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# Research on Hybrid Energy Storage for Stand-alone PV System

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***ABSTRACT:*** *Standalone PV system with hybrid energy storage could be a promising solution for powering up off-grid or that have no access to grid electricity. The objective of the control of this hybrid energy storage standalone PV system is to maintain the stability of the DC bus voltage, at the same time to supply the desired power to the load of the PV and hybrid energy storage through coordinated control of power electronic converters. In this paper implementation for a hybrid system in a photovoltaic system with battery and supercapacitors to maintain continuity in the supply is presented. Virtual resistance droop (VRD) controller is proposed to regulate battery converter and a virtual capacitance droop (VCD) controller is implemented for supercapacitor (SC) converter. The SC is used to minimize the imbalance power in the system, due to the slow dynamics of the battery. thus Supercapacitors are used to reduce the stress and increase the life of the battery by providing or absorbing peaks powers as demanded by the load. The photovoltaic cells are connected to DC bus with boost converter and controlled with MPPT algorithm, Supercapacitor and batteries are linked to the DC bus through the buck-boost converter and the load is connected to the DC bus. The effectiveness of proposed scheme is shown by simulation studies in MATLAB/SIMULINK.*

***Keywords:*** *Battery, Hybrid energy storage system, Photovoltaic, Stand-alone, supercapacitor*

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## I. INTRODUCTION

Solar energy is the primary source of energy and the largest contributors to the world [1]. It is renewable and eternal. There are two kinds of PV systems connected to the grid and stand-alone [2,3]. Stand-alone power generation systems are utilized by many communities off-grid. Solar energy photovoltaic produce a variable energy that is influenced by the change of irradiance solar, temperature, humidity, and partial shadings effects [4-5].Due to the variable nature, quick fluctuations of load demanding to require an ESs used to solve the problem [6]. However, ESs are used to increase power quality, stability, and reliability. Different ESs have different power density, energy density, life cycle, response time. Unfortunately, no single type of ES fulfills all expected features. In the hybrid energy storage inherits large energy supply and high power supply at the same time, achieves fast dynamic performance and their complementary characteristics. combination of batteries and supercapacitors is an interesting solution for improving system performance and to reduce the stress in the battery to form a HESS. Thus, supercapacitors are offering higher power density and a long cycle life, currently used as short-term power buffers in renewable energy[8-9]. This combination can solve the varying power and is generally used to stabilize the DC Bus voltage in a standalone PV system with less stress in battery storage system.

Many works have been done in the modeling and simulation of a hybrid system. This study presents hybrid design approach by using a combination of supercapacitors and batteries for the storage of stand-alone PV systems and proposes a control strategy consisting of virtual resistance droop (VRD) controller for battery converter and a virtual capacitance droop (VCD) controller for SC converter. The cooperation of VRD and VCD to maintain DC bus voltage and continuity in the supply. to improve the performance of the PV system, an MPPT system and a DC-DC converter are employed. The DC-DC converter is used to improve the strength of the source voltage and the MPPT system is responsible to track (MPP) the maximum power point of the PV system.

This paper is organized as follows. The overall system architecture in Section II with the PV cell and energy storage system. As well as the Control Method in Section III. The simulation results and discussion are presented in Section IV this is followed by a conclusion in Section V.

## II. SYSTEM ARCHITECTURE

A standalone PV system consisting of battery and supercapacitor arrangement is shown in Fig. 1. The PV array is connected to the load using a boost converter. The function of the boost converter used here is to extract the maximum power from PV cell using Perturb & Observe maximum power point tracking (MPPT) algorithm. Hybrid ESS is connected to the load using bi-directional DC/DC converters. The bidirectional DC/DC converter works in two modes: 1) charging mode during surplus energy when generation is higher than load demand, and 2) discharging mode when the generation is lower than the load demand. Hybrid ESS is used to maintain the constant DC Bus voltage even if there is a mismatch between generation and demand. In this paper, The supercapacitors and the batteries are connected to a DC bus with the voltage of Vdc= 400V. Thus, during any variation of loads, the Hybrid ESS will charge and discharge to keep the output voltage of the system constant. The system modeling is detailed in the following.

### 2.1Photovoltaic cell

PV cell is a semiconductor device that absorbs and converts the energy of photon comes from sunlight into DC electric power. A PV is characterized by its short circuit current (Isc), open circuit voltage (Voc), maximal power point voltage (Vm), maximum power point current (Im) and the maximum power point power (Pm) [10].Those parameters shape the $I_{PV}$ and $V_{PV}$ curve as shown the simulation result on Fig. 4 and 5. The Photovoltaic model was simulated by using Matlab Simulink as shown in Fig.3, The PV output voltage also depends on the load. The equivalent circuit of the ideal PV cell is shown in fig. 2 [11].

The current generated by PV can be calculated by using this equation:
(V+IRs)/Rsh can be ignored compared with Photon current cause Rsh is between 100Ω and 10000Ω.

$$I = I_{LG} - I_d - I_{Rsh}$$

$$I = I_{LG} - I_O\left\{\exp\left[\frac{q}{AkT}(V + IR_S)\right] - 1\right\} - \frac{V + IR_S}{R_{Sh}} \quad (1)$$

Where,

$$I_{OS} = I_{or}\left[\frac{T}{Tr}\right]^3 \exp\left[\frac{qE_{GO}}{Bk}\left(\frac{1}{Tr} - \frac{1}{T}\right)\right] \quad (2)$$

$$I_{LG} = \left[I_{SCR} + K_I(T - 298)\right]\frac{S}{1000} \quad (3)$$

$$I = I_{SC}\left\{1 - C_1\left[\exp\left(\frac{V}{C_2 V_{OC}}\right) - 1\right]\right\} \quad (4)$$

At the maximum power point, when V= Vm, I=Im,

$$I_m = I_{SC}\left\{1 - C_1\left[\exp\left(\frac{V_m}{C_2 V_{OC}}\right) - 1\right]\right\} \quad (5)$$

Under normal temperature,

$$\exp\left(\frac{V_m}{C_2 V_{OC}}\right) \gg 1, \quad C1 = \left(1 - \frac{I_m}{I_{SC}}\right)\exp\left(\frac{-V_m}{C_2 V_{OC}}\right) \quad (6)$$

$$0 = I_{SC}\left\{1 - \left(1 - \frac{I_m}{I_{SC}}\right)\exp\left(\frac{-V_m}{C_2 V_{OC}}\right)\left[\exp\left(\frac{1}{C_2}\right) - 1\right]\right\} \quad (7)$$

Under normal temperature,

$$\exp\left(\frac{1}{C_2}\right) \gg 1, \quad C_2 = \left(\frac{V_m}{V_{OC}} - 1\right) \Big/ \ln\left(1 - \frac{I_m}{I_{SC}}\right) \quad (8)$$

We took the standard condition at temperate 25°C, 1000 W/m$^2$. Symbol-related to PV cell with meaning and parameters can be obtained from table 1 and 2.

#### 2.1.1 MPPT Algorithms

Since the output of the PV is less efficient, an MPPT algorithm is adopted to enhance the PV power. The search for the maximum point of a PV by optimization techniques is relatively complex because the characteristic of the cells is highly dependent on solar irradiation and ambient temperature, MPPT utilizes several methods to extract that point. In recent years, several MPPT methods have been published [12] [13] [14]. Among these methods, we have chosen in this paper the P&O algorithm (Perturb and Observe) which is one of the most used methods.

In this algorithm P&O, the PV current I(k) and the voltage V(k) are the inputs. Thus the power of the PV has calculated accordingly.
Delta P = P(k) – P(k-1)
Delta V = V(k) – V(k-1)
If delta P and delta V are positive then the duty cycle is decreased ; D = D – delta D.
And if delta V is negative and delta P is positive duty cycle is increased; D = D + delta D.
In doing this repeatedly, the maximum power point (MPP) is tracked and the output power of the PV system is maximized. The flowchart and simulation model of P&O MPPT algorithm is given in Fig. 6 and 7.

### 2.1.2 DC/DC Boost Converter

Since the output voltage of PV system is low, a DC/DC boost converter is used either to step up the PV Voltage. The boost converter will force the PV system to work at a current which will define by the MPPT unit. The parameters of the DC/DC Boost converter proposed are represented in Table.3.

### 2.2Battery

Energy storage applications in a system can improve the efficiency, enhance the stability and reliability of an electrical utility, correct voltage disturbances. Lead acid batteries are the most commonly used batteries in a PV system, in the system should be able to operate in two ways in which the battery must be able to charge to store excess energy and to discharge depending on load requirement [15] [16].Due to that reason, a bidirectional DC/DC converter is needed to ensure continuity of power flow between the DC bus and energy storage.

### 2.3 Supercapacitor

Supercapacitors are electrical energy storage devices, leading to a very high power density and extremely high cycling capacity. The most significant advantage of SCs over batteries is that they are capable of very fast charge and discharge in short-term (from seconds to minutes) [17, 18].Supercapacitors can last for millions of charge/discharge cycles without losing energy storage capability, Thus can supply power when there are surges or energy bursts.

## III. CONTROL METHODE

For the power management of HESS, it is expected that battery compensates low-frequency power mismatch and SC buffers fast fluctuations. Meanwhile, bus voltage should be regulated at the nominal value to improve power quality and ensure lifetime operation of the voltage sensitive load. Fig.8. shows the control architecture for HESS under the proposed strategy. The classical cascaded PI control is employed for inner current tracking and voltage regulation of the two bidirectional DC/DC converters. A VRD strategy is proposed for battery controller and the VCD strategy is employed for SC converter regulation. They will compensate power mismatch between source and load to maintain DC bus voltage. The current relationship at DC bus is expressed as;

$$\begin{cases} i_0 = i_{load} + i_l \\ i_{0B} + i_{0SC} = i_0 \end{cases} \quad (9) \qquad V_{0B} = V_{0SC} = V_{Bus} \quad (10)$$

where $i_0$ is the equivalent load current of HESS and can be either positive or negative and $V_{bus}$ is the voltage of the common bus. The output voltage-current (V-I) relationship of the battery converter under the VRD control and SC converter under the VCD control are derived in equation (11) and (12).

$$V_{0B} = V_{nom} - R_V I_{oB} \quad (11)$$

$$V_{SC} = V_{nom} - \frac{1}{sC_V} i_{SC} \quad (12)$$

Where; V nom is the nominal voltage; $Vo_B$ and $Io_B$ are output voltage and current of the battery converter and $V\ o_{SC}$ and $io_{SC}$ are output voltage and current of the SC converter; C v is the virtual capacitance. The virtual resistance Rv is determined by the maximum bus voltage deviation ΔV max and converter current rating $Io_{B,\ max}$ .

$$\mathrm{Ri} = \frac{\Delta V_{\max}}{I_{B,\max}} \qquad (13)$$

As the role of the HESS is to compensate power mismatch between PV and load. Current sharing between battery and SC can be obtained as.

$$\begin{cases} i_{OB} = \dfrac{1}{sR_V C_V + 1} . i_O \\ i_{OSC} = \dfrac{sR_V C_V}{sR_V C_V + 1} . i_O \end{cases} \qquad (14)$$

To generate the compensation current, the output current of battery converter is compared with the output current of SC converter and can be added to dead zero input of VCD strategy is depicted in Fig.9. and expressed as,

$$I_{OSC} = k\, I_{OB} + X \qquad (15)$$ Where; k is slope

The SCs reply directly to a need of the load by providing or absorbing peaks currents.

1) $X_1 \le I_{OB} \le X_2$ $\quad I_{OSC} = 0$ (16)

The SCs begin to charge when the solar panels give a higher than desired power (Ppv>PLoad) and the batteries can't absorb the difference of power.

2) $I_{OB} \ge X_2$ $\quad I_{OSC} \rangle 0;$ $\quad I_{OSC} = k\left(I_{0B} - X_2\right)\rangle 0$ (17) Battery charge.

The supercapacitors begin to discharge when the photovoltaic panels fail to give the desired power (Ppv <PLoad) and the batteries can't complete the desired power by the load.

3) $I_{OB} \langle X_1$ $\quad I_{OSC} = k\left(I_{0B} - X_1\right)\langle 0$ (18) Battery discharger.

## IV. SIMUL ATION RESULTS AND DISCUSSION

Fig 10 to 18 presents the results of the simulation model standalone PV system with a temperature of 25°C. Fig 10 represents the first simulation a variation of solar irradiation with a constant load and successively passing through the following values: 800, 1200 and 1000 W/m2. Thus the power and the voltage vary depending on irradiance. Fig 11 and 12 represent the variations of the power of the photovoltaic cells $P_{PV}$, power load $P_{LOAD}$, the output power of the buck-boost converter batteries $P_B$ and supercapacitor $P_{SC}$ respectively. The DC Bus voltage is equal to 400V ($V_{BUS}$=$V_{OB}$=$V_{OSC}$). It is shown in fig 13 and fig 14 represent output current of the buck-boost converter battery ($I_{OB}$) and SCs ($I_{OSC}$). Fig 15 is the second simulation represents a variation of the load with a constant solar irradiation 1000W/m2. The variation of different powers is shown in fig 15 and 16. Thus the DC Bus voltage is equal to 400V ($V_{BUS}$=$V_{0B}$=$V_{0SC}$). It is shown in fig 17 and fig 18 represent output current of the buck-boost converter battery ($I_{OB}$) and SCs ($I_{OSC}$).

In the two modes of proposed simulations, the batteries and SCs are able to respond the demands of the load. During transitions of the solar irradiance for the first test or the transitions of the load for the second test of simulation, the battery and SCs reply directly of the need of the load by providing or absorbing peaks power as demanded by the $P_B$ and $P_{SC}$. The simulation time period is 15s.The difference in the PV generator and Load powers is covered by the battery and supercapacitor through its power converter in fig 11,12,15 and 16. This is the current of $I_{OB}$ and $I_{OSC}$ compensate between PV and load any time of variation shown in fig 14 and 18. The DC bus voltage $V_{BUS}$ is illustrated in figure 13 and 17. It varies into a very small range at 3s, 5s and 8s, because of the variation of load. At this moment, the battery and SC power sharply increase. Immediately DC BUS voltage keeps constant value 400V with output voltage buck-boost converter battery ($V_{OB}$) and SC ($V_{OSC}$). With the selected system proposed it is possible to compensate successfully for the PV generator power and maintain DC Bus voltage constant for a few seconds.

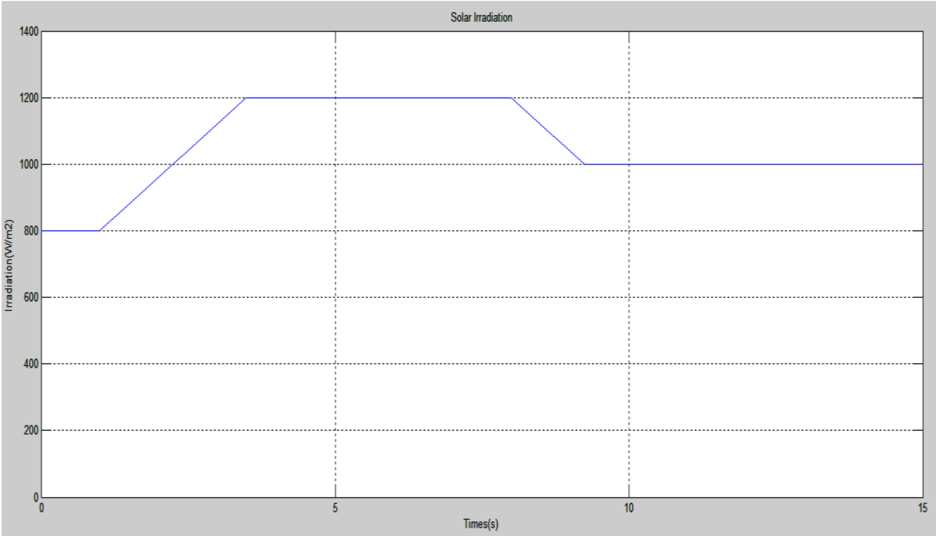

**Figure10:** Variation of solar radiation.

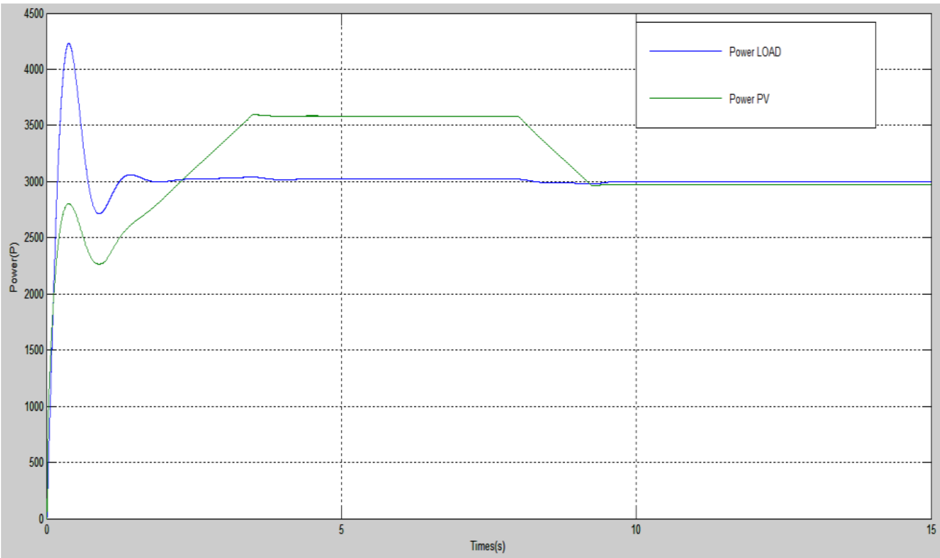

**Figure11:** Ppv and $P_{LOAD}$ with variation irradiation.

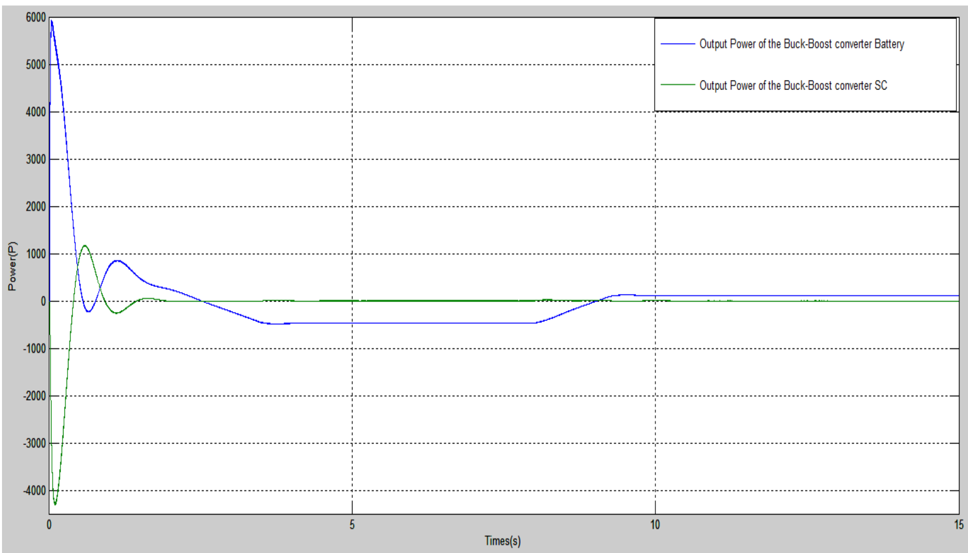

**Figure12:** Output Power of the Buck-Boost converter Battery and SC with variation irradiation.

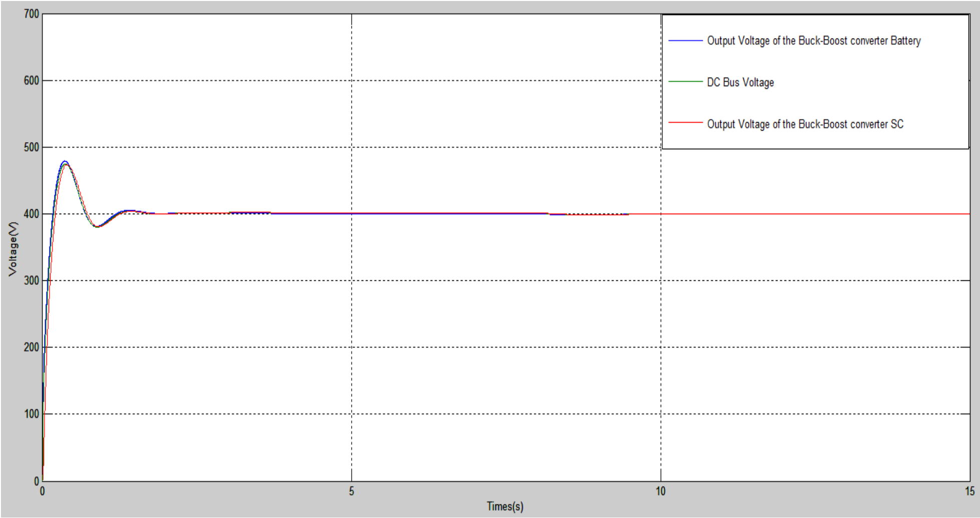


**Figure13:** DC Bus Voltage and Output Voltage of the Buck-Boost converter Battery and SC with variation irradiation.

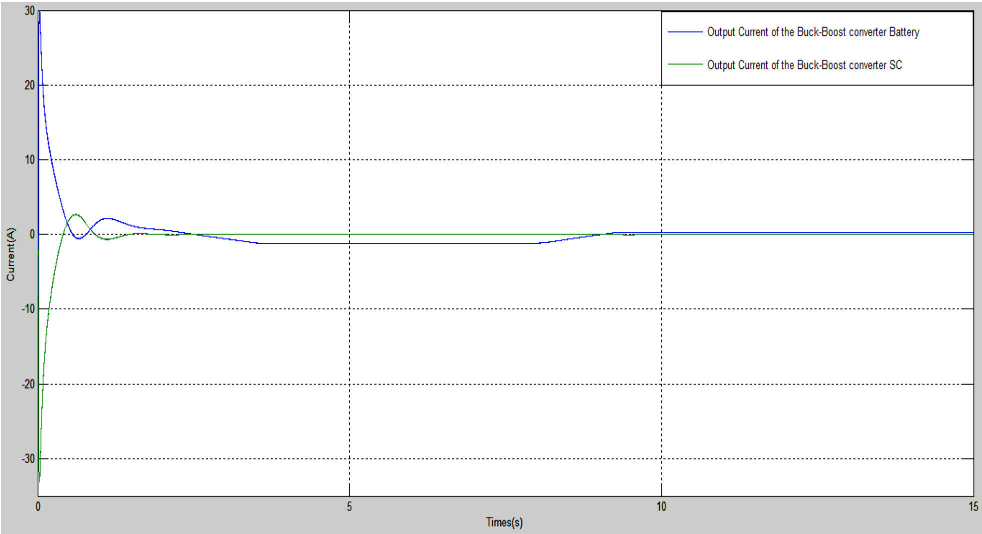


**Figure14:** Output Current of the Buck-Boost converter Battery and SC with variation irradiation.

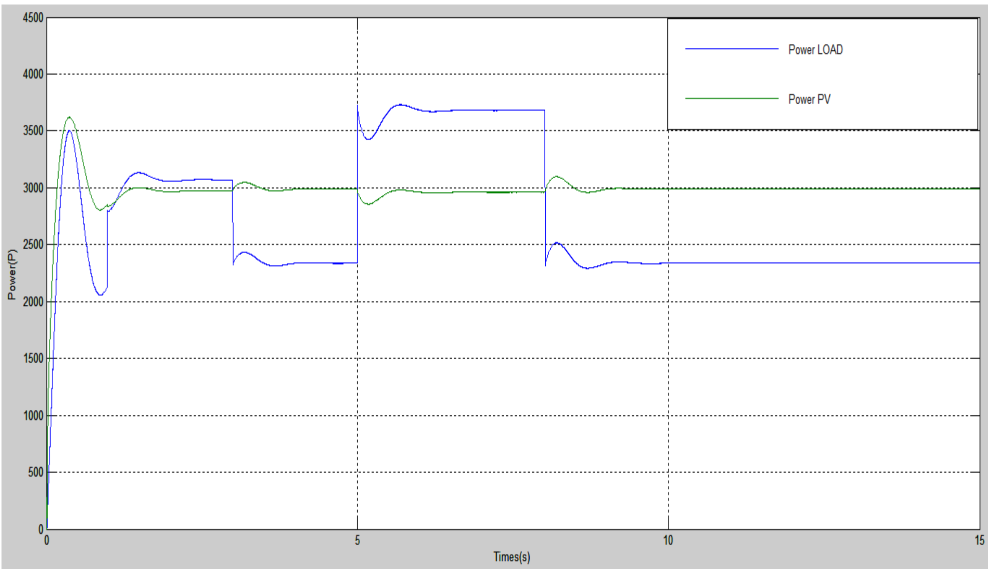


**Figure15:** Ppv and $P_{LOAD}$ with variation Load.

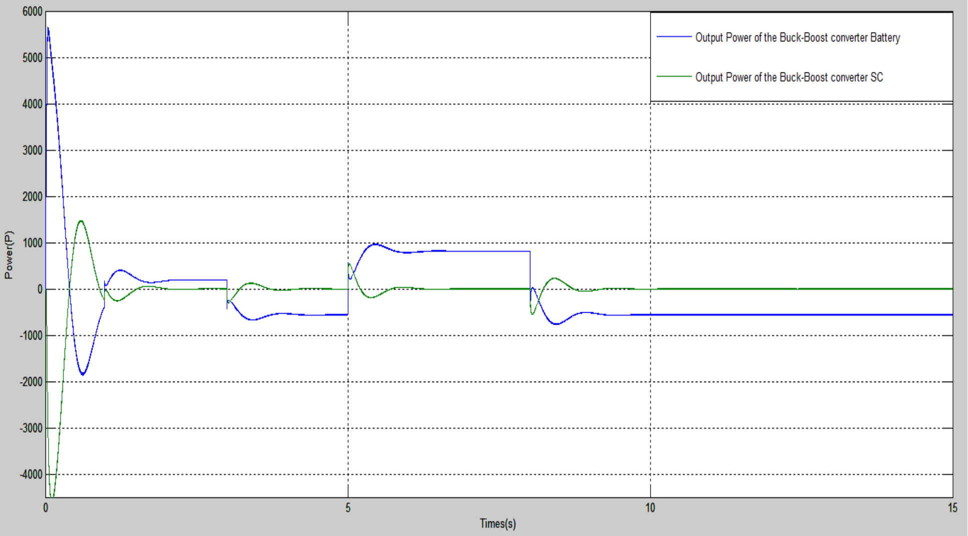


**Figure16:** Output Power of the Buck-Boost converter Battery and SC with variation Load.

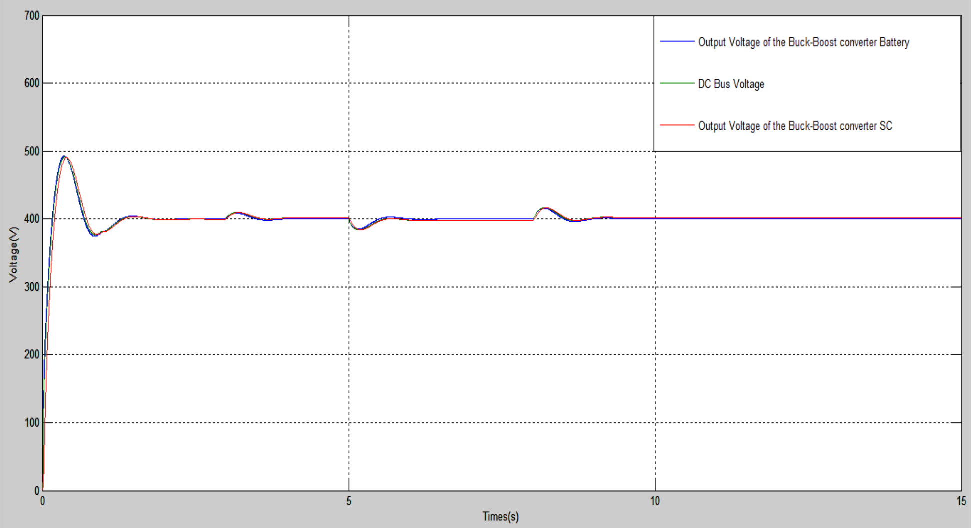


**Figure17:** DC Bus Voltage and Output Voltage of the Buck-Boost converter Battery and SC with variation Load.

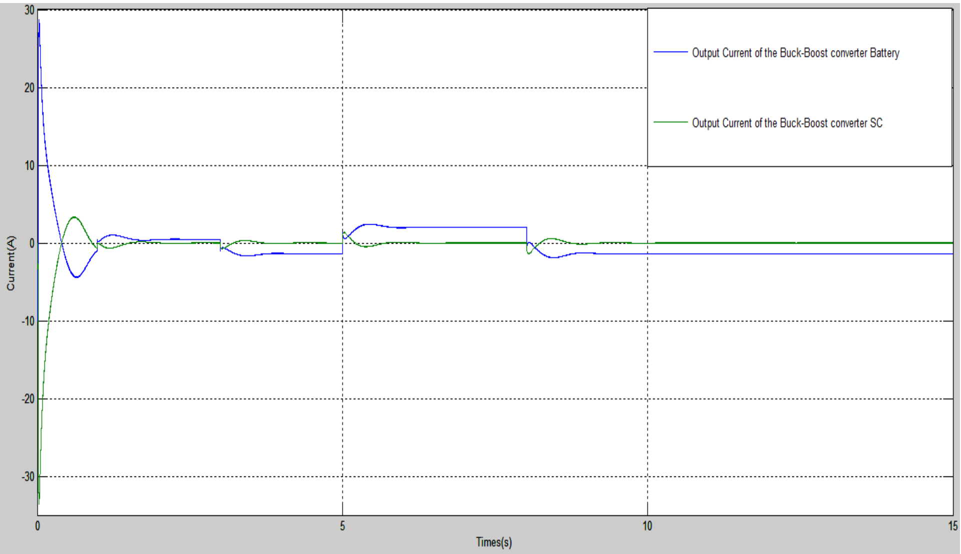

**Figure18:** Output Current of the Buck-Boost converter Battery and SC with variation Load.

## V. CONCLUSION

In this paper, the photovoltaic energy by using a hybrid energy storage with MATLAB/Simulink has been presented. First, simulation results show that by applying MPPT unit to the model, the PV system is able to operate at its MPP and the hybrid energy storage model is able to function as a back-up to follow the load variation. Second, a strategy of control and regulation of the maintain DC bus voltage was proposed, to deal with the variation of solar irradiation and/or the variation of the load. this controller gives the better an efficient energy management and ensures continuity of supply by using battery and Sc to ensure stable voltage on the DC bus of 400V and able to supply desired power. It is also shown that SCs can absorb rapid changes in current to reduce the stress on batteries. finally, performances of the proposed strategy are validated by simulations.

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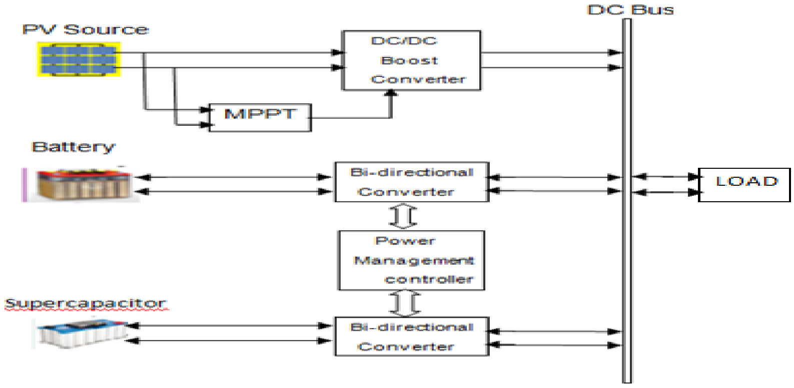
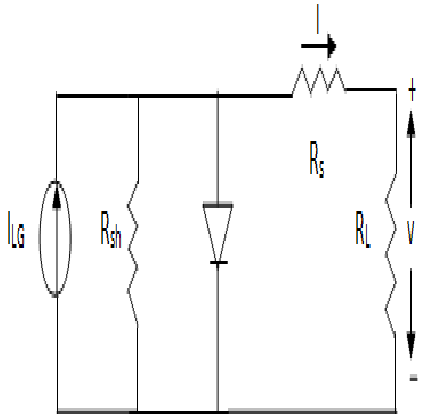



**Figure1**: Stand-alone PV system with battery and supercapacitor storage structures.



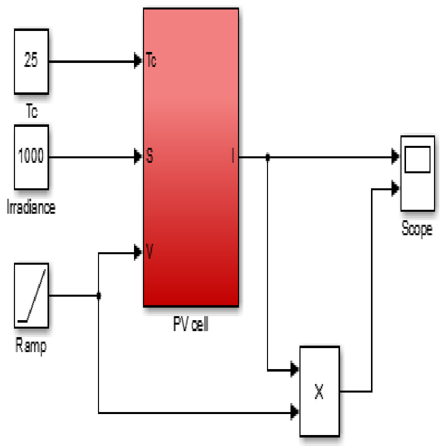




**Figure2**: The Equivalent Circuit of the Ideal PV cell. **Figure3**: Photovoltaic model in Matlab Simulink.

The simulation result in figure 4 shows the $I_{PV}$ & figure 5 shows the $V_{PV}$ for the PV cell.

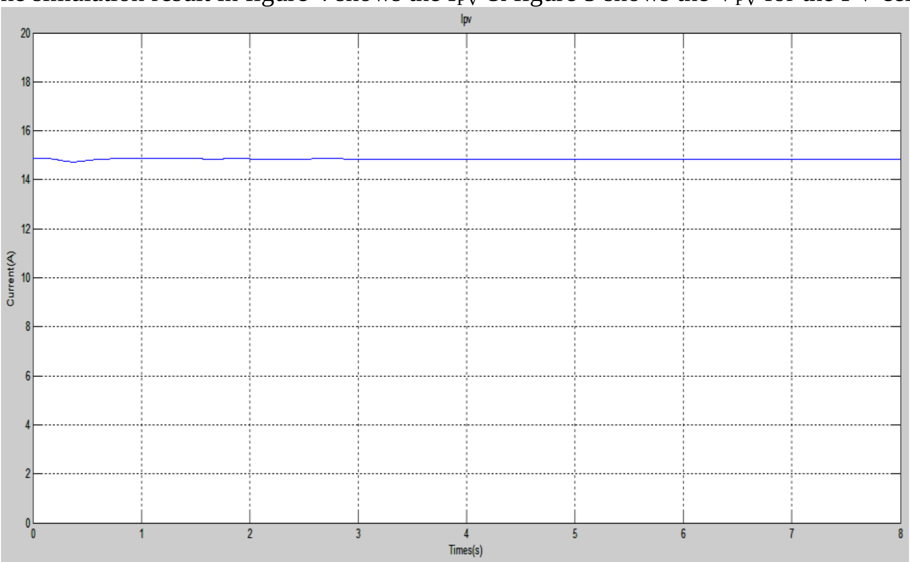



**Figure4**: $I_{PV}$ curve for PV cell.

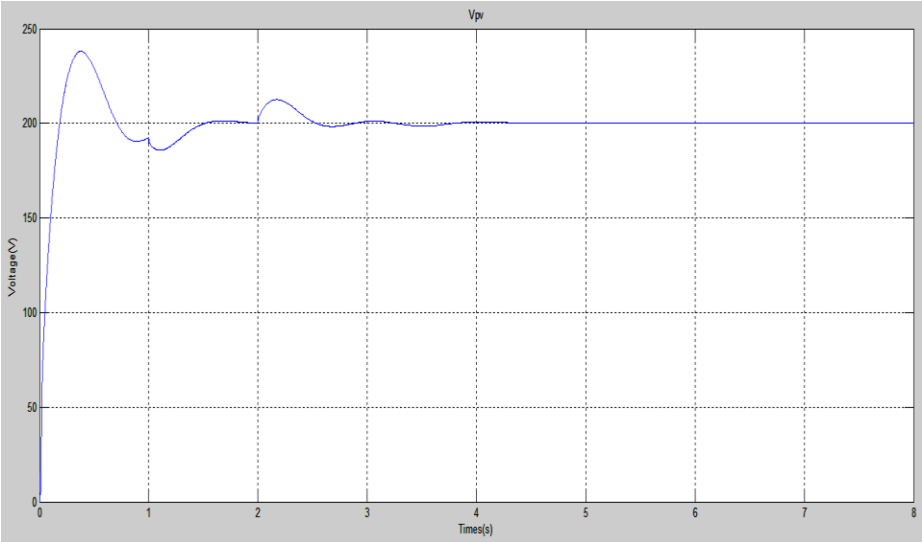



**Figure5**: $V_{PV}$ curve for PV cell.

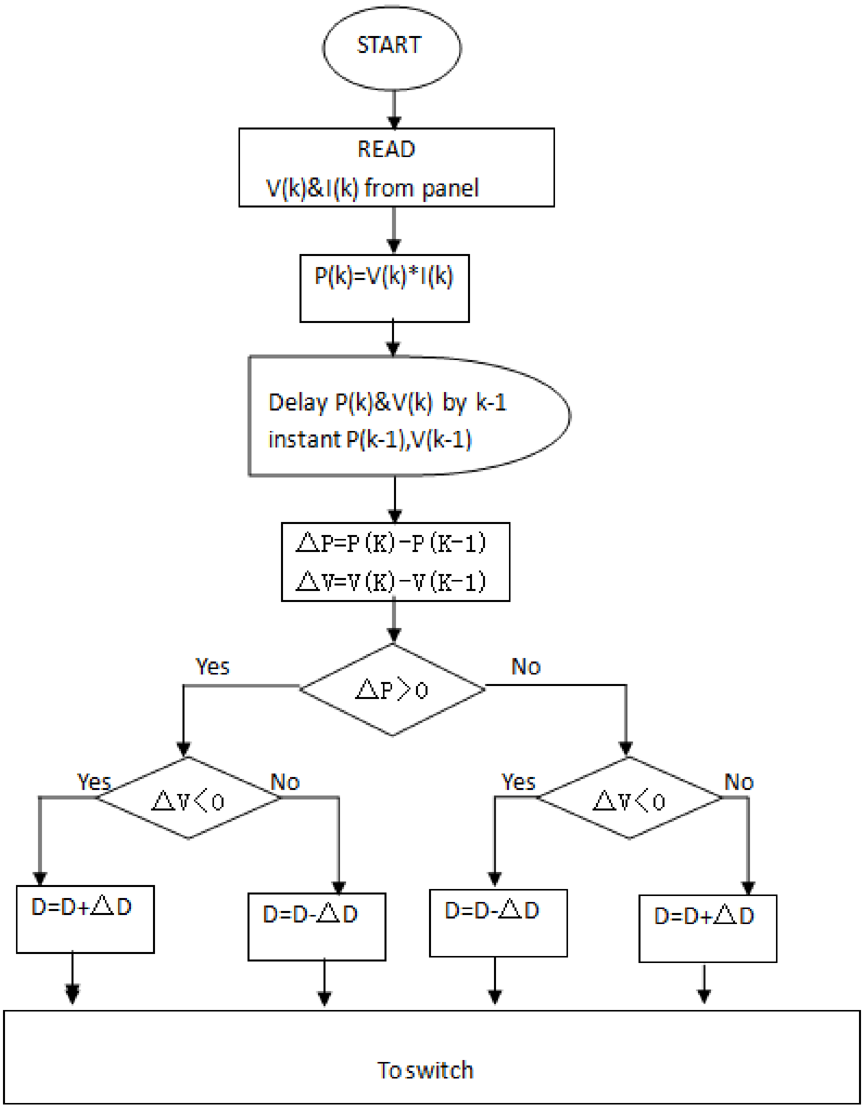



**Figure6**: Flowchart of P&O Method.

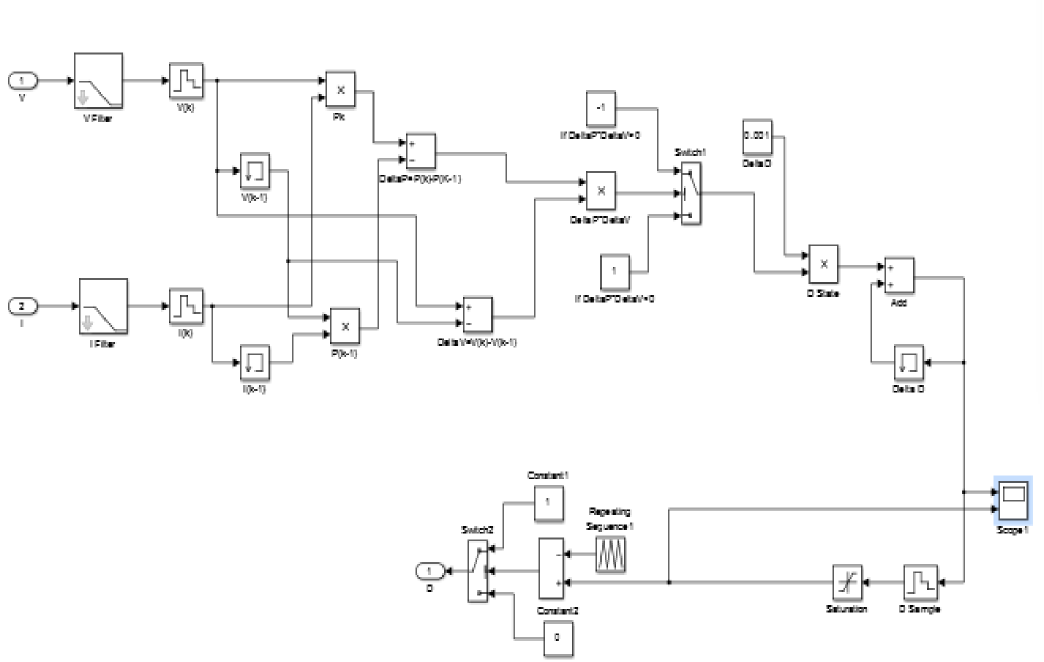



**Figure7**: Simulation Model for P&O MPPT.

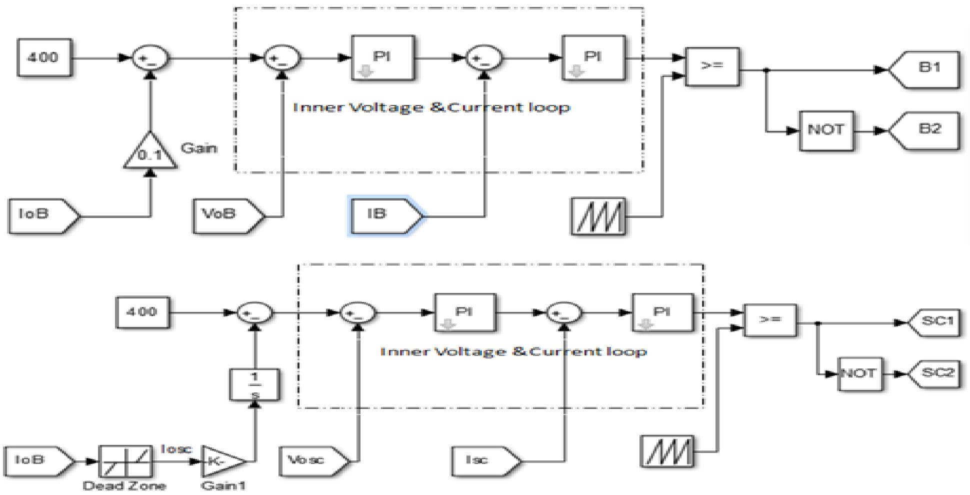



**Figure8**: Control architecture under the proposed strategy

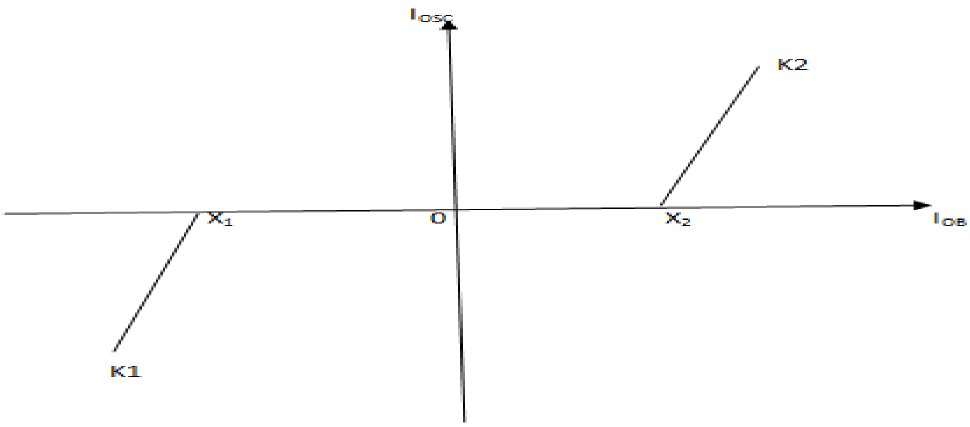



**Figure9**: $I_{OSC}$-$I_B$ characteristics.

**Table1**: Symbol related to PV cell with meaning. .

| Symbol | Meaning of symbol |
|---|---|
| V | PV Cell output voltage (V) |
| I | PV Cell output Current (A) |
| $I_{LG}$ | Photon current (A) |
| Ios | Reverse saturation current of PV cell's (A) |
| T | Operating temperature of PV cell ($^0$K) |
| Q | Charge of an Electron=1.6*10$^{-19}$C |
| K | Boltzmann's constant=1.38*10$^{-23}$J/$^0$K |
| $K_1$ | Temperature coefficient |
| $I_{SC}$ | Short circuit current (A/$^0$K) |
| S | Operating solar radiation (W/m$^2$)<br>Short circuit current at STC(A) |
| $E_{G0}$ | Band gap energy of the semiconductor(J) |
| A, B | Ideality constant between 1 and 2 |
| Tr | Absolute temperature at Standard Test Condition of PV cell=301.18$^O$K |
| $I_{0R}$ | Reverse saturation current of PV cell's at temperature Tr(A) |
| $R_{SH}$ | Intrinsic parallel resistance of PV cell (Ω) |
| $R_S$ | Intrinsic parallel resistance ofPV cell(Ω) |

**Table2**: Parameters of PV Cell

| Parameter | Symbol | Value |
|---|---|---|
| Voltage at maximum power | $V_m$ | 35.20 V |
| Current at maximum power | $I_m$ | 4.95 A |
| Open circuit voltage | Voc | 44.20 V |
| Short circuit voltage | $I_{sc}$ | 5.20 A |
| Temperature coefficient of Short circuit current | a | 0.015 A/$^0$K |
| Temperature coefficient of open circuit voltage | b | 0.70 V/$^0$K |
| Internal series resistance | $R_s$ | 0.217Ω |
| Reference solar radiation | $S_{ref}$ | 1000 W/m$^2$ |
| Reference temperature | $T_{ref}$ | 25$^0$C |

**Table3**: Parameters for DC/DC Converter model.

| Parameter | Symbol | Value |
|---|---|---|
| Inductor | L | 0.05 H |
| Capacitor | C1 | 0.003 F |
| Capacitor | C | 0.002 F |
| Resistor | R | 500Ω |

## APPENDIX A

ESs: Energy Storage System
HESS: Hybrid Energy Storage System
SCs: Supercapacitors

Hoche Omar Hoch "Research on Hybrid Energy Storage for Stand-alone PV System." American Journal of Engineering Research (AJER), vol. 06, no. 12, 2017, pp. 349-360.