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Charge-discharge behaviour of lead acid battery and lead carbon hybrid ultra-capacitors as anintegrated system for solar power applications

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The paper discussess ome of the practical issues on direct parallel integration of lead acid battery and lead carbon hybrid ultra-capacitor to form an integrated energy storage system for solar power applications. The integrated energy storage system is subjected to various C rates to analyze the behavior of charging and discharging of HUC. The percentage contribution of HUC, in charging and discharging of the integrated energy storage system would be a useful information, while coupling battery and HUC in solar power applications. In view of this, experimental studies have been carried out at different C rates and results are presented.

Keywords: *Pb - C HUC/HUC - Lead carbon Hybrid Ultra-capacitor, C rates, an integrated energy storage system.*

1.0 INTRODUCTION

In 21st century, energy is a vital requirements of human being. Burning of fossil fuels for energy generation causes a serious damage to eco system by disturbing the carbon levels in the atmosphere[1]. For preserving the natural resources, alternative/ renewable sources of energy are being explored. Renewable energy sources such as solar, wind, biomass etc, would produce clean, efficient and reliable energy. In order to get continuous electric energy from renewable sources, it is essential to integrate renewable sources of energy with main grid. Renewable sources of energy cannot be directly coupled to main grid due to intermittencies of solar energy availability from dawn to dusk, discontinuous wind power due to turbulences, etc[2]. Due to these intermittencies there is a need for energy storage in renewable energy storage systems[3]. In the present study, some of the practical issues of lead acid battery and lead carbon hybrid ultra-capacitors for solar power applications have been studied, with reference to charge discharge behavior.

2.0 STUDIES ON LEAD ACID BATTERY, LEAD CARBON HYBRID ULTRA CAPACITOR AND NECESSITY TO INTEGRATE

2.1 Lead acid battery

Lead acid batteries from its invention, had been a default energy storage system in industrial, domestic, commercial, transport, automation, and solar power applications. Lead acid batteries have an advantage of 99.9% recyclability, high energy density, safety of operation and maintenance free[4]. They suffer from some of the disadvantages as low cycle life, unable to charge on cloudy days due to mass transfer phenomenon, longer charging times, and sulphation[5].

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2.2 Lead carbon hybrid ultra-capacitors

Lead carbon hybrid ultra-capacitors (Pb – C HUCs) are asymmetric ultra-capacitors, with hybrid asymmetric characteristics. These are the next generation energy storage devices with matured technology of lead acid battery involved in them. These capacitors have two current collecting terminal electrodes. Positive electrode is lead oxide electrode similar to that of lead acid battery and the negative electrode is activated carbon coated graphite electrode. Unlike electrostatic and electrolytic capacitors, where dielectric is the medium of charge transfer, hybrid ultra-capacitor (HUC) is an electrochemical capacitor with electrolyte as the medium of charge transfer. Here energy is stored in the form of electric double layer capacitance at graphite electrode electrolyte interface and in form of pseudo capacitance at lead oxide electrode of the HUC [6]. Mathematical equation governing the capacitance for electrostatic capacitor is equally applicable for HUC also. It is represented in eqn (1).

$$C = \frac{\varepsilon A}{d} \quad ...(1)$$

Interface 'd' is very thin in dimension of armstrong and 'A', area of interface is very large. Hence, the capacitance, 'C', offered by HUC is in kilo farads.

Pb - C HUCs have the advantage of 95% recyclability, long cycle life, fast charging on cloudy days also, due to absence of mass transfer. Higher cell voltage than zinc, manganese or nickel HUCs [7]. Pb – C HUCs are considered for the present study. So HUCs and Pb-HUCs are considered as synonyms.

2.3 Necessity to couple Pb – C HUCs with Pb acid batteries

HUCs along with the advantages explained in section 2.2, experience some of the disadvantages as:

- Low capacity.
- Linear discharge voltage characteristic preventing the use of all the available energy in some applications, and need a special discharge circuit.
- Power is available only for short duration.
- High self-discharge rate (much higher than batteries).

As the HUCs are of high columbic efficiency, fast charge capability and high cycle life, these can be used as main energy storage in solar power applications, but since the HUCs have low capacity and high self-discharge rates, the autonomy of electric supply can be provided by lead acid battery. Hence, in order to get a continuity of electric supply, integration of battery with HUC will be one of the suitable options of energy storage system in solar power applications.

2.4 Choice of HUC and battery for coupling

Connecting batteries of equal power density in parallel will add up the charge capacities of the integrated battery storage system. If current of X amps, charges two batteries of equal power density 40AH and 40AH each, there will be a current sharing of X/2 amps in each during charging and discharging. Conventional lead acid battery systems are charged discharged at C rates of C/10 and C/5. HUC has the advantage of getting charge at higher C rates up to 5C.

Power density of HUC is 10 times more than lead acid batteries, i.e., HUC can be safely charged at C rate, whereas battery at C/10 rate ~~in~~for solar power applications.

To charge HUC and battery with equal currents in an integrated system, AH capacities of HUC and battery are chosen in a ratio of 1:10.

Behavior of HUC is analyzed at various C rates in the integrated system by undertaking the studies on direct coupling of battery on HUC with charge AH ratios of 10:1.

3.0 EXPERIMENTAL

A lead acid battery of 12 V/40 AH capacity of M/s. Amaron make and a lead carbon HUC of 12 V/2500 F range of M/s Mesha Energy Solutions Ltd, Bangalore are considered for the study. Specifications of energy devices used in the study are summarized in table I.

TABLE 1
DETAILS OF BATTERY AND HUC SELECTED FOR THE STUDY

Sl. No	Parameter	Lead acid battery	Lead carbon HUC
01	Voltage	12V	12V
02	AH rating	40 AH	4 AH
03	Weight	40 kg	10 kg
04	V_{max}	14.4 V	13.8 V
05	V_{min}	10.8 V	4.62 V

The selected battery and HUC are characterized for their capacities and found to deliver charge outputs of 40 AH and 4 AH respectively for their respective standard test protocols.

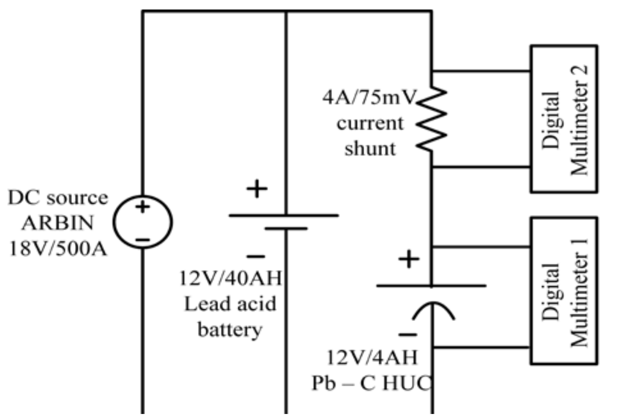

FIG. 1. SCHEMATIC DIAGRAM OF INTEGRATED ENERGY STORAGE SYSTEM

Charge capacity of battery and HUC are in the ratio of 10:1. Battery and HUC open circuit potentials are checked, and when both the voltages match, battery and HUC are directly coupled to each other in parallel through a shunt of 20A/75mV as shown in Figure 1. Two 4½ digit multimeters are used for HUC voltage & current measurements. One is connected across HUC to record voltage and other is connected across current shunt to measure HUC current.

Battery voltage and current are recorded in ARBIN instrument. ARBIN is the energy source that provide charging and discharging currents and voltages to the combination of battery and HUC. The experimental setup made at laboratory is shown in Figure 2. The digital multimeters (DMM) are connected to computer to record the voltage and current values.

FIG. 2. EXPERIMENTAL SETUP OF INTEGRATED ENERGY STORAGE SYSTEM IN LABORATORY

3.1 The Choice of C rates

Coupling a battery of 40AH in parallel with HUC of 4AH, charge capability of an integrated system would be 44AH. When lead acid battery and HUC are directly coupled, the possible C rates of charge discharge can be considered such that the battery life is not affected. In reference to the life expectancy, safe operation of battery and for understanding the behavior of HUC in the integrated system, three C rates are considered in the study. The three C rates are 'C/10', 'C/5' and '3C/10'.

3.2 Test procedure to charge discharge the integrated energy storage system

After combining HUC and battery in parallel, the open circuit potential (OCP) of the combination is measured. The integrated system is charged/ discharged at different C-rates to analyze the behavior of HUC in the system.

The following program is written in DC source, ARBIN, to charge and discharge the integrated system:

Step 1: Rest the system for 05 min.

Step 2: Charge the system with I_c till 13.8V

Step 3: Charge the system with constant voltage of 13.8V for 3 hours.

Step 4: Rest the system for 05 min.

Step 5: Discharge the system with I_{dis} till 10.8V. The procedure was repeated for three selected "C – rates" of I_c/I_{dis}, and the results are explained in the section of results and discussion.

4.0 RESULTS AND DISCUSSION

In this section, the behavior of battery, HUC, and percentage of HUC charging and discharging in integrated energy storage system for the three selected C rates (refer to 3.1) is discussed in three different sub sections as follows.

The three C-rates considered for studies are

(i) I_c/I_{dis} = C/10 = 40AH/10 = 4A,

(ii) I_c/I_{dis} = C/5 = 40AH/5H = 8A, and

(iii) I_c/I_{dis} = 3C/10 = 40AH/3.33H = 12A.

On applying these currents to integrated system one of the three behaviors may be expected.

1. Current can be equally or partially divided across the two energy storage devices.
2. If battery offered higher impedance in the integration, HUC can safely take currents of 4A to 12A.
3. If HUC offers higher impedance, battery can safely take currents from 4A to 12A.

Hence the three C rates considered for studying the dynamics of integrated system are 4A, 8A and 12A.

4.1 Performance analysis from charging and discharging integrated system at C rate of 4A

At C rate of 4A, the integrated system of battery and HUC is charged discharged at constant current of 4A. The V-I characteristics of battery and HUC are individually plotted as Figure 3(a) and Figure 3(b), respectively. From Figure 3(a), it can be seen that the amount of current taken by battery to charge to 13.8V is almost 4A. From Figure 3(b), the amount of current taken by HUC to charge to 13.8V is nearly 0.125A. Due to parallel connection, battery forces the HUC voltage to reach 13.8V. The amount of ampere hour charge taken by HUC during charging and discharging can be analyzed from Figure 4.

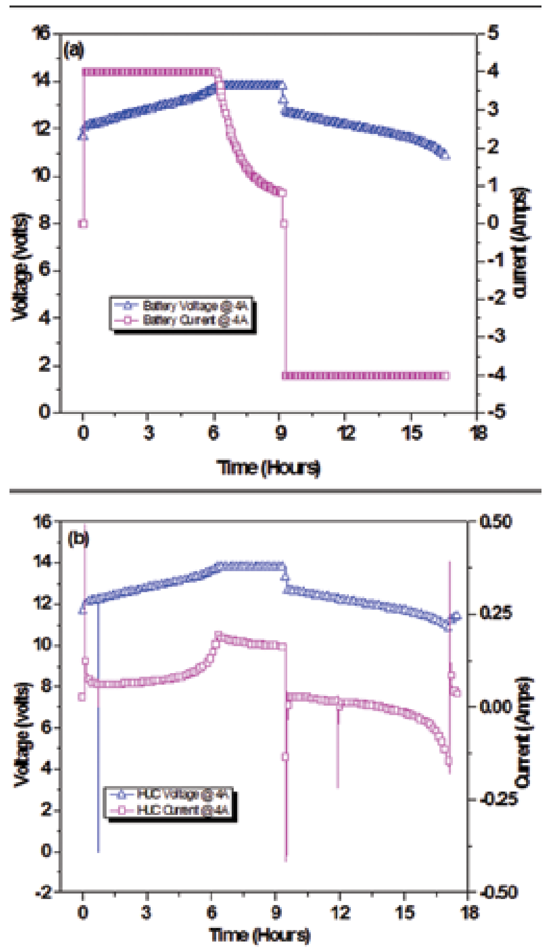

FIG. 3: BEHAVIOR OF BATTERY AND HUC WHEN INTEGRATED SYSTEM IS CHARGED AT 4A. 3(A) BATTERY,3(B) HUC

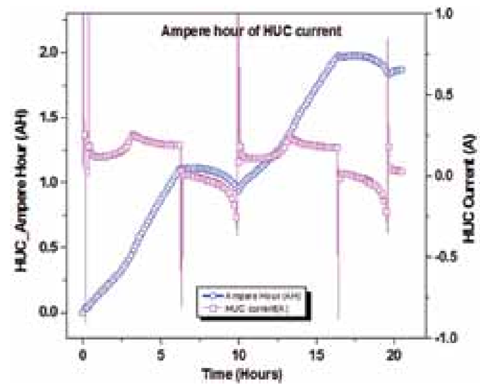

FIG. 4. HUC AH AND CURRENT WITH RESPECT TO TIME FOR 4A C.

The observation is, during charging at 4A C rate, HUC is able to store charge AH of 1.12 AH compared to its rated AH of 4AH, and battery is able to store charge AH of 28.63 AH compared to its rated AH of 40AH. Similarly, during discharging from 4A C rate, HUC is able to discharge AH of 0.12 AH, whereas battery is able to discharge 27.44 AH. The percentage contribution of HUC in charging and discharging can be seen as 3.84 and 0.42 respectively.

4.2 Performance analysis from charging and discharging integrated system at C rate of 8A

At C rate of 8 A, the integrated system of battery and HUC is charged discharged at constant current of 8 A.

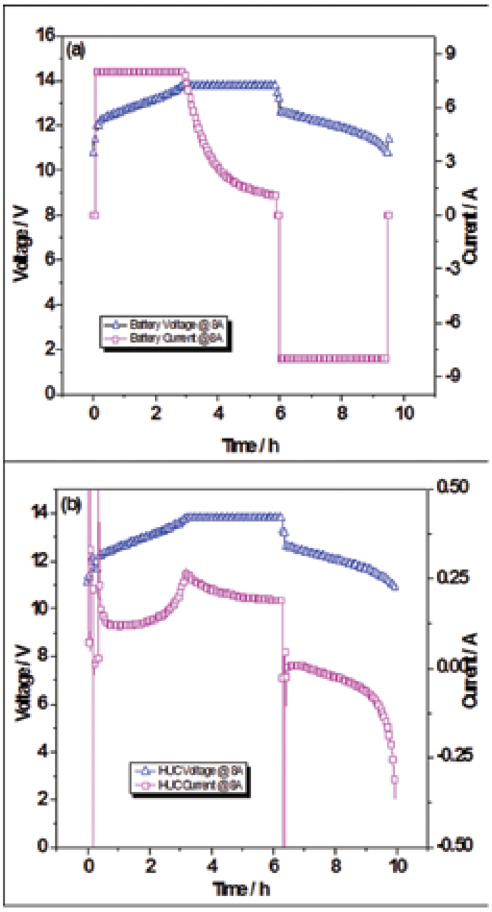

FIG. 5: BEHAVIOR OF BATTERY AND HUC WHEN INTEGRATED SYSTEM IS CHARGED AT 8A. 5(A) BATTERY, 5(B) HUC

In Figure 5, the V-I characteristics of battery and HUC are individually plotted as Figure 5(a) and Figure 5(b) respectively for charge discharge rate of 8A. From Figure 5(a), the amount of current taken by battery to charge to 13.8V is almost 8 A. From Figure 5(b), the amount of current taken by HUC to charge it to 13.8V is nearly 0.225 A.

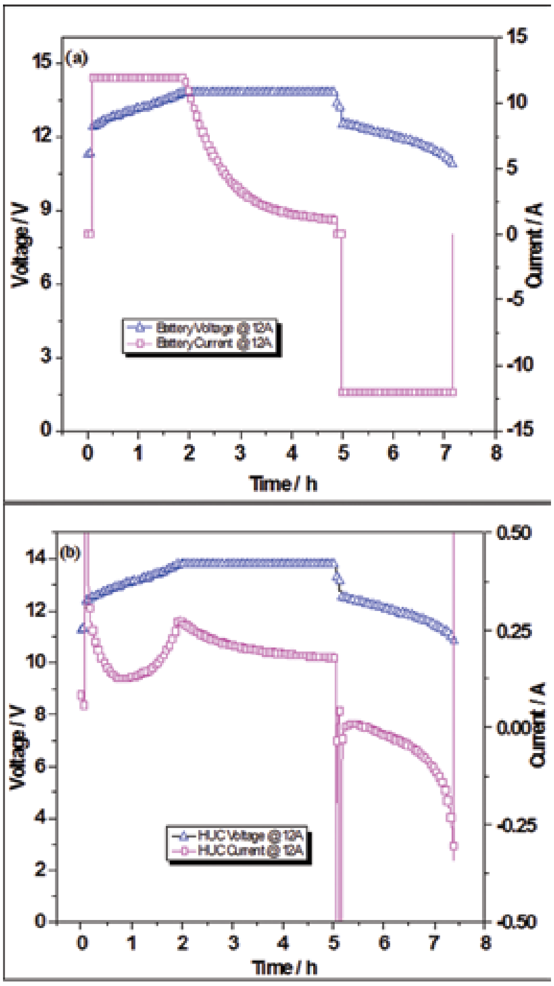

FIG. 6: BEHAVIOR OF BATTERY AND HUC WHEN INTEGRATED SYSTEM IS CHARGED AT 12A. 6(A) BATTERY, 6(B) HUC

HUC and battery are able to store charge AH of 1.1 AH, and 28.57 AH, respectively. Similarly, during discharging from 8 A C rate, HUC is able to discharge AH of 0.18 AH, whereas battery is able to discharge 27.35 AH. The percentage contribution of HUC in charging and discharging can be seen as 3.73 and 0.66 respectively.

4.3 Performance analysis from charging and discharging integrated system at C rate of 12A

At C rate of 12 A, the integrated system of battery and HUC is charged discharged at constant current of 12A. In Figure 6, the V-I characteristics of battery and HUC are individually plotted as Figure 6(a) and Figure 6(b) respectively for charge discharge rate of 12A. From Figure 6(a), the amount of current taken by battery to charge to 13.8 V is almost 12 A. From Figure 5(b), the amount of current taken by HUC to charge it to 13.8 V is nearly 0.23 A. HUC and battery are able to store charge AH of 0.98 AH, and 31.54 AH respectively. Similarly, during discharging from 8A C rate, HUC is able to discharge AH of 0.12 AH, whereas battery is able to discharge 26.17 AH. The percentage contribution of HUC in charging and discharging can be seen as 3.01 and 0.47 respectively.

Table 2

PERCENTAGE OF AH CONTRIBUTED BY HUC DURING CHARGING AND DISCHARGING A PARALLEL COMBINATION OF BATTERY AND HUC OF 10:1 CAPACITIES

C-RATE	OVERALL CHARGE AH ($X = X_{HUC} + X_{BATT}$)	OVERALL DISCHARGE AH ($Y = Y_{HUC} + Y_{BATT}$)	HUC CHARGE AH (X_{HUC})	HUC DISCHARGE AH (Y_{HUC})	BATTERY CHARGE AH (X_{BATT})	BATTERY DISCHARGE AH (Y_{BATT})	% HUC CONTRIBUTION	
							CHARGE AH (X_{HUC}/X)	DISCHARGE AH (Y_{HUC}/Y)
0.1C	29.76121	27.56732	1.124592	0.124264	28.63662	27.44306	3.8433%	0.4203%
0.2C	29.68523	27.53949	1.109814	0.182358	28.57542	27.35713	3.7386%	0.6622%
0.3C	32.52385	26.29837	0.981134	0.124212	31.54272	26.17416	3.0167%	0.4723%

From results, shown in Figure 3, 5, 6 and Table II, it can be analyzed that the current given to charge the integrated system, is completely charging battery alone. Besides, the absence of mass transport and acceptability of higher currents, HUC will not get charged and discharged, when it is combined in parallel with battery of 1:10 capacity. The experiment is performed for 3 C rates, to verify variations in charge acceptability of HUC at higher or lower currents.

During the experiments by connecting HUC and battery in parallel at equal OCP, no thermal runaway condition was experienced.

As the contribution of HUC in charge/discharge is almost negligible, it was found that a power conditioner between HUC and battery would improve the impact of HUC for using HUC as an energy storage system in parallel with battery.

5.0 CONCLUSION AND SCOPE OF FUTURE WORK

1. Lead acid battery and lead carbon hybrid ultracapacitor of 10:1 AH ratio (battery AH: HUC AH) can be connected in parallel at equal OCPs.
2. Connecting HUC and battery in parallel at equal OCP will not lead to thermal runaway conditions.
3. Charging and discharging the HUC - battery combination will charge/discharge battery alone.
4. Contribution of HUC in charge/discharge is almost negligible and hence for using HUC as an energy storage system, a power conditioner between HUC and battery would improve the impact of HUC.

Combining HUC and battery through proper power conditioner adaptable to voltage discharge curves of HUC and battery combination is the scope for future work.

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