Photovoltaic storage system enhancement-based supercapacitor control

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ABSTRACT

This paper discusses the improvement of the storage system by getting a stable voltage, with a large inrush current for the battery. The battery system (BESS) is the most important component of a photovoltaic (PV) system. Its large size allows it to provide the desired high peak discharge currents and extend its lifespan. Our work focuses on control the integration of super capacitors (SC) with batteries in order to maximize the battery's power supply, reduce the ripples caused by light changes photovoltaic cells, improve the battery lifespan and supply the useful high peak power for a short periods of time for the big loads (like motors, trains, and big mechanisms,), Super capacitors (SCs) can do that since their internal architecture does not include chemical solutions, which will result in high power densities and higher charge and discharge currents, also lower energy densities. These lower energy densities will be compensated by a combination and integration with the battery, especially the lead-acid battery. Focusing on the lead acid due to drawbacks like short lifetime, low number of cycles. from that combination by switching the control circuit, it can increase the battery lifetime and remove the stress, especially in high current loads, reducing abnormal battery temperature, and ensuring a significant mass reduction of the energy storage system as all. Also, by supporting the SC with a buck boost converter control, keeping the voltage stable, preventing the PV voltage changing problems from the PV cell to any storage systems.

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1. INTRODUCTION

The need for clean, renewable energy alternatives has been much more intense in recent years. As a result, a variety of methods and instruments tailored to harness and store the energy that is all around us have grown rapidly. One such tool is the supercapacitor, which is an electrochemical device that stores electric energy through physical processes like electrostatic fields. It charges quickly and regains its maximum voltage and current in a short amount of time. The construction of the supercapacitor (SC), consists essentially of two electrodes, a positive and a negative one as well as a separator. The main distinction between a regular capacitor and the SC is the electrolytes that are employed and the separator that sits between the two electrodes, which increases the capacitance process more than twice as often as usual. In our example, the significance of the super capacitor is demonstrated experimentally by connecting to storage media, such as batteries, and getting a number of positive good outcomes, including high peak power supply when required, particularly power density. The sun ability to shine through a photovoltaic (PV) cell is not always constant. Energy storage methods enable energy to be stored during sunny weather and released at cloudy or night, it could seem like a straightforward idea, because the sun does not always shine [1], [2].

The lead-acid battery has many disadvantages, lies the disadvantages in limited life time, low efficiency at high peak power, and charging problems like If you want to drain, your battery will take more time to recharge. The last 20% of the battery power can take more than 80% of the total time to charge again. If you plan to charge overnight, this is not a good idea, but if you are in a hurry, this can be a real problem. Also, inefficient energy use. If you want to squeeze every ounce of energy you have got out of your battery, you will be disappointed here as these batteries waste 15% of your total energy. From our information every 100 amps of power, you only store 85 amp-hours [1]–[4].

The faster you use the energy in a lead-acid battery, the less energy you can get out of it, making this battery an overall energy waste and loss at the same time. As shown in Figure 1 show the comparison charge/discharge curve SC with battery, Figure 2 comparison lithium ion battery respect to lead acid we can find a big difference Li-ion battery also have a far superior discharge curve such that the battery voltage falls very little until almost fully discharged, whereas for lead acid batteries, their voltage drops significantly throughout the discharge rate, So Due to the lead acid battery importance and the most common usage this days, and the biggest advantages like low cost with comparison lithium ion battery can be integrated with SC to be get max efficient. Such a big SC characteristics and specifications, like big inrush current make super capacitors especially suitable for the integration in hybrid energy storage systems, *e.g.*, to support with lead acid and Li-ion battery, especially in case of high peak power demands.in Table 1 clear comparison between SC, lead acid battery and lithium ion one, there are difference in parameter variation for each one, the most significant the energy density and efficiency parameter for lead acid, our deal to enhance and try to enhance efficiency, to reach like the lithium ion one, we will concentrate on lead acid battery due to short life time, and lower number of charging/discharging cycles. It is very important to note that the integration of electrochemical capacitors with battery requests an accurate calculation to prevent any problem related to the use of such technology, especially in the photovoltaic (PV) environment, and all other systems will use a storage media at all. We will observe in our work experimentally in this model by MATLAB/Simulink how that combination and the switching on/off integration with SC will support peak power when excess(over) current loads and increase battery life time by reduce the stress caused by distorted charging wave form, and by supporting boost/buck boost converter to keep the voltage stable for battery/SC [5]–[7].

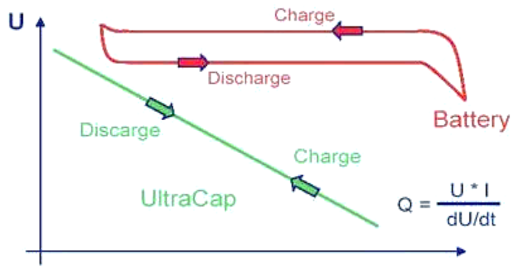


Figure 1. Battery/SC curves [8]

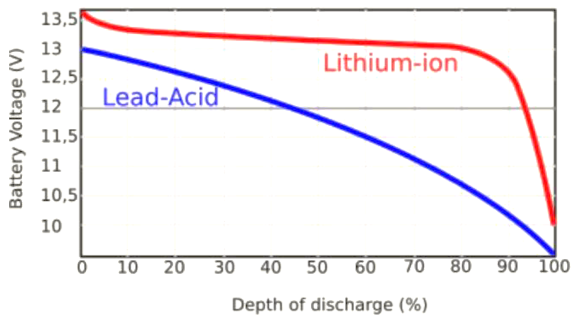


Figure 2. Lithium/Lead-acid comparison [8]

Table 1. Different energy systems comparison [1], [2], [4]

Parameters	Lead-acid	Lithium-ion	Super capacitor (SC)
Energy density (Wh/kg)	10-100	150-200	1-10
Power density (W/kg)	<1000	<2000	<10000
Charge time	1-5 h	0.5-3 h	0.3-30 sec
Discharge time	0.5-2 h	0.3-3h	0.3-30 sec
Charge-discharge efficiency	70-80%	99%	85-99%

Figure 3 shows the PV model with hybrid storage system (HSS) block diagram, which consists of SC with BESS, supported with a boost converter, the function of boost converter to stabilize the voltages across BESS keeping accurate voltage because the daily changes output from the PV cell, also the SC is connected to a buck boost converter. The control switching circuit is connected over the SC terminals to insure fix any unbalanced overload current by switching on/off the battery integration with the SC, the SC works to enhance the BESS O/P and I/P, resulting in smooth charging and stable discharging, especially at high load current. by taking the specification of the SC the result will effect in increasing the battery life time due to unstress when applying big current load, also reduce the temperature of the BSS cells lead to increasing the efficiency, the SC life time will also increase due to in continuous working, all this result will give a positive result to the lead acid battery which is very important related to the another BESS types. In Figure 2 shows the discharge curve discuss the drawbacks of the lead acid battery compared with the lithium ion. It is clear that the difference in state of discharging (SOD), state of charging (SOC), from the curve we can extract the decreasing voltages within depth of discharge with respect to lead acid battery, the integration model shown in Figure 4 by MATLAB, and the flow chart in Figure 5 discuss our work, again our target is to reduce the battery stress, get a stable voltage, remove the ripples, on another hand by avoiding this disadvantages it can be more common used in most application for a long working time [8]–[10].

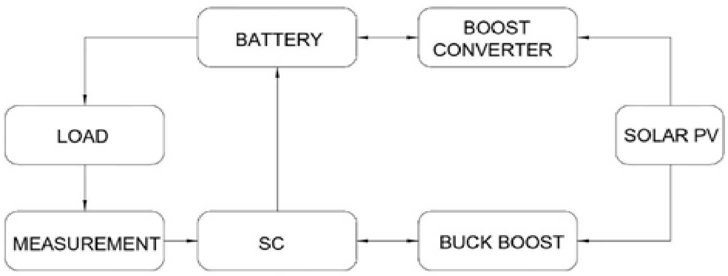


Figure 3. Supercapacitor/battery integration block diagram

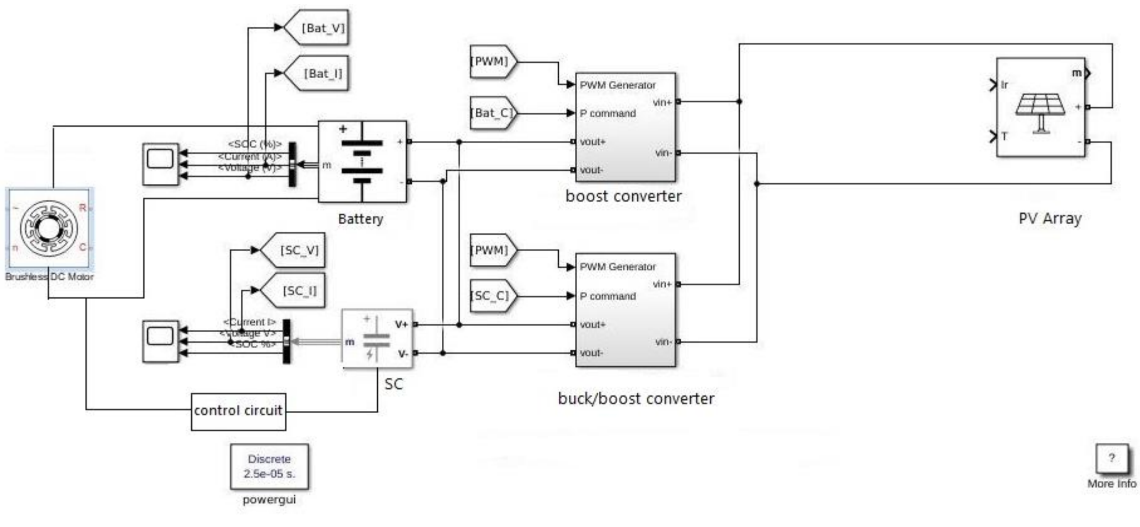


Figure 4. The SC/battery Simulink MATLAB circuit [11]–[15]

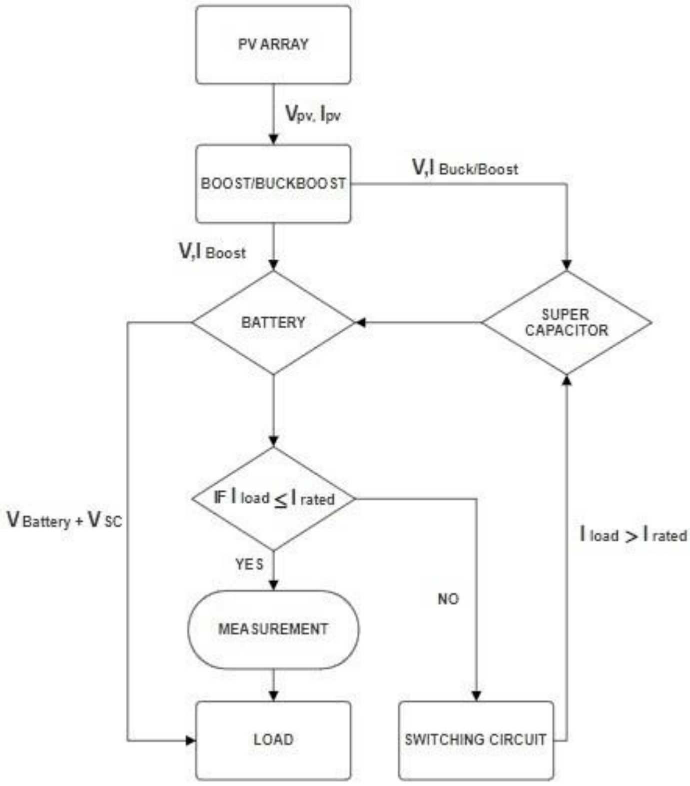


Figure 5. Supercapacitor/battery flow chart [16], [17]

2. METHOD

By taking the main SC advantages and descriptions, the following describe the main equation of the SC and in Figure 3 the enhancement process block diagram consist of PV array, buck boost converter, boost converter, battery, and the most important is the control circuit to make feedback to check the load current and the flow chart in Figure 5 shows the main procedure of the circuit, the Table 2 shows the main model parameters for each component, the PV, battery, SC. Equation (1) discuss the SC voltages as described, also the basic function of the buck boost converter to regulate the voltage for each SC capacitor and the boost converter do the same thing for the battery, buck boost and the boost converter to avoid miss matching between the two voltages and do stabilization for the all model [18].

The supercapacitor equation

$$V_{SC} = \frac{N_S\, Q_T\, d}{N_p\;\, N_e\, \varepsilon\, \varepsilon_0\, A_i} + \frac{2\, N_e\, N_S\, R\, T}{F}\;\, sinh^{-1}\left(\frac{Q_T}{N_p\, N_e^2\, A_i\, \sqrt{8\, R\, T\, \varepsilon\, \varepsilon_0\, C}}\right) - R_{SC} \cdot i_{SC} \quad (1)$$

The equation describes the SC output voltage (V_{SC}) and the role of the SC in stability of the current for a short time, making a sustainable till reaching the threshold SC voltage, the current will trickle down. Where:

$$Qt\ 1 = \int i\, sc\; dt$$

To represent the self-discharge phenomenon, the super capacitor electric charge is modified as follows (when I SC = 0):

$$Qt\ 2 = \int i\;\; dis\; dt.$$ [2]

Table 2. Model parameter [4]

Parameter	Irradiance (W/m²)	Temperature (T)	Voltage (V)	Nominal current (I)	Capacity F	Discharge current (A)
PV array	1000	25	42	7.35	---	---
Supercapacitor	Null	25	16	10	500 F	50
Battery	Null	25=33	26.4	2.5	6.6 Ah	6.5, 13, 32

2.1. Model explanation

The following block diagram for our model and the buck-boost converter, as shown in Figure 3, the regulator circuit, and switching regulators (measurement block) offers three big advantages compared to linear regulators. First, one switching efficiency can be much better. Second, because less energy is lost in the transfer, smaller components and low thermal management are required. Third, the energy stored by an inductor in a switching regulator can be transformed to output voltages that can be greater than the input (boost), negative (inverter), or can even be transferred through a transformer to provide electrical isolation with respect to the input. The parameters used in this integration model are summarized in Table 3 (Integration model parameters). The control switch (measurement block) with the MOSFET can control the SC entrance for a certain time on/off, and in Figure 4, more details are modeled by MATLAB.

Table 3. Integration model parameters

Parameters	Boost converter	Buck boost converter	Motor(load)
Input voltage (Vin)	5:40	5:40	26 v
Output voltage (Vout)	26	16	-
Inductor L (mH)	1e-3	1e-3	0.00022
Resistance Rout Ohms	0.1	0.1	0.013
Capacitance C	250e-9	250e-9	
Initial current	8.17	14.7	12,14,15

The SC entrance time for battery supporting determined and controlled by the switching circuit, by condition when sense by the load current, since the load current greater than the rated battery so the control circuit will open to connect the SC with the battery for enhancement and support the battery, otherwise the SC is off [11], [12].

The total circuit power

$$P_L = P_B \pm P_{sc} \quad (2)$$

$$P_{sc} = 1/2\, C_{SC} V^2, \quad (3)$$

When

$$P_L = P_B - P_{sc} \quad (4)$$

When $IF\ i\ load\ > irated$

$$P_L = P_B + P_{sc} \quad (5)$$

Where P_L is the total load power, P_{sc} the super capacitor power when switched on, P_B the battery power (4) represent the total power when the load is stable and no over load current, equation (5) when the load gets irritable and withdrawn current exceed the rated battery value so due to the SC entrance will reduce the battery over current, so the battery along time will not stressed and the temperature will not increase as shown in (6) which represent the inversely proportional [19]–[25].

$$P_L = P_B + P_{sc}\, 1/\propto TB \quad (6)$$

$$TB\ 1/\propto\ Lifetime\ battery$$

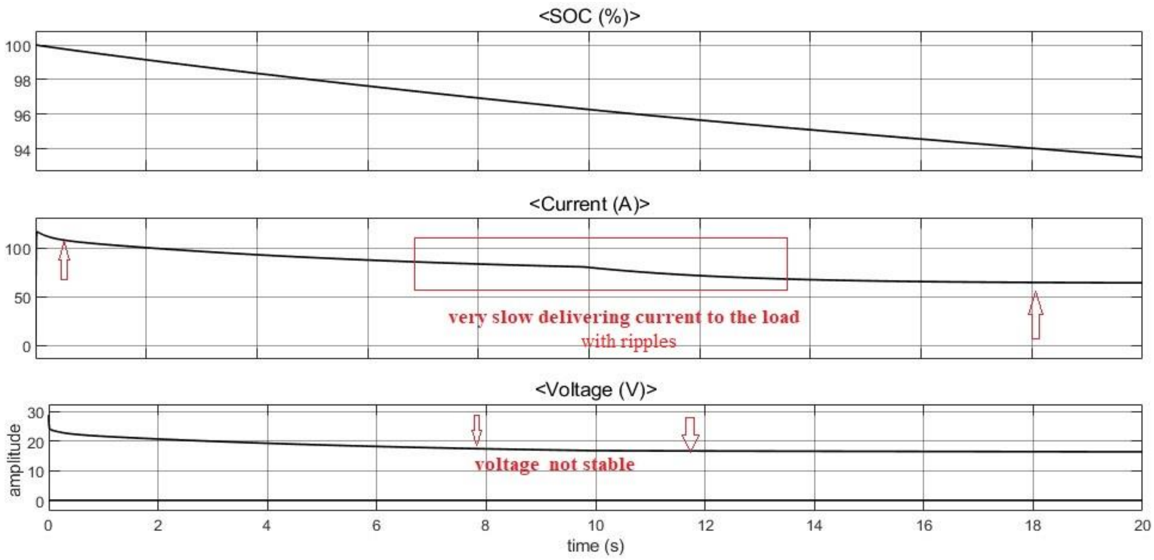
where TB is the battery temperature

2.2. Related work

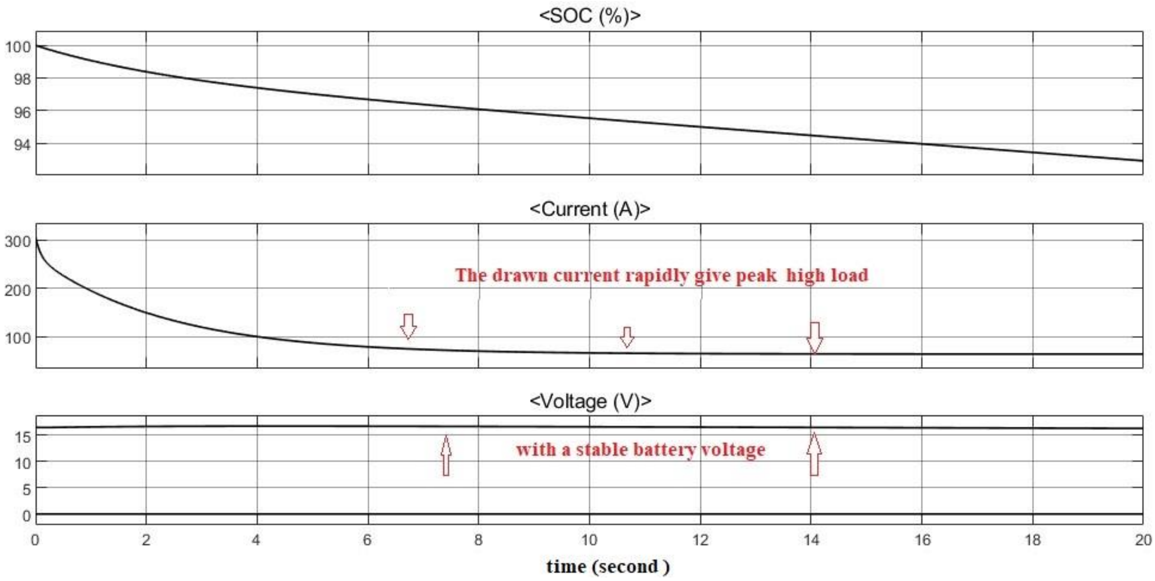
No more related work in IJECE. There are related works with different goals, in different journals, such as in the analysis of the SC renewable system to managing fluctuation system [4]. A hybrid battery/ultra capacitor energy storage solution for PV systems, conference [10], super capacitor in energy conversion, conference [12], only in IJECE management fuzzy logic power management for a PV/wind micro grid with backup and storage systems [19], Also hybrid energy storage system for life cycle improvement [26], optimized supercapacitor energy storage system (SCESS) [27], also [28]. [29], [30] our work is different and new in how to control in the SC to save the BESS.

3. RESULTS AND DISCUSSION

An output without SC integration shows clear fluctuation on the battery current and voltage as shown in Figure 6(a) and after the system going up by the SC the output will be more stable as shown in Figure 6(b). Current and voltage respectively shows a clear smooth in charging and discharging, the current curve can start give high load current from 300 A and capable to deliver to less than 100 A and go down to 50 A in 20 second to be stable to the rated load current while without SC, max will deliver load current 150 A and the not stability V, I with using the SC the more stable V, I.



(a)



(b)

Figure 6. Voltage stability waveform (a) o/p without SC – (b) o/p with SC

As shown in Figure 6 and Table 4, we found an improvement in charging discharging curve also the SC life time will be more than 1000000 cycle that mean will be doubled due to switching control circuit which help to switching on and off when any increasing big load current. The regulator circuits like boost converter is to keep balancing the voltages on the battery stable while changing PV irradiance to avoid any fluctuation coming from changing the sun light, also the buck boost converter to keep the SC in stable voltage and separated from the battery boost converter However, when a sudden change occurs, a vast dip in fluctuation is noted. The integration of the super capacitoris introduced to manage the dip and oscillation, as shown in Figure 6. Noted in Table 4, the max current with SC, the max efficiency the max approx. Life time for battery when connected SC and without as noted.

Table 4. Output results with/without SC

Parameters	Battery with SC	Battery without SC	(SC)
Voltage variations	~17,7 v	25-17.5 v	16- 15,4 v
Current (A)	75-300	75-150	> 200 A
Life time approx.	≈> 75%	≈< 70%	≈> 10000000
Charge-discharge efficiency	≈80-90%	≈70-80 %	85-99%

4. CONCLUSION

Our contribution in this paper is to enhance the battery storage, the SC role in our integration model is to enhance the battery efficiency by reducing the battery stress due to the big drawn current from any big load so the battery temperature will be very low and this will increase the battery cells life time, will improve the all PV system and the most expensive part inside the photovoltaic systems by taking the benefit of the SC, for any storage system will save more inrush current specially at starting big load like motors, heaters, trucks and so on, The advantages of the presented methodology are effective power sharing, rapid charge, and ripple limitations. MATLAB-Simulink-based simulation results have shown the validity of the proposed system, and like the used model will be effective in most high-inrush big load, keeping the battery in good case, the paper will add to the scientists and to the researchers how to use the integration with high capacity SC to enhance and improve the battery storage system, future work and we can use this integration in the future work with electric vehicles for more research.

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AUTHOR CONTRIBUTIONS STATEMENT

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Ashraf Naser Eldeen	✓		✓			✓		✓			✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are openly available at any time when you contact me, the corresponding Author, and do not hesitate to ask by email, *ahmed_seleman20@yahoo.com,* and also will be available on Google Scholar ID for the corresponding author or *ORCID.com* for all authors directly after publication.

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