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Analysis of Ultracapacitor for High Power Applications

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***Abstract*— Different types of material available to be used for fabrication and which provides the best solution for the Ultracapacitor is the requirement of the time to store high energy density and have high power density at the same time. Electrolyte selection plays another role in decreasing the performance of energy storage. The performance of high power release is dependent on the value of Equivalent Series Resistance. This paper discusses the types of models used commonly and choses the model that includes the non-linear behaviour. Matlab/Simulink software was used for simulation and analyses the behaviour of Ultracapacitor by varying the internal resistance (equivalent series resistance). This analysis helps in identifying the advantage performance of high power release that it is dependent on the value of equivalent series resistance.**

***Keywords*— Electrochemical Supercapacitor, Energy Storage, Equivalent Series Resistance, Supercapacitor, Ultracapacitor.**

I. INTRODUCTION

The energy in this world generated from different types of power plants using renewable and non-renewable resources are utilized as generated. The energy generated using fossil fuels have been considered as unsafe for some time. The researchers in the search of clean energy generation have started research and subsequently started generation with non-conventional methods using renewable and clean resources. This also leads to the research of storage system which can store clean energy generated to be used at later time. They can be temporarily stored in certain energy storage that has limited storage capacity. All the energy generated from a power plant can never be possible to store in one place or no single storage system or may be many combined storage devises together can do the storing. It is always only about some fractions in percentage of the overall generated energy. There is growing demand for developing efficient storage system in the field of electric and hybrid vehicles, consumer electronics, renewable energy systems like solar and wind, generating plants and electric energy distribution grid with varying performance characteristics.

The storage systems that are available today are not ideal to meet all the technical and economic constraints of the increased demand.

Some of the storage systems which see competition amongst the devices are pump hydro, flywheels, electrochemical batteries, Superconducting Magnetic Energy Storage, Fuel Cells, compressed air energy storage etc. The need in developing a clean and higher energy storage system has led to the introduction of Ultracapacitor and it has matured over the decade which also has higher power density. The information depiction of different energy storage systems is shown in figure 1[3] which compare the specific energy density with specific power density. In almost all the application that requires constant energy, battery is used to supply energy but when repeated high or peak load is supplied, the battery easily damages which decreases life span. While using Ultracapacitor, the repeated high or peak load demand is easily supplied at burst.

II. WORKING OF ULTRACAPACITOR

The energy storage device that can substitute battery in many applications is the Ultracapacitor (UC), also known by other names as Supercapacitor (SC) or Electric Double Layer Capacitor or Electrochemical Capacitor (EDLC). This storage device offers high power density and high capacitance utilizing high surface area electrode materials and very thin electrolytic dielectrics to achieve capacitances several orders of magnitude much larger than conventional capacitors [1-5].

Ultracapacitor works on the same principle of conventional capacitor where electrostatic charge is accumulated on the conductors while in UC; charges are accumulated at interface between the surface of a conductor and an electrolytic solution. Schematic diagram of Ultracapacitor is presented in figure 2. This storage of energy or conversion of energy process does not involve chemical reaction oxidation. Thus the internal resistance of the UC which controls the charging and discharging of UC is low. This internal resistance effect of all the connection circuitry is called equivalent series resistance (ESR), a property to deliver high power burst. Ultracapacitor stores energy in the similar manner as capacitor but has very high capacitance as defined by the following relations.

$$C_{UC} = \frac{Q}{V};\ C_{UC} = \varepsilon \frac{A}{D} = \varepsilon_o \varepsilon_r \frac{A}{D}\ \&E = \frac{1}{2} C_{UC} V^2$$

Where C is capacitance; Q is charge; V is voltage; ε is permittivity; A is area; D is distance and E is energy.

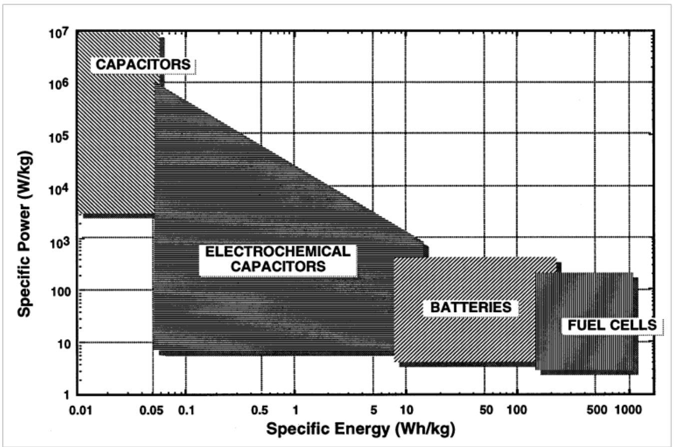

Figure 1: Ragone Plot to specify Energy Storage Devices

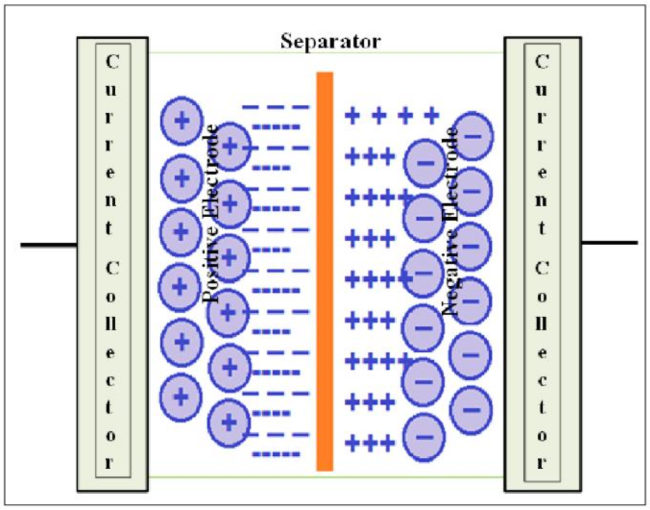

Figure 2: Schematic diagram of Ultracapacitor

Ultracapacitor can be differentiated by different criteria based on type of electrode material used, the type of electrolyte or the design of a cell. Depending on the type of material utilized in making the electrode of Ultracapacitor, there are three main types of Ultracapacitor: carbon electrode, polymeric and metal oxide materials. Based on the possible materials suitable for making Ultracapacitor is presented in the review [5].

The materials of both the electrodes are made of carbon materials then the charge formation in Ultracapacitor is electrostatic (Helmholtz layer) and when any of the electrode or both uses metal oxide or conducting polymers then charge storage is faradaic [1].

A. Electrode

The electrode of the Ultracapacitor can be of carbon materials such as Activated Carbons, Carbon Aerogels, Carbon Nanotubes or Carbon Fibers in EDLCs. In case of pseudocapacitors, Conducting Polymers or Metal Oxides are used along with or without carbon electrodes. The classification of Ultracapacitor based on the types of materials used in preparation electrode is shown in figure 3.

B. Electrolyte

Ultracapacitor can also be classified based on the type of electrolyte used. There are basically two types of electrolytes used in UC: Aqueous/Non-Aqueous and Organic/Inorganic. The greater the contents of ions in electrolyte higher are the conductivity. Electrolyte plays a major role in deciding the performance, safety and lifetime of UC. It is the physical and electrochemical property of electrolyte that also determines the value of ESR and power ratings.

Aqueous/Non-Aqueous: Aqueous electrolytes limits the cell voltage of electrochemical capacitors to typically 1 V, but there is advantage which provides higher conductance and less rigid during purification and drying. They have high ionic conductivity with electrochemical operating window about 1.2 V of which it is neither reduced nor oxidized [3]. Water solvent when treated with alkalis such as potassium hydroxide, acids such as sulfuric acid, or salts such as sodium perchlorate, quaternary phosphonium salts, lithium perchlorate or lithium hexafluoride arsenate, water gives relatively high conductivity. Non-Aqueous electrolyte is preferred because of higher operating voltage range thus higher energy & power densities.

Organic/Inorganic: The available capacitors uses organic electrolyte as it can achieve high per unit cell voltage which may be above 2 V. To further increase, some companies go for float voltage up to 3.2 V where extreme purification procedures of special electrolyte have to be applied [8]. Inorganic aqueous electrolytes are basically sulphuric acid, potassium hydroxide, ammonium salt dissolved in propylene carbonate. Organic electrolytes are of Tetraethylammonium Tetrafluoroborate, ester based solvent Propylenecarbonate, Acetonitrile [1].

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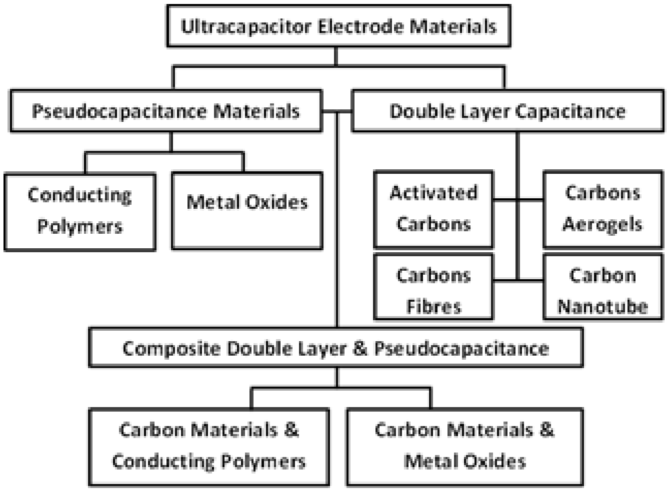

Figure 3: Ultracapacitor based on Electrode Material

III. Simulation Analysis Of Ultracapacitors

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A. Ultracapacitor Model

An energy storage device Ultracapacitor which has the working principle similar to conventional capacitor but with the formation of double capacitance and high capacity to store energy at the same time release high power as compared to capacitor.

The current flowing though the capacitor is governed by;

$$I_{UC} = \frac{dQ}{dt}$$

The charge stored in the capacitor is

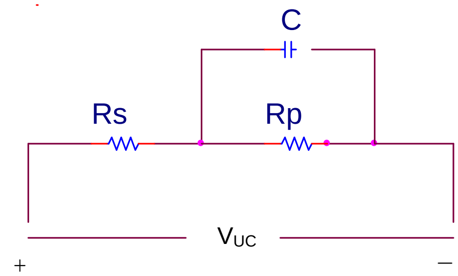
$$Q = C_{UC}V_{UC} = \int I_{UC}\, dt$$

Where C_{UC} is the capacitance of the Ultracapacitor; V_{UC} is the voltage across the Ultracapacitor

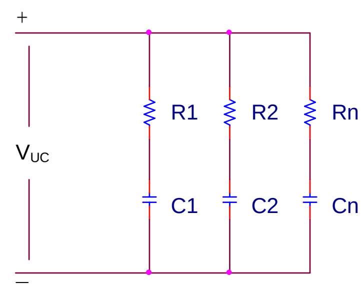
So to find the capacitance of UC from the data available from the manufacturer, one can use the equation;

$$C_{UC} = \frac{dQ}{dV_{UC}}$$

There are many electrical models available for the Ultracapacitor which the researchers have developed as per the application or as per their requirement of accuracy in the application. Some of the commonly used electrical equivalent models of Ultracapacitor are listed down.



(a)



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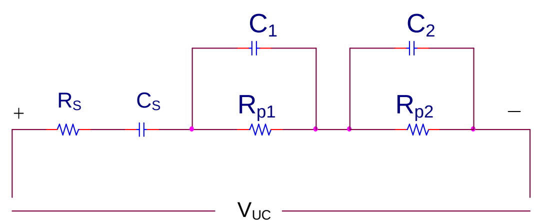

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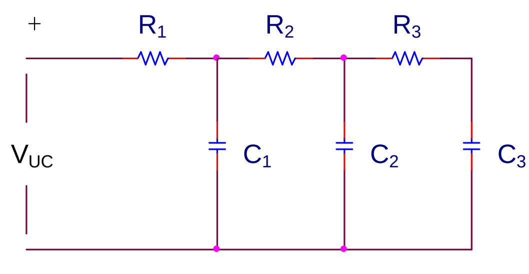

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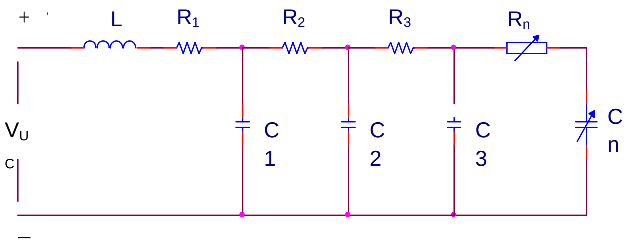

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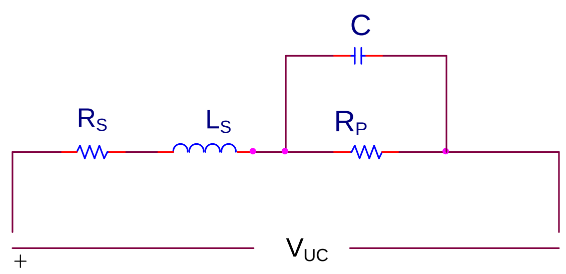

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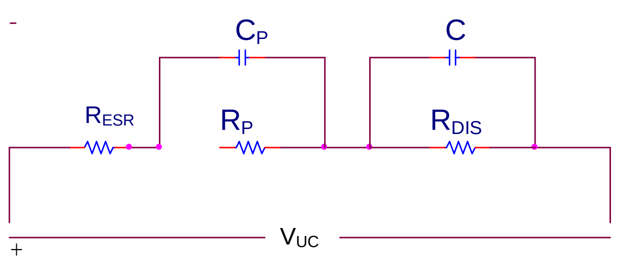

(g)

Figure 4: Equivalent Model of Ultracapacitor commonly used: (a) Equivalent RC series Model (b) Equivalent Series RC Parallel Model (c) Equivalent Parallel-Series RC Model Linear Consideration. (d) Equivalent RC Transmission Line Model (e) Equivalent RC Non-Linear Model (f) Equivalent First Order RC Model (g) Equivalent Parallel-Series RC Model with Non- Linear Consideration.

The equivalent circuit given in figure 4(g) is model of a Ultracapacitor manufactured by ECOND which is used in simulation to find the behavior. The measurement process to extract the details of UC is done by following certain procedure. First the UC is charged for certain period till the UC is fully charged and kept in this condition for some minutes to check the state of Ultracapacitor self-discharge. Now the Ultracapacitor is applied with negative source to allow forceful discharge to find the behavior during release of energy from Ultracapacitor when load is connected.

Thus the values of the model are calculated using the relations:

For calculating values of equivalent model in figure 4(g):

- The main capacitance of the UC which tells how charged is handled, amount of energy stored and the rate of energy variation level.

$$C = \frac{Q}{V_{UC}}$$

Where C is capacitance, Q is charge and V_{UC} is the voltage level

- The resistance R_{ESR} which is the equivalent series resistance of UC which accounts the charging and discharging voltage drop. This parameter decides the release of power from Ultracapacitor.

$$R_{ESR} = \frac{dV}{dI}$$

Where V is voltage drop, I is current, this small change in voltage and current can be found from the charging and discharging curve.

- The self-discharge behavior of the Ultracapacitor is represented by R_{DIS} in the model cannot be easily found from the measurements data whose value has to be a large one as the self-discharge is generally very small.

The capacitance connected in parallel C_P value is to be taken as one thirteenth of C, the main capacitance. This is the relation as suggested by the manufacturer considering the internal physical condition of the Ultracapacitor whose impact in the accuracy is very small and the resistance connected in parallel R_P is again hard to find as it is not visible to the data measured from the curve so it is assumed with best matching from data where C_P and R_P are included in the modeling to define the nonlinear behavior of the Ultracapacitor [9-10].

B. Simulation of Ultracapacitor Model

The proposed model is simulated using the calculated values and choosing certain values as best suitable as shown in table 1.

TABLE 1

Values of Ultracapacitor Model

Parameter	**Value**
Nominal Voltage	12 V
Nominal Main capacitance, C	300 F
Equivalent Series Resistance, R_{ESR}	2 mΩ

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The Ultracapacitor is charged with 50 ampere for duration of 7 minutes till it is fully charged then kept for about 10 minutes to find the self-discharge behavior of UC. There after the UC is forcefully discharged with 100 ampere negative source to allow discharging for depth discharge analysis. The simulation result of charging and discharging as per desired durations to analyze the effect is given in figure 5. Along X axis is the time duration and along Y axis is the Ultracapacitor voltage and charging/discharging current. It is observed that after UC is fully charged, it drops for some voltage when the charging source is removed but is very low indication that self-discharge is very low. At the end of force discharge interval about 2 minutes, UC has still some voltage to show the charge availability. To further investigate when the UC will fully discharge, the negative source application interval is increased to 4 minutes. Now, as is clearly shown in figure 6, that the UC is completely discharged at about 3 minutes 23 seconds after the application of force discharge step.

To further investigate the behaviour of the Ultracapacitor model, the Equivalent Series Resistance is varied from a minimum of 0.1 mΩ to 1Ω resistance in the model and checked the result as shown in figure 7. It is evident from the result that for normal operation of ESR values around the calculated value, there are some charges left out in UC but as the ESR increases the discharging action increases during the same interval of forced discharge process. It is found that at 220 mΩ of resistance the discharge is completed discharge state. There after the UC starts charging in opposite polarity that will eventually degrade the life of Ultracapacitor in long run.

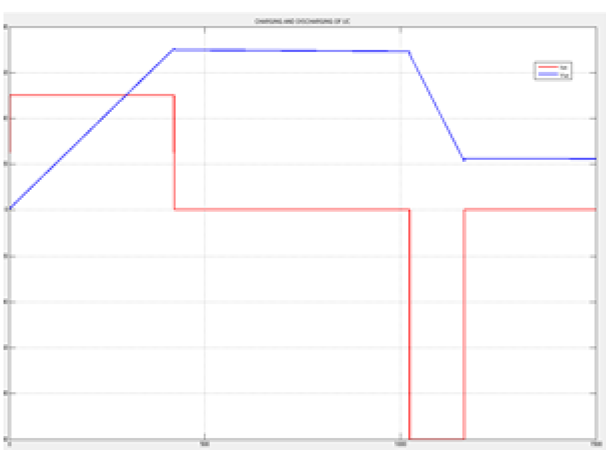

Figure 5: Charging and Discharging of Ultracapacitor (Voltage & Current Vs Time)

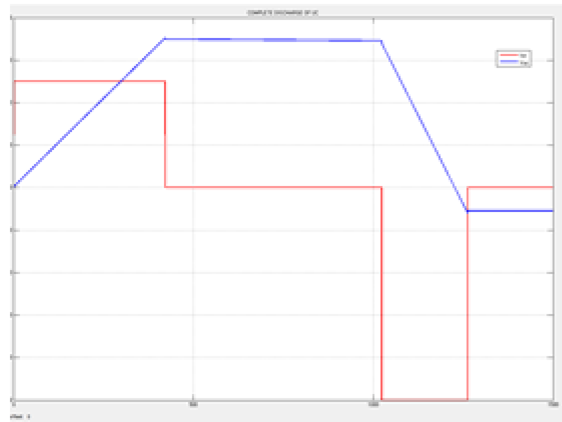

Figure 6: Ultracapacitor with complete discharge (Voltage & Current Vs Time)

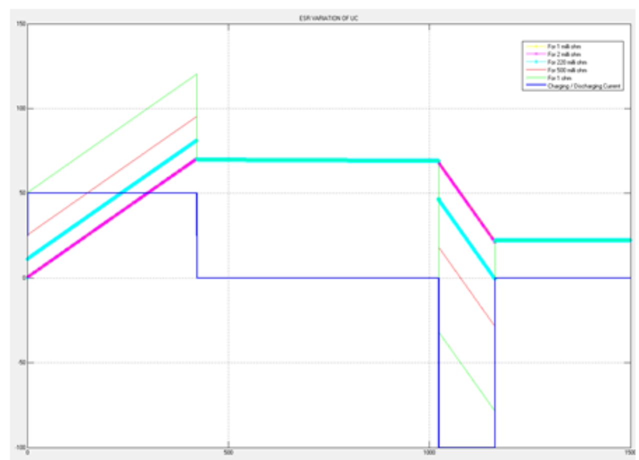

Figure 7: Ultracapacitor for Different Values of ESR (Voltage & Current Vs Time)

IV. CONCLUSION

All of the applications where batteries were used as primary source of power, with the advancement of new technology of energy storage, can be replaced by Ultracapacitor. The Ultracapacitor from the analysis found that there is some self-discharge seen after the constant voltage, a small decrement at the starting of discharge process indicates the double breakdown but of little significance. It continues to retain certain voltage level unless otherwise it is forcefully discharged. The high burst of power from the Ultracapacitor is the affected with the value of ESR. The variation of ESR results that higher the value of resistance lower the power burst which means capable of storing higher energy.

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Proper selection of electrolyte is required to maintain suitable ESR. Thus the Ultracapacitor can be used where the peak load demand is of higher priority and at the same time it can also store large amount of energy which facilitates many applications where high power and high energy is required that failed by batteries to deliver high peak load.

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