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# Evaluating the Performance of Hybrid Ultra Capacitor (HUC) in a 1.5kw Solar Powered Microgrid with Hybrid Energy Storage System (HESS)

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## Abstract

Batteries used in conventional solar micro grid applications for energy storage, experiences several micro cycles and deep discharges which have an adverse impact on the overall life of the battery. To handle such fluctuations, the batteries are being oversized. One solution to the above problem is usage of Hybrid Energy Storage System (HESS) comprising of Hybrid Ultra Capacitors (HUC) and Batteries wherein the HUCs' will smoothen the battery current during surges, in turn aids in enhancing the battery's life[1–3]. This paper discusses the performance analysis of 1.5kW micro grid based on HESS by evaluating the electrical parameters across different scenarios.

**Keywords:** Electric Vehicles, Hybrid Ultra Capacitors, Power Batteries, Solar Micro-grid

## 1. Introduction

Solar based micro grid is gaining prominence in energy sector owing to the supply and environmental challenges faced by the conventional energy sources. Green buildings have become a key focus in harnessing solar power. Since the availability of solar energy is limited by time and its intensity is further dependent on several factors battery back-up is essential for seamless delivery of power. Traditionally lead acid based batteries are used for such solar based micro grids applications catering to residential and commercial buildings. In solar based applications, Batteries experience several micro cycles owing to fluctuations in PV and load. These micro cycles accelerate the ageing of batteries as observed by a gradual increase in ESR and a sudden fall in its capacity[4,5]. To overcome this problem Ultra Capacitors are used in parallel with batteries to smoothen the battery current. Batteries are energy density devices and are good at delivering steady load, whereas Ultra Capacitors are power density devices and are good at delivering sudden surge loads[3,4]. Energy Management System (EMS) is incorporated to manage the discharge from HUC and Battery by sensing the load requirements. In this study 1.5kW base residential load is considered and the same is catered by Solar powered micro-grid system with batteries and HUC based HESS and the performance of HESS in handling surge power demands is analysed.

## 2. Literature Review

Capacitors are usually classified as Electrostatic, Electrolytic and Electrochemical capacitors. The former two types are limited to the range of micro farad to few milli farads. Electrochemical capacitors use an electrolyte instead of a separate dielectric akin to the battery. However unlike batteries in Electrochemical capacitors the charges are stored on the interfacial surface between the electrode and the electrolyte, and they are in the order of few hundred Farad to few Kilo Farad[6–8]. There are three types of Electrochemical capacitors viz., Double layer Capacitors, Pseudo capacitors, Hybrid capacitors. EDLCs are constructed using two carbon-based materials as electrodes, an electrolyte and a separator. EDLCs can either store charge electrostatically i.e. anon-faradic process, which involves no transfer of charge between electrode and the electrolyte. Materials used in EDLC could be activated carbons, Carbon Nanotubes, Carbon Aerogels etc. Pseudo capacitors store charge via faradic process, it involves charge transfer between electrode and electrolyte. This helps pseudo capacitors to achieve higher specific

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capacitance and energy densities compared to EDLCs. In Pseudo capacitors, electrodes are made of either metal oxides or conducting polymers. Both EDLC and Pseudo capacitors offers diverse advantages, the former offers better cyclic stability, high power performance while the later offers higher specific capacitance. Hybrid Capacitors are designed to leverage the advantages of both, by having positive electrode as battery-like electrode and negative electrode as EDLC type[9,10]. In this work, Hybrid Ultra Capacitors based on Asymmetric electrode with aqueous electrolyte is studied.

# 3. Methodology

## 3.1 Experimental Setup

The experimental setup consists of 3kW solar micro grid (PV Array, Inverter and accessories), 48V/600Ah Lead-Acid Battery Bank, 48V/625F HUC Bank, Energy Management System (EMS), AC loads and Data logger. The system capacity was chosen twice that of load just as a safety factor against the transient surges simulated in the experiment. In this study 8 HUCs' were used (4 in series and 2 strings in parallel). The rating of HUC units used in this study is 12V, 1250F, Electrodes- $PbO_2$ (+) and Activated Carbon (-), Gel Electrolyte (aq.$H_2SO_4$). The load profile used for the experiment includes a constant 1.5kW lighting load (base load) and 1hp motor to simulate surge conditions. A timer circuit was used to switch on the motor for 2 seconds. System architecture is depicted in Figure 1. The V.I.P.E(Voltage, Current, Power, Energy) parameters were monitored using data logger at the output terminals of PV array, Battery bank, HUC bank and the AC Load.

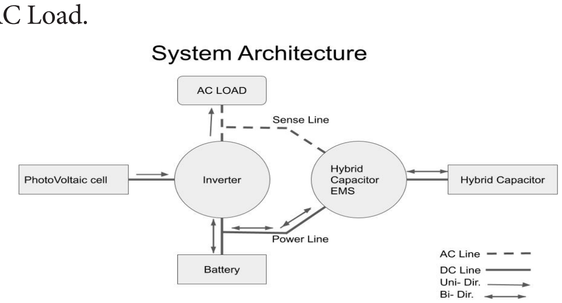


**Figure 1.** System Architecture.

## 3.2 Scenarios Studied

Four experimental scenarios were studied with ON/OFF conditions of PV output and HUC Banks for the same load profile as depicted in Table 1.

**Table 1.** Experimental Scenarios Studied

| Scenario | PV | Battery | HUC | Load |
|---|---|---|---|---|
| A | OFF | ON | OFF | ON |
| B | OFF | ON | ON | ON |
| C | ON | ON | ON | ON |
| D | ON | ON | OFF | ON |

This paper presents the analysis of V.I.P.E parameters monitored at the output terminals of system components for the above mentioned scenarios.

## 3.3 Load Profile

The load profile used for study is depicted in Figure 2. The load lasts for 5 seconds in which the 1hp motor was ON for 2 seconds. The load profile in Figure 2 is chosen so as to analyse the performance of HESS in handling surge power demands. Analysis of the system performance was studied under three sections.

1. Section A - Entire load profile of 5s duration
2. Section B –Transient Portion (2s duration) of load profile during which base load and surge load was ON
3. Section C - Sub-transient state condition (73ms duration) in which the load current oscillated before stabilizing

The load profile has been generated with same sequence of switching operation of lighting loads for all the 4 scenarios studied.

# 4. Experimental Results and Analysis

## 4.1 Analysis of Entire Load Profile (Section A)

A snapshot of the waveforms captured during the experiment are depicted in Figures 3,4,5 and 6. Each of those four figures represent one of the 4 scenarios studied. In each figure the voltage and current waveforms of PV, Battery, HUC and Load are depicted as applicable to the respective secnarios. The data mentioned in the Tables 2,3,4 have been drawn from detailed analysis of these figures. However to avoid redundancy, waveforms studied for analysis of power, energy, performance during transient and sub-transient period are not depicted in this paper, since the analysis and the conclusions can be inferred from the Per Unit (P.U) values mentioned in the Tables 2,3,4.

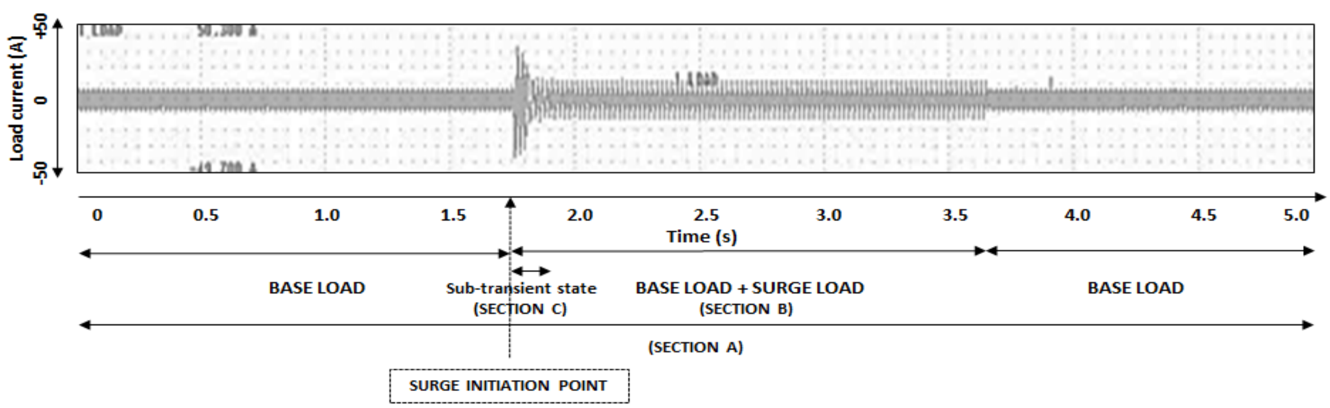


**Figure 2.** Load Profile.

**Table 2.** Analysis of entire load profile (Section A)

| Parameters and Base Value | Scenario | Per Unit (P.U). Values | | | |
|---|---|---|---|---|---|
| | | PV | Bt. | HUC | Load |
| Analysis of entire load profile | | | | | |
| **Voltage**<br>Solar = 66.91V Avg.<br>Battery = 50.54V Avg.<br>HUC = 46.05V Avg.<br>Load = 229.85V RMS | A | - | 1.00 | - | 1.00 |
| | B | - | 1.00 | 1.00 | 1.00 |
| | C | 1.00 | 1.06 | 1.03 | 1.00 |
| | D | 0.99 | 1.06 | - | 1.00 |
| **Current**<br>Solar = 23.92A Avg.<br>Battery = 32.48A Avg.<br>HUC = 4.17A Avg.<br>Load = 6.39A RMS | A | - | 1.00 | - | 1.00 |
| | B | - | 0.91 | 1.00 | 0.96 |
| | C | 1.00 | -0.00 | 1.59 | 1.19 |
| | D | 1.04 | -0.00 | - | 1.15 |
| **Average Power**<br>Solar = 1599.5W Source<br>Battery = 1632.2W Source<br>HUC = 86.825W Source<br>Load = -1337.8W Sink | A | - | 1.00 | - | -1.00 |
| | B | - | 0.90 | 1.00 | -0.95 |
| | C | 1.00 | -0.00 | 2.61 | -1.16 |
| | D | 1.03 | -0.01 | - | -1.13 |
| **Energy**<br>Solar = 7999.3Ws Source<br>Battery = 8167.5Ws Source<br>HUC = 1228.5Ws Source<br>Load = -6711.5Ws Sink | A | - | 1.00 | - | -1.00 |
| | B | - | 0.91 | 1.00 | -0.95 |
| | C | 1.00 | -0.18 | 1.23 | -1.16 |
| | D | 1.03 | -0.16 | - | -1.13 |

The following observations were made from Table 2:

*Load parameters:* Use of HUC along with battery in the system has not lead to any noticeable fluctuations in the load voltage as seen from the same P.U values of the load voltage RMS.

Despite same switching sequence was followed for lighting loads, the current values, average power and Energy for Scenario C and Scenario D are higher compared to the Scenario A and Scenario B suggesting that presence of solar might aid in quick deliverance of power during surges. Hence it may be a good case to study whether solar based system are morecapable in handling surge loads compared to a non-solar based system.

*Battery parameters:* The Initial battery voltage is higher for Scenario C and Scenario D compared to the Scenario A and Scenario B suggesting higher Initial State of Charge (S.O.C) for battery owing to the presence of Solar. So if we hypothesize that solar based system has extra capability to handle surges it is a good case to study whether that extra capability is due to higher initial S.O.C of battery or is it due to quick deliverance of surge power from the solar panels.

The current values, average power and Energy for Scenario C and Scenario D indicate that battery has overall acted as a sink rather than as a source i.e. in presence of solar, battery has been charging during the experiment because the solar potential was almost twice higher than the average load. Hence the study concludes in favour of the hypothesis that extra capability to deliver surges is due to the quick deliverance of surge power from the solar panels instead of higher initial S.O.C of battery in this case.

In order to obtain accurate measurements of S.O.C, lead-acid battery manufacturers recommend an Open Circuit rest period of 24 hours[11]. Since such measurements are impractical during active duty, in this study the terminal voltage of Battery and HUC are taken as an indicator for the unit's S.O.C.

*HUC parameters:* The Initial HUC voltage is higher for Scenario C compared to the Scenario B suggesting higher Initial State of Charge (S.O.C) for HUC owing to the presence of Solar.

The current values, average power and Energy for Scenario C are higher compared to the Scenario B suggesting that performance of HUC has been aided by the presence of solar with respect to deliverance of power during surges.

It is also observed from the average power and Energy values of Scenario C that the presence of solar has aided the power output of HUC significantly higher than the energy output of HUC, whereas upon comparison of the average power and Energy values of Battery in Scenario C, it is seen that the presence of Solar has aided the energy deliverance (in this case consumption) capacity of battery rather than the power deliverance ability.

*Solar parameters:* The current values, average power and Energy for Scenario D are higher compared to the Scenario C suggesting that in absence of HUC, the Solar has to accommodate major portion of the surge load. This indicates the effectiveness of HUC in a solar based system.

## 4.2 Analysis of Transient Part of the Load Profile (Section B)

**Table 3.** Analysis of Transient part of the load profile (Section B)

| Parameters and Base Value | Scenario | Per Unit (P.U). Values | | | |
|---|---|---|---|---|---|
| | | PV | Bt. | HUC | Load |
| Analysis of Transient part of the load profile | | | | | |
| **Average Power**<br>Solar = 1588W Source<br>Battery = 1961W Source<br>HUC = 614W Source<br>Load = -1611.4W Sink | A | - | 1.00 | - | -1.00 |
| | B | - | 0.66 | 1.00 | -0.94 |
| | C | 1.00 | -0.07 | 1.08 | -1.13 |
| | D | 1.06 | 0.18 | - | -1.16 |
| **Energy**<br>Solar = 3450Ws Source<br>Battery = 3725.5Ws Source<br>HUC = 1228Ws Source<br>Load = -3078.9Ws Sink | A | - | 1.00 | - | -1.00 |
| | B | - | 0.69 | 1.00 | -0.98 |
| | C | 1.00 | -0.08 | 1.18 | -1.30 |
| | D | 0.72 | 0.22 | - | -0.91 |

The following observations were made from Table 3:

*Load parameters:* The Average power and Energy for Scenario C and Scenario D are higher compared to Scenario A and Scenario B suggesting the case that as mentioned, despite same load switching sequence, the presence of solar aids in quick deliverance of power during surges.

*Battery Parameters:* Upon comparison of Scenario A and Scenario B, it is seen that the Average power and Energy delivered during the transient period by the battery in Scenario B is significantly less compared to that of Scenario A suggesting the effectiveness of HUC in handling the surge loads.

Upon comparison of the Average power and Energy of the battery in the Scenario C and Scenario D, it is seen that battery has acted as a sink during the transient period in the Scenario C whereas it has acted as a source during the transient period in the Scenario D. This again indicates the effectiveness of HUC in a solar based system.

*HUC Parameters:* The average power and Energy for Scenario C are higher compared to the Scenario B suggesting that the performance of HUC has been aided by the presence of solar with respect to deliverance of power during surges.

## 4.3 Analysis of Sub-transient Part of the Load Profile (SectionC)

**Table 4.** Analysis of Sub-transient part of the load profile (Section C)

| Parameters and Base Value | Scenario | Per Unit (P.U). Values | | | |
|---|---|---|---|---|---|
| | | Solar | Battery | HUC | Load |
| Analysis of Sub-transient part of the load profile | | | | | |
| **Current Surge**<br>Solar = 23.66A Avg.<br>Battery = 207A Max.<br>HUC = 25A Max.<br>Load = 68.80A Peak-Peak | A | - | 1.00 | - | 1.00 |
| | B | - | 0.97 | 1.00 | 0.99 |
| | C | 1.00 | 0.71 | 0.92 | 1.16 |
| | D | 1.06 | 0.76 | - | 1.20 |
| **Voltage drop**<br>Solar = 9.4V<br>Battery = 8.6V<br>HUC = 25.2V<br>Load = Nil | A | - | 1.00 | - | - |
| | B | - | 0.84 | 1.00 | - |
| | C | 1.00 | 0.79 | 0.81 | - |
| | D | 0.98 | 0.81 | - | - |
| **Average power**<br>Solar = 1684.4W Source<br>Battery = 4902W Source<br>HUC = - 17.95W Sink<br>Load = -3979W Sink | A | - | 1.00 | - | -1.00 |
| | B | - | 0.93 | - 1.00 | -0.89 |
| | C | 1.00 | 0.69 | 7.12 | -1.19 |
| | D | 1.02 | 0.74 | - | -1.27 |
| **Average energy**<br>Solar = 113.73Ws Source<br>Battery = 355.14Ws Source<br>HUC = - 4.389Ws Sink<br>Load = -291.85Ws Sink | A | - | 1.00 | - | -1.00 |
| | B | - | 1.04 | -1.00 | -1.00 |
| | C | 1.00 | 0.64 | 2.00 | -1.10 |
| | D | 0.91 | 0.62 | - | -1.05 |

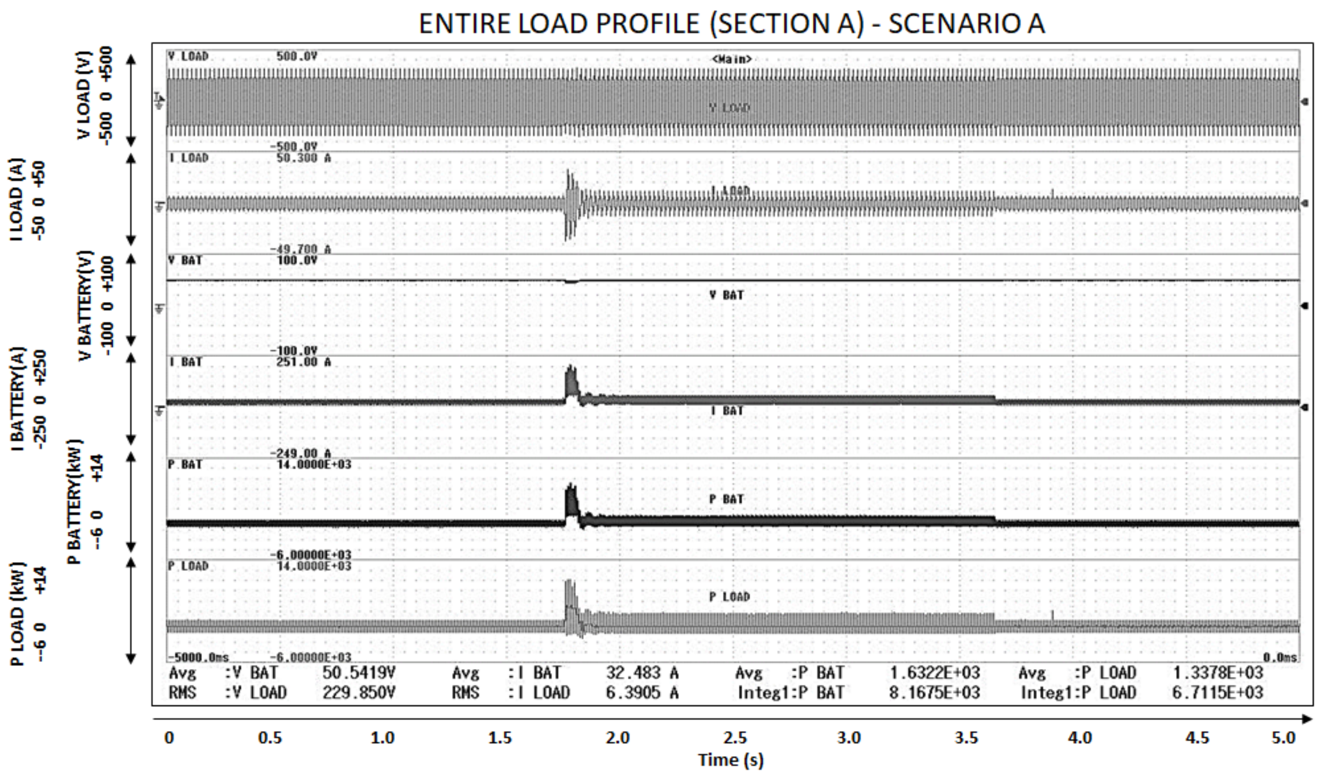


**Figure 3.** Analysis of entire load profile (Sec A) - Scenario A.

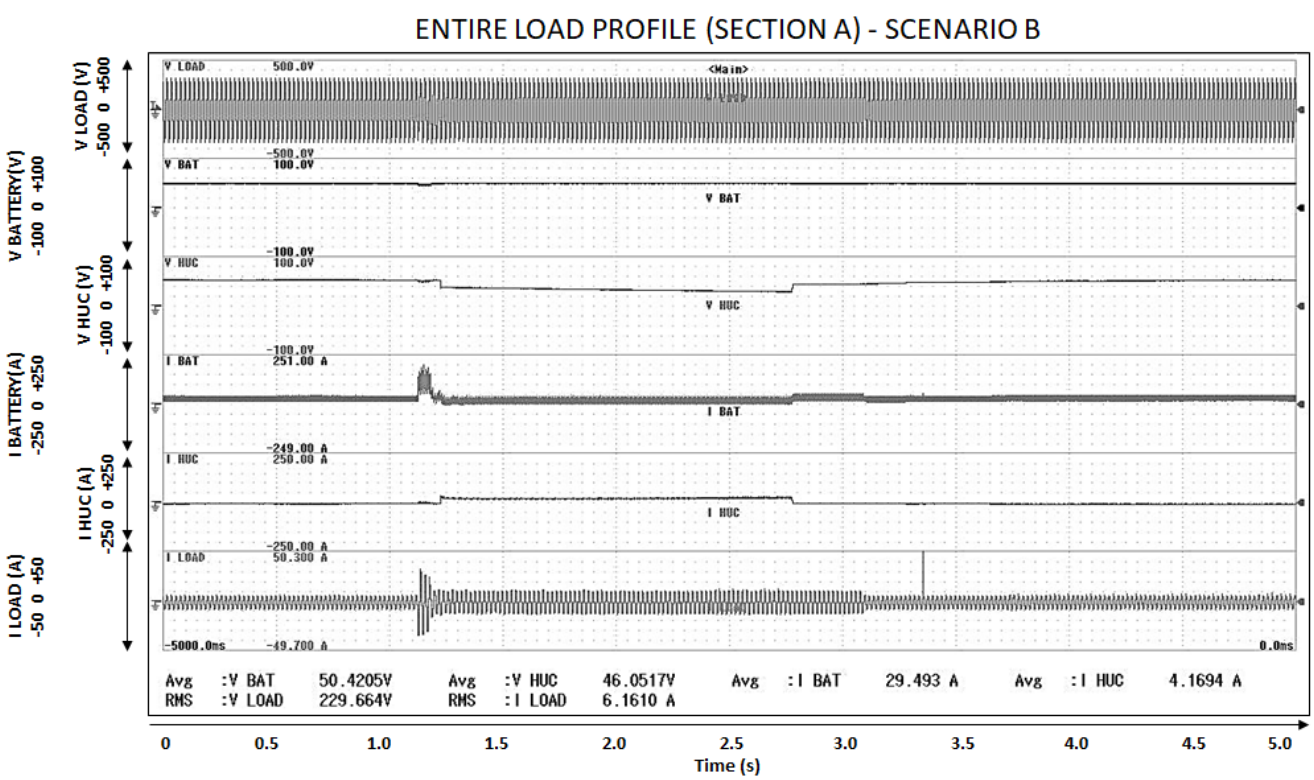


**Figure 4.** Analysis of entire load profile (Sec A) - Scenario B.

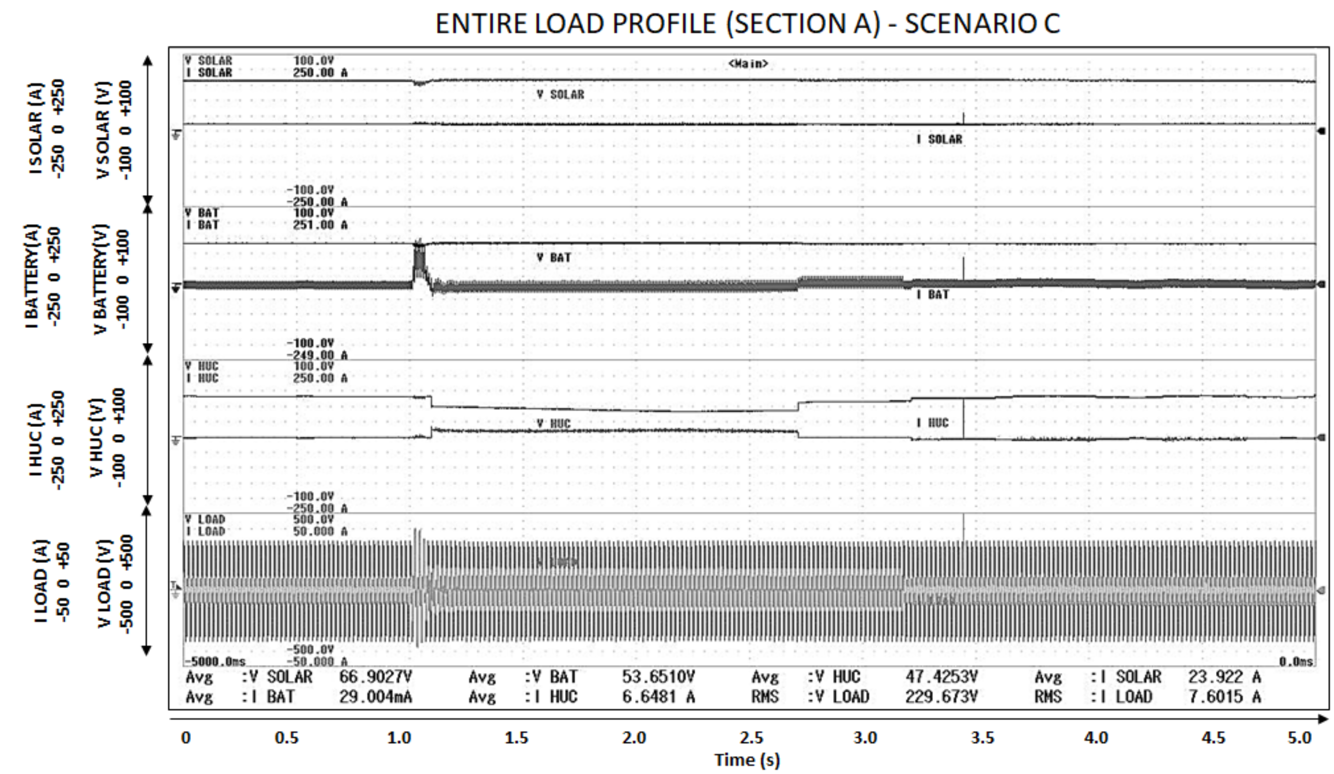


**Figure 5.** Analysis of entire load profile (Sec A) - Scenario C.

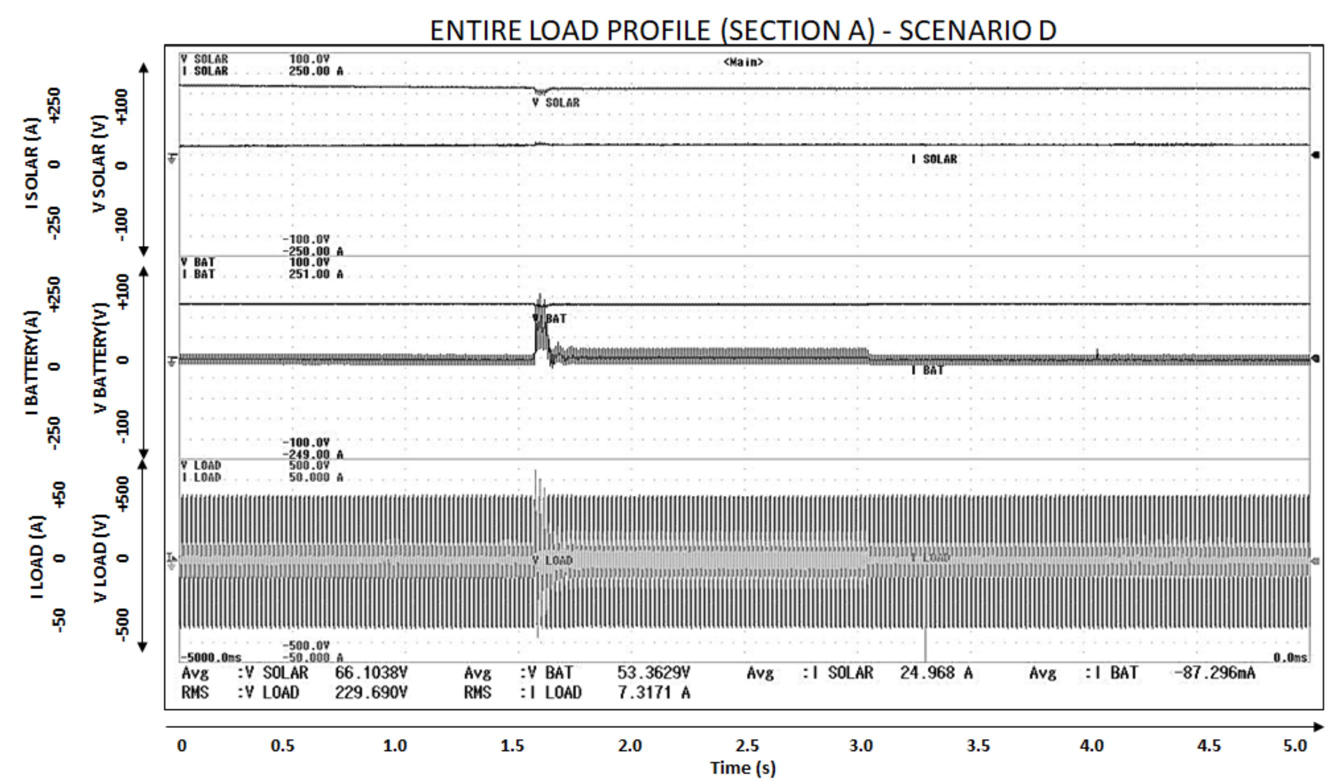


**Figure 6.** Analysis of entire load profile (Sec A) - Scenario D.

The following observations were made from Table 4:

*Load parameters:* The current values, average power for Scenario C and Scenario D are higher compared to the Scenario A and Scenario B suggesting that the presence of solar aids in quick deliverance of power during surges.

*Battery parameters:* Upon comparison of Scenario A and Scenario B, it is seen that the surge current, voltage drop, average power, Energy delivered during the sub-transient period by the battery is significantly lower in presence of solar as seen in Scenario C and Scenario D however not significantly better compared to that of Scenario A questioning the effectiveness of HUC in handling the sub-transient surge loads.

*HUC parameters:* It is observed that during the sub-transient period, HUC has acted as a sink (i.e. charging) instead of acting as a source in the presence of Solar. This could be attributed to the fact that the solar potential was almost twice higher than the average load in the study.

It is also observed that in Scenario B though HUC has acted as a source the comparison of base values of current surge, average power and Energy of HUC vis-a-vis that of battery indicates that base values of HUC are very low compared to that of battery thereby questioning the effectiveness of HUC in handling the sub-transient surge loads.

In the above study, it is observed that HUC was effective in handling transient surge loads, but it was ineffective in handling sub-transient surge loads. Upon further analysis it was observed that HUC delivered for 1.5530sec out of 2sec transient period and HUC delivered after 103ms from the start of the sub-transient part (refer Figure 7) whereas battery delivered after 2ms from the start of transient. It is to be noted here that the sub-transient phase lasted for only 72ms and HUC has started delivering only after 103ms after the surge initiation point, this supports our observation that in the present study, HUC has not been effective in handling sub-transient surge loads. The cause is attributed to the delay of 103ms taken by HUC in responding to the surge power requirement.

There could be 2 factors involved in this delayed response

- The very small pore size on the surface of HUC's amorphous carbon electrode hindering the charge mobility.
- Propagation delay in the EMS circuit.

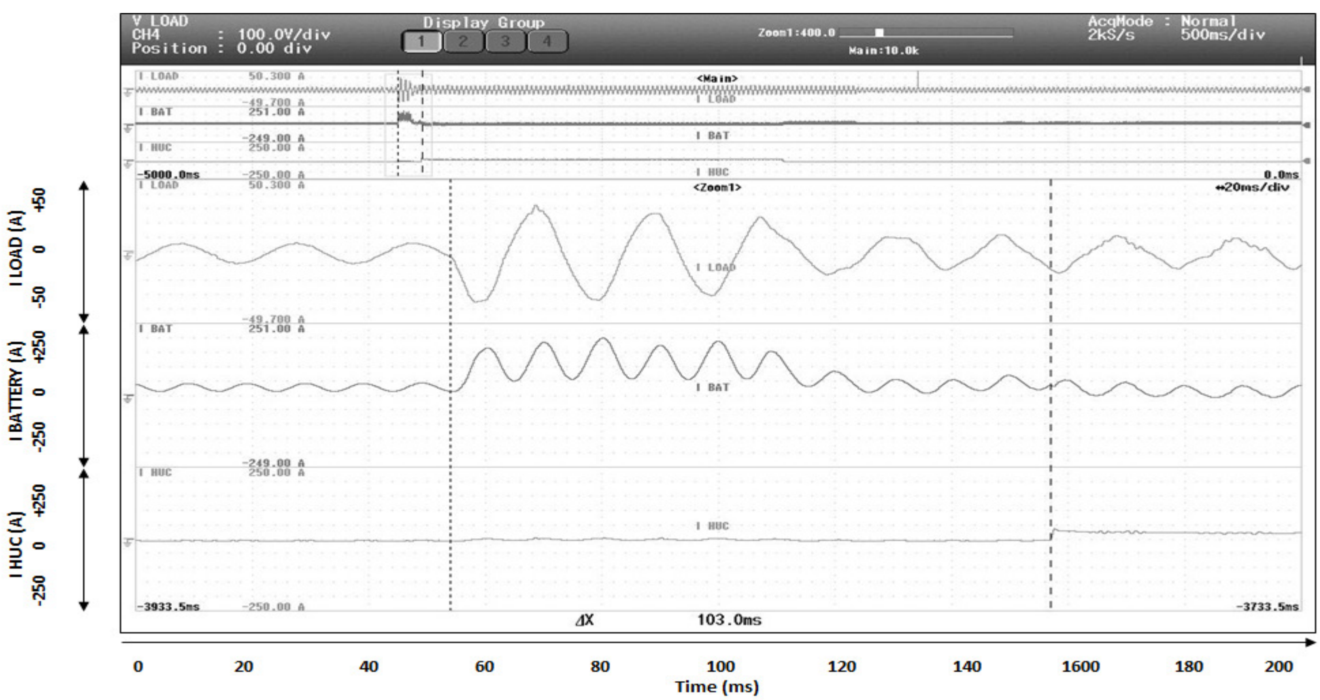


**Figure 7.** Delay analysis from the current profiles.

Upon detailed observation, it was noticed that the rate of rise of HUC current is very steep and the rise time of HUC current is less than 1ms indicates that the delayed response could be better attributed to the propagation delay of the EMS circuit rather than charge mobility issues of the HUC's electrode.

## 5. Conclusion

In this study, use of HUC along with battery in the system has not lead to any noticeable fluctuations in the load voltage. Solar based system was found to more capable of handling surge loads compared to non-solar based system. HUC was found to be effective in handling transient surge loads, but it was found to be not so effective in handling sub-transient surge loads. Upon further analysis it was observed that HUC has started delivering only after 103ms after the surge initiation point due to the propagation delay of the EMS circuit.

It is inferred in this study that, the usage of Hybrid Energy Storage System (HESS) comprising of HUC and Batteries is a better technical proposition in solar based micro grid compared to that of a battery alone system. While designing of EMS it is important to study the time domain discharge characteristics of HUC at milli seconds scale as a propagation delay of even 0.1s can hamper the performance of HESS in handling steep or high frequency surges.

## 6. Acknowledgement

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