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An Analytical Approach to Charging Characteristics of Super capacitors for Different Equivalent Circuits using DC and Photovoltaic Sources

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Abstract: Super capacitors have recently emerged as efficient energy storage devices. Unlike batteries these devices can be charged and discharged continuously without appreciable degradation in the devices. In this paper, the charging characteristics of a super capacitor have been studied and analysed using the different types of equivalent circuits of the super capacitor and the best-fit equivalent circuit has been identified by simulation results using DC source. This identified equivalent circuit is then applied for charging super capacitors by solar photovoltaic module. On comparison, the simulated results of the charging characteristics using photovoltaic module is seen to tally closely with the experimental ones. The paper also describes the charging characteristics of the conventional capacitor and super capacitor using mathematical expressions of the solar photovoltaic cell and again compares the characteristics using the experimental results. These charging characteristics as derived mathematically are also found to closely follow the same.

Keywords: Supercapacitor, Transmission branch model, RC branch model, Energy storage system, Solar photovoltaic equation

I. INTRODUCTION

Super capacitors are energy storage devices and they are similar to both batteries and conventional capacitors. Super capacitors can store electrical energy unlike batteries which store chemical energy. Super capacitors are also called electrochemical capacitors or electric double-layer capacitor (EDLC)or ultra capacitors[1]. Now-a-days, batteries are being replaced by super capacitors due to the different drawbacks of the batteries. It has some advantages such as higher power density, low equivalent series resistance (ESR) due to the composition of the material and specific design structure [2].Super capacitors have the highest capacitive density over batteries. The most significant advantage of the super capacitor is that for an electric double layer capacitor, capacitance values vary upto10,000 F. Moreover, unlike batteries super capacitors have the ability to charge and discharge continuously without degradation [3][11][12].

Super capacitors are basically based on carbon technology. Such a capacitor consists of two electrodes separated by a dielectric material. When an electrical charge is applied to the material a double electric field is generated which acts like a dielectric. The thickness of the double layer is extremely small. The surface area of the activated carbon layer is extremely large. A large amount of ions are absorbed by the large surface area. When ion absorption layer is formed on the electrodes of activated carbon, charging and discharging occurs in a super capacitor[1][10].

Though super capacitors have several advantages, in order to fully utilize their advantages it is important to know the super capacitor's unique features during the development of the product and application system design. So we have to analyse different equivalent circuits in order to study the unique features of a super capacitor[4].There are a number of different types of equivalent circuits, such as, RC two branch model, transmission branch model and RLC model etc.[2][4][5][6][7][8][13][14][15][16].Different equivalent circuits have different charging and discharging characteristics. A Supercapacitor can be charged by a DC source and also by solar photovoltaic source (PV). Photovoltaic energy is the most popularly-used renewable energy which can be stored by charging the super capacitor[7]. Although some equivalent circuits such as R-C two branch model, transmission branch model and RLC model are already developed there is no comparison available about the charging characteristics of these equivalent circuits of the super capacitors. In this paper we focus on charging the equivalent circuits of a bank of

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super capacitors using a DC source and also using a PV source. A comparative analysis is done on the charging characteristics of different equivalent circuits using Simulink. The charging characteristics obtained from Simulink are also compared with the experimental results to find out the equivalent circuit which provides close compliance with the experimental results. The paper also focuses the comparison between the charging of a normal capacitor and a super capacitor using mathematical equations of PV cell and a super capacitor using Simulink. Again, we have made a comparative analysis between the Simulink results and the experimental results. Section III of this paper deals with preliminary description of equivalent circuits. Section IV compares the charging characteristics of different equivalent circuits of the super capacitor and gives the graphical analysis accompanied by the simulation results using DC and PV sources. Section IV also analyses the charging characteristics of a normal and a super capacitor using mathematical equations of PV cell. Experimental results are also cited in section IV. The conclusion of the paper is given in section V.

II. BACKGROUND

A simplified model of a double layer capacitor has been proposed in [5]. This paper describes an RC-branch model of the super capacitor to provide its electrical characteristics. The model has sought to identify the different parameters of the super capacitors. In paper[4] different electrical equivalent circuits of the super capacitors have been discussed. It also provides a conversion of model parameters from one circuit model to another circuit model. The paper [2] has considered charging characteristics of the RC-branch model of super capacitors using only constant current charging mode. The method of calculation of resistance and capacitance from the equivalent circuits of the super capacitors. Is described in [9]. The paper [7][16]describes the transmission branch equivalent circuit of the super capacitors and compares the charging characteristics of this super capacitor by simulation and experimental results using solar photovoltaic energy source. The paper [6] describes the electrical and mathematical model of the super capacitor and compares the simulation and experimental results of its charging and discharging characteristics.

III.EQUIVALENT CIRCUITS OF A SUPERCAPACITOR

Three different equivalent circuits of a super capacitor have been considered. The equivalent circuit of a super capacitor of the Transmission Line Branch Model consists of three parts. These are access resistor Ra, transmission line(in RC branches) and complementary branches consisting of a capacitor, Ci and a resistance Ri. The transmission line consists of n cells, each one having a resistance R/n and a capacitance C/n. The equivalent circuit of the super capacitor considers a combination of transmission line behaviour, a parasitic inductor charge redistribution model and a self-discharging current model[9]. The proposed transmission line consists of (n= 2) RC branches, each having a resistance R/2 and a capacitance C/2. If the number of RC branches are more, the charging characteristics will be closer to the experimental results. The resistance and the capacitance for the Maxwell BCAP01000 super capacitor were characterized in [9]. With the help of these data the super capacitor is charged using Matlab/Simulink[7][16].

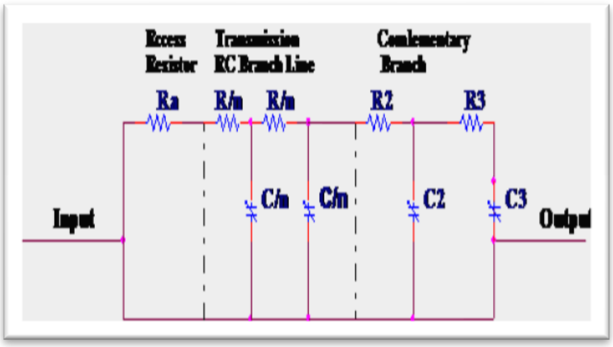

Fig.1: Transmission Line Branch Model

The RC parallel branch model is used to simulate the actual behaviour of the super capacitor during charging. When the super capacitor is charged, the voltage at the terminal will increase rapidly. Two different time constants of the branches are chosen to simulate the super capacitor's charging characteristics. The RC parallel branch model is shown in Fig. 2.The three branches are called the fast-term branches comprising R0 and C0, medium-term branch composed of R1 and C1 and the slow-term branch composed of R2 and C2.Each RC branch has a different time constant. The fast-term branch is responsible for charging and discharging of the capacitor. The medium-term branch maintains the behaviour over the charging period and slow-term branch is used to provide the long-term charging characteristics. The RC parallel branch model reflects the internal charge distribution process very well within the given time span and it is the advantage of RC parallel branch model. The RC branch model is more popular than other equivalent circuits of the super capacitor. This RC branch model provides good response of charging and discharging. The parameter can easily be extracted from experimental results and the accuracy is better as compared to other equivalent circuits of the super capacitor[5].The resistance and the capacitance for the Maxwell 350F super capacitor were characterized in [2].

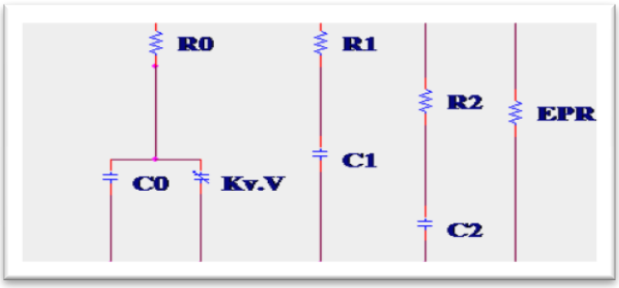

Fig. 2: RC Parallel Branch Model

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The equivalent capacitance can be expressed as
C_s = C0 + K_v. V where C_s is the capacitance of a super capacitor.
Each super capacitor cell contains 2.7 V. So, to get 13.5 V we have to connect five super capacitors in series.
The total capacitance for the 5 super capacitors in series is

$$C_{total} = C_s/5$$

The total equivalent series resistance, R_{eq}= 5 x EPR
The RLC branch model is shown in fig. 3.

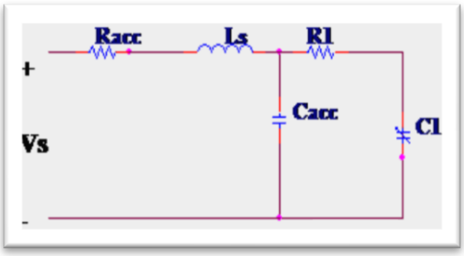

Fig.3: RLC Branch Model

It consist of R_{acc}, L_s, C_{acc}, R_1 and C_1. This type of equivalent circuit is preferred to increase the energy efficiecy and energy density[8].

IV. CHARGING CHARACTERISTICS OF DIFFERENT EQUIVALENT CIRCUITS OF THE SUPERCAPACITOR

The different equivalent circuits of the super capacitors are implemented using the MATLAB /Simulink. Figs. 4, 5 and 6 show the charging profiles of the super capacitor for the transmission branch model, RC parallel branch model and RLC model respectively using 18Volts DC source.

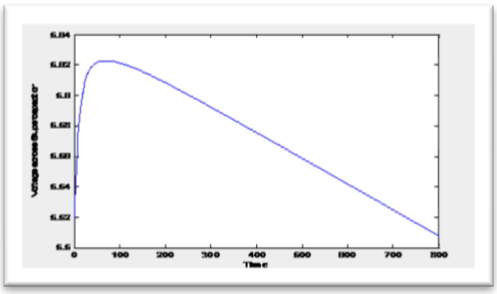

Fig.4: Voltage across Supercapacitor of Transmission Branch Model using DC source

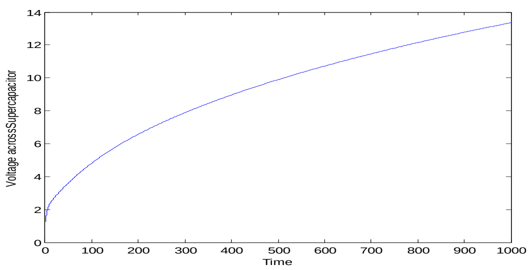

Fig. 5: Voltage across Supercapacitor of RC Parallel Branch Model using DC source

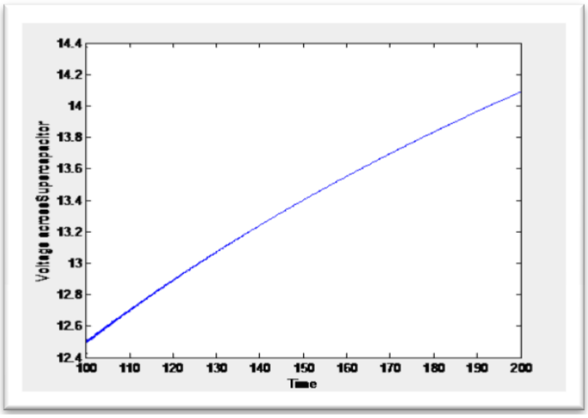

Fig.6: Voltage across capacitor of RLC Branch Model using DC source

From these results it is observed that the simulated charging characteristics of the RC branch model using DC source is closer to the theoretical characteristics of the super capacitor.
The charging profile of the super capacitor is shown in Fig. 7 for RC parallel branch model using 18Volts,2APhotovoltaic source.

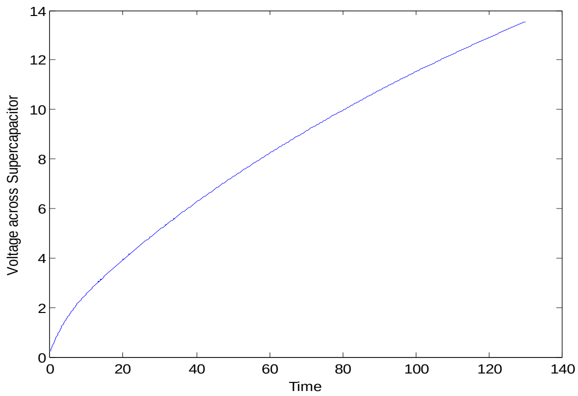

Fig.7 Voltage across capacitor of RC parallel branch model using photovoltaic source

An evaluation set-up is designed and implemented to verify the charging characteristics of super capacitors. This is used to test and monitor the charging characteristics of the super capacitors using both DC source and photovoltaic source. Fig. 8 shows the experimental set-up of the super capacitor.

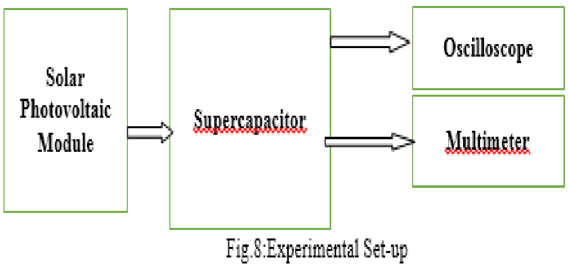

Fig.8:Experimental Set-up

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The system consists of a DC power supply, a super capacitor, solar photovoltaic module, multimeter and oscilloscope. The DC power supply is used to directly charge the super capacitor or the super capacitor can directly be charged from the photovoltaic (PV) system.

The charging current that flows through the circuit is 2 amperes and charging voltage of the five series combination of super capacitors is about 13.5 volts. So,18 volts photovoltaic system is used to charge the bank of super capacitors.

The fig. 9 shows the charging profile of the bank of super capacitors using photovoltaic source.

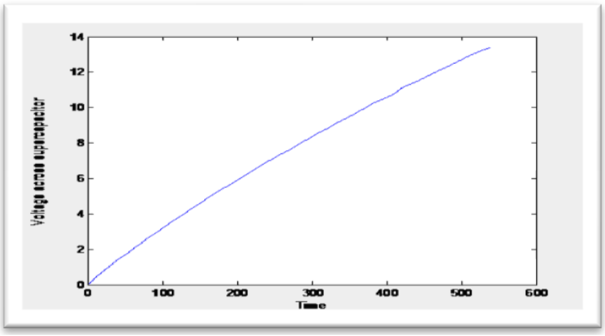

Fig. 9: Experimental charging profile of the bank of super capacitors using photovoltaic source

From these results it is observed that charging characteristics of RC branch model using solar photo voltaic source are closer to the experimental results.

Mathematical Analysis

We consider the current equation of a solar photovoltaic cell for a normal capacitor. The charging equation is:

$$\int \left[\frac{1}{\left(Isc - Io\exp\left(\frac{qnv}{\eta kT} - 1\right)\right)}\right] dv = \frac{1}{C}\int dt$$

$$or\ \frac{\frac{1}{Isc}\int\left(Isc - Ioe^{\frac{qnv}{\eta kT}} + Ioe^{\frac{qnv}{\eta kT}}\right)}{\left(Isc - Ioe^{\frac{qnv}{\eta kT}}\right)dv} = \frac{1}{C}\times t$$

$$or \int dv + \int \frac{Ioe^{\frac{qnv}{\eta kT}}}{Isc - Ioe^{\frac{qnv}{\eta kT}}}dv = \frac{Isc\times t}{C}$$

$$Let, Isc - Ioe^{\frac{qnv}{\eta kT}} = z$$

$$or\ -\frac{q.Ion}{\eta kT}e^{\frac{qnv}{\eta kT}}dv = dz$$

$$or Ioe^{\frac{qnv}{\eta kT}}dv = -\frac{\eta kT}{qn}dz$$

$$or\ v - \frac{\eta kT}{qn}\int\frac{dz}{z} = \frac{1}{C}\times t$$

$$or v - \frac{\eta kT}{qn}\log(Isc - Ioe^{\frac{qnv}{\eta kT}}) = \frac{1}{C}\times t + c1$$

$$At\ , v = 0\ and\ t = 0\ \ c1 = -\frac{\eta kT}{qn}\ln\left(Isc - Io\right)$$

$$So, v = \frac{1}{C}\times t + \frac{\eta kT}{qn}[\ln\left(Isc - Ioe^{\frac{qnv}{\eta kT}}\right) - \ln\left(Isc - Io\right)]$$

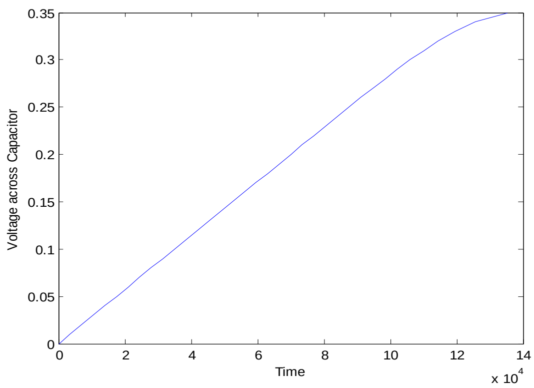

Fig. 10 shows the variation of voltage across capacitor with time as obtained mathematically.

Next, we consider the mathematical equation of a solar photovoltaic cell for a super capacitor. The charging equation is:

$$\int \frac{C + Kv.v}{Isc - Ioexp\left(\frac{qnv}{\eta kT}\right)}dv = \int dt$$

$$\Rightarrow \int \frac{dv}{Isc - Ioexp\left(\frac{qnv}{\eta kT}\right)} + Kv\int\frac{v\,dv}{Isc - Ioexp\left(\frac{qnv}{\eta kT}\right)} = \int dt$$

$$\Rightarrow \frac{C}{-Io.qn/\eta kT}\int\frac{-Io.\eta kT.\exp\left(\frac{qnv}{\eta kT}\right)}{\exp\left(\frac{qnv}{\eta kT}\right)(Isc - Ioexp(\frac{qnv}{\eta kT})}dv = t$$

$$Let, Isc - Ioexp\left(\frac{qnv}{\eta kT}\right) = z$$

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$$\Rightarrow -Io.(qn/\eta kT)\exp\left(\frac{qnv}{\eta kT}\right) = dz$$

$$\Rightarrow \frac{C}{\frac{qn}{\eta kT}.Isc}\int\left(\frac{1}{(z-isc)}-\frac{1}{z}\right)dz = t$$

$$\Rightarrow \frac{C}{\frac{qn}{\eta kT}.Isc}.\log\left(1-\frac{Isc}{z}\right) = t$$

$$v = \frac{\log z}{qn/\eta kT} \quad dv = \frac{dz}{z.\frac{qn}{\eta kT}}$$

$$\Rightarrow \frac{1}{qn/\eta kT}\int\frac{\log z}{\frac{qn}{\eta kT}.z(Isc-Io.z)}dz = t$$

$$\Rightarrow \frac{-Io}{(\frac{qn}{\eta kT})^2}\int\frac{\log z}{-Io.z(Isc-Io.z)}dz = t$$

$$\Rightarrow \frac{-Io}{Isc.(\frac{qn}{\eta kT})^2}\int\log z\left(\frac{1}{-Io.z}-\frac{1}{Isc-Io.z}\right)dz = t$$

$$\Rightarrow \frac{1}{Isc.\left(\frac{qn}{\eta kT}\right)^2}\int\frac{\log z}{z}dz - \frac{-Io}{Isc.\left(\frac{qn}{\eta kT}\right)^2}\int\frac{\log z}{Isc-Io.z}dz = t$$

$$Let, \log z = p$$

$$\Rightarrow \frac{1}{Isc.\left(\frac{qn}{\eta kT}\right)^2}\int p\,dp - \frac{-Io}{Isc.\left(\frac{qn}{\eta kT}\right)^2}\int\frac{\log(-Io.z)-\log(-Io)}{(Isc-Io.z)}dz = t$$

$$\Rightarrow \frac{1}{Isc.\left(\frac{qn}{\eta kT}\right)^2}\left(\frac{\log z^2}{2}\right) - \frac{1}{Isc.\left(\frac{qn}{\eta kT}\right)^2}\frac{\log(-Io.z)\,d(-Io.z)}{Isc+(-Io.z)}$$

$$+\frac{-Io.\log(-Io)}{Isc.\left(\frac{qn}{\eta kT}\right)^2}\int\frac{dz}{(Isc-Io.z)} = t$$

$$\Rightarrow \frac{1}{2Isc.\left(\frac{qn}{\eta kT}\right)^2}\log z^2 - Li_2\left(\left(\frac{-Io.z}{Isc}\right)-\log(-Io.z).\log\left(\frac{-Io.z}{Isc}+1\right)\right)$$

$$+\frac{\log(-Io)}{Isc.\left(\frac{qn}{\eta kT}\right)^2}\log(Isc-Io.z) = t$$

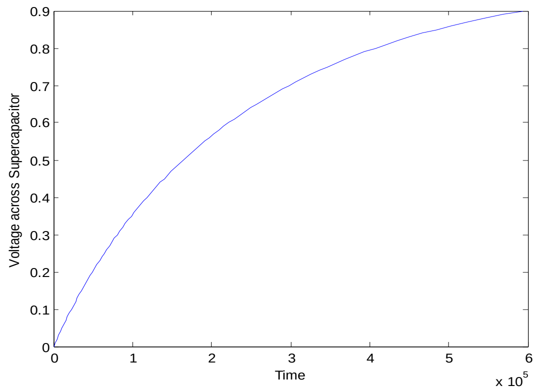

Fig.11 shows the charging profile of a super capacitor using photovoltaic cell.

It is observed that the charging characteristics as obtained by simulation and mathematical analysis for both normal capacitor and super capacitor closely follow the experimental results.

V. CONCLUSION

This paper presents the comparison of the charging characteristics of different equivalent circuits of the super capacitors using both DC and PV sources. At first, the charging characteristics of the super capacitors are simulated using a DC source. Then the equivalent circuit closest to the characteristics of the super capacitors is found out. It is seen that the RC parallel branch model is well-suited for providing the closest characteristics of the super capacitors. The RC parallel branch model is then applied using a PV source. It is again compared with the experimental results and it is observed that the RC branch model provides the best charging characteristics as compared to those of the experimental results. The paper also verifies the charging characteristics of the normal and super capacitor using mathematical current equations of the PV cell. It was observed that these characteristics as derived and verified mathematically also closely follow the experimental results.

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