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Experimental Investigation Results Super-capacitors vs. Batteries

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Abstract Energy Storage is an essential component of renewable energy systems and micro-grids. The main objective is to investigate which is the more suitable type of short term storage to be included in the MGS; batteries or super-capacitors. To evaluate electrical energy storage in batteries and compare it with advanced super-capacitor technology, an experimental set up is designed and constructed. A set of experiments were conducted to investigate the different characteristics and their suitability to charging and discharging conditions. The results showed that super capacitor has higher power density than battery, while battery surpasses the super capacitor in energy density. Hence, the results confirm the understanding that super-capacitor is more suitable for rapid charging and discharging processes than battery which is more suitable for long charging and discharging times. Also, from the economic point of view battery is still more economical than super capacitors. The results are expressed mainly in terms of specific power efficiency and charge/discharge efficiency; they show that, batteries very useful for high energy density application while super-capacitors have high power density. Further investigations are conducted to compare the performance and efficiency of lead acid battery in cycles charge and discharge to those typical for super-capacitor.

Keywords Energy Storage System, Conventional Batteries, Super-Capacitors, Charge/Discharge Rate, Energy Density, Power Density

1. Introduction

Today, the most applicable renewable energies used in generation plants are solar (photovoltaic or thermal) and wind energy. The major disadvantage of these types of renewable energy is its generation interruption, so energy storage becomes a vital factor. A renewable energy generation stand with its corresponding energy storage system can perform as a constant power generation at least for time period in the order of half an hour to a day, based on the energy storage capacity. Energy storage needs evaluating; according to the application, energy density performance, power density through charge and discharge operations, efficiency, life period and system cost.

Electrical energy storage knowledge's for inactive applications are evaluated. Particular notice is compensated to pumped hydro electric storage, compressed air energy storage, battery, flow battery, fuel cell, solar fuel, superconducting magnetic energy storage, flywheel, capacitor/super-capacitor, and thermal energy storage [1]. Comparison is completed among these technologies in terms of technical characteristics, applications and deployment status. Energy Storage System (EES) is directly needed by the conventional electricity generation industry, Distributed Energy Resources (DER) and intermittent renewable energy supply systems. EESs have abundant applications enveloping a wide spectrum, ranging from large-scale generation and transmission-related systems, to distribution network and even customer/end-user regions. The EES technologies afford three primary functions of energy management: bridging power, power quality and reliability.

In another study [2], an overview of the recent and future energy storage technologies used for electric power applications is approved. The majority of the technologies are in use nowadays while others are still under detailed research and development. A comparison between the various technologies is described in terms of the mainly important technological characteristics of every technology. The comparison presents that each storage technology is dissimilar in terms of its ideal network application environment and energy storage level. This has led to the emergence of storage as a vital element in the management of energy from renewable sources, permitting energy to be released into the grid through max out hours whilst it is more valuable. Maximum power required and long-or short term storage are two main characteristics used of electricity storage techniques. These characteristics will hand out to make comparisons to decide the most suitable technique for each type of application

Lately, a new group of reversible electrochemical energy storage systems have been expanded that use: (a) electrical double-layer capacitors (EDLCs), and (b) pseudo-capacitors [3]. While EDLCs with capacities of many tens of farads per gram of the electrode material have been accomplished employing high surface-area carbon powders or fibers or felts, much higher capacitance values are achieved with pseudo-capacitors employing high surface-area oxides or conducting polymers. These capacitors are investigated for several applications to balance the storage batteries. Brief summary to scientific fundamentals and technological applications of electro-chemical super-capacitors is presented.

Super-capacitor becomes the one of the most new energy storages that established to the market today. Super-capacitors are elements for energy storage, dedicated for applications where both power density and energy are required. Even though their energy density is ten times less than the batteries energy density, super-capacitors propose new options for applications where energy storage is essential [4]. Super-capacitor has low energy density but high power density. Super-capacitor is able to be used as extra energy storage for hybrid photovoltaic and wind system [5]. It can be associated in parallel with the battery for charging or discharging high power in a small period of time. It charges energy as it is windy or sunny and discharges when no power produced from renewable sources because of the sudden passing clouds interruption or low wind speed. Super-capacitors can be a good growth for batteries in the operation of wind and photovoltaic energy storage mainly through heavily changeable weather conditions. Therefore, it is very crucial to determine and recognize the characteristics of the super-capacitor especially in its voltage and energy responses during charging and discharging.

An easy, global model for the optimal mixture of ultra-capacitor and battery for electrical energy storage is developed in [6]. The hybrid storage technology aim is to decrease the system life-cycle cost by building utilization of an ultra-capacitor’s declared long cycling-life to supplement relatively inexpensive, but cycle-limited battery storage. The model is developed of two independent sub-models that permit flexibility in the relative part of system energy storage. An analysis performed in this research showed that ultra-capacitor/battery storage systems might be cost effective for high-cycle claims. The results illustrated that high cycling applications are presented in various regions of the electrical power system. The value of this simple model is to present that a small quantity of ultra-cap storage may well decrease battery-based smoothing system overall lifetime cost. This gives the motivation to study additional claims including issues as more complicated modeling for each part and techniques of implementation of hybrid storage system.

Most of the stand-alone photovoltaic (PV) systems need energy storage to provide continuous energy to the load when there is insufficient solar irradiation. Usually, Lead Acid batteries are used for this application in this research [7]. An alternative method of supplying large fractures of current is to combine batteries and super-capacitors to structure a hybrid storage system, where the battery can supply permanent energy and the super-capacitor can supply the on the spot power to the load. Function of the super-capacitor in a PV Energy Control Unit (ECU) by using MATLAB/SIMULINK models is studied. The ECU observes and optimizes the power flow from the PV to the battery-super-capacitor hybrid and the load. Three various load conditions are investigated; a peak current load, vital current load and a constant current load. The simulation results present that the hybrid storage system be able to attain higher specific power than the battery storage system.

Another research look at both the potential of and barriers to grid-scale energy storage playing a substantive function in transitioning to an efficient, reliable and cost-effective power system with a high penetration of renewable energy sources. Anya Castillo and Dennice F. Gayme provide an outline the current methods to evaluate grid-integrated storage, review key findings, and highlight ongoing challenges to large-scale approval of grid-scale energy storage [8]. Focusing on one particular area that is critical to in cooperation the efficient use of energy storage in the power grid with its long-term economic viability: the conflict between the technical benefits of this resource, which can provide both power, energy related grid-services and the economic challenges of compensating these services within the market structures.

An extra research attempts the optimal discharge scheduling of energy storage systems problem in micro-grids, in view of renewable generation. The trouble merges generation and load profiles in the micro-grid getting the optimal possible discharge scheduling of the energy storage system that reduces the consumption from the national grid. This methodology can be simply adapted to resolve the discharge scheduling of energy storage systems problem by using an evolutionary algorithm as global approach [9]. The performance of the planned approach has been evaluated in a real micro-grid, with different scenarios of generation and load profiles, obtaining around 5% reduction of the energy consumption from the utility grid.

This paper is divided into three sections. In the first section, an overview of different energy storage system is carried out, taking into account storage capacity, voltage and current ratios, and energy availability. The second section shows devices module tests specifications. And the third section is focused in compassion results between lead acid battery and super-capacitor.

2. Energy Storage System

Hence, Energy Storage System (EES) is an essential component of a smart micro-grid, which should be scalable, autonomous and ready to cooperate with other grids. The micro-grid and EES should in general be connected to the network; even if a particular smart micro-grid is not connected to a grid,

Despite recent developments, intermittent renewable energy generators still face technical and economic barriers to deployment. The application of energy storage offers numerous complementary services for intermittent generators and as renewable energy penetration increases over time, it is likely that these services will provide more value to both renewable energy proponents and to network operators [1]. Battery technologies also offer the unique advantage that they can easily be scaled to suit many applications. There are many types of energy storage and this paper focused in conventional batteries and super-capacitors as detailed below.

2.1 Electrochemical Energy (batteries)

Electrochemical energy storage techniques convert electricity to chemical for storage and reverse again. Batteries can be divided into three main groups: conventional, flow and high temperature. Vital battery technology has a history longer than pumped hydro storage (PHS), while cost effective means of storing bulk energy in batteries has been a challenge. Different some other storage techniques, batteries have shown restricted cycling times due to mainly electrode fouling and electrolyte degradation. Advanced batteries are also the key focus of research into developing storage technology, with advances in designs and materials arranged at a fast rate.

2.1.1. Conventional Battery Technology

Conventional batteries include anode and cathode electrodes in a sealed cell with disconnected by a substance named an electrolyte. Through the charging cycle the electrolyte is ionized, for the period of discharge an oxidation-reduction reaction picks up the energy. There is a large range of battery types called for the electrolyte employed that include lead-acid, nickel-cadmium and lithium-ion. Table 1 presents summary characteristics of electrochemical energy storage [10].

Table 1: Summary characteristics of electrochemical energy storage technologies [10]

Technology	Cost ($/kW)	Cost ($/kWh)	Efficiency	Cycle Limited	Response Time
Lead acid Batteries	950-5,800	350-3,800	75-90%	2,200->100,1000	Millseconds
Li-ion Batteries	1,085-4,100	900-6,200	87-94%	4,500->100,000	Millseconds
Sodium Sulfur	3,100-4,000	445-555	75%	4,500	Millseconds
Flow Batteies	3,000-3,700	620-830	65-75%	>10,000	Millseconds

2.2 Electromagnetic Energy Storage

Electricity is difficult to store, and most storage techniques, concept is to store electrical energy by first switching it to a different shape. Two techniques store electrical energy as electricity are capacitors and superconducting electromagnets [11]. Super-capacitors store energy in huge electrostatic fields between two conductive plates, which are separated by a little distance. Electricity can be rapidly stored and released via this technique to produce small fractures of power. Super-capacitors are low-energy density and high-power devices that are able to respond very quickly. Applications contain frequency and stabilizing voltage in power systems plus energy recovery on engine breaking systems [12].

2.3 Comparison between Storage Technologies

Choosing a storage type should be based on intended application and the characteristics of candidate storage types such as; power capacity, discharging time, efficiency, and cost. Batteries are able to provide short-to-medium term storage for a large range of output capacity.

There are vital variation between batteries and capacitors that impact their possible applications owing to their different ways of operations. Super-capacitors, (sometimes called Electric Double-Layer Capacitor (EDLC) and Ultra-Capacitor) and batteries do have a few overlapping applications. There are numbers of applications of super-capacitors in three sections: power consumer electronics for high power pulses, hybrid electric vehicles that deploying their performance and economic accessibility, and renewable energy system for grid stability-isolated application-power quality.

Basic difference between batteries and super-capacitor are as follows:

- Batteries store chemical energy but super-capacitors store electrical energy.
- Battery involves ideal voltage source connected in series with internal resistance but in Ultra-capacitor capacitance associated in series way with an equivalent resistance.
- Super-capacitors are able to be completely charged and discharged in seconds up to a million times, even in several degrees below zero.
- Super-capacitors have much higher power density than batteries.
- Super-capacitors have very low energy density compared to batteries
- Super-capacitors have very high self-discharging compared to batteries.
- Super-capacitor cycle efficiency can be over 95% so, no need for maintenance.
- Super-capacitor is light weighted in contrast to batteries.

Specification comparison between batteries and super-capacitors are presented figure 1 [13]. Table 2 illustrates performance comparison between Super-capacitors and LI-ON battery [14].

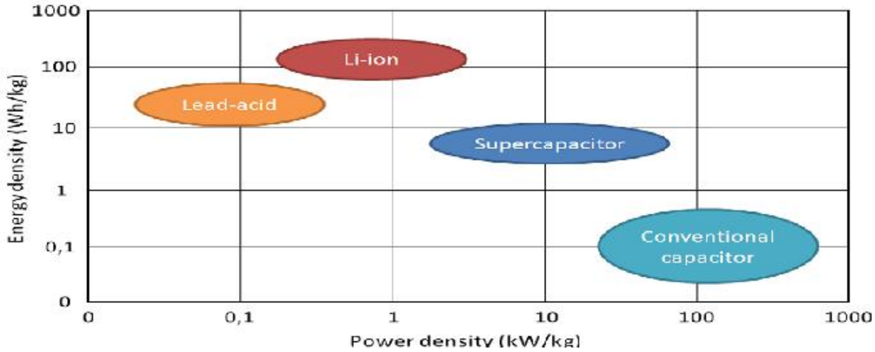


Figure 1: Super-Capacitor Specifications vs. Alternatives [13]

Table 2: Performance Comparison between Super-Capacitors and LI-ON battery [14]

PERFORMANCE COMPARISON	BETWEEN SUPERCAPACITOR AND LI-ION	
Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6 to 3.7V
Specific energy (Wh/kg)	5 (typical)	100–200
Specific power (W/kg)	Up to 10,000	1,000 to 3,000
Cost per Wh	$20 (typical)	$0.50-$1.00 (large system)
Service life (in vehicle)	10 to 15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

3. Super-Capacitor and Batteries Experimental Testing

3.1. Super-Capacitor Module

The super-capacitor used in the tests is a 15F, 2.7V, 6g module, manufactured by VISHAY technologies [15]. Where, capacitance value C_R is known by discharges current I_D, time t and rated voltage U_R, according to the equations 1&2:

$$C_R\,[F] = \frac{ID\,[A]\times(t2\,[s]-t1\,[s])}{U1[V]-U2\,[V]} \quad \text{(Eq.1)}$$

C_R: rated capacitance in farad, U_R: rated voltage in volt, U_1: starting voltage as $0.8\times U_R$ in volt, U_2: ending voltage as $0.4\times U_R$ in volt, U_3: voltage drop at internal resistance in volt, t_1: time from start of discharge until voltage $U_1$is reached in second, t_2: time from start of discharge until voltage U_2 is reached in second, I_D: absolute value of discharge current in ampere.

$$C = \varepsilon_0\times\varepsilon_r\times\frac{A}{D} \quad \text{(Eq.2)}$$

where C is the capacitance, ε_0 is the dielectric constant of free space, ε_r is the dielectric constant of the medium among the two layers, A is the surface area, and D is the distance between the two layers.

The energy stored in a super-capacitor equal in a conventional capacitor is [84]:

$$E = \frac{1}{2}\times C\times V^2 \quad \text{(Eq.3)}$$

Where, V is the super-capacitor voltage.

The discharge rate is defined by [16]:

$$T = \frac{E}{P} \quad \text{(Eq.4)}$$

Where, P is the super-capacitor power.

3.2. Lead Acid Battery Module

The battery used in this test; to be compared with the super-capacitor, was selected from the lead acid conventional batteries available in the markets. It consists of 8 cells in series, and a nominal, one-hour capacity of 1.2Ah, 12V [17]. The battery size was chosen to be comparable with the used super-capacitor. Super-capacitor and battery set-up detailed module components are assembled as shown in figure 3.

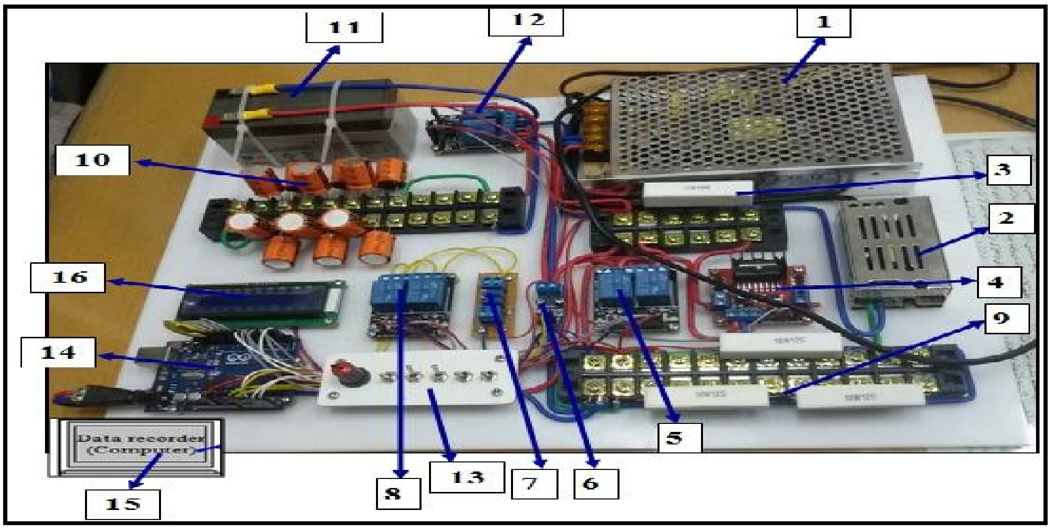


Figure 3: Super-Capacitor & Battery Set-up System components

The system consists of:

1. Power Supply-12 V

1. Power Supply-5 V

3. Current Limiter

Current limiting is used to set the maximum current that will through pass to be fit to super-capacitor as shown in the following equation.

$$\text{Maximum Current} = \frac{\text{Maixmum Voltage}}{\text{Current limiter Resistance}} \quad \text{(Eq.5)}$$

4. Voltage Regulator -Variable DC Voltage Source (H-Bridge)

This is used to regulate and organize voltage of power supply during charging mode that operating on Pulse Width Modulation (PWM) principle.

5. Relays

Group of two relay (2-kit) is used to separate completely the current from ground.

- No. 5: Relay 1: switch load or power supply or switch off each item.
  Relay 2: charge or discharge process.
- No. 8: Relay 3: separate Arduino from signals.
- No.12: Relay 4: switch super-capacitors or battery.

6. Current Sensor

7. Signal Conditioner-Variable Resistor

This resistance is used to read the voltage and compares it with voltage of regulator and manage voltage rate that goes Arduino.

8. Load (Resistors)

Arduino Current is between 0 and 5A, using referencing method current becomes roughly 1A. The voltage is 12V and current 1A, so load resistor will be 12 ohm and capability changing resistors to measure system performance.

10. Super-capacitor bank (15F, 2.7V), two parallel strings; each consist of 6 super-capacitors connected in series, are connected together to obtain 5 farad equivalent capacitance. As in next equation [80], the current and capacitance of Super-Cap is defined as follows:

1 F = 0.277 mAh/V (3.6)

11. Lead Acid Battery

13. Toggles Switches - Potentiometer

- On/Off for the system board completely (SW 1).
- Super-capacitor or Battery (SW 4)

- Charging or Dis-charging mode (SW 3)
- Edit/Change (SW 5)
- Duty Cycle (on-off time) (SW 2), A potentiometer enables to edit and change voltage.

14. Microcontroller Arduino
15. Data Acquisition Unit (Computer):
16. Display:

Case Name			Case No	→ Row 1
Volt (Pot)	Volt Value	Current Value	Operation Time	→ Row 2

System during charging and discharging schemes are presented in figures (4, 5) respectively.

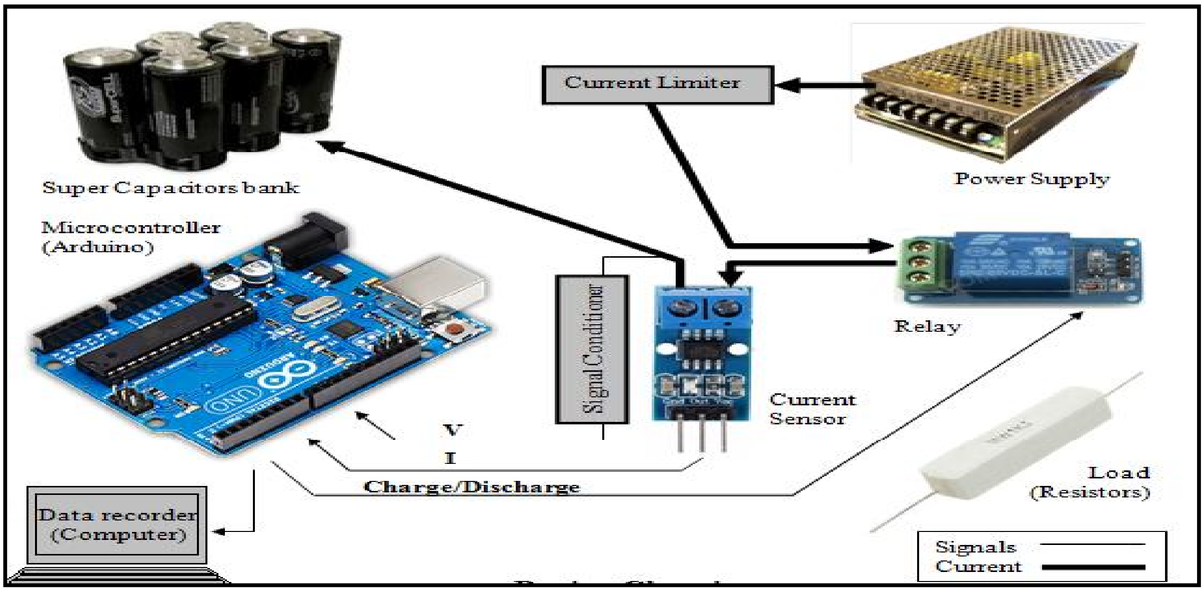


Figure 4: System Scheme during Charging

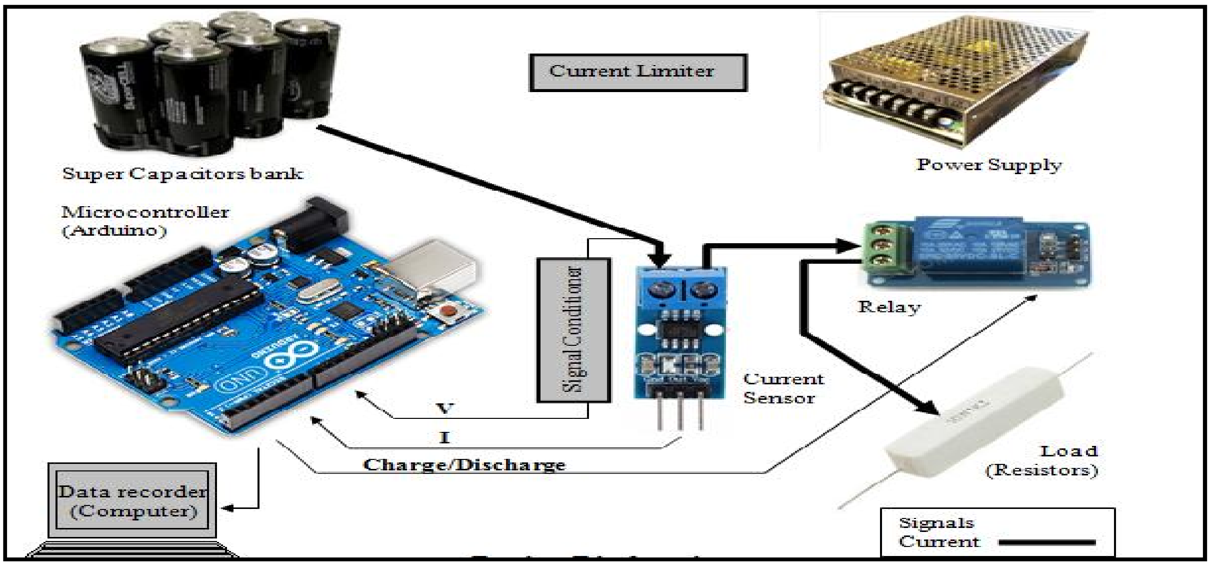


Figure 5: System Scheme during Discharging

Electrical circuit was programmed by mini Arduino software program that is shown in appendix A and the operations of charging and discharging modes are recorded by PLX-DAG v 2.11 Excel software.

4. Comparison Results

For the sake of comparing the performance of super capacitors and batteries (charging and discharging) under different values of operating voltage, load and current, the experimental set up that was designed and prepared is used. The first group of experiments is for measuring super- capacitor performance parameters (volt and current); while the second is for battery performance.

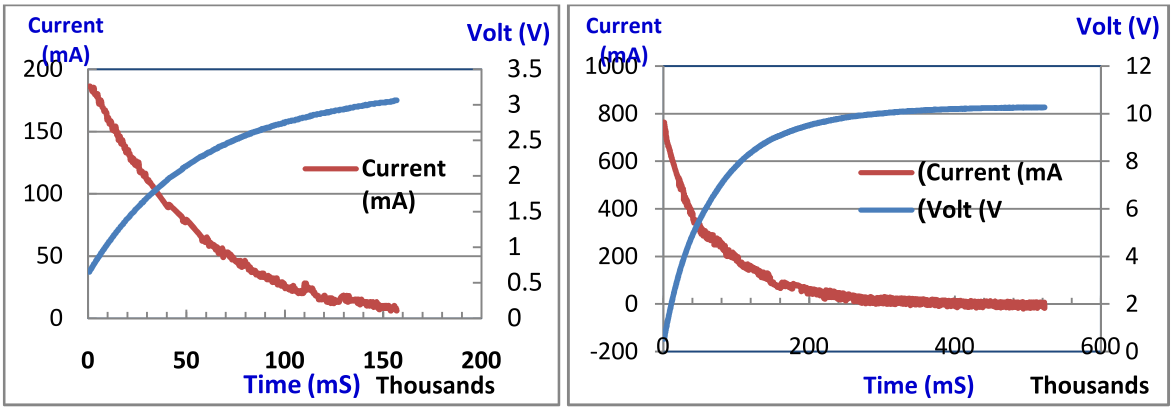
4.1. Super-Capacitor Experimental Results

a) Case of charging

In charging case the super capacitor performance is measured for different voltage at different current values. Different current values are achieved using current limiters.

Current limiter is a resistor that limits the flowing current to a certain maximum value. In the first case one limiter (a resistor which in these experiments is of 12Ω is used in the circuit. The resistance equals 12Ω, then the maximum current will be equal to 1 A (12 V/ 12Ω). Super capacitors were charged to different values of voltages 3V, 4V, 5V, 6V, 7V, 8V, 9V, 10V, and 11V. Figure 6-a, and 6-b illustrates the I-V relations for V= 3 volts and 11volts; respectively. The selected cases are for voltage values; 3 and 11 volts representing the lowest and highest voltage values. A collective chart of these curves is shown in figure 7.

In the second case 2 resistors are placed in parallel to each other to reduce the resistance value to half the resistor value (12/2 = 6Ω), hence the maximum value of current will be 2 A. Similarly, in the third case 3 limiters are placed; also parallel to each other, which cause the resistance to drop to one third of the resistor value (12/3 = 4Ω). Thus in this case the current will be 3 A. The collective chart the two current limiters case is exhibited in figure 8, and three limiters case in figure 9.



a) V vs. I at 3 volts *b) V vs. I at11volts*

Figure 6: Voltage-Current Curves of Super-Capacitor charging at Different Voltages (One current limiter, i.e. Current] 1 A)

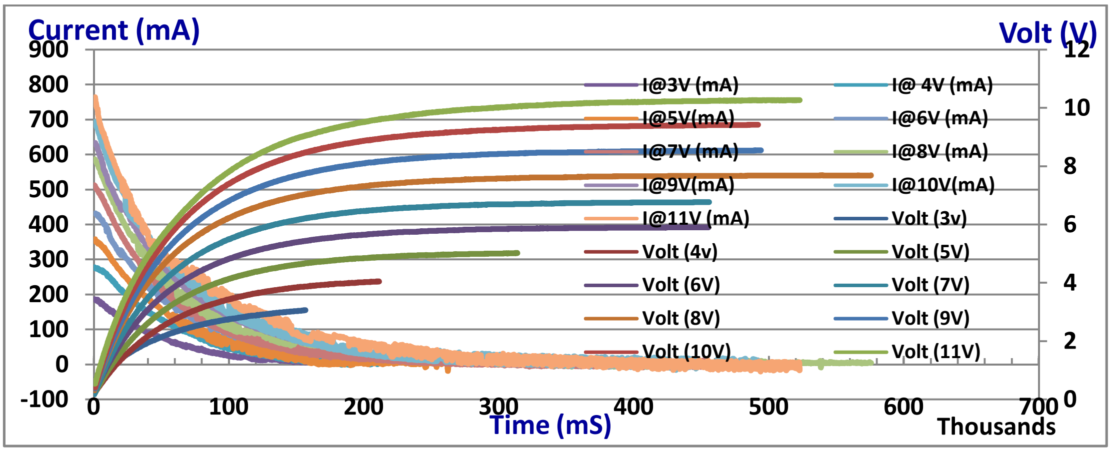


Figure 7: Collective Chart of Super-Capacitor Charging at Different voltages (One current limiter, i.e. Current] 1 A)

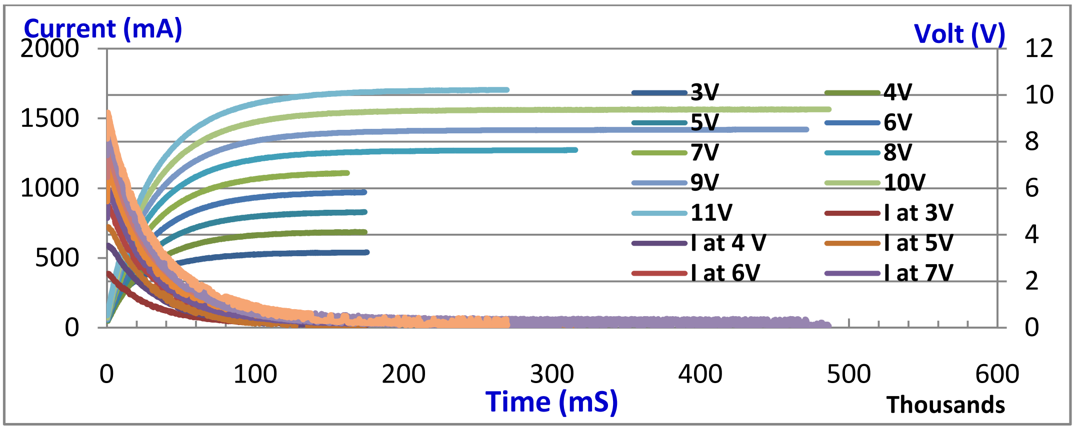


Figure 8: Collective Chart of Super-Capacitor Charging at Different Voltages (2 parallel current limiters, i.e. Current] 2 A)

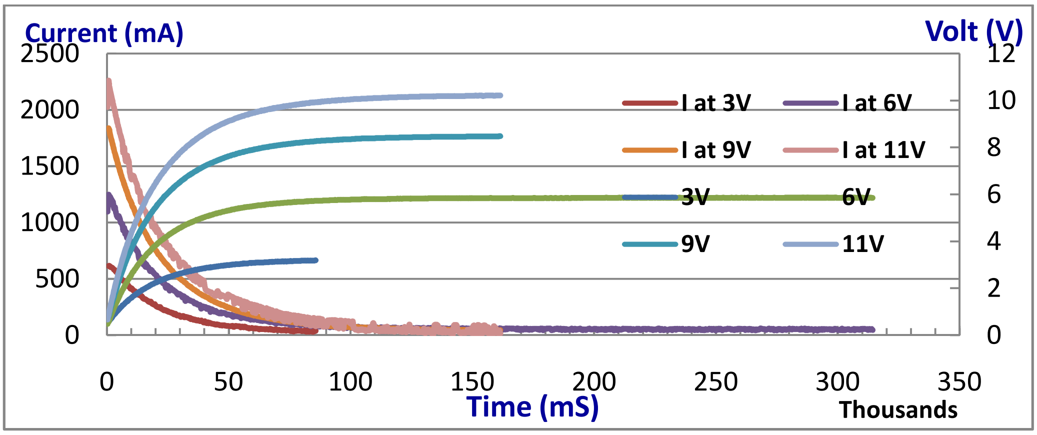


Figure 9: Collective Chart of Super-capacitor Charging at Different Voltages (3 parallel current limiters, i.e. Current] 3 A)

From the above figures it could be noticed that charging the capacitor bank to the predefined voltage values (from 3 to 11), in the first case (3 V), the starting voltage was 0.7 V, and it took about 150sec to reach the defined value of 3 V. The starting charging current; as expected, increases with the increase of the targeted voltage.

b) Case of discharging

In discharging case the super capacitor performance is measured for different voltage at different load values. Similar to the charging case, three different load values were investigated; 36, 24, 12 Ω, using load resistors each of 12Ω -15W each, connected in series. Collective chart of super capacitors discharging operations are shown in figure 10, 11, and 12.

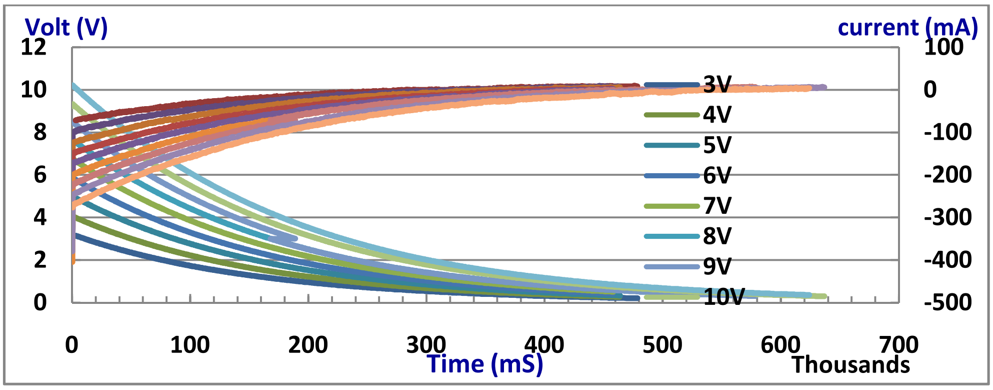


Figure 10: Collective Chart of Super-capacitor Discharging at Different Voltages (Load= 36 t)

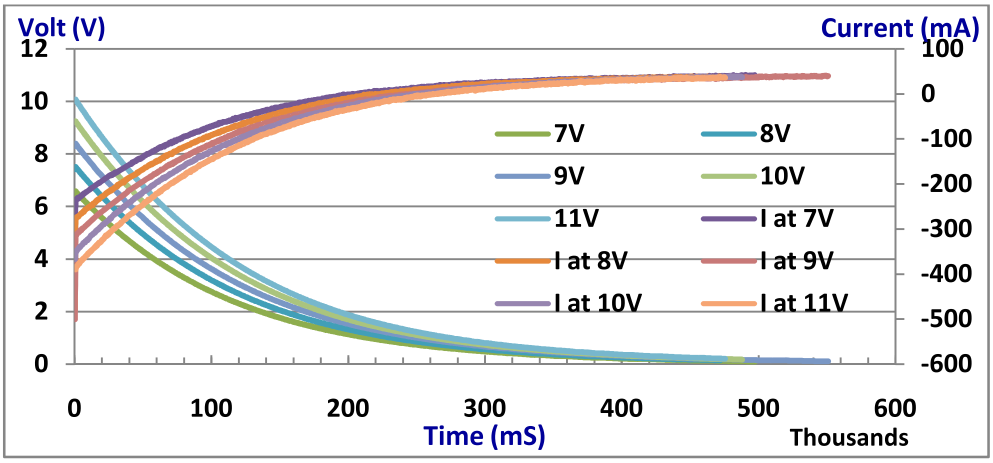


Figure 11: Collective Chart of Super-Capacitor Discharging at Different Voltages (Load= 24 t *)*

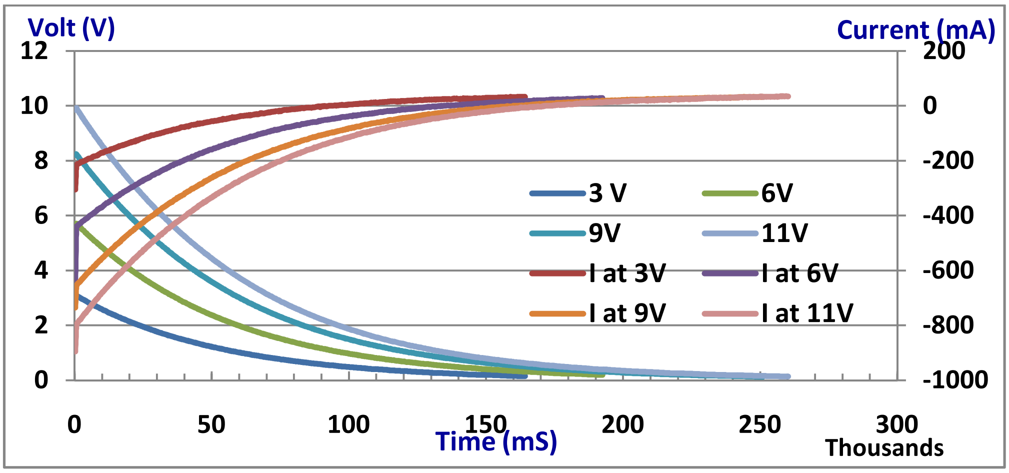


Figure 12: Collective Chart of Super-Capacitor Discharging at Different Voltages (Load= 12 t *)*

From figures 7, 8 and 9, it is clear that during charging super-capacitor the charging time decreases with the increase of current which is achieved in these experiments by adding current limiter (parallel resistors). In discharging mode, time decreases with the decrease of load value as shown in figures 10, 11, and 12. A set of remarks are noticed from above figures which are summarized in table 3-a, and 3-b.

Table 3: Summary of Super-Capacitors Results (a- Charging, b- Discharging)

a- Charging						
	3V			**11 V**		
No. of Current limiters (Max. Current)	1 (1A)	2 (2A)	3 (3A)	1 (1A)	2 (2A)	3 (3A)
Time (sec)	150	70	50	520	280	160

b- Discharging						
	3V			**11 V**		
No. of resistors (Ω)	3 (36)	2 (24)	1 (12)	3 (36)	2 (24)	1 (12)
Time (sec)	500	190	170	620	490	250

It should be mentioned that during charging the voltage did not reach 11V, hence discharging, began from 10V on the average.

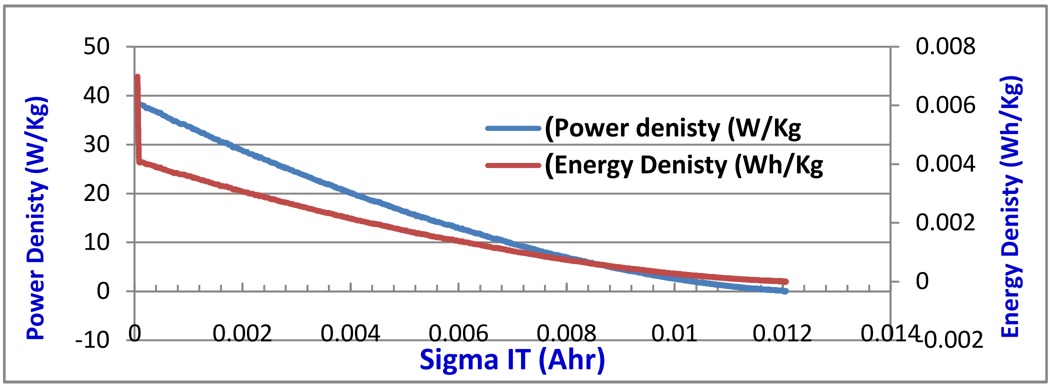
c) Super-capacitor energy & power density

To calculate power & energy density, the discharging experiment was based on the case of 11V as it the maximum value used. Figure 13 (a, b and c) illustrate energy density vs. power density of super-capacitor discharging process (in case of 11V voltage) for 3 different loads according to following equations [15]:

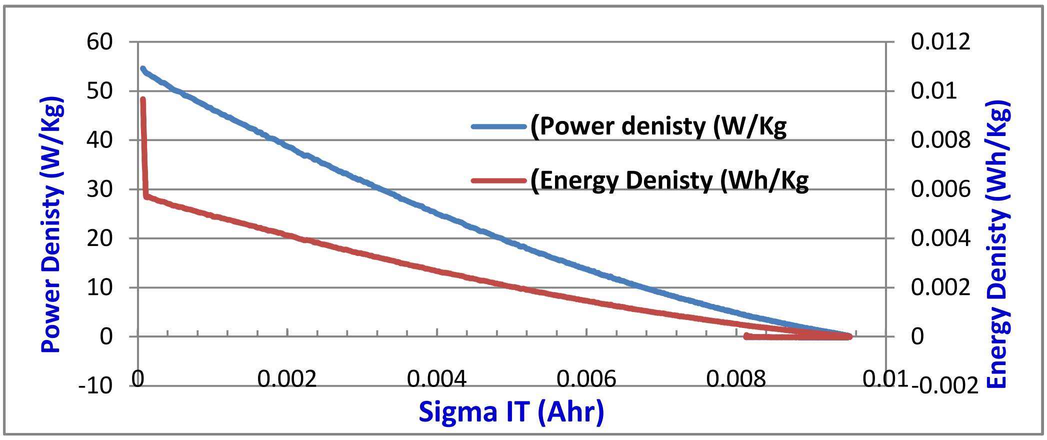
Power Density (W/Kg) = $\frac{\textbf{Voltage (V)} \times \textbf{Current (A)}}{\textbf{mass (Kg)}}$ (Eq.6)

Energy Density (Wh/Kg) = Power Density (W/Kg) × Δ Time (sec) (Eq.7)

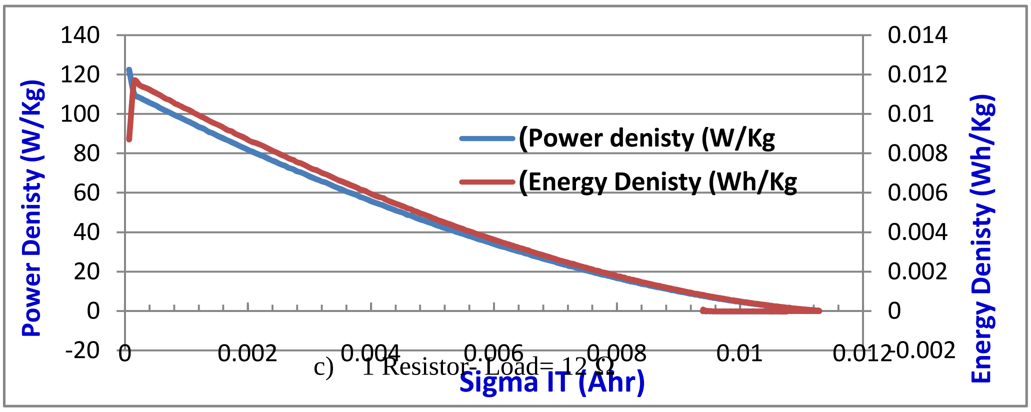
Summary of super-capacitors power & energy density results is exhibited in table 4.



a) Base case: 3 Resistors- Load = 36 Ω



b) 2 Resistors- Load = 24 Ω



c) 1 Resistor- Load= 12 Ω

Figure13: Power-Energy Density Curves of Super-Capacitor Discharging at Different Load Values (36, 24, and 12Ω)

Table 4: Summary of Super-Capacitors Power & Energy Density Results

Load	Time	Drawn Current (Ahr)	Power Density (W/kg)	Energy Density (Wh/kg)
3 R (36Ω)		0.012	39 to zero	0.07 to 0.004 0.004 to zero
	sec	482	537	2.5 537
2 R (24Ω)		0.0095	55 to zero	0.0096 to 0.0055 0.0055 to zero
	sec	178	265	3 265
1 R(12Ω)		0.011	123 to 110 110 to zero	0.011 to zero
	sec	172	0.6 174	174

As expected, decreasing the number of resistors increases the power density while decreasing energy density and the amount of drawn current.

4.2. Battery Experimental Results

a) Case of charging

A battery charger of (10A, DC 6/12V) is used to charge the battery. Battery charging time; to reach maximum voltage, is about 35 minute.

b) Case of discharging

Collective chart during discharge operations at different load is presented in figure 14.

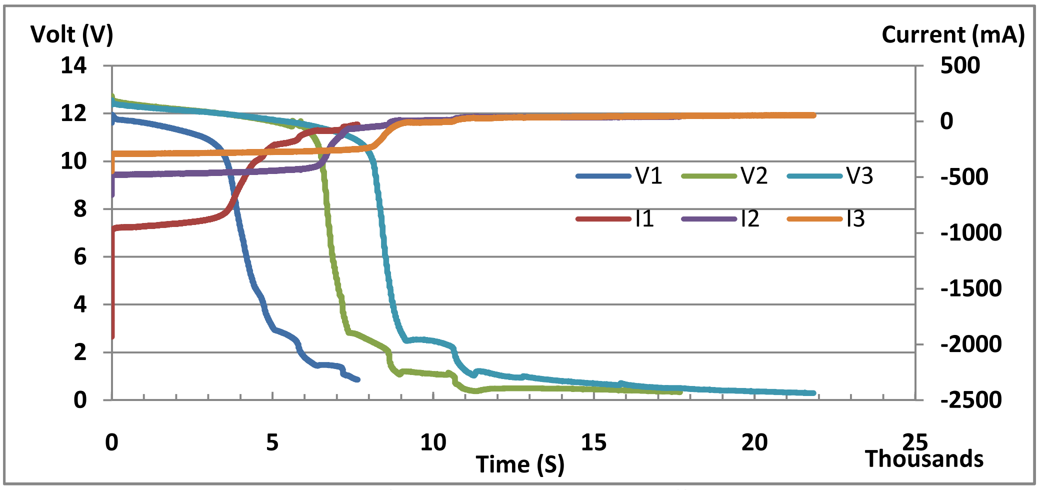


Figure 14: Collective Chart of Battery Discharging at different Load Values (36, 24, and 12Ω)

From above figure, it is clear that discharging time decreases when the load decrease. It is also noticed that at low rate of discharging current, the voltage drops slowly. For example in case of 12Ω load at the beginning of discharging the discharging current was about 1000mA each one second while the voltage dropped from 12 to 10V in the first four seconds. In the 2nd period, from the fourth second to the fifth the rate of the discharging current increased, causing a rapid decrease in voltage (from 10 to 4V).

c) Battery energy & power density

Figure 15 illustrates energy density vs. power density of battery discharging process for the base case (36 Ω load).

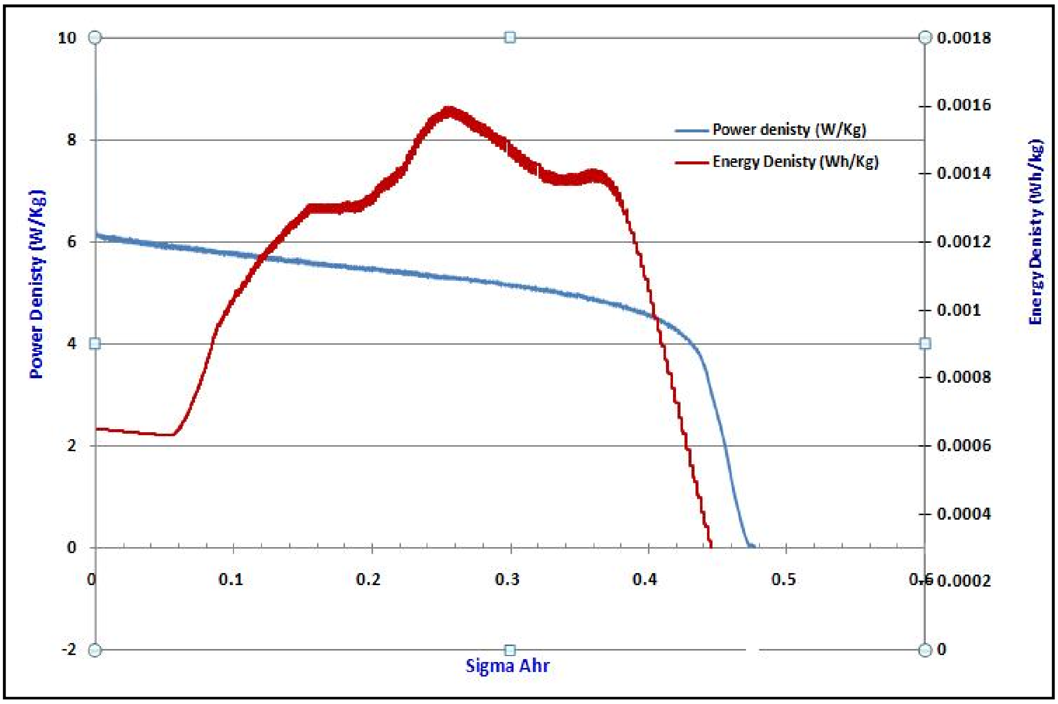


Figure 15: Power-Energy Density Curves of Battery Discharging (36Ω)

From figure 15, a summary of battery power & energy density results is exhibited in table 5.

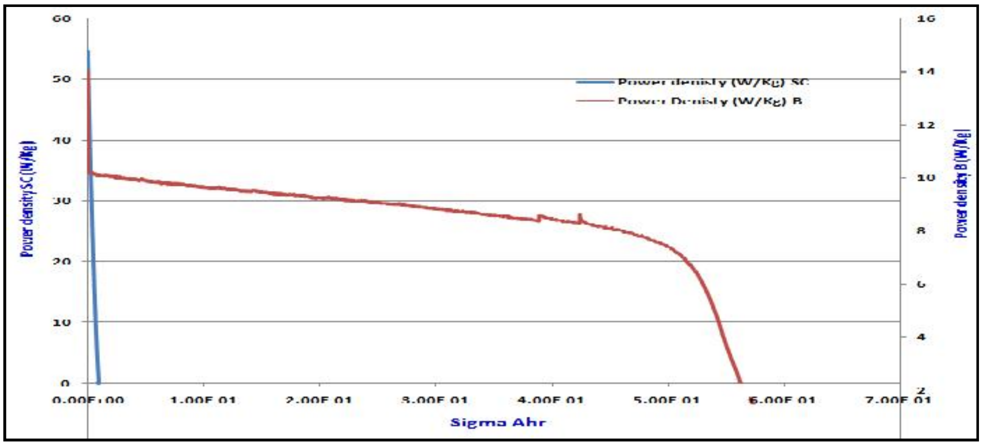
Table 5: Summary of Battery Power &Energy Density Results

Load	**Time**	**Drawn Current (Ahr)**	**Power Density (W/kg)**	**Energy Density (Wh/kg)**
		0.47	9.36 to 6.38	0.006 to 0.0014
3 R (36Ω)			6.38 to zero	0.0014 to zero
	sec	9439	0.640	2766
			9439	8418
		0.62	14 to 10.63	0.001to 0.0027
2 R (24Ω)	sec		10.63 to zero	0.0027 to zero
		12957	0.639	2839
			10822	8745
		0.59	38 to 19.7	0.002 to 0.00187
			14 to zero	0.00187 to 0.0023
1 R(12Ω)	sec			0.0023 to zero
		4953	0.640	616
			5303	1025
				5303

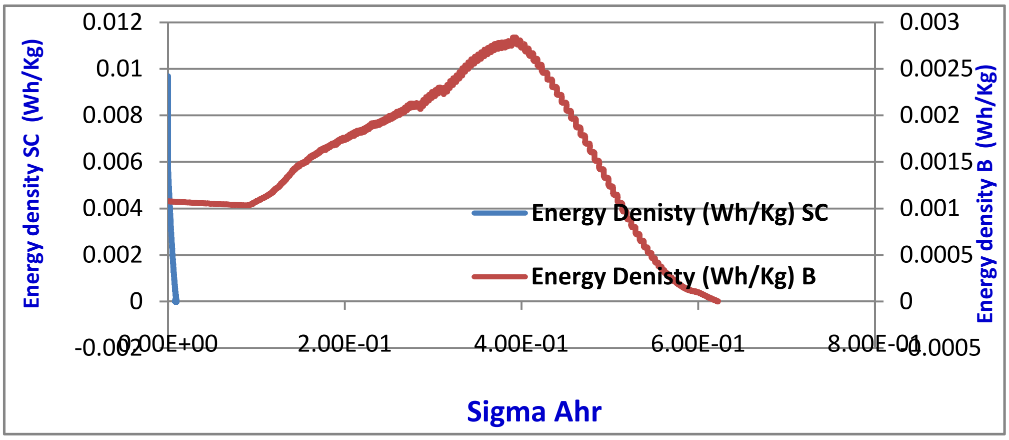
As expected, decreasing the load (number of resistors) increases the power density while the amount of drawn current and energy density is decreased. The power density consumption per second; in case of 24Ω, is 0.001W/kg while in case of 12Ω it is ≅0.0026W/kg. The reason is that as the load increases the current decreases and that time to fully discharge the battery increases and the battery efficiency (percentage capacity) increases.

4.3 Energy & Power Density Comparison of Super-Capacitor & Battery Storage

Figure 16-a, and 16-b, shows power and energy density of the super capacitors and battery at 24 Ω resistors load.



a- Power Density Super-Capacitor vs. Power Density Battery



b- Energy Density Super-Capacitor vs. Energy Density Battery

Figure 16: Power & Energy Density Comparison of Super-Capacitors and Battery

From figure 16, it is clear that the super-capacitors release its power and energy in small time period compare to the battery. A summary of super-capacitor/battery comparison is presented in table 6.

Table 6: Summary of Super-Capacitor/Battery Comparison

	Drop in Power Density (W/kg)	**Time (sec)**	**Time/Specific Power (sec)**	**Drop in Energy Density (Wh/kg)**	**Time (sec)**	**Time /Specific Energy (sec)**
Super-Capacitor	55	265	4.8	0.0096	268	26800
Battery	10.63	10822	1018	0.0023	5303	2305652

There is a big difference in time/specific power for between super-capacitor and batteries in the above table this is compatible to the known characteristics of batteries and super-capacitors. As from the above numbers it is concluded that the battery discharging time is about 100 times the super-capacitor discharging time for the same specific energy. Note that the measured battery full discharging time is 3hrswhilesuper-capacitor discharging time is 10.5 min.

To conclude this section, there are at least four reasons to use super-capacitors in a system:

- High current capability
- Long cycle life
- Ease of maintenance
- Light weight

In addition to the above reasons, there are other advantages such as [18]:

- Very high efficiency
- Wide voltage range
- Condition monitoring (state of charge)
- Long operational life

Hence, super-capacitors are mainly used in transit mode (high discharge current in short time) while batteries are normally preferred in cases of charging/discharging for long periods of time. In addition to the economic aspect where battery is mostly used due to its reasonable price compared to super-capacitor. Hybrid system management conditions and actions summary are shown in table 7.

Table 7: Hybrid System Conditions and Actions

	Renewable	Battery SOC	Super-Capacitor SOC
Supply Load	> 0	High	High
Charge Battery	> Load	Low	Low/High
Charge Super-Capacitor	> Load	High	Low
Shutdown	None	Low	Low

5. Conclusion

Energy Storage is an essential component of renewable energy systems and micro-grids. In the current study, capacitors and lead acid batteries are evaluated based on charge and discharge operation, energy density performance, power density, efficiency and cost. Super capacitor/battery experimental setup was presented. Hence, an experimental setup was built and a number of experiments were performed to compare between two energy storage alternatives; super-capacitor and battery. The results validate the assertion that super-capacitor is more suitable for rapid charging and discharging processes than battery which is more suitable for long charging and discharging times. Also, from the economic point of view super-capacitors price is much higher than batteries. A new storage technology combining the two technologies; known as super-capacitor battery, is now under a thorough investigation. This technology would be suitable to replace battery and super-capacitor to modify the I-V characteristics; as the battery exhibits problems during charging while super capacitor problems appear during discharging.

The experimental results of super-capacitor and battery led to the following conclusions:

- In case of charging the super capacitor, the charging time is inversely proportional to the current, while in discharging the time is directly proportional to the supplied load.
- The experimental results of discharging super-capacitor showed that power density, and the amount of drawn current increase with the decrease in load value, while energy density decreases.
- The battery has high energy density and low power density which is a characteristic opposite to the super-capacitor.
- Although the super-capacitor has power density seems comparable to that of the battery and high drawn current, super-capacitor reduces the discharging efficiency and consequently reduces the super-capacitor usable energy.

References

[1]. Haisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, and Yulong Ding," Progress in electrical energy storage system: A critical review", Progress in Natural Science, a Vol.19, pp.291–312.2012.

[2]. Ioannis Hadjipaschalis, Andreas Poullikkas and Venizelos Efthimiou, "Overview of current and future energy storage technologies for electric power applications", Renewable and Sustainable Energy Reviews, a Vol.13, pp.1513–1522, 2015.

[3]. A.K. Shukla, S. Sampath and K. Vijayam ohanan, " Electrochemical super-capacitors: Energy storage beyond batteries", Current Science, a Vol.79, no.12, 2013.

[4]. Philippe Barrade, Alfred Rufer, Current Capability and Power Density of Super-capacitors: Considerations on Energy Efficiency, LEI, STI-ISE and EPEL, CH-1015 Lausanne, Switzerland EPE 2012.

[5]. F. Rafik, H. Gualous, R. Gallay, M. Karmous, A. Berthon, Contribution to the Sizing of Super-capacitors and their Applications, Ecole d'ingénieurs Arc, CH-2400 LE LOCLE, Switzerland L2ES-UTBM-Univ.Franche comté, Rue T.MIEG, F90010 BELFORT, France, MAXWELL Technologies, CH-1728 Rossens, Switzerland.

[6]. William Henson, "Optimal battery/ultra-capacitor storage combination", Journal of Power Sources a Vol.179, pp.417–423, 2015.

[7]. M.E. Glavin, Paul K.W. Chan, S. Armstrong, and W.G Hurley and IEEE Fellow. "A Stand-alone Photovoltaic Super-capacitor Battery Hybrid Energy Storage System", 13th International Power Electronics and Motion Control Conference, Galway, Ireland. 2015.

[8]. Anya Castillo and Dennice F. Gayme, " Grid-scale energy storage applications in renewable energy integration: A survey", Energy Conversion and Management, a Vol. 85, pp. 885-894, 2014.

[9]. R. Mallol-Poyato, S. Salcedo-Sanz, S. Jim_enez-Fern_andez, and P. Díaz-Villar, "Optimal discharge scheduling of energy storage systems in Micro-Grids based on hyper-heuristics", a Vol. 83, pp. 13-24, 2015.

[10]. Ken Dragoon, " Energy Storage Opportunities and Challenges", Ecofys, USA, Apr.2014.

[11]. Energy Storage Operators Forum, "A Good Practice Guide on Electrical Energy Storage Report", National Solar Centre, 2014. http://dx.doi.org/10.2172/968186.

[12]. Todd Olinsky-Paul, "State & Federal Energy Storage Technology Advancement Partnership (ESTAP)", Clean Energy States Alliance (CESA), U.S., 2015.

[13]. P. Patel: http://spectrum.ieee.org/energy/the-smarter-grid/batteries-that-go-with-the-flow, 2013.

[14]. Vuorilehto, K. and Nuutinen, M., "Super-Capacitors Basics and Applications", Skeletontech, 2014.

[15]. Electrical Double Layer Energy Storage Capacitors Power and Energy Versions, 220 EDLC ENYCAP™, Vishay BC components, Jan 2016.

[16]. Guerrero, M., Romero, E., Barrero, F., Milanés, M. and González, E., "Super-capacitors: Alternative Energy Storage Systems", Power Electronics & Electric Systems (PE&ES), School of Industrial Engineering, University of Extremadura, 2015.

[17]. http://www.batteryspace.com/sealedleadacidbattery12v12ahs.aspx, 2017.

[18]. Energy Storage–The Role of Electricity", Commission Staff Working Document, European Commission, 2017.