A New Control Scheme for Battery-Supercapacitor Hybrid Energy Storage System for Standalone Photovoltaic Application

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Abstract—In this paper, a battery-supercapacitor (SC) hybrid Energy Storage System (ESS) is employed in a standalone photovoltaic (PV) system to maintain continuity in the supply. The battery ESS is characterized by high energy density, low power density, degradation due to frequent and partial charge/discharge cycles. By incorporating SC ESS which has high charge/discharge rates, a system having both high energy and power capabilities can be designed. In the presented control scheme, high frequency current reference along with battery error current is utilized as the reference for the SC ESS resulting in an improved voltage profile as compared to that of the conventional methods. Also, an improvement in the life span, reduction in size and cost of the battery and better generation-demand power balance can be obtained. The control scheme is validated using Matlab/Simulink models under varying conditions of irradiation and load.

Index Terms— battery, bidirectional dc-dc converter, hybrid energy storage system, standalone photovoltaic system, supercapacitor.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>V_{pv}, V_b, V_{sc}</td>
<td>Terminal voltage across the PV module, battery and supercapacitor respectively.</td>
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<tr>
<td>I_{pv}, I_b, I_{sc}</td>
<td>Terminal current of the PV module, battery and supercapacitor respectively.</td>
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<td>V_{oc}, I_{sc}</td>
<td>Open circuit voltage and short circuit current of the PV module respectively.</td>
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<tr>
<td>P_{pv}</td>
<td>Instantaneous power delivered by PV panel</td>
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<td>P_{mpp}</td>
<td>Maximum power delivered by the PV module</td>
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<tr>
<td>L_{pv}, I_{b}, I_{sc}</td>
<td>Filter inductance of PV panel, battery and SC respectively.</td>
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<tr>
<td>SW_1-SW_5</td>
<td>Control switches using IGBT technology</td>
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<tr>
<td>C</td>
<td>Filter Capacitance</td>
</tr>
<tr>
<td>R</td>
<td>System Resistive load</td>
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<tr>
<td>I_ph</td>
<td>Photo-current or light generated current</td>
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<tr>
<td>I_s</td>
<td>Reverse saturation current of diode</td>
</tr>
<tr>
<td>Q</td>
<td>Charge of an electron</td>
</tr>
<tr>
<td>a</td>
<td>Diode ideality constant</td>
</tr>
<tr>
<td>K</td>
<td>Boltzmann’s constant</td>
</tr>
<tr>
<td>T_e,T</td>
<td>Absolute temperature of PV cell and operating temperature respectively.</td>
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</table>

N_p, N_i | Number of PV cells in series and parallel respectively. |
E, E_o | Battery no load voltage and battery constant voltage respectively. |
r | Internal resistance of battery |
i | Battery current |
SOC | State of Charge of battery |
A, B | Battery constant parameters |
Q | Capacity of battery (Ah) |
V_{ref}, V_{out} | System reference voltage and system output voltage respectively. |
I_{ref} | Total reference current generated |
I_{b_ref}, I_{sc_ref} | Reference current generated for battery and supercapacitor respectively. |
I_{hifc_ref}, I_b_err | High frequency current reference and battery error current respectively |
P_{b_uncomp} | Uncompensated battery power |
K_{p_pv}, K_{i_pv} | PI controller gains for boost converter control |
K_{p_b}, K_{i_b} | PI controller gains for bidirectional dc-dc converter1 control |
K_{p_sc}, K_{i_sc} | PI controller gains for bidirectional dc-dc converter2 control |
f_{sw} | Switching frequency of the converters used |

I. INTRODUCTION

The low emission and low maintenance benefits of solar photovoltaic (PV) generation are offset by high cost and the intermittent nature of solar energy. Fortunately, the increased activity in the PV market has led to decreasing costs due to increased production of solar panels and improvements in the technology. The intermittency issue for standalone PV systems can potentially be addressed by large-scale interconnections with complementary energy sources such as wind or natural gas operated generation units, however the most self-contained approach is to add storage to the system, thus creating a hybrid PV-storage system that can balance the PV generation with the load. Though there are many available storage technologies including supercapacitors, pumped hydro, compressed air, superconducting magnetic and thermal storage, the most cost effective and mature technology on a small scale is battery storage. Lead-acid batteries remain for the moment the most cost effective solution, as well as the most mature with respect to recycling at the end-of-life. Batteries possess high energy density but low power density which means it has low charge/discharge...
rates [6]. The supercapacitors are a new form of energy storage which stores energy by means of static charge. When compared to batteries, SC possesses high power density but low energy density which means it has high charge/discharge rates [7]. In Table I performance of the battery and the supercapacitor is compared [5]. When only battery is employed as storage, then it has to be oversized to take care of the peak load demand which may be required for a very short duration of time. An ideal ESS in a standalone PV system should have both high energy and power capacities to handle situations such as solar irradiation changes and load step changes. Thus, the objective is to harness the advantages of both the storage systems to design a hybrid energy storage system with high power and energy density. By utilizing a battery-supercapacitor hybrid ESS the following merits can be achieved: i) longevity of battery life ii) reduction in battery size and hence the cost iii) reduction in battery stress and iv) improvement in balance between generation and load demand. Various control strategies have been reported in literature [1]–[11], for coordinating power sharing between battery and super capacitor. N. Mendis et al. [3] has addressed the advantages of including a SC to a battery storage system in a wind based hybrid remote area power supply (RAPS) system. An energy management algorithm (EMA) has been established between the battery storage system and SC to operate both the storage systems in a designated manner. Authors in [6] have utilized hybrid ESS for microgrid applications. Amine Lahyani et al. [10] have presented an analysis on the reduction in battery stress with the help of SC. Authors in [11], have shown that hybrid ESS reduces the battery cost and enhances the overall system efficiency. The fundamental idea of all the control strategies reported so far is that battery provides low frequency component of power and SC provides high frequency component of power momentarily. In this paper, a new control strategy is demonstrated for hybrid ESS consisting of PV, battery, SC and load. The presented method is based on decoupling of low and high frequency current components. It utilizes the error current of battery in addition to the high frequency current reference to control the SC while the rest of the current is used as reference to control the battery ESS. This paper is organized as follows. In Section II system structure and its modelling is given. The proposed control structure is designed and discussed in Section III. Simulation results are reported in Section IV.

### TABLE I. Comparison of lead-acid battery and supercapacitor

<table>
<thead>
<tr>
<th></th>
<th>Lead acid battery</th>
<th>Supercapacitor</th>
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<tbody>
<tr>
<td>Specific energy density (Wh/kg)</td>
<td>10 - 100</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Specific power density (W/kg)</td>
<td>&lt;1000</td>
<td>&gt;10000</td>
</tr>
<tr>
<td>Life cycle</td>
<td>10^6 cycles</td>
<td>10^6-10^8 cycles</td>
</tr>
<tr>
<td>Charge/discharge Efficiency</td>
<td>70 – 85%</td>
<td>85 – 98%</td>
</tr>
<tr>
<td>Charge time</td>
<td>1 – 5 hr.</td>
<td>0.3 – 30 sec.</td>
</tr>
<tr>
<td>Discharge time</td>
<td>0.3 – 3 hr.</td>
<td>0.3 – 30 sec.</td>
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</table>

A standalone PV system consisting of battery and SC arrangement is shown in Fig. 1. The PV panel 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 panel using incremental-conductance maximum power point tracking (MPPT) algorithm. Hybrid ESS is connected to the load using bi-directional DC/DC converters. Hybrid ESS is used to maintain the constant DC voltage ($V_{out}$) even if there is a mismatch between generation and demand. When the demand is more than generation, $V_{out}$ drops from its reference value, consequently Hybrid ESS will discharge to provide the surplus demand. Similarly, when the demand is less than the generation, $V_{out}$ increases from its reference value.
consequently Hybrid ESS will be charged to absorb the surplus power. Buck-boost converter is used as a bi-directional converter to facilitate the bi-directional power flow between the load and Hybrid ESS. In this paper, the total load is represented as DC load with resistance $R$. In Fig. 2 $V_{pv}$, $V_b$ and $V_{sc}$ are PV panel, battery and SC voltages respectively, $I_{pv}$, $I_b$ and $I_{sc}$ are PV panel, battery and SC current respectively, $L_{pv}$, $L_b$ and $L_{sc}$ are PV panel, battery and SC filter inductance respectively, $V_{out}$ is output voltage, $C$ is filter capacitance and $R$ is load resistance. SW1, SW2, SW3, SW4 and SW5 are control switches.

B. PV Module

The photovoltaic (PV) cell is basically a p-n junction fabricated in a thin wafer of semiconductor. The solar energy is directly converted to electricity through photovoltaic effect. The equivalent circuit of PV module is as shown in Fig. 3. PV cell exhibits a nonlinear P-V and I-V characteristics which vary with cell temperature and solar irradiance. The P-V and I-V characteristics for an irradiation of 1000 W/m² are given in Fig. 4,5 respectively.

\[ I_{pv} = N_p I_{ph} - N_p I_{sc} \left( e^{\frac{V_{pv} I_{pv}}{N_p R_{sh}}} - 1 \right) - \frac{N_p V_{pv}}{N_p + I_{pv} R_{sh}} \]

\[ (1) \]

Various parameters can be obtained from specifications given in [13].

C. MPPT Controller

The switching of the boost converter is controlled by the MPPT controller which utilizes the incremental-conductance algorithm for its operation. The flowchart of the algorithm is shown in Fig. 6. The method exploits the assumption that the ratio of change in output conductance is equal to the negative output conductance. We have,

\[ P_{pv} = V_{pv} I_{pv} \]

\[ (2) \]

Applying the chain rule for the derivative of products yields to

\[ \frac{\partial P_{pv}}{\partial V_{pv}} = \frac{\partial (V_{pv} I_{pv})}{\partial V_{pv}} \]

\[ (3) \]

At maximum power point, as

\[ \frac{\partial P_{pv}}{\partial V_{pv}} = 0 \]

\[ (4) \]

The above equation could be written as

\[ \frac{\partial I_{pv}}{\partial V_{pv}} = - \frac{I_{pv}}{V_{pv}} \]

\[ (5) \]

The MPPT regulates the PWM control signal of the dc-dc boost converter until the condition,

\[ (\frac{\partial I_{pv}}{\partial V_{pv}}) + (\frac{I_{pv}}{V_{pv}}) = 0 \]

\[ (6) \]

is satisfied.
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Fig. 6. Flowchart for incremental-conductance algorithm

Fig. 7 shows the PV power obtained for an irradiation of 520W/m² when MPPT algorithm is enabled at t= 0.11 s. This leads to an increment in the PV power is from 251.25W to 488.65W.

The battery model characteristics for discharging currents of 1.5 and 3A is as shown in Fig. 9. Other parameters can be obtained using [14].

**D. Battery**

Lead acid batteries are the most commonly used batteries in a PV system. It is modelled using a simple controlled voltage source in series with a constant resistance. The battery is modelled as a nonlinear voltage source as shown in the Fig. 8 using the following equations [14],

\[ E = E_0 - \frac{KQ}{Q} + A e^{-\beta \frac{1}{Q} \int dt} \]  
\[ V_b = E - Ri \]  
\[ \% SOC = (1 - \frac{1}{Q} \int idt) \times 100 \]
III. THE CONTROL STRUCTURE

Fig. 11 shows the block diagram of the proposed control strategy. The objective of this algorithm is to reduce the stress on battery and hence increase the lifetime of battery. In this algorithm, the DC output voltage ($V_{out}$) is compared with reference voltage ($V_{ref}$), and the error is fed to the proportional integral (PI) controller. The PI controller generates the total current required ($I_{ref}$) from hybrid energy storage system. $I_{ref}$ is separated into low frequency component and high frequency component as,

$$I_{b,\text{ref}} = \text{lowpassfilter}(I_{ref})$$

$$I_{sc,\text{ref}} = I_{ref} - I_{b,\text{ref}}$$

The low frequency component of current is given as the reference current to battery. $I_{b,\text{ref}}$ is compared with the actual battery current ($I_b$), and the error ($I_{b,\text{err}}$) is given to the PI controller. The PI controller generates the duty ratios. These duty ratios are fed to the PWM generator to generate switching pulses corresponding to battery switches (SW2, SW3). Due to the slow dynamics of the battery, $I_b$ may not be able to track the $I_{b,\text{ref}}$ instantly.

Therefore, the uncompensated battery power is given as

$$P_{b,\text{uncomp}} = (I_{b,\text{ref}} - I_{b,\text{err}}) \times V_b$$

This uncompensated battery power is to be compensated by SC. Therefore, the reference current of SC is taken as

$$I_{sc,\text{ref}} = P_{b,\text{uncomp}} / V_{sc}$$

$I_{sc,\text{ref}}$ is compared with the actual SC current ($I_{sc}$), and the error is fed to the PI controller. The PI controller generates the required duty ratios. These duty ratios are given to the PWM generator to generate switching pulses corresponding to SC switches (SW4, SW5).

IV. SIMULATION RESULTS

The presented control strategy is validated using Matlab/Simulink for the following cases: i) variation in solar irradiation and ii) variation in load demand. The objective is to maintain the output voltage at $V_{ref} = 50$ V. The nominal parameters of the system are given in Table II. The initial State of Charge (SOC) of the battery is set at 50%. The PI controller gains of the outer voltage loop, inner current loop of battery and inner current loop of SC are $K_{p, v} = 1.477$, $K_{i, v} = 3077$, $K_{p, b} = 0.043$, $K_{i, b} = 0.65$, $K_{p, sc} = 0.41$ and $K_{i, sc} = 14800$ respectively.

**TABLE II. Parameters used in simulation**

<table>
<thead>
<tr>
<th>System Component</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>$V_{oc} = 37.5V$, $I_{sc} = 33.2A$, $P_{mpp} = 882.7W$</td>
</tr>
<tr>
<td>Battery</td>
<td>Lead acid- 24V, 14Ah</td>
</tr>
<tr>
<td>SC</td>
<td>29F, 32V</td>
</tr>
<tr>
<td>DC-DC Converters</td>
<td>$L_{pv} = 0.352mH$, $L_{b} = 0.3mH$, $L_{sc} = 0.355mH$, $C = 390uF$, $V_{out} = 50V$, $R = 5\Omega$, $f_{sw} = 16kHz$</td>
</tr>
</tbody>
</table>

Fig. 12. Simulation results for an increase in solar irradiation showing PV power, output voltage and load power using the proposed control scheme
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Fig. 13. Simulation results for an increase in solar irradiation showing the output voltage using the conventional control scheme

A. Variation in solar irradiation
- Increase in irradiation:
  In the study, initially maximum PV power extracted with irradiation 450W/m² and T= 25°C is 315W. At t= 1s, the irradiation is increased to 650W/m². At this value of irradiance, the power supplied by the PV module is 465W, but the load demand is 502W. To maintain $V_{out}$ at its reference value, the surplus supply is to be absorbed by the storage system. Fig. 12 shows the waveforms of PV power, output voltage and the load power using the proposed control scheme. Using the conventional control scheme [6], the output voltage waveform obtained for the same conditions is shown in Fig. 13. It is observed that during the transient, the voltage is suddenly increased to 58.1V. It can be seen that the percentage increase in voltage is reduced from 16.2% to 0% using the new method. Unlike the conventional methods, the sudden change in the voltage due to the slow dynamics of the battery is removed by utilizing the battery error current.

Fig. 14. Simulation results for a decrease in solar irradiation showing PV power, output voltage and load power using the proposed control scheme

- Decrease in irradiation:
  In the study, initially maximum PV power extracted with irradiation 550W/m² and T= 25°C is 388W. At t= 1s, the irradiation is decreased to 450W/m². At this value of irradiance, the power supplied by the PV module is 315W, but the load demand is 502W. To maintain the voltage at its reference value, the surplus demand is to be supplied by the storage system. Fig. 14 shows the waveforms of PV power, output voltage and the load power using the proposed control scheme. Using the conventional control scheme [6], the output voltage waveform obtained for the same conditions is shown in Fig. 15. It is observed that during the transient, the voltage is suddenly decreased to 45V. It can be seen that the percentage decrease in voltage is reduced from 10% to 0% using the new method. Unlike the conventional methods, the sudden change in the voltage due to the slow dynamics of the battery is removed by utilizing the battery error current.

Fig. 15. Simulation results for a decrease in solar irradiation showing the output voltage using the conventional control scheme

B. Variation in load demand
- Increase in load power:
  In the study, initially PV panel is operated at constant irradiation of 550W/m², T= 25°C and R= 5Ω. At t= 1s, the load demand is suddenly increased by decreasing R to 2.7Ω. At this instant, the power supplied by the PV module is 390W, but the load demand is 920W. To maintain $V_{out}$ at its reference value, the surplus demand is to be supplied by the storage system. Fig. 16 shows the waveforms of PV power, output voltage and the load power using the proposed control scheme. Using the conventional control scheme [6], the output voltage waveform obtained for the same conditions is shown in Fig. 17. It is observed that during the transient, the voltage is suddenly decreased to 44V. It can be seen that the percentage decrease in voltage is reduced from 12% to 0% using the new method. Unlike the conventional methods, the sudden change in the voltage due to the slow dynamics of the battery is removed by utilizing the battery error current.
Fig. 16. Simulation results for an increase in load demand showing load power, output voltage and PV power using the proposed control scheme

Fig. 17. Simulation results for an increase in load demand showing the output voltage using the conventional control scheme

- **Decrease in load power:**
  In the study, initially PV panel is operated at constant irradiation of 550W/m², T= 25°C and R= 3.3Ω. At t= 1s, the load demand is suddenly decreased by increasing R to 10Ω. At this instant, the power supplied by the PV module is 390W, but the load demand is 250W. To maintain V_{out} at its reference value, the surplus supply is to be absorbed by the storage system. Fig. 18 shows the waveforms of PV power, output voltage and the load power using the proposed control scheme. Using the conventional control scheme [6], the output voltage waveform obtained for the same conditions is shown in Fig. 19. It is observed that during the transient, the voltage is suddenly increased to 55.9V. It can be seen that the percentage increase in voltage is reduced from 11.8% to 0% using the new method. Unlike the conventional methods, the sudden change in the voltage due to the slow dynamics of the battery is removed by utilizing the battery error current.

Fig. 18. Simulation results for a decrease in load demand showing load power, output voltage and PV power using the proposed control scheme

Fig. 19. Simulation results for a decrease in load demand showing the output voltage using the conventional control scheme
V. CONCLUSION

In this paper, a new control strategy for coordinating the power sharing between battery and SC hybrid system has been established. The proposed method is based on extraction of low frequency and high frequency component of power. It utilizes error current of battery to control the SC unlike the conventional methods. The low frequency power component was managed by battery storage system while the high frequency component along with the error current of the battery was managed by SC. The simulation results show that the proposed method is able to maintain the constant DC output voltage during change in PV generation and load demand. Hence, power balance between the generation and demand is achieved.

REFERENCES


