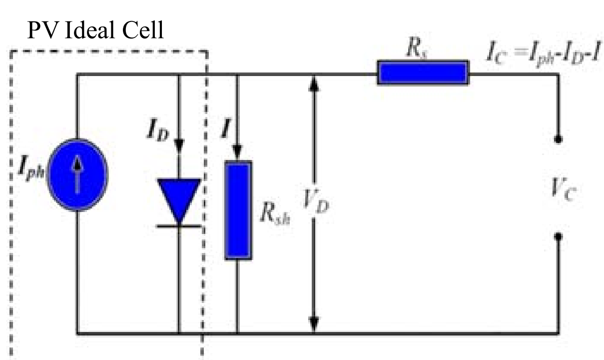

Figure 3. Photovoltaic cell model.

$$I_{ph} = \left[\mathrm{I_{SCr}} + \mathrm{K_i} \left(\mathrm{T_k} - \mathrm{T_{refk}} \right) \right] * \frac{\lambda}{1000} \tag{1}$$

$$I_{rs} = \frac{\mathrm{I_{SCr}}}{\left[\exp\left(\mathrm{q*Voc} \big/ \mathrm{Ns*k*A*T} \right) - 1 \right]} \tag{2}$$

$$I_o = I_{rs} \left[\frac{T}{T_r} \right]^3 \exp\left[\frac{q*Eg0}{AT} \left\{ \frac{1}{T_r} - \frac{1}{T} \right\} \right] \tag{3}$$

The output current module Ipv: This single-diode photovoltaic module has been illustrated below.

$$I_{pv} = \mathrm{N_p * I_{ph}} - \mathrm{N_p * I_o} \left[\exp\left\{ \frac{\mathrm{q*}\left(\mathrm{V_{pv}} + I_{pv} R_s \right)}{\mathrm{Ns*k*A*T}} \right\} - 1 \right] - \mathrm{V_{pv}} + \frac{I_{pv} R_s}{R_{sh}} \tag{4}$$

$\mathrm{R_{sh}} = \infty$

$$I_{pv} = \mathrm{N_p * I_{ph}} - \mathrm{N_p * I_o} \left[\exp\left\{ \frac{\mathrm{q*}\left(\mathrm{V_{pv}} + I_{pv} R_s \right)}{\mathrm{Ns*k*A*T}} \right\} - 1 \right] \tag{5}$$

q: Electron charges ($1.602^{*}10^{-19}$c)
k: Boltzmann Constant
I_C: PV output current (A)
I_{ph}: Photocurrent, Function of radiation level and junction temperature
I_O: diode reverse saturation current (A) (0.0002A)
R_s: Cell Serial Resistance (0.001 Ohm)
T_r: cell function reference temperature (20 °C)
V_{pv}: cell output voltage (V)

General photovoltaic equivalent circuit module is shown in Figure 4 due to condition of temperature value and different radiation for simulation. In this study, the radiation and temperature are assumed constant.

Power and current's changes diagram in terms of voltage are shown for different states of temperature and solar radiation changes. According to the diagrams, the photovoltaic cell power varies greatly during solar current radiation.

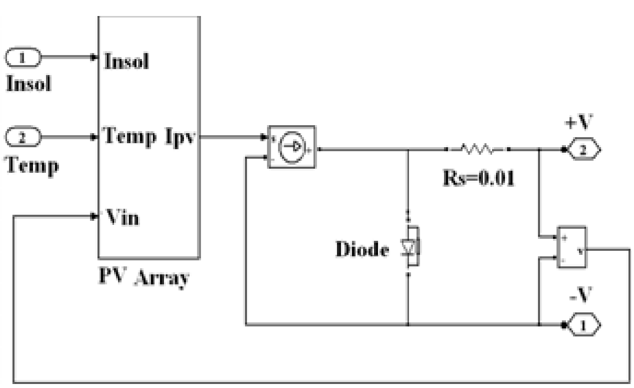

Figure 4. The simulated model of the general photovoltaic module circuit.

We will have changes in voltage due to temperature changes in solar cells. This variation intensity is much lower than solar changes. Therefore, we will see fewer changes in solar cell power.

$$SSOC = SOC_{intial} + \frac{1}{Q_{bat}} \int_0^t i_{bat}(t)\,dt \tag{6}$$

2.1.1 Battery Model

Batteries in hybrid systems can be used for two purposes: Storage of generated excess energy - Provision of additional power requested by the load. It's possible to charge or discharge the battery due to its charging state. Control on the battery terminal voltage is workable by adjusting the power output of the photovoltaic power-generation system. When the power generated by photovoltaic system is more than power requested by load, State of Charge **(SOC)** increases and when power provided by photovoltaic power generation system is lower than power requested by load, **SOC** will be reduced[9,10].

Since the load's dynamic is much faster than responding ability of the photovoltaic system, it can be said that a change in batteries' charging mode occurs based on change in power level of load.

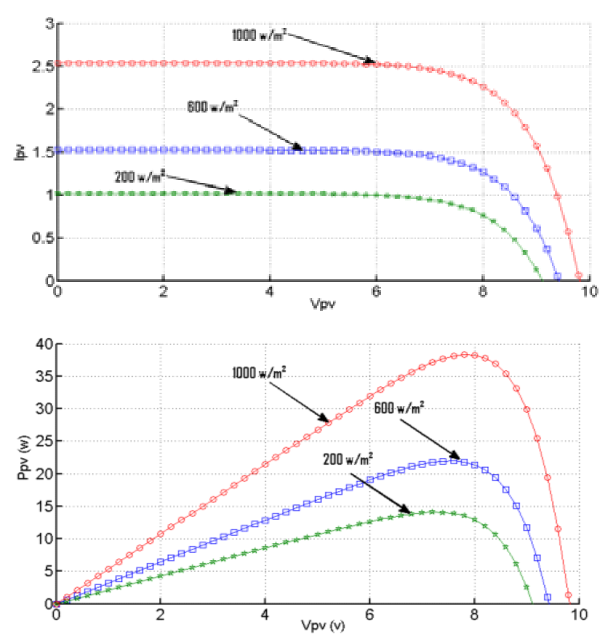

Figure 5. I-V and P-V graph profile with various radiations and constant temperature (30° C).

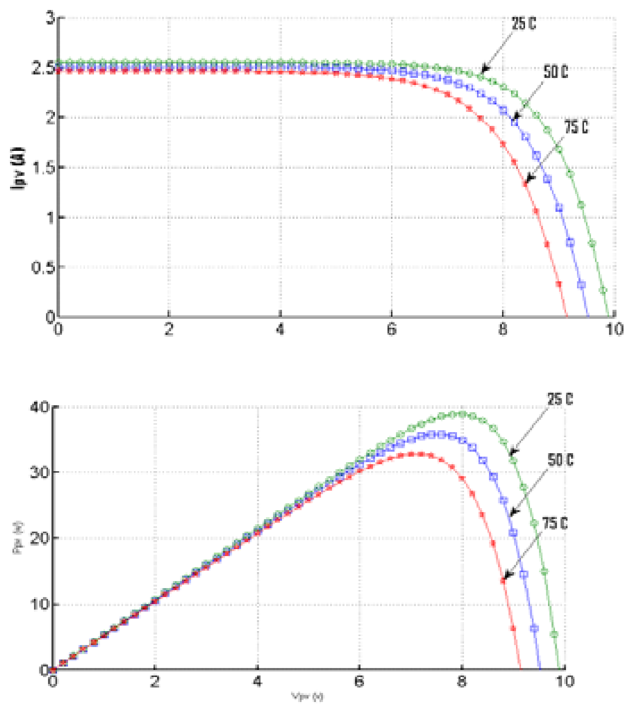

Figure 6. I-V and P-V graph profile with constant radiation (1000W/m^2) and variable temperature.

The equation below illustrates the battery charge state in terms of battery capacity:

In this study, we model the battery using the simulated model in Simulink **Matlab**[16]. Figure 7 shows the schematic model:

The equations of lead-acid battery in both charging and discharging modes are shown below. As it can be seen, charging and discharging modes of battery are as a function of current, ampere hour and battery exponential function[8].

Discharging mode: ($i^* > 0$)

$$f_1(\mathrm{it}, \mathrm{i}, \mathrm{Exp}) = E_0 - K * \frac{Q}{Q - \mathrm{it}} * i^* - K * \frac{Q}{Q - \mathrm{it}} * \mathrm{it} + \mathrm{Laplace}^{-1}\left(\frac{\mathrm{Exp}(s)}{\mathrm{Sel}(s)} * 0\right) \quad (7)$$

Charging mode:

$$(i^* < 0)\, f_1(\mathrm{it}, \mathrm{i}, \mathrm{Exp}) = E_0 - K * \frac{Q}{Q - \mathrm{it}} * i^* - K * \frac{Q}{Q - \mathrm{it}} * \mathrm{it} + \mathrm{Laplace}^{-1}\left(\frac{\mathrm{Exp}(s)}{\mathrm{Sel}(s)} * \frac{1}{s}\right) \quad (8)$$

In the following figure, three parts of battery discharge's graph states are shown[3]. This part includes the following states:

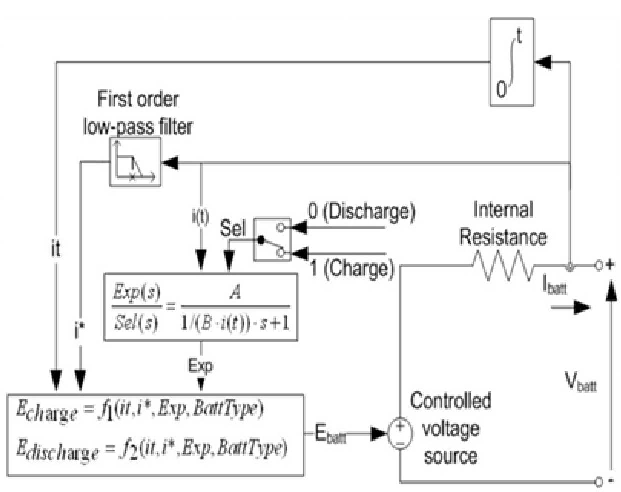

Figure 7. The battery electrical equivalent circuit.

2.1.2 Super Capacitor Model

Several models have been defined for modeling of the super-capacitor. Among the models which are defined, the most common and the most popular one is known as an **EPR-ESR** model that is used to model the capacitor. This model includes a Capacitor **(C)**, an Equivalent Series Resistance **(ESR)**, represents the resistance of the charging and discharging and Equivalent Parallel Resistance **(EPR)** which representing the self-discharging loss. It's worth mentioning that equivalent parallel resistance in leakage rate affects the energy storage operation in long term[9,10].

This model is used mostly because of its simplicity and accuracy.

$$V_t = V_c - ESR.i \quad (9)$$

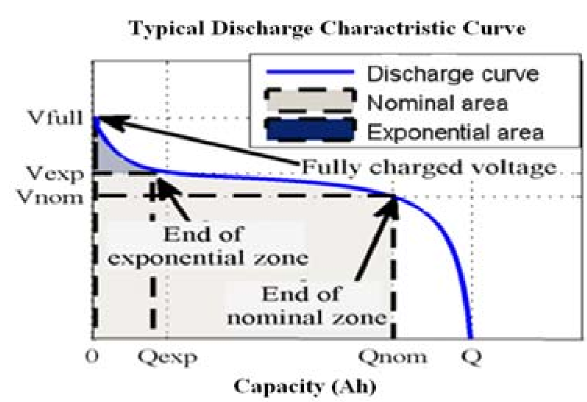

Figure 8. Different Sections of the battery discharging graph[11].

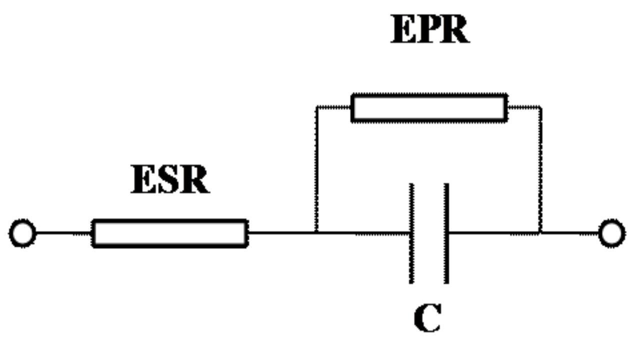

Figure 9. ESR-EPR Equivalent Circuit.

$$V_c = V_c^0 - \frac{1}{c}\int_0^t i_c d_t \tag{10}$$

$$i_L = \frac{V_c}{EPR} \tag{11}$$

$$i_c = i + \mathrm{iL} \tag{12}$$

According to the simplicity and almost good accuracy of this model, it's easy to simulate its transfer function.

$$G(S) = \frac{V(S)}{I(S)} = \frac{ESR + EPR + C.ESR.EPR.S}{1 + EPR.C.S} \tag{13}$$

2.2 Modeling and Simulation of Power Management System

One of the most important parts of power generation systems is the power management system which can have a vital role in controlling of power consumption, costs and system's lifetime[12].

In this study, the power management system has been used in appropriate moments to control and monitor the generation system, charging and discharging battery and super capacitor. The input of this system is a State of Charge (**SOC**) and power consumption, which controls the battery and super-capacitor output in states of step-up converter and step-down converter[13].

The flowchart below illustrates how the power management system functioning.

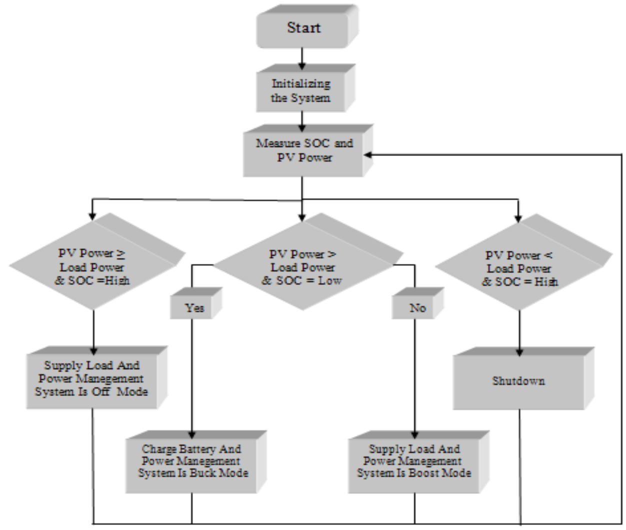

Figure 10. Flowchart of power management system's functioning.

3. The Simulation of the Photovoltaic Hybrid Model

Energy balance between generator and load would be too difficult and economically costly without using energy storage supply. It reduces the lifetime of the power-system as well. In this section of paper, distinct aspect of simulation has been discussed. These aspects include- Simulating of photovoltaic hybrid stand alone.

- Simulation of hybrid photovoltaic via the battery energy storage - Simulation of hybrid photovoltaic via the battery energy storage and super-capacitor.

In these simulations, a dc micro-grid connected to the solar array by maximum power tracer module, step-up converter, **DC-DC** bidirectional converter, battery and super capacitor are used to show the distinct conditions[13,14].

3.1 Modeling Assumption

The values of temperature and solar radiation are considered to be constant in this simulation.

- The light intensity of the photovoltaic array is 0.8 kw/m^2.
- The temperature of the photovoltaic array is 30 °C. The operating voltage of the photovoltaic cell is 0.59 V.
- According to the condition above with 10 modules; the panel can generate 306 watt power. Photovoltaic current is 17 Amperes, and the output voltage is 18 volt. Value of resistance of numerical load is 12 Ohm for the condition above.

In this paper, simulation is done for states as given in bellow:

- The Stand alone Simulation of Photovoltaic Power Generation System's Hybrid Circuit.

- Simulation of Photovoltaic Hybrid Model with Battery Storage.
- Simulation of Hybrid Photovoltaic with Battery Energy Storage - Super Capacitor.

In this simulation, is considered DC micro grid that connected PV system also for increasing efficiency is used MMPT (Maximum Power Point Tracer) Simulation[15–18].

3.1.1 *Simulation of Hybrid Photovoltaic with Battery Energy Storage - Super Capacitor and Comparisons with other Alternative*

For studying and analyzing the simulation of this state, load is considered in accordance with a hybrid photovoltaic system with battery energy storage. So the unbalanced power, which has been described in last status, is connected to the two storage elements. The unbalanced power or power imbalance is going to be shared between these two energy storage s in this condition. The battery storage and the super capacitor are controlled by the dc-dc bidirectional converter[19]. Controlling of the dc-dc bidirectional converter is done by power management system by changing the status from buck to the boost or vice versa[20,21]. Figure 11 shows the simulation of this case.

Since the power changes of micro-grid which causes voltage instability and imbalance of dc grid, this is used for comparison with source power value. The difference between changes of source and actual values to control the storage systems is done by the power management system. The extreme changes of current that causes a reduction in battery SOC and increases the intense pressure of battery,

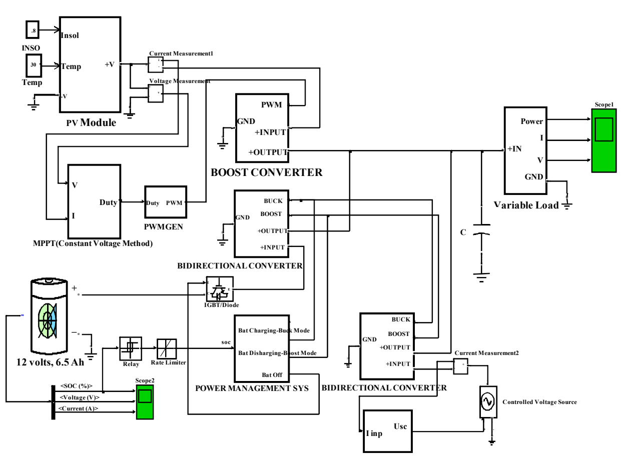

Figure 11. Simulation of Hybrid Photovoltaic model with Battery Storage - Super Capacitor.

which contributes to lessen the lifetime. Therefore, battery has the duty to provide a stable dc current and a super-capacitor has to provide current with rapid fluctuations. Battery and super-capacitor will charge and discharge in accordance with load condition in order to keep dc grid voltage constant.

In Table 1 it is shown that the result of simulation for generation system with PV, battery and super capacitor (comprehensive model) and is described differences between generation and load. In Table 2 it is illustrated results of simulation with comprehensive model and without super capacitor and the status of battery **(SOC)** is described.

The initial **SOC** of battery and super capacitor has been considered 80.00025 percentages. Due to load nature, the

Table 1. The simulation results of power generation with the battery energy storage super-capacitor and photovoltaic

Parameters	Power Supply	Time (second)	Voltage (Volt)	Current (Ampere)	Power (w)	Difference Power Supply and Load
Power Generator	PV+ Battery+ Capacitor	0–0.05	18	17	306	0
		0.05–0.1	18	17	306	0
		0.1–0.15	18	17	306	0
Power Consumption	Load(ohm)	Time (second)	Voltage (Volt)	Current (Ampere)	Power (w)	difference power supply and load
	12	0–0.05	57	4.64	265	+41
	9	0.05–0.1	57	4.64	346	−40
	15	0.1–0.15	57	4.64	230	+76

Table 2. The simulation results of the energy storage including Battery, PV, and super-capacitor and without super-capacitor

Parameters	Power-Generation Supply	Time (second)	Voltage (Volt)	Current (Ampere)	SOC	State of Power Management System
Power Generator	Battery+ PV	0–0.05	13.05	0	80.0025	Off mode
		0.05–0.1	12.92	+6.5	80.0012	Incremental mode
		0.1–0.15	13.94	−4.5	80.0025	Reducing mode
Power Generator	Battery+ PV+ Super capacitor	0–0.05	13.05	0	80.0025	Off mode
		0.05–0.1	12.96	+5	80.0013	Incremental mode
		0.1–0.15	13.06	−0.5	80.0014	Reducing mode

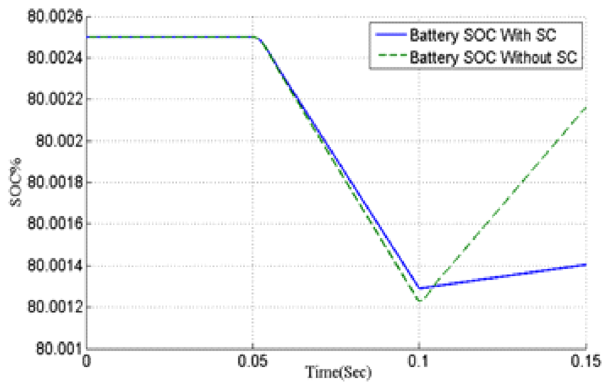

Figure 12. Comparison of battery SOC in both status of the photovoltaic hybrid system with battery and battery-super capacitor.

amounts of voltage and battery **SOC** and super-capacitor change unequally. The table below shows the results of battery parameters in combination status with super-capacitor and photovoltaic.

The comparison of voltage, current and power for load and PV and also voltage, current and battery SOC has shown in both cases, the photovoltaic power-generation system with battery and battery combination with super-capacitor. The flow of current from battery has intensive fluctuations with high values, if we want to talk only about battery. However, battery current becomes more fluent and soft in hybrid storage of battery and super-capacitor status. In addition, the current rate reduced significantly. The status of battery **SOC** in hybrid storage mode has improved at the end of energy balancing operation. The battery **SOC** is 80.0021 in a standalone mode at the end or the end 0.15 seconds of the operating, so this value of storage has improved to 80.0014 in hybrid mode. While the battery **SOC** is increasing, the Depth of Discharge **(DOD)** which is equal to 1–**SOC** decreases. The number of charging and discharging cycles will be reducing by decreasing of **DOD**. This reduction of charging and discharging a cycle's number makes battery lifetime, increase reliability relatively[22].

DOD is status of battery depth of discharge.

4. Conclusion

The following results were achieved through the systems simulation above. Instability of voltage in dc micro-grid occurs while the load power is changing in a standalone mode of the power-system. This system has a very low efficiency, and in terms of economy is costly. The photovoltaic hybrid system is another system, which is used to improve previous discussed status. In this status, the battery has been used as storage in a photovoltaic hybrid system. The battery performance is directed and controlled in connection to the dc micro-grid by the power management system. Power management system exported the charging and discharging performance of battery to the grid. This method greatly benefited from the maximum efficiency of a photovoltaic power generation system. Since the photovoltaic hybrid system with battery storage and super-capacitor use the super-capacitor energy storage, problems caused by sudden changes and extreme load will destroy in short time. The usage of combined super-capacitor with high-power density and a battery with high-energy density by fine strategy of controlling in order to share imbalance power between supply and load in dc micro-grid will increase the battery lifetime, voltage and grid power stability, increase of utilization efficiency of photovoltaic power generation system, reducing of economic costs caused by battery replacement, reducing environmental pollution caused by frequent replacement of batteries.

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