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Dynamic Applications of Supercapacitors

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Abstract: In this manuscript, applications with dynamic nature of supercapacitor have been reviewed, also the theoretical as well as practical limitation of this technology have been discussed. Supercapacitor follows the same laws for upon which capacitors works but employs large surface area, thinner dielectric which gives high capacitance and hence, great energy densities as compared to conventional lead acid-battries. If employed in electric vehicals and power packs instead of battries, the initial cost as well as operating cost can be reduced considerably bue to low cost and light weight.

Key words: Electric double-layer capacitors, activated carbon, energy storage device, charge-discharge cycle high power density applications

INTRODUCTION

Electric double-layer capacitors is commercially known as supercapacitor and ultracapacitor made by Nippon Electric Company (NEC), Japan and Pinnacle Research Institute (PRI), USA, respectively is an emerging technology which have enormous energy densities which have been commercially harnessed in late 1960's, is a potentially strong candidate to replace conventional lead-acid battries in the fields like electric transportation and power back-pack. The Eqivalent Series Resistence (ESR) of a supercapacitor is favourably low by 100 times to that of battery which also results in extremely low charging time. Supercapacitor operates closely like capacitors works but due to large surface area and thinner dielectric, it is capable of accumulating high energy densities comparable to that of battries while retaining the property of significantly high power density (Guidi and Kawamura, 2010).

Conventional capacitors consist of two conducting electrodes separated by an insulating dielectric material. Which accumulate opposite charges on the surfaces of each electrode (Bullard *et al*., 1989). The charges are kept separate by the dielectric, thus producing an electric field that allows the capacitor to store energy. Here, the capacitance C is defined as the ratio of stored (positive) charge Q to the applied voltage V:

$$C = \frac{Q}{V}$$

For a conventional capacitor, C is directly proportional to the surface area A of each electrode and inversely proportional to the distance D between the electrodes:

$$C = \epsilon_0 \epsilon_r \frac{A}{D}$$

The product of the first two factors on the right hand side of the last equation is a constant of permittivity of free space and dielectric constant of the insulating material between the electrodes. Also, the power density can be calculated as a quantity per unit mass or volume. The energy E stored in a capacitor is directly proportional to its capacitance:

$$E = \frac{1}{2}CV^2$$

Also, power P is the energy expended per unit time. To determine P for a capacitor, it is assumed that capacitors are generally represented, as a circuit in series with external and internal resistances which is measured in aggregate by a quantity known as the Equivalent Series Resistance (ESR). The voltage during discharge is determined by these resistances. The maximum power P_{max} is given by:

$$P_{max} = \frac{V^2}{4 \times ESR}$$

This relationship shows how the ESR can limit the maximum power of a capacitor. Conventional capacitors have relatively high power densities but relatively low energy densities when compared to electrochemical batteries and to fuel cells. That is, a battery can store more total energy than a capacitor but it cannot deliver it very quickly which means its power density is low. Capacitors, on the other hand, store relatively less energy per unit mass or volume but what electrical energy they do store can be discharged rapidly to produce a lot of power, so their power density is usually high. Despite greater capacitances than conventional capacitors, supercapacitor have yet to match the energy densities of mid to high-end batteries and fuel cells (Hwang *et al.*, 2011).

CLASSIFICATION

Supercapacitors can be divided into three general classes on the basis of its unique mechanism for storing charge (Fig. 1). These are respectively, non-faradaic, faradaic and a combination of the two (Muyeen *et al.*, 2009).

Electrochemical double-layer capacitors: These are constructed from two carbon-based electrodes, an electrolyte and a separator to store energy. Because there is no transfer of charge between electrolyte and electrode, there are no chemical or composition changes associated with non-faradaic processes. For this reason, charge storage in EDLCs is highly reversible.

The different carbon compounds which can store energy between metallic electrodes are:

Activated carbon: It is the most commonly used electrode as it less expensive and possesses a higher surface area than other carbon based materials. Activated carbons utilize a complex porous structure composed of surface irregularities ranging from micropores to macropores (i.e., 20-500 A) to achieve a high surface areas. It have been observed that larger pore sizes correlate with higher power densities and smaller pore sizes correlate with higher energy densities.

Carbon aerogels: These are formed from a continuous network of conductive carbon nano-particles with interspersed mesopores. Carbon aerogels do not require the application of an additional adhesive binding agent. As a binderless electrode, carbon aerogels have been shown to have a lower ESR than activated carbons hence, it yields higher power.

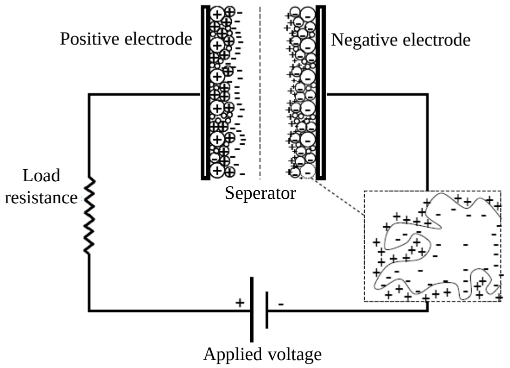

Fig. 1: Schematic of an electrochemical double-layer capacitor

Carbon nanotubes: Electrodes made from this material commonly are grown as an entangled mat of carbon nanotubes, unlike other carbon based electrodes, the mesopores in carbon nanotube electrodes are interconnected, allowing a continuous charge distribution that uses almost all of the available surface area. Thus, the surface area is utilized more efficiently to achieve capacitances comparable to those in activated-carbon-based supercapacitors, even though carbon nanotube electrodes have a modest surface area and lower ESR compared to activated carbon electrodes.

Pseudocapacitors: These store charge through the transfer of charge between electrode and electrolyte. This is accomplished through the faradaic processes of electro sorption, reduction-oxidation reactions and intercalation. This results in a greater capacitances and energy densities than EDLCs. There are two electrode materials that are used to store charge which are:

- Conducting polymers
- Metal oxides

Hybrid capacitors: Hybrid capacitors attempt to create an optimal balance between the advantages and disadvantages of EDLCs and pseudocapacitors to realize better performance characteristics. Utilizing both faradaic and non-faradaic processes to store charge, hybrid capacitors have achieved energy and power densities greater than EDLCs without the sacrifices in cycling stability and affordability that have limited the success of pseudocapacitors (Bullard *et al.*, 1989).

PRINCIPLE OPERATION

The equivalent circuit models employ mathematical or computer models of fundamental electric circuit components, such as resistors and capacitors to model complex electrochemical processes of porous electrodes (Fig. 2). These equivalent circuits are applied to demonstrate the behaviour of the double-layer at the interface between the electrode pores and electrolyte solution to capture additional faradaic effects observed in capacitors (Miller, 2010).

A treatment of the capacitance in porous electrodes resulted in each pore being modelled as a transmission

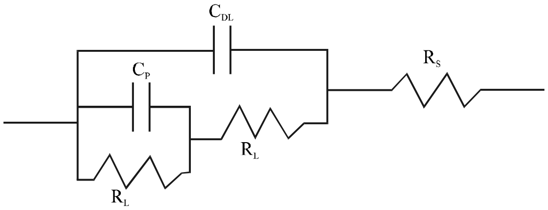

Fig. 2: Equivalent circuit of supercapacitor

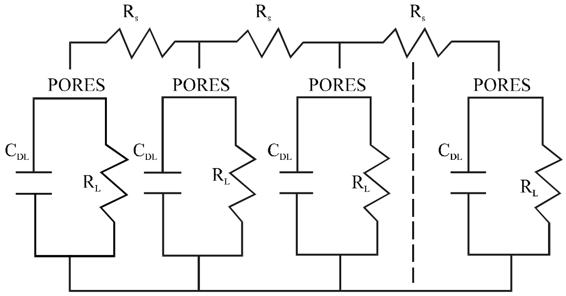

Fig. 3: Supercapacitor modelled as transmission line

line. The transmission line models a distributed double-layer capacitance and a distributed electrolyte resistance that extends into the depth of the pore. To achieve an estimation of the double-layer capacitive effects, straight, cylindrical pores of uniform diameter and a perfectly conducting electrode are assumed that this equivalent circuit could be modified to model a porous pseudocapacitor electrode by incorporating the faradaic pore equivalent circuit (Takahare *et al.*, 2002).

Charged supercapacitors are in a higher state of potential energy than discharged supercapacitors, there is thermodynamic pressure for a supercapacitor to discharge (Fig. 3). This pressure sometimes manifests itself in the undesirable phenomenon known as self-discharge which occurs when a capacitor discharges internally on an open circuit. Self-discharge is intrinsic to all electrochemical energy storage systems including batteries as well as capacitors (Hwang *et al.*, 2011).

APPLICATIONS

Electrochemical supercapacitors have yet to experience widespread use. This has originally been due to their limited power and energy capabilities and they therefore, only saw use in low-power, low-energy applications, such as for memory backup for maintenance-free power sources for IC memories and microcomputers due to high equivalent series resistance (Guidi and Kawamura, 2010). Recently, however significant advances have been made in improving both energy and power density and new applications for EDLCs are being developed at an increasing rate. Among newly proposed applications for large size super capacitors are load levelling in electric and hybrid vehicles, as well as in the traction domain, the starting of engines, applications in the telecommunication and power quality and reliability requirements for Uninterruptable Power Supply (UPS) installations (Jinrui *et al.*, 2006). In general, supercapacitors may be adapted to the following two application domains. The first one corresponds to the high power applications where the batteries have no representative access. The EDLCs will allow new opportunities for power electronics. All applications where short time power peaks are required can be provided by these capacitors.

The second one corresponds to the low power applications where the batteries could be more suitable where supercapacitors, bring enough advantages to substitute the batteries. EDLCs have been employed in various applications such as:

- Uninterrupted Power Supply (UPS); the energy supply is for a limited time at a voltage much higher than that of batteries is easier to perform with these capacitors (Takahare *et al.*, 2002)
- Starter; the energy required to crank a small or big engine is stored in either Pb or NiCd batteries whose initial peak current is limited because of their high internal resistance, hence they have to be oversized. The fast battery discharging and the cold environmental temperature affect heavily their properties. The supercapacitors have a better power behaviour and environmental acceptance (Guidi and Kawamura, 2010)
- Cellular applications; during the short 0.5 msec pulse of 1 A, the battery voltage drops considerably. If it is below a certain limit, the phone is not longer operable. With a supercapacitor the voltage drop is reduced significantly and it takes much longer until the critical low voltage is reached during the pulse. Hence, the operation time of the phone is extended (Miller, 2010)
- Transportation
  - In hybrid vehicles (Fig. 4)
  - Elevators
  - Cranes and pallet trucks
- Military; radars and torpedoes
- Medical; defibrillators and cardiac pacemakers
- Industry; pulsed laser and welding
- Power quality improvement (Guidi and Kawamura, 2010)

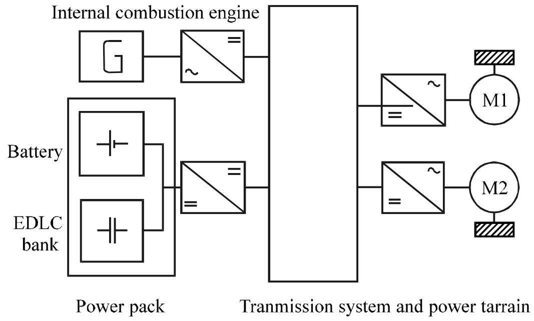

Fig. 4: Hybrid vehicle system

APPLICATIONS BASED UPON ELECTRIC DRIVES

ELDCs have been employed as engine starters for large engines in tanks and submarines and with more efficient power electronic drives these have attracted attention in the electric car industry where their ability to charge much faster than batteries made them instantly successful for regenerative braking applications.

The development of supercapacitors for the transportation have succeeded in two different paths, i.e., as a primary-secondary fuel hybrid system and as a solo, ELDC based plug-in vehicle for mass transit and local commutation purpose. Although, high energy density device, such as fuel cells and conventional fossil fuels provide the average load requirements and a high-power supercapacitor bank are utilised to meets the peak load requirements that result from accelerating or climbing up hills, not as a primary energy source due to its higher discharge rate. For example, the mean power of a small car is about 30 kW and its peak power should be about 60 kW. The supercapacitors may supply the power to the electrical vehicle required to meet the city road traffic conditions. Nevertheless in most of the cases, there is a need for an additional battery to insure a certain amount of autonomy and to reach the range requirement. The utilisation of super capacitor also makes regenerative braking very efficient and therefore, increases the fuel efficiency of the vehicle (Kawashima *et al*., 2006).

China is experimenting with a new form of electric bus (capabus) that runs using large onboard EDLCs which quickly recharge whenever the bus is at any bus stop and fully charge in the terminus. A few prototypes were being tested in Shanghai in early 2005. The developer of these buses, Sinautec Ltd., estimates that one of its buses has one-tenth the energy cost of a diesel bus and can achieve lifetime fuel savings of $200,000. The buses also consumes less electricity even than an electric trolley bus, mainly because they are lighter and have the regenerative braking benefits (Jinrui *et al*., 2006).

ADVANTAGES

In spite being in a nascent stage, this technology has been favored by industries and academicians to be utilized for various applications in a wide spectrum in a very short span of time. This is because of numerous possible advantages over the existing technologies. EDLCs are generally expected to outgrow and replace electrochemical batteries. Some advantages which be mentioned here are:

High rate of charge and discharge: EDLCs have a charging time of around a fraction of seconds to a few minutes as compared to hours what it take to charge batteries.

High power density: This helps in catering the demands of loads with fluctuating loads as it can charge quickly and can provide instantaneous reliable ride-through power.

Free from any harmful chemicals: The main objective of development of this technology is to reduce the reliability upon highly priced and polluting fossil fuels and to reduce the cost, as well as environment de-gradation, the main ingredient of EDLCs are carbon which is abdunt in nature.

Light weight and small size: The EDLCs enjoy being easily fabricated and small in size. As there is no complex components involved in it, it unit weight per volume is also very low.

Stability: Unlike batteries, these are chemically inert and stable and does not show any operational changes upon variation of temperature.

Modular nature: Due to its advantage over the prospect of size, weight and chemical as well as physical stability, EDLSc are extremely modular and hence, its hassle free during transportation, storage and operation which makes it suitable of small and medium requirement power packs.

No degradations due to deep discharge and load with fluctuating current demand such as during acceleration (Muyeen *et al*., 2009).

CONCLUSION

EDLCs may be used wherever high power delivery or electrical energy storage is required. Therefore, numerous applications are possible. The use of supercapacitors allows a complementation of normal batteries. In combination with batteries the supercapacitors improve the maximum instantaneous output power as well as the battery lifetime. Supercapacitor banks have been designed for higher terminal voltage on order to supply higher voltage loads and with the help of DC-DC converter as seen in various test setups, these EDLCs have found to successfully operate electric drive loads with varying speed and terminal current to stimulate the scenario of mass transit and transportation implementation.

With further improvements in the designing aspects of electric double layer capacitor in order to utilize maximum surface area of electrode and proper penetration of electrolyte over the surface in order to reduce the ESR and therefore, increasing the terminal voltage, these can enjoy wide spectrum of applications ranging from low power data processing system to high powered drives and transportation deployments.

LIMITATIONS

The biggest advantage of rapid charge-discharge cycle is also its main disadvantage as it cannot supply load for a very long duration of time. The lack of EDLCs capability to store abundant amount of energy is also a deterrent for its fruitful implementation as primary energy source in electric drives. Similar to such limitations, others can be enlisted as the following:

High initial cost: The mass manufacturing process is still under development and hence the initial cost are higher as for developing prototypes as compared to that of lead-acid batteries.

Low terminal voltage: The maximum available voltage under test condition is 3 volts and that of, for the practical implementation is around 2.3 volts which is very low for any instantaneous consumption, except for the direct feeding to a microprocessor.

In order to increase the voltage output of the system, various EDLC can be connected in series to obtain the desired output voltage but this also affects to total unit capacitance.

Low energy density: A typical EDLC have an energy density of 3 Wh kg^{-1} while an Ni-Cd battery have an energy density of 300 Wh kg^{-1}, this implies that EDLSc can supply instantaneous power of huge density but cannot sustain it for a respectable time durations.

Requirement of DC-DC converter: As it is known that the output voltage is very low, it is connected with various DC-DC converters which modifies the power output according to the demand. This implementation results in higher costs and complex operations due to semiconductor converters like buck-boost, isolated boost and push-pull converter (Muyeen *et al.*, 2009).

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