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How and where to use super-capacitors effectively, an integration of review of past and new characterization works on super-capacitors

Sambit Satpathy[a,*], Sanchali Das[a], Bidyut Kumar Bhattacharyya[b]

[a] CSE, NIT Agartala, Jirania, Agartala, Tripura, India
[b] ECE, NIT Agartala, Agartala, Tripura, India

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ABSTRACT

The Electric double-layer capacitor (EDLC) or super-capacitors are becoming increasingly popular for their high specific power and for integrating that feature with batteries, which have a high specific energy. Due to the above reason, we have attempted to understand how to use super-capacitors and characterized them, so that both battery and super-capacitors can be used together, or for low power green energy applications, like various electronics gadgets, how to use only super-capacitors. In this paper, we described the known properties of a super-capacitor relative to a conventional lithium-ion battery. The structural design of the Super-capacitors and also various engineering-based applications, related to consumer electronics, transportation *etc.* are also described, as a review, in this paper. As we all know, that Super-capacitor's voltage would decay over time as we draw power from it, therefore maintaining the output voltage constant for any DC-DC converter without any battery is difficult. Thus, in this paper we have shown, how we have developed a DC-DC converter circuit, without any battery, which has both feed-back and feed forward control loop, in order to maintain constant output voltage. We also have developed a mathematical equation related to super-capacitor to show the requirement for having a feed-back loop can be eliminated while using super-capacitors which have very low Equivalent Series Resistance (ESR). We have also found that for some super-capacitors one cannot pump infinite current to charge a super-capacitor because the effective parallel resistance reduces as one try to pump large current and therefore charging these capacitors to a given desire voltage may not be possible. Therefore, in order to enhance the efficiency and to reduce the charging time of super-capacitor, we proposed and developed an algorithm having gamma function-based charging methodology for super-capacitor.

1. Introduction

Renewable and environmental-friendly energy resources play a vital role in residential and industrial applications.

Hydro powers, wind energy, solar powers are gaining a great deal of attention [1]. However, the generation of electricity from these sources' dependent on climatic conditions. If the climate changes rapidly, then one may need to store energy faster, and that fast charging requires low ESR (Equivalent Series Resistance). And therefore, super-capacitors can be an ideal storage device due to its lower ESR compare to any other storage devices known so far. Lower ESR also causes less power loss. The small values of ESR have many advantages when the load condition changes. As an example, when the output load condition changes that may cause a drop in the power supply, mainly due to the internal resistance of the power supply [2, 3]. That, in turn, will deteriorate the power supply quality and the performance of the electronic circuit, which makes, sometimes, the electronics components to get "*hanged*" all of a sudden, which we have found many times even in telephone or in laptop computers. Lower ESR reduces the probability for electronic gadgets to get "*hanged*" due to power supply voltage drop. Similarly, the uses of handheld devices are increasing day by day and also require higher Amp-H. In some applications, one may require initially high current, and that requires low internal battery resistance [4]. As an example, if the voltage of a lithium-ion Battery is at 3.7 V and the corresponding internal resistance is 300 mΩ, then it can deliver maximum current no more than 13Amp, and the internal resistance also causes the higher power dissipation inside the battery. If one wants to charge the battery faster using a higher current than nominal, this will cause an accident [5] and an explosion. This has been found in various cases where people get injured on various occasions while charging an electronics gadget. For super-capacitors, if the internal resistance is (5-10) mΩ or less, then one can pump even 10 Amp to charge while the

* Corresponding author.
E-mail address: sambitmails@gmail.com (S. Satpathy).

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capacitors will dissipate less than 1Watt. This was never possible before for any energy storage devices. The super-capacitor also found to have high power density, short charging time, as described above, and also eco-friendly. These capacitors were found to be more reliable, cost-effective than a battery, which was found to satisfy the power requirement of the daily usages of various electronics gadgets [6, 7]. Researchers were combing the super-capacitor technology along with the battery and made a new energy storage system which will be applicable in various industrials and other regular applications. These two technologies (battery and super-capacitors) is required for solving simultaneously two different problems. (1) For delivering instantaneously high current (*Capacitor applications*) for starting any electronics gadgets or motors at a lower frequency (in the range of 1–1000 Hz) and also to deliver constant power at constant voltage without a DC-DC converter, (which will be a battery application).

The combination of both super-capacitors, along with the battery, can help one to define a new energy storage system [8]. This is because the lithium-ion battery has the potentials to have a high value of specific energy, and that feature played a vital role in developing batteries, which can have 500 Wh/kg. In the USA, the department of energy funded a program to generate 500 Wh/kg battery cells [9]. At this point, it may be worth to mention, that a Swiss startup company name "Innolith" [9] developed a battery having 330 Wh/kg for cars to travel 621 miles when the battery is fully charged on a single shot.

This paper has been organized into seven different sections. We have given the introduction about super-capacitor in Section 1, in Sections 2, 3 we discuss prior related work and the importance of energy storage. In Section 4, we talk about an electrical energy storage system that includes conventional battery, flow battery, capacitor and also superconducting magnetic energy storage system. In Section 5, comparative studies have been done between the super-capacitor vs. conventional lithium-ion battery by considering energy density, power density, current drawn, power loss, reliability, and the relevant cost for production. In Section 5.4, we have taken the data from AVX corporation on the reliability of super-capacitors, which were taken at 4.5 V at 85C. We have also used the same capacitors to generate similar curves at various other different voltages (2V-5 V) at 85 C. This is the section where we have first time integrated our work with the work done in industries to find the physics behind the reliable super-capacitors and their performances. The model of those supercapacitors used was also described in Section 5.4. In Section 5.5, we described our modeling method and showed for the first-time gamma function-based "charging methodology", for the NIPPON DDLE super-capacitor. In Section 5, we have performed an experiment to determine the power loss of the super-capacitors vs. lithium-ion battery, and the requirements of the cooling fans to cool the batter or the super-capacitors while drawing higher current from batter or from super-capacitors.

In Section 6, we show different manufacturer based and transportation (Capa-bus) based applications of super-capacitor. The said applications can use our newly developed mathematical expression, which we have developed, and that expression will dictate if we require any feedback loop, depending on the parasitic of various circuit component's. The feed- forward loop is always needed when one uses super-capacitors since the capacitor's voltage is dropping continuously as the output load draws power from the capacitors. This is different than when one uses the battery. For battery, no feed-forward is not used, since the voltage of the battery remains constant when the output draws power. In this connection for fast charging, a new gamma function-based charging algorithm for a super-capacitor is also discussed in Section 6. Finally, in Section 7, we will end with the conclusion and also by showing references that are used while preparing this manuscript.

2. Prior related work

Recent works [10, 11] have shown that the combinations of super-capacitor and lithium-ion batteries provide excellence in the various fields related to the energy storage system (ESS). A lot of work has been done on the design of hybrid vehicles [12], wireless power transfer (WPT) [13], wind power [14], energy storage devices using super-capacitor. Hannan et al. combined a battery module and a super-capacitor module as an energy storage system (ESS) to design an efficient hybrid vehicle [15]. The lithium-ion battery has higher specific energy than super-capacitor, which provides extra power for a more extended period of time. Super-capacitor has more specific power than the lithium-ion battery, which makes it more efficient for delivering instantaneous energy in nominal time due to low ESR. This combination increases the lifetime of the combined modules, as developed by Hannan et al. WPT is the convenient charging method for electric vehicles (EVs) driven by a lithium-ion battery and super-capacitor [16, 17]. This combined technology, characterized by high power density, was found to have the following features. These features are short charging time for longer life cycles. Since the wind power is intermittent, one needs to match the storing of wind power into electric power, either by use of a battery or by supercapacitors. Mendis et al. proposed a wind farm dealing with the two-layer constant power control scheme, which is equipped with wind turbines doubly-fed by induction generator (DFIG). Each DFIG is equipped with a super-capacitor and also with an energy storage system for wind farm supervisory controller (WFSC) [18]. Sudevalayam et al. have proposed a new charging method for a wireless sensor node using Supercapacitor. Super-capacitor enables the sensor node to operate for a lifetime of 20 years without any maintenance [19]. A super-capacitor can be helpful for the operation for running an elevator for uninterruptible power supplies, where the super-capacitors manage themselves as complete autonomy of the system [20]. Mahdiyeh et al. proposed a hybrid model for an electric vehicle, where super-capacitor used for the regenerative braking system [21]. The advantages are to allow higher accelerations and lower energy loss due to the degradation of the main battery. Many researchers worked on various projects where super-capacitor and lithium-ion battery both are used to run a hybrid vehicle, elevator systems, and also wind power system [22, 23]. But the presence of the battery makes this proposed, and existing methodology requires a feedback loop due to the battery has significant ESR compare to super-capacitor. Researchers have fabricated and design nano or Pico super-capacitor which are applicable towards the system on chip (SoC) circuits to reduce the dimensions of various new consumer electronics (CE) gadgets [24, 25]. Various articles have been proposed [26, 27] on the pulse width modulation (PWM) technique for switching the DC-DC buck converter. The two most widely used methods are voltage programming and current programming. For simplification of the control loop together with, to improve the transient analysis pulse train (PT), a technique was introduced [28]. This technique needs an external power supply, which is different than our objective. This objective was to design a converter which will operate without battery or any external power supply. Few articles describe the Current Control Mode (CCM) for controlling the DC-DC converter. But this technology also required external power supply for generating the reference voltage or voltages, which makes this topology incompatible for our design [29]. Given a super-capacitor has low internal resistance compared to the external loads, one can eliminate the feedback loop from the output for all practical purposes. This is equivalent to less power consumption inside the capacitors for other external circuits, which increases the lifetime of the super-capacitors.

3. Important of energy storage technology

To store energy, a good energy storage system is required when one generates excessive energy. That is one part, but delivering that energy from that good energy storage system also brings various challenges in the future. The challenges are: storing excessive electricity and delivering that energy without power interruption [30, 31] when required, at a lower cost. Future technology will require innovations in power engineering. To reduce global emissions and fulfill the energy demand, the world moves towards the direction of renewable energy such as tide solar, geothermal, and wind. However, these renewable power generation systems depend on the climatic conditions and some other factors that are beyond our control. New hybrid (battery with super-capacitor) energy storage technology is helpful to overcome this problem by storing renewable energy and utilized during the period of peak demand [32]. Due to sudden change in load Power fluctuation occurs, and to stabilize the voltage on the power lines, one requires millions of dollars. This survey report is according to the Lawrence Berkeley National Laboratory (LBNL). It was reported that the government of the US spends US$80 billion annually for maintaining the power interrupt for their consumers [33]. This enormous amount of expenditure can be reduced by using new energy storage technology. That technology can provide long term back up power when massive power failures occur in various local grids or next to where the consumers are using their required power. These back up power storage can be super-capacitors modules having lower ESR or battery modules or a combination of both.

4. Over view of electrical energy storage system

On the basis of response characteristics, energy storage systems are classified into six different types, such as Electrical storage, Hybrid storage, Chemical storage, Electro-chemical storage, Mechanical storage, and finally, Thermal storage [34]. In Fig. 1 below, we describe in detail the electrical energy storage system only. There are many electrical storage technologies; we considered only four of them, which we are going to describe below.

- Conventional-Batteries (Lead-Acid, Nickel Cadmium, lithium-ion, Sodium Sulphur)
- Flow battery energy storage
- Capacitors (Ultracapacitor, Super-capacitor)
- Superconducting magnetic energy storage

4.1. Conventional-Batteries

In a battery storage system, electrical energy is obtained from chemical energy. This energy storage system consists of several technologies, such as Lead-Acid, lithium-ion, Nickel Cadmium. Lead-acid energy storage technology is the oldest and versatile among all battery storage technology. Lead acids widely used in battery storage technology like in uninterrupted power supply due to its advantages such as low self- discharge rate, low cost, and requires very little maintenance. Still, it has disadvantages like low power density, high weight due to the presence of lead and not eco-friendly for high toxicity, [23] because of acid inside these lead batteries. Sometimes it is also required to put distilled water if it is outside in the heat in the summer time. Sodium Sulphur batteries have a wide range of power storage capabilities, and multiple devices can be allowed to connect together to increased power capacity. It is high-temperature battery technology, operated at (300–350) C. It has a solid electrolyte, one of the electrodes is molten sodium, and another one is molten sulfur, and cell reaction occurs between them. As we all know that sodium some time behaves like an explosively, which makes the system unreliable [7]. Similarly, in Japan, 2012, a fire was reported from sodium-sulfur battery installation. In the real-life application, lithium-ion battery is pretty much controlling all the portable electronics markets and also the medical equipment. The advantages of this technology are the following: - (1) high energy density, (2) can be recycled, (3) low memory effect, and (4) very less leakage current.

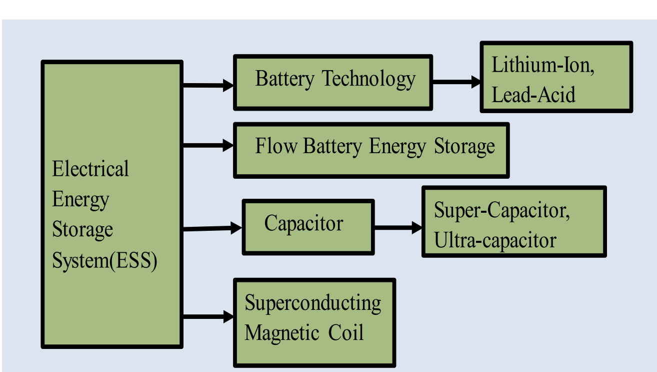

Fig. 1. Various types of Electrical storage system.

4.2. Flow battery energy storage

It is a rechargeable battery, where charging of the battery will be done by two chemical Components that mixed in the liquid, and a membrane, which separates these chemical components. Both fuel cell and the battery have similar characteristics where liquid energies are helpful to generate the electrical energy and also helps that battery system to recharge. One of the most significant advantages of this energy storing system is that it can be charged in a reasonable time, depending on Amp-H, and it has very low self-discharging (due to the electrolytes) property than other systems. But the charging time for such batteries is still less significant compare to super-capacitors. It has relatively a long-life span (about 3–4 years) and requires low maintenance. But, because of their form factor, the flow battery is not utilized for quick power generation [39].

4.3. Capacitor as energy storage device

A capacitor keeps energy in the form of an electric charge. It is constructed by two metal plates, separated by an insulating material called dielectric [28]. The total energy stored is 0.5 CV^2, where C is the value of the capacitor, and V is the corresponding voltage between the two conducting plates. When any load is connected between these two plates, current flows through the load till the voltage (V), goes to zero. Super-capacitors are also called Electro-Chemical Double Layer Capacitors (EDLC). These capacitors have a very large surface area and a very thin dielectric layer and hence the spacing thickness. Consider a very thin insulator; both sides are coated with metals, one side works as power, and the other side works as ground. If a dielectric paper is rolled in the form of the cylinder [7], then one gets a large surface area, and that makes the value of capacitance very large. The advancement of technology in future will help to reduce the thickness of the dielectric, and then the value of the capacitance per unit area will increase inversely as that thickness.

4.4. Superconducting magnetic energy storage

The magnetic energy stored occurs in the form of a magnetic field, which is created by a high DC current flows through a superconducting coil. The magnitude of this current can be over 2×10^5 A/cm^2 for niobium superconductors [50]. This high current makes the energy stored inside, in any coils having finite inductance is very large. Usually, this energy can be taken out to store in various devices in the network. The network may have the capacitors also.

The process of storing such large energy is still a hot research topic. This process requires building an intelligent control circuit to make sure the efficiency of energy transfer from magnetic to other energy remains high, preferably close to 95% [45].

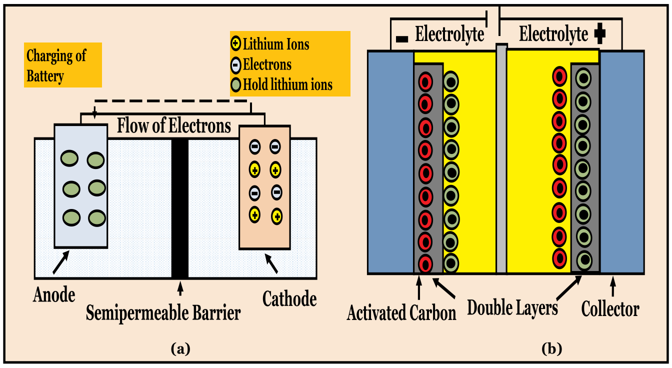

Fig. 2. (a). Design structure of a lithium-ion Battery. (b). Design structure of a super-capacitor.

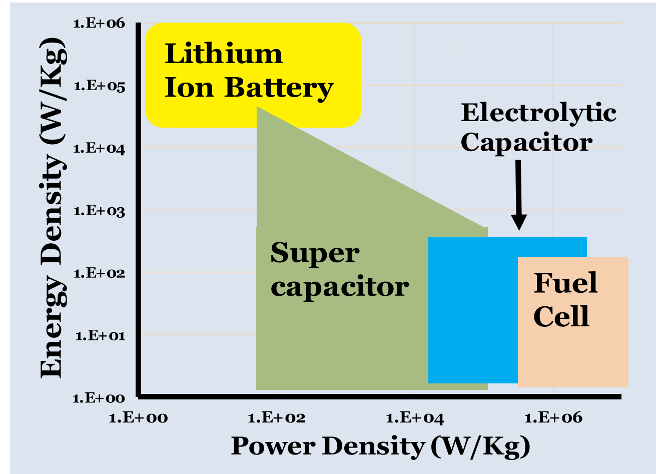

Fig. 3. Comparison of the energy density and power density of super-capacitor and Lithium-ion.

5. Comparisons of energy storage technology: super-capacitor vs. lithium-ion

5.1. Design structure

A super-capacitor differed from a regular capacitor in two different ways. Firstly, the parallel plates have larger surface area; secondly, the distance between them is much smaller. The electrodes are coated with activated carbon powder, and at the interface of activated carbon and electrolytes, an electric double layer will form. When we charge the super-capacitor, the –ve ions having on + ve electrode and the + ve ions on the –ve electrode side are arranged across the interface, as shown in Fig. 2b. This kind of arrangement of cations and anions are called an "electrical double layer". The purpose of "*activated carbon*" on the electrode increases the surface area. Larger the surface area, larger will be the charge storage, and hence the capacitance value will increase. The physical movement of electrons causes this layer to form, and no chemical reactions are involved like a conventional lithium-ion battery. It makes the super-capacitor higher charging and discharging the life cycle [29] compared to any battery technology. This double-layer structure of super-capacitor design leads to less ESR (equivalent series resistance), which makes the super-capacitor fast charging possible compare to the conventional lithium-ion battery [30].

In the present days, there are various efforts researchers are making to increase the surface area of the electrodes for batteries and also the surface area of the cathode and anode of the super-capacitors. Researchers are working on Sodium-ion batteries as an alternative to a lithium-ion battery because of higher technical improvement, higher energy density, less toxicity (because of earth-abundant), and having low cost than other conventional battery [35] technology. MOF (Metal-organic framework) is a class of organic compound where researchers put a great effort to increase the surface area of electrodes and hence to increase the efficiency and capacity of energy storage system for sodium-ion, lithium-ion and also for super-capacitor [36]. In the energy storage system, electrical conductivity has been given much more importance. To enhance this, Li et al. used cobalt doped nickel phosphides (bimetallic) [37]. But it is necessary to use the appropriate ratio of nickel and cobalt (4:5) to design the 2D nanosheets, which make the energy storage system more efficient [38]. For higher capacitance, researchers have been used nickel-based material. It has low conductivity (higher ESR), and the doping with conductive nano materials results in an increase in the conductivity, and that helps to raise the capacitance [39].

5.2. Energy density vs. power density

In every day, real-life applications such as portable electronics, medical equipment lithium-ion batteries have already proved its excellent performance [40]. A typical lithium-ion battery has a high energy density; it is also recyclable and works at a higher temperature, namely 60 C. This can be an *ambient* (not junction temperature inside the chips) temperature inside any personal computer. The other promising characteristics of the lithium-ion batteries have low memory effect, having 10–100 Wh/kg high specific energy, the 1000–3000 W/kg specific power, and reasonably long battery life ranging from 2000–30,000 cycles [41]. Super-capacitor has the longest life cycle with low energy density, and it is due to not having any chemicals or chemical reactions inside the super-capacitors. Fig. 3 shows the comparison power density and the energy density of super-capacitor with other systems like a lithium-ion battery, an electrolytic capacitor, fuel cell, etc. In a super-capacitor, the charges are stored on the electrode since the power density is considerably higher (See Fig. 3 along the horizontal axis) than the lithium-ion battery. And also, it has few orders of magnitude less ESR compare to lithium-ion battery [42, 43].

Fuel cell (FC) can generate electricity by making the chemical reaction between anode and cathode through an electrolyte. The FC is found to have a high conversion efficiency rate of fuel to electric energy, low emission, high reliability, and durability [44]. FC has some drawbacks such as low energy density [(1–100) W/kg], high response time, and cost per unit is more compare to other energy storage devices. The amount of power drawn is the efficiency of FC. If one draws more power from FC, then efficiency will be reduced [45–47].

5.3. Comparison of current drawn vs. power loss

In Fig. 4, we show the comparison between the Current delivered and power loss properties of super-capacitor versus the lithium-ion battery. This was a measured data, measured at NIT Agartala laboratory [65]. The green curve is the power consumption by super-capacitor due to its ESR, while the purple one is the power consumption by the lithium-ion battery. The black dotted line signifies that battery may require fans to cool if power drawn is approximately more than 10 W. The lithium-ion battery, when operating over 10 W or more power, then it may burst if no cooling system is provided to cool the battery. These types of overheating cases were seen in various places. In South Korea, a battery of Samsung mobile has caught fire. A similar incident has happened in 2012, March, in which Samsung Galaxy (Model- S2) battery exploded in a student pocket [7]. But super-capacitor has very less ESR due to which it dissipates less power than a lithium-ion battery and may not require any cooling fan.

5.4. Reliability of super-capacitor

Before the release of any products, like super-capacitors, it is

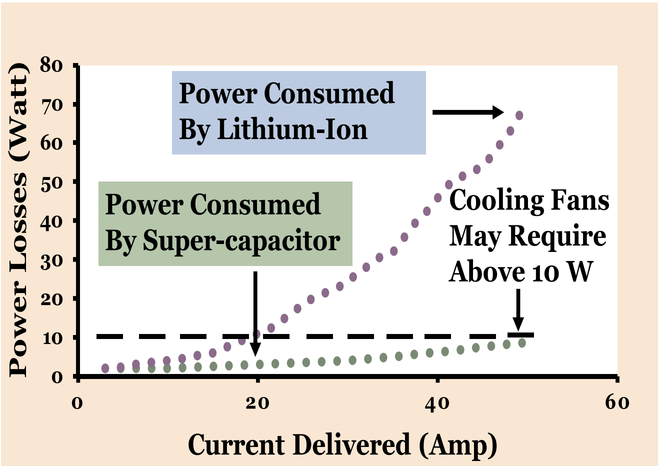

Fig. 4. Comparison of the Current delivery with power loss of super-capacitor vs. Lithium-ion Battery.

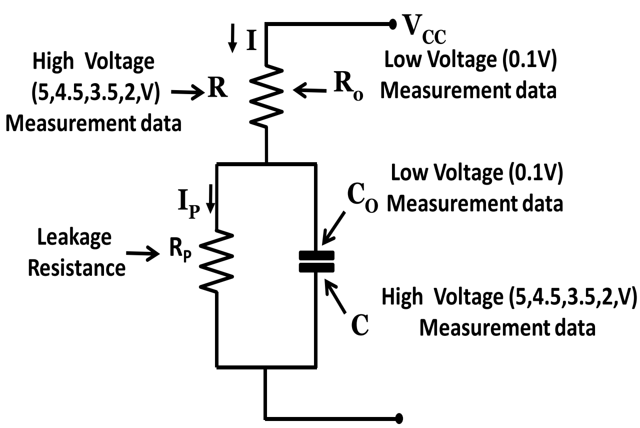

Fig. 5. (a). Equivalent Circuit of super-capacitors. (b). Capacitance, ESR of AVX super-capacitor vs. Time.

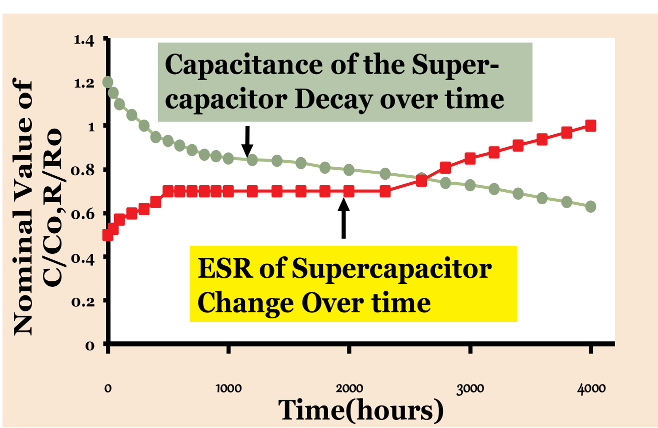

Fig. 5. (*continued*)

essential to make sure that these capacitors are reliable. The reliability and quality of a given component have to be well determined before one can sell a product in the market. That also includes safety. Accelerated testing procedures determine an average lifetime of the part, and that is an essential number to quantified, as one ramp towards the higher volume productions [48, 49]. In Fig. 5a, we show the equivalent circuit of the super-capacitors. In that Fig. 5a, R_p, the leakage resistance. The resistance R is called ESR.

This value of R is measured at various high voltages (5 V, 4.5 V, 3.5 V, and 2 V), which are shown in Fig. 5a at the top left side. This we call high voltage measurement. The Values of R_O are measured at low voltages, which are less than 100 mV using an impedance analyzer; this is shown in Fig. 5a on the top right corner. Similarly, the values of C and Co are measured at higher voltages (namely 5 V, 4.5 V, 3.5 V, and 2 V) and voltages less than 100 mV, respectively. In Fig. 5b, we show the measurement done by AVX corporation for their super-capacitor, called them SCMT22C505MRBA0 [46, 47] at 85C at 4.5 V. In that Fig. 5b, they plotted *(C/C$_o$)* and *(R/Ro)* as a function of time. We have also measured (R/R_o) and (C/C_o) values at the center of innovation at NIT Agartala at 2 V, 3.5 V, 5 V as a function of time. So, we have data at four different voltage values for the SCMT22C505MRBA0 super-capacitor developed by AVX. All these capacitors were kept in an oven at 85 C for about 4000 h [49]. At 2600 h, the capacitance value for these capacitors was dropped by 30%, and ESR values were also found to be creeping up, as can be seen from Fig. 5b, from the measurement which was done by AVX. It is interesting to note that at any given time, the value of (RC/R_OC_O) for AVX data is almost constant. This plot of these measured data, as taken by AVX, is shown in Fig. 6a, using solid blue circles. The averages of all these solid blue circles are close to 0.6. A horizontal dotted blue line shows this average value.

AVX data were taken at 4.5 V at 85C temperature. To understand this constant value of 0.6 for AVX data, one can assume the resistance increases because the separation between the two conductors of the super-capacitors increases. This increase is caused by having these super-capacitors exposed for longer time in an oven at 85C, while maintaining the voltage across the capacitor's terminals at 4.5 V. Since the spacing between the conductor increases, therefore the capacitance value reduces as the distance between the two conductors increases. In order to validate these flat constant values, we have also taken data at 5 V, 3.5 V, and 2 V. These are also plotted in Fig. 6a. The black triangles,

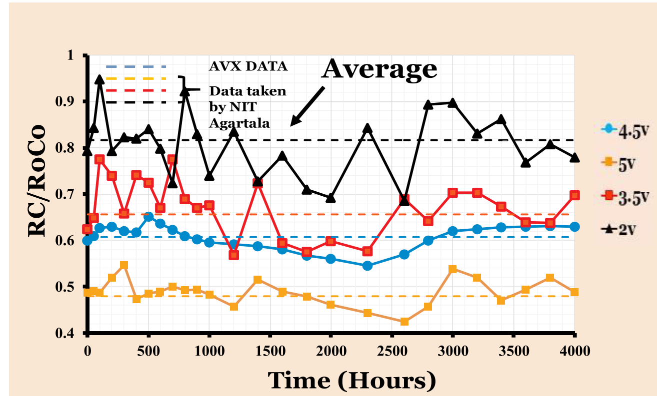

Fig. 6. (a). Ratio of product of time constant to the nominal value of time constant Vs. time. (b) RC time constant vs. charging voltage (Slope).

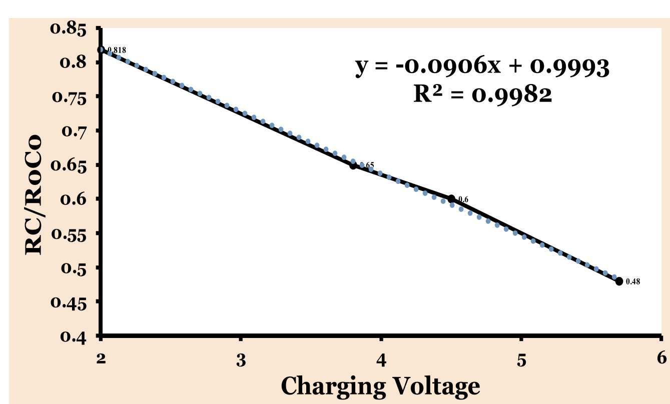

Fig. 6. (*continued*)

in Fig. 6a, are taken at 2 V, red rectangles are taken at 3.5v, blue circles are taken at 4.5v (AVX data), and brown rectangles are taken at 5v. All these data show that the value of (RC/R_OC_O) is constant and independent of time. But the magnitude of these constant values depends on the applied voltages to these super-capacitors in the oven at 85C. In Fig. 6b, we have plotted these constant values as a function of the applied voltage. It is interesting to observe that as the voltage at which these capacitors are kept in the oven reduces to zero. Then the value of (RC/R_OC_O) of these capacitors increases, and eventually, it goes to a unit, which can be seen from Fig. 6b. Thus, these capacitors, EDLC, have interesting characteristics where (RC/R_OC_O) remain constant and independent on how long the parts kept is an oven at 85C.

It is also important to say, even after 2600 h (Fig. 5b) In the oven, the operating conditions for these super-capacitors can still beat or equivalent to any lithium-ion battery in terms of the following properties: 1. Operating voltage, 2. Lower ESR values, 3. May have less Charging time and 4. Also, the capabilities to deliver the maximum peak current. Therefore, both these two technologies can be integrated to develop any hybrid energy storage system.

5.5. Charging methodology of super-capacitor

In (1) and (2), we show how the super-capacitors will charge and discharge. All the parameters are described in Fig.5a. The model used is also Fig.5a. for getting (1) ad (2). V_{cc} is the saturated voltage across the resistor R_p. V_p is the voltage drop across the capacitor, which is time-dependent. In the limit of time goes to infinity, the voltage at the super-capacitor become V_p, which is basically the current I_p passing through the resistor R_p, times the value of the same resistor $R_{p,}$ this is shown in (3).

$$\frac{V_P}{V_{cc}} = \left(1 - e^{\left(-\frac{t}{(R_p+R)C}\right)}\right) \tag{1}$$

$$\frac{V_P}{V_{cc}} = \left(e^{-\frac{t}{R_PC}}\right) \tag{2}$$

$$V_P = I_P R_P \tag{3}$$

When the capacitor is totally charged, then the current I_p is precisely the same as the current coming out from the power supply, V_{cc}. In Fig.7a, we show the charging of the Nippon super-capacitors using 600 mA current using a power supply (PSD3304, Scientific Company), which was supplying the said current (600 mA) at 3.478 V. We have also assumed the total capacitance value of the Nippon DL-super-capacitors at 60C to be around 700F at 2.5 V. We were also monitoring the voltage of the super-capacitors, once the voltage of the super-capacitor reached at 2.5 V, we shut the power off. In Fig.7b, we show the natural log plot as a function of time to determine the time constant of the (2) which is (Rp + R) C. The least-square regression shows the value of (Rp + R) is about 5.807 Ω, this is when we were charging the super-capacitor using 0.6A current. This set of data is documented in row number 2 in Table. 1. We have used various values of current to charge these super-capacitors, and the values of (Rp + R) obtained are shown in Table 1 column 3. In order to determine the value of R_p, we have considered the self-discharge characteristics of the super-capacitors, to get the value of $R_{P,}$ only. Fig. 7c shows the self-discharging, and Fig.7d shows the natural log plot as a function of time, to determine R_pC value. The Eq. (2) is used for the calculation of self-discharge time constant.

The slope of the curve from Fig. 7d shows the value of $1/(R_pC)$, which is about 2.466×10^{-4}/sec. This gives the value of R_p close to about 5.793Ω, assuming $C = 700$F. In Table 1, the fourth and fifth column shows the values of R_p, parallel leakage resistance, and the series resistance, R respectively. It is essential to mention that the values of R calculated is very small (shown in column 5th., Table 1) compare to lithium-ion batteries, which are in the range of 300 mΩ [7].

The average value of R for the super-capacitors, we have measured is close to, about 6mΩ. It is also important to see the value of R_p depends on how we are charging the super-capacitors. The value of R_p is larger when the current is low for this Nippon DL super-capacitor. In Fig. 8a, we show the plot of the value of the resistance R_p as a function of the total current I (See Fig. 5a), coming out of the power supply, V_{cc}. The empirical relation between resistances Rp vs. current coming out of the power supply is given by the following Eq. (4) below. The residual sum of square (χ^2 distribution) is about 0.98 (See Fig 8a), which indicates that our data fits well.

$$R_P \approx 9.62e^{-1.017I_p} \tag{4}$$

From the above Eq. (4), one can calculate the value of the voltage drop across Rp (see Fig. 5a), given the super-capacitor is fully charged. When the capacitor is fully charged, then the current through R_P is the same as the total current supplied by the power supply having voltage V_{cc}. Thus, the voltage drop across R_P can be written using the equation below. In Fig 8b, above, we show the plot of voltage drop (V_p) vs. current supplied by the power supply when the capacitor is fully charged.

$$V_P = I_P R_P \approx 9.628\ I_P e^{-1.01 I_P} \tag{5}$$

It can be seen that if we need to charge these capacitors to 3.5 V, then we can only pump maximum current, close to about ∼1Amp. Above that current, the capacitor will not charge to 3.5 V. The perception that one can pump large current through any super-capacitors to charge these capacitors in a short time is not an accurate statement. As described that one needs to pump only ∼1Amp to charge these capacitors to 3.5 V, above that 1Amp current it will charge up to some value of voltage, which is less than 3.5 V, depending on the Fig. 8b. It is essential to mention that one can use this plot, Fig. 8b, to design a control circuit which will help one to charge the capacitors in the shortest time. In Section 6.5, below, we will describe a flow chart showing how to maximize the charging time using the Fig. 8b, as shown above.

5.6. Cost per productions of super-capacitors

The usages of super-capacitor are increasing day by day. Researchers have tried to design the super-capacitors from Low-cost materials having higher efficiency and also by choosing materials which has a lower loss to reduce the values of ESR. As a result, the cost of the production of super-capacitor has decreased from 80 cents per Farad in 1996 to 10 cents per Farad in 2010 [51]. Now a day these capacitors can be built at much smaller cost, which is around 2–3 cents/Farad. These data are plotted in Fig. 9, in that figure we show the cost per Joule. In Table 2, we collected all comparison data of super-capacitor with lithium-ion batteries, which can be handy to start or to initiate a design, which can be an effective energy storage system. In that Table 2, one can see that there are various features in supercapacitors that are superior to the lithium-ion battery. One of the disadvantages that a super-capacitor always requires a DC-DC converter to maintain a constant output voltage. But the lithium-ion Battery can supply constant voltage during its whole operation time [53].

6. Applications of super-capacitor, future scope and issues

In this section below, we will discuss in detail about the recent emerging applications of super-capacitor, future trends, and issues related to super-capacitors. Fig. 10 tells about different types of applications of super-capacitors, which consist of various sub-modules such as structural and design-based applications, product-based applications, and finally, various engineering applications.

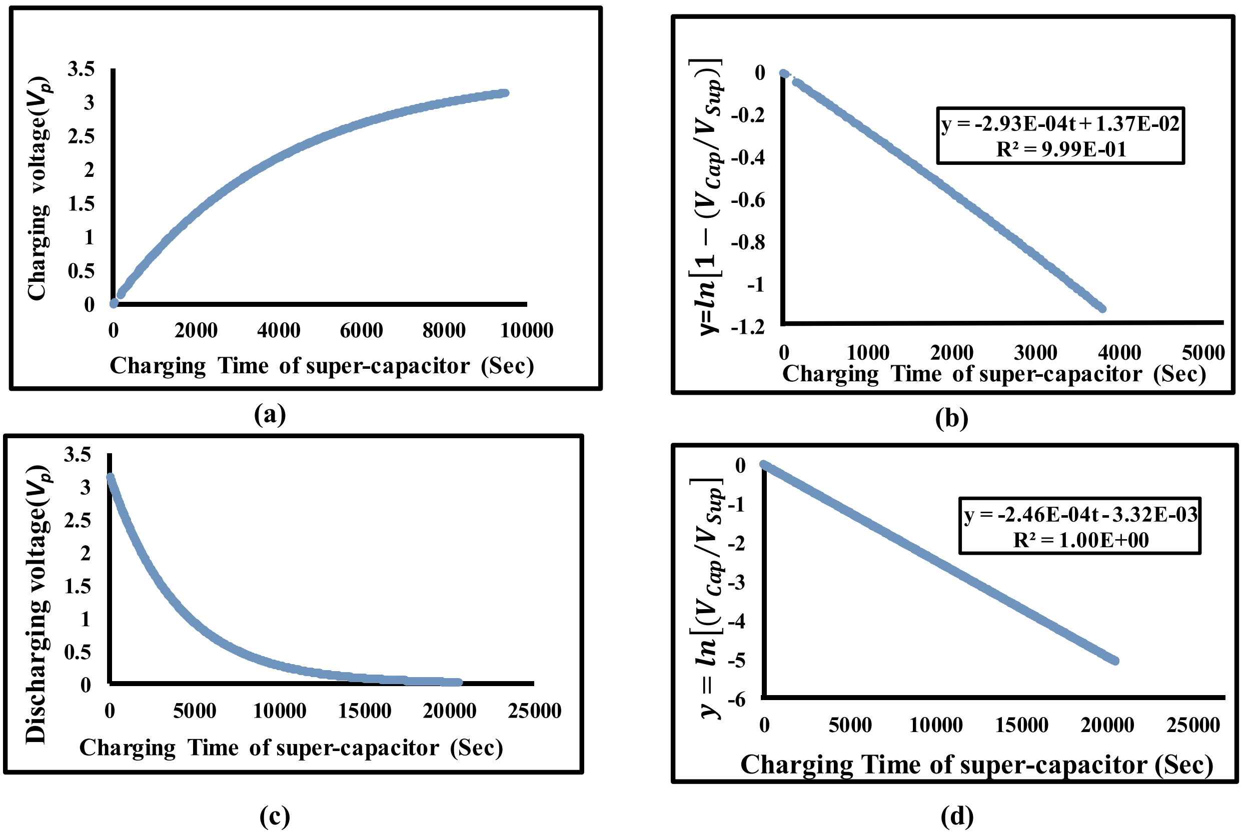

Fig. 7. (a). Charging of super-capacitor using 600 mA Constant current, (b). Natural log plot as a function of time to get the value of the time constant (Rp + R) C. (c). Self-discharging of super-capacitor after the capacitors are being charged using 600 mA constant RpC.

Table. 1
Experimental data for charging super-capacitor with different values of constant current.

Power Supply(v)	Different Current value	Rp + R (Charging) in Ω	Rp (Discharging) in Ω	R (Ω)
3.8	0.25	7.21	7.202	0.008
3.478	0.6	5.807	5.79	0.014
3.308	1.0	3.208	3.203	0.005
3.26	1.25	2.602	2.601	0.001
3.21	1.5	2.201	2.197	0.004

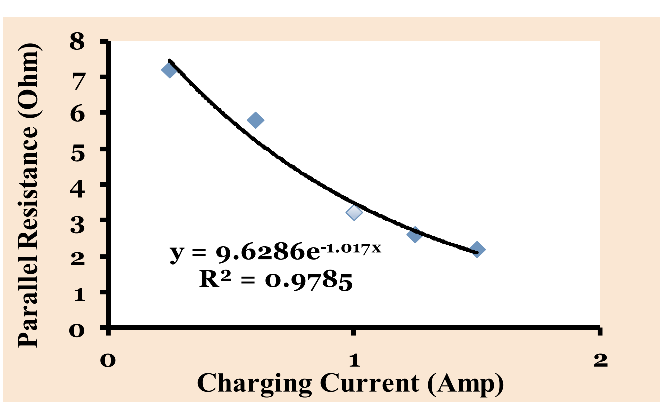

Fig. 8. (a). Charging current of super-capacitor Vs Parallel resistance. (b). Charging current of super-capacitor Vs Voltage drop in Rp.

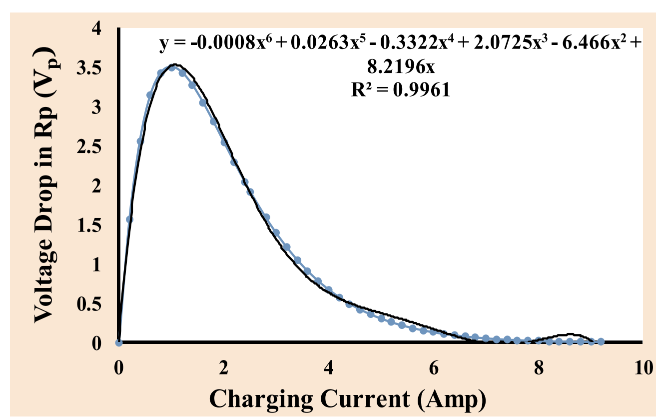

Fig. 8. (*continued*)

6.1. *Applications of super-capacitor on manufacturing basis*

Super-capacitors have three main components, such as an electrode, electrolyte, and dielectric separator. The electrodes are rolled into a jelly roll configuration, such as an aluminum electrolytic capacitor. Phosphorous separator is present between the electrode to prevent short circuits.

The terminals of the electrodes are present outside of the capacitors. The Maxwell technology, which is the world's leading manufacturers, standardized the diameter to 60 mm, and the specific height of SC helpful to achieved desired capacitance. Pouch super-capacitors are designed for better heat dissipation while charging or discharging these capacitors [55, 58] It offers a simple, flexible, lightweight solution, suitable for high power density instead of using cylindrical SC. But it also has one issue, i.e., the whole capacitor is sealed in a plastic bag,

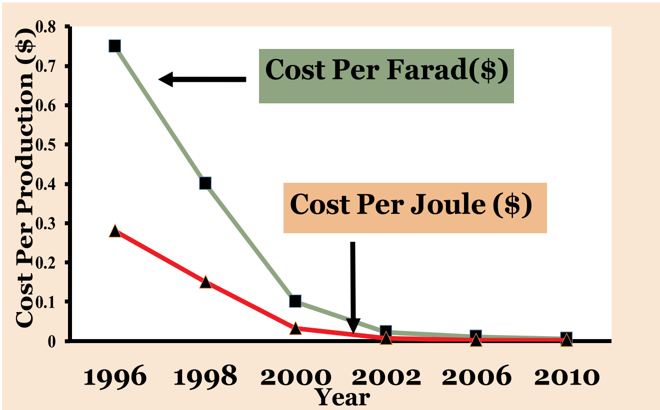

Fig. 9. Cost Per production of super-capacitor with time.

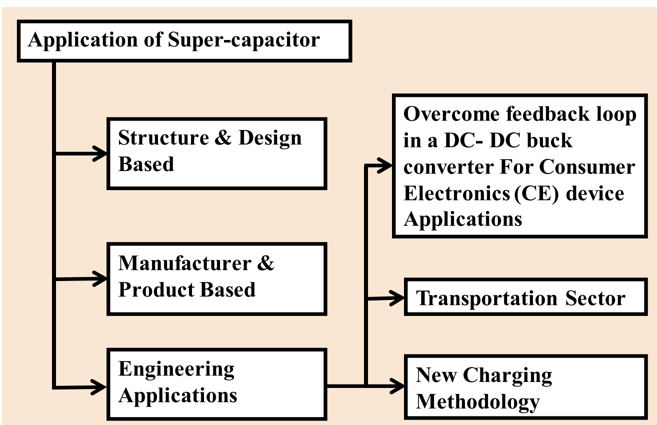

Fig. 10. Applications of super-capacitor.

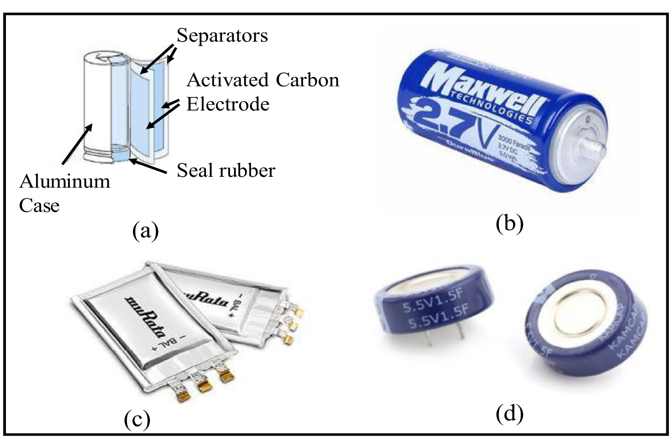

Fig. 11. (a). Internal structure of cylindrical super-capacitor [52]. (b). Maxell super-capacitor [54] (c). Pouch super-capacitor [55]. (d). Button super-capacitor [56]. (e). Equivalent circuit model of pouch super-capacitor.

which increases the packaging cost. For higher voltage applications and smaller portable devices, one used button super-capacitor. It is useful for devices like a cordless phone, medical devices, wireless sensor devices, a portable sensor used in the airport. This type of SC swelled up if one charges these capacitors too rapidly. These button super-capacitors do not have any safety vent during charging. In Fig. 11e, we show the equivalent circuit for the Pouch super-capacitors. Interestingly it can be used to power up any op-amp with both Positive and negative voltages applied to any operational amplifier. These two capacitors can be connected either in series or in Parallel for getting higher voltage and

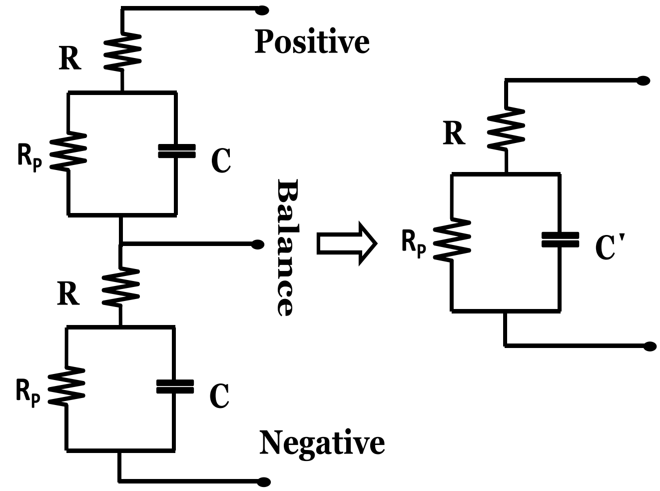

Fig. 11. (*continued*)

total capacitance value close to C/2. While in Parallel the total capacitance will be 2C with maximum voltage according to the specifications as per manual of the manufacturers.

6.2. Super-capacitor manufacturers and their products

This section describes a comparative study and analysis of different types of super-capacitor manufacturers and their product specifications. In Table 3, we consider seven SC manufacturers such as Maxwell technology, Nippon Chemi-Con, Nec Tokin, Panasonic, Yunasko, LS Mtron. The key features of the super-capacitors are described in columns 4 to 7 in Table 3. These features are capacitance value, cell voltage, and energy density. North America based SC manufacturing company Loxus is represented in the first row of Table 3 [57]. It offers the highest standards and producing the most flexible problem-solving methods for storing and also for power delivering in a short time. The products of Loxus are used for backup power supply, hybrid drive trains, wind-mill pitch control, and crane hybrid gen-sets. The Second world's leading SC manufacturing company is now Maxwell Technology. They are a global leader in developing and manufacturing power delivery solutions for renewable energy, UPS, heavy transportation, wireless communication, etc. [58]. All SC manufacturers are providing symmetric super-capacitors except Nippon Chemi-Con, and Yunasko. They offer some hybrid models. But most of the time, the manufacturers are providing a customized module that adapted to the power and energy requirement of each customer, which may be applicable for a specific application. It was found that Panasonic Company centers its whole product line on the super-capacitor cells and coin super-capacitors [61], as shown in Fig. 11d.

As described before, these capacitors can deliver a very large instantaneous initial current, which is required for application for running any electrical Motor. This can be a car engine or can be a central Air Conditioning Units in any house. If the current initially is not sufficient, then the reliability of motors also reduces, and hence the lifetime of those motors also reduces. Thus, having a super-capacitor to pump initial current requirement, to start any electric motor can, in principle, increase the reliability of products. Finally, in Table 3, we describe applications and various power and energy density properties for someone to choose an appropriate vendor for one's specific application.

6.3. Applications of the super-capacitor to over-come feedback loop in a DC-DC buck converter

In order to run any DC electric motor or any electronics gadgets using only a super- capacitor, one needs to build a DC-DC converter.

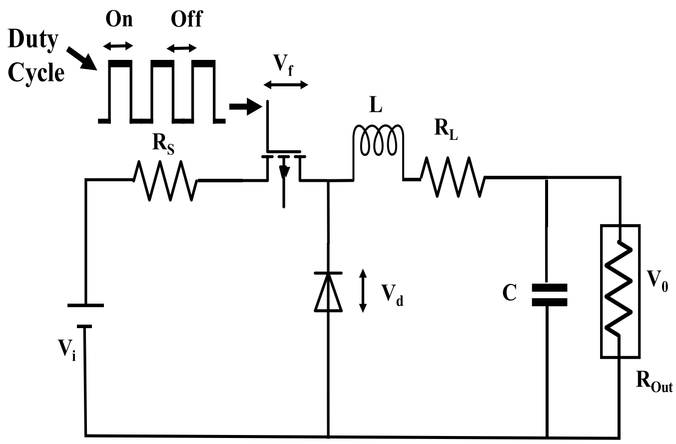

Fig. 12. DC-DC buck converter in continuous mode with non-linearity.

This then can provide the desired current at a constant voltage. In Fig. 12, we show a simple DC-DC converter which is running without any battery, having a constant input voltage $V_{i.}$ In Table 4, we show the definition and values of all the parameters of the converter, which is described in Fig. 12 below. When the buck converter (DC-DC) is operating in CCM (continuous conduction mode), in the ideal case, the pulse applied at the switch has a duty cycle, which is ratio between output and input voltage, i.e. $D = V_0/V_i$. During this, parasitic of each and every active and passive component are negligible. But in real-world (non-ideal case) buck converter has parasitic, and the exact DC relationship is represented by (6). The exact low-frequency DC relationship is shown below.

$$V_0 = \frac{(V_i - V_f)D - V_d(1 - D)}{1 + \frac{R_L}{R_{Out}} + \frac{DR_s}{R_{Out}}} \tag{6}$$

In Fig. 13, we show the actual DC-DC converters that we have designed in our center of innovation laboratory, which runs without any battery. If the output load resistance changes or any other parasitic resistance of the circuit changes, then for a given duty cycle, the output voltage will also change [63, 64]. In that case, the load fluctuation can

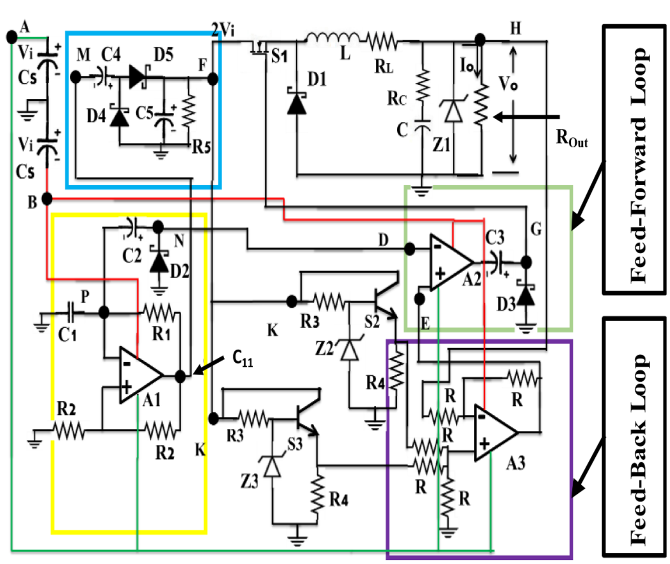

Fig. 13. Buck topology solely working using super-capacitor module.

Fig. 14. Capabus in Kai Tak, Hong Kong [66].

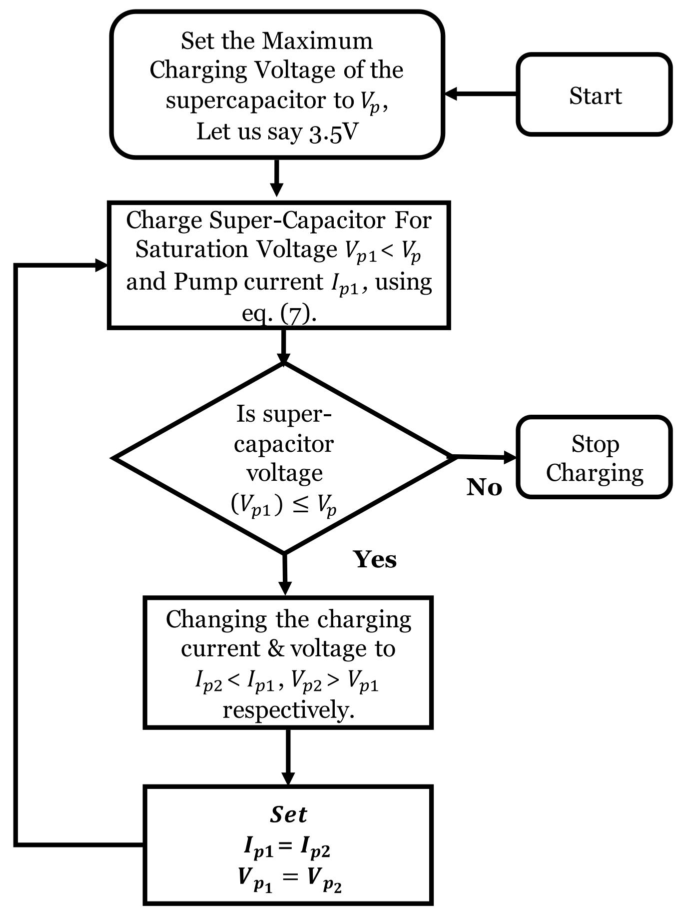

Fig. 15. New gamma function-based charging methodology of super-capacitor.

be stabilized by a feed-forward and feedback loop. This, in turn, changes the duty cycle and amplitude of the voltage at point 'G'. In this way, this buck topology is useful to produce a constant voltage during all kind of loads fluctuation, while using super-capacitors only. This is a unique buck topology where the whole circuit is operating by two super-capacitor modules. V_i and C_s are voltage and capacitances for

Table.2
. Performance comparison between super-capacitor and lithium-ion battery.

Parameter	Super-capacitor	Lithium-ion Battery
Voltage (Volt)	2.5	3.7
ESR (Equivalent Series Resistance)	8mΩ {Measured using impedance LF Analyzer} [Table.1]	300mΩ
†Energy Density	55 J/cm^3	89 J/cm^3
††Leakage Current	100μA (30 Days to Discharge)	58μA (70 Days to Discharge)
†Specific Energy	1–10 Wh/kg	10–100 Wh/kg
†Specific Power	Up to 10,000 W/kg	1000–3000 W/kg
†Efficiency	98%	75–90%
†Cyclability	5×10^5–2×10^7	500–1000
†Life	10–15 years	5–10 years
Capacitor Values	700F	780F (From Amp-H Calculation)
††Time to Charge	2–6 Min	120 Min
§Reliability	It passes through Six different tests	Less reliable than Supercapacitors.
§§ Deep discharge, Thermal runaway, Overload, Risk of explosion	No	Yes
*DC-DC converter essential for working	Yes	No

*Ref. [7], †Ref. [52], ††Ref. [24], §Ref. [5], §§ Ref. [23].

each super-capacitor modules, respectively. A positive voltage of the super-capacitor is denoted by cyan color, negative voltage represented by dark red color. The whole topology consists of five modules. They are triangular wave generator, voltage doubler circuit (VDC), DC-DC buck converter, feedback, and feed-forward loop modules. The circuitry inside the yellow border line generates V_i dependent triangular wave. The voltage doubler circuit represents by a blue box. The feed-forward loop and feedback loops are represented by a green and purple color box, respectively. A bipolar triangular wave at node 'P,' generated by the circuit enclosed by the yellow box and the clamper circuit, converted it into a unipolar triangular wave that followed by point 'N,' which connects to the node 'D'. A reference voltage is generating at point 'E', which compares with the triangular wave at 'D' and producing a bipolar switching pulse at Op-amp, A_2, *at* point 'G', which is the output of the Op-amp A_2. Again, a clamper circuit used to make the bipolar signal into a unipolar switching-pulse (S_1) with a required duty cycle to make a constant output voltage of the DC-DC buck converter. The triangular wave which is generated at point 'C_{11}' is feeding to the VDC, which is a voltage doubler circuit (blue box), with output voltage almost $2V_i$ at *'F,'* which act as an input for the buck converter. It is shown that all the components of our buck topology consumed the same amount of power with the same discharge rate from both super-capacitor modules, which indicate our circuit performs well.

The Eq. (6) can be used to see the output voltage is not dependent on load when R_s and R_L are very small compared to the load resistance R_o. That means if the load changes, then the output voltage will not change. An operational buck converter was developed and built at the center of Innovation [67] at NIT, Agartala. We measured that the average internal resistance of super-capacitor was ~8mΩ (see Table 2), and the resistance of the inductor is about 50mΩ (See Table 4). We also measured the super-capacitors resistance by deploying 4-terminal methods, using an impedance analyzer at very low frequency in the range of 1 Hz to 100 Hz. The estimated lead inductance value measured for these super-capacitors is in the ranges of (20–50) nH. This is negligible compared to the series inductor used for this converter, which is about 100mH. For 500 mA applications, for handheld devices that run at ~4 volts and having an output load of ~ 8Ω, the percent of voltage fluctuation will be less than 1.5% when the load reduces by a factor of two (4Ω). This is why we are using super-capacitors, which are known to have lower internal resistance, which for all practical purposes, may eliminate the feedback loop requirements from the output. This happens due to the low resistance of the interconnects and the source of internal resistance. For Li battery, the internal resistance is about ~300 mΩ. Thus, one can see from (5) that the voltage fluctuation will be over 10% when the output load reduces by a factor of two (from 8Ω to 4Ω). Therefore, the output feedback loop will be required to meet the Power Supply specifications for silicon chips used for handheld devices while using lithium-ion. The advantage of super-capacitor over Li is shown in Table 2.

6.4. Transformation sector

Super-capacitors are providing new technology that offers to store 20 times more energy than other electrolytic capacitors, which was found to enhance its application in the field of the transportation sector. One more characteristic of super-capacitor (SC) is, it has better specific power than the lithium-ion battery that leads to fast charging and discharging properties of SC without deterioration of performance. These properties of SC provide benefits to locomotives for better design of synchronized regenerative braking of any given high-speed moving vehicles for every compartment of the locomotives [43]. China is experimenting with some Capa-Bus (Electric bus run by SC) that runs

Table.3
Super-capacitor companies, their product and applications.

No, Company Name, Country	Application	C	Cell (Farad) (V)	Energy density (Wh/Kg)	Power density (KW/Kg)	Rev- enue
1. Loxus, USA [57]	UPS, Transportation.	100–3000	2.3, 2.7	6.4	23- 34	$160.1 Million
2. Maxwell Technology [58]	Renewable energy Transport.	10–3000	2.2, 2.7	6	2.4–14	$130.4 Million
3. Nippon Chemi-Con, Japan,1931 [59]	backup power systems. Various electronic component.	1–3000	2.1, 2.3	4	4.9–6.5	$1.02 Billion
4. Nec Tokin, Japan, 1938 [60]	Energy & Network Devices.	350–2300	2.7,3.8	4.2	3.5–6.1	$24.0 Billion
5. Panasonic, Japan [61]	Electronics Devices	0.015–70	2.1–2.3	5	.29–0.0035	$71.8 Billion
6. Yunasko, Ukraine, 2010 [62]	Transport, Electronics, Energy	480–1700	2.7	5.8	7.1–41	$50.2 Billion
7. LS Mtron, South Korea [62]	Electronics, Transport, Energy	100–3000	2.5	5.9	.9–2.4	$4.2 Billion

Table.4
Name of all parameters and their values as shown in Fig. 11.

Input elements	Name of input elements	Specifica-tions
V_i	Super-capacitor Voltage used as input voltage for buck converter	≤ 2.5v
V_O	Output voltage of the converter	2v (Load Dependent)
L	Inductor	250uH
C	Capacitor	330uF
V_g	Maximum amplitude of the Pulse applied at the gate of mosfet	10V
F	Operating frequency	100kHz
R_S	Internal resistance of power supply or super-capacitor	30mΩ or 8mΩ
R_L	Internal Resistance of inductor	(0.05–0.1) Ω
V_d	Voltage drop across the diode under forward biased condition	0.7v
V_f	Voltage drop across the mosfet (MOSFETSi2308BDS) when the switch is closed	0.5v

without overhead lines using power and energy stored by EDCL. Electric umbrella immediately charged this SC in few seconds that are present at any bus stand (once in every 4.8 km) [66] around 2003. In 2010 onward, there are buses where SC banks are present under the bus seats, which get charged when the bus stops in every bus stop to pick up or drop off passengers. Researchers also worked on SC banks charged by Solar panels [63,64], which make these buses to travel uninterruptedly for 32 km, as shown in Fig. 11. The fast-charging depends on the high current deliverable capabilities by solar cells. It estimated that each Capa-bus [67] has consumed one-tenth of the energy compare to the conventional petrol/diesel bus and save approximately 200 thousand US dollars around 2009 [41] for 12 years' lifetime. That translates to saving about 15 gallons per day per Capa-bus. And it will be more savings now since one can store more energy in a super-capacitors bank under the seats of every Capa-bus. If one has to charge a super-capacitor to run an electric trolley and if one has to charge a lithium-ion battery to run the same electric trolley, then one can find in case of super-capacitors one uses about 40% [68] less electricity. It is worth mentioning here that when the super-capacitors are used for an electric trolley, it cost less and also survives more years than a lithium-ion battery. Also, to remember, at the same time, the super-capacitors are comparably cheaper. Due to the above advantages, lots of companies are trying to design SC buses. Some examples are Foton American Bus Company built some Capa-bus and put in New York City, Chicago, and Florida. Similarly, GSP Belgrade of Serbia, Sofia city of Bulgaria, Gaza city of Austria has launched some SC buses with the help of Chinese manufacturers [69]. This Chinese design had features where short, and intermediate recharging method was integrated into their Capa-bus design.

6.5. New charging methodology of super-capacitor

Fig. 8b. Demonstrated, the voltage drop across the super-capacitor as a function of time behaves like gamma function; see Eq. (7). Based on that, a new charging methodology of a super-capacitor module is also developed in our laboratory. For Nippon DDLE-super-capacitors, the maximum charging voltage is 3.5 V; to do that, one can only inject 1 Amp constant current. If one pump more or less current, then the capacitor will not be charged to 3.5 V (see Fig. 8b). This 3.5 V is the maximum peak value of the voltage one can use to charge the Nippon DDLE-super-capacitors. Next, a question can be asked how to charge up supercapacitors at a faster rate. It is important to see from Fig 8b that one cannot pump infinite current to change super-capacitors in a short time. There are some limitations which are controlled by the Fig. 8b. Thus, we have developed a flowchart to determine how to generate a fast charging scheme of super-capacitors, where the value of R_p depends on the current (I_p) passes through that resistors (See Fig.5a).

This flow chart is shown in Fig.15. Here, one can charge the supercapacitors to the peak voltage, $V_p = 3.5$ V, by pumping 1Amp constant current. Another option is to pump high current and charge the capacitor up to a certain lower voltage (≤3.5 V) and then drop the current to charge the capacitors to some higher voltage and keep doing it till we get 3.5 V. In the last stage of charging, we will be driving close to 1Amp. The equation to perform the above- described task is shown below (maximum current 6 Amp).

$$V_{P1} = -0.0008I_{P1}^6 + 0.026I_{P1}^5 - 0.3322I_{P1}^4 \\ 2.0725I_{P1}^3 - 6.46I_{P1}^2 + 8.219I_{P1} \tag{7}$$

7. Conclusion

This paper provides a full description of the electrical performance, characteristics, and various applications of super-capacitors. Here, the super-capacitors are compared with conventional battery (lithium-ion, sodium-ion battery) on various different prospective such as energy density, power density, reliability, life cycle, a high instantaneous current application. This low ESR is also an important factor in understanding the requirement of the feedback loop for any electrical converter, and a mathematical model was developed for engineers to find that requirements. The feed-forward loop is always required when one uses super-capacitors since the capacitor's voltages are dropping continuously as the output load draws power from the capacitors. The circuit design for this feed-forward loop, developed by us, is also given in this paper.

We have also discussed structural design, transportation sector (Capa-bus), the manufacturer based specific product of super-capacitor, their corresponding advantages, and disadvantages. Finally, the merit of having both super-capacitor and battery is also described in terms of initial current requirements and the steady- state performances for various applications.

This paper integrates our work with the work done in industries to find the physics behind a reliable super-capacitor and their electrical performances. The experiment was done to determine the power loss of the supercapacitors vs. lithium-ion battery, and the requirements of the cooling fans to cool the battery or the supercapacitors after a given power level. We have also studied and taken the super-capacitor data from AVX corporation and used the same capacitors (SCMT22C505MRBA0) to generate the similar curve at various voltages (2V-5 V) at 85 C. We, for the first time revealed that the ratio of the time constant at any given time, during the reliability test, with respect to the nominal RC time constant is pretty much constant and that ration does not depend on time. The test time used was 4000 h. But that value was found to reduces as one performs this reliability test at high voltages. And this ratio was found to drop linearly as the voltage increases. We have also determined experimentally that the leakage resistance (R_P) depends on the charging current. This leads to an interesting observation related to the value of the leakage resistance R_P vs. current for NIPPON DDLE super-capacitor. This leads to the development of a gamma function-based "charging methodology" for the above-described super-capacitor. The flow chart is also developed for fast charging for those super-capacitors where R_P is depending on charging current.

Declaration of Competing Interest

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.est.2019.101044.

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Sambit Satpathy is currently a Ph.D. scholar in the Department of Computer Science and Engineering, NIT Agartala. Currently he is working on design of dc-dc converter with feedback controlling system, modeling of super-capacitor.2

Sanchali Das is working as a Ph.D. scholar of Computer Science Department in NIT Agartala. She has completed B. Tech and M. Tech from IET Lucknow and NIT Agartala respectively. Currently she is working on super-capacitor modeling.2

Bidyut Kumar Bhattacharyya is working as professor of electronics and communication department at National Institute of Technology, Agartala. He received the B.Sc., M.sc and Ph.D. from the Presidency College, the IIT Kanpur and from the State University of New York at Buffalo, NY, USA in 1976, 1978 and 1983 respectively. He was awarded the IEEE Fellow in 2000 for his contributions to the electronic packaging. He is the author of 27 patents and more than 60 papers.2