Improved Method for Characterization of Ultracapacitor by Constant Current Charging

Varsha A. Shah, Prasanta Kundu, and Ranjan Maheshwari

***Abstract*- Ultracapacitors are creating new horizons in the field of energy storage systems (ESS). The reason behind the popularity is its unmatched characteristics like very high power density, long cycle life, deep discharge capacity, high efficiency and low ESR. Hence these types of devices can be effectively used in pulse power applications in power system, communication system and hybrid electrical vehicles. Different types of Ultracapacitor models have been analysed and proposed since many years.**

This paper introduces a simplified three branch dynamic model of Ultracapacitor using constant current charging method .The detailed test procedure for 150 farad and 350 farad ultracapacitors was followed in the laboratory to develop dynamic model of ultracapacitors under charging current of 5A .The model includes R-C branches along with an inductance, EPR (Equivalent Parallel Resistor) and ESR (equivalent series resistance). Ultracapacitor equivalent model is built with the consideration of linear and nonlinear factors, temperature variation & effect of leakage current. The experiment has been implemented with simple laboratory instrument like constant current supply, voltage & current data logger and computer. Computational time required for parameters calculation is minimum & simple compared to other methods followed by different authors. Final results are verified by comparing experimental results with results obtained by simulating the derived equivalent circuit model in MATLAB/Simulink. Finally some applications of ultracapacitor are discussed.

***Index Terms*—Ultracapacitor (UC), Dynamic Model, Constant Current Charging, ESS, Equivalent series resistance(ESR)**

I. INTRODUCTION

Electrical double layer capacitors (EDLCS) are popularly known as Ultracapacitor (UC) or Super capacitor (SC). These devices are emerging very fast as green energy storage devices in the field of Hybrid Electrical Vehicle, UPS system, along with FACTS devices in power system, electric drive application and utility application. Attractive features of UC are its high capacitance, short duration peak power delivery capacity i.e. high power density, reduced space, environmentally safe, low power to weight ratio, safe & very long cycle life. UC's are fabricated with two electrodes of carbon material & the distance between two electrodes is so small, that the operating voltage of ultracapacitor is less than 3V. They are commercially available up to 30,000 F. High voltage/ high current can be achieved by connecting more no. of capacitors in series / parallel. UC's are of different types based on the material to

be used for both +ve& -ve electrode, Construction & the electrolyte. UC can be charged or discharged faster than batteries & have 10 to 20 times more power density than conventional batteries. Energy density Offered by UC is 10 to 100 times more than conventional capacitors. A comparison between batteries, UC & capacitor is shown Table I. [1], [2].

TABLE I. A COMPARISON OF CONVENTIONAL STORAGE TECHNOLOGIES

Available Performance	*Lead Acid battery*	*Conventional Capacitor*	*Ultra Capacitor*
Charge Time	1 to 5 hrs	10^{-3} to10^{-6} s	0.3 to 30 s
Discharge Time	0.3 to 5 hrs	10^{-3} to10^{-6} s	0.3 to 30 s
Energy (Wh/Kg)	10 to 100	< 0.1	1 to 10
Power Density	< 1000	< 100000	< 10000
Cycle Life	< 1000	> 500000	> 500000
Charge / Discharge Efficiency	0.7 - 0.85	> 0.95	0.85– 0.98

The purpose of UC detailed modelling is to predict its electrical & energetic behaviour with high accuracy before implementation of UC in the actual system.

Therefore it is required to establish an equivalent circuit model of UC with its electrical parameters. Equivalent circuit models of UC are mainly categorized in to two group (1) Time domain model (2) Frequency domain model [2]. In this paper time domain model is discussed.

Fig. 1(a) represents the simplified model of UC which is used only for principle verification. Simple RC model cannot predict non-linear behaviour of UC. To model UC precisely, a distributed parameter model is required, which can replicate the charge distribution and self-discharge phenomenon with UC's proper equivalent circuit parameter values.

In this paper, different UC models proposed by various authors are discussed in section 2. In section 3, the RC parallel branch model and measurement of equivalent circuit parameters with mathematical equations are discussed. In section 4, simulation and experimental results are shown. It is observed that for a selected 3-branch model, simulated & experimental results are closely matched & hence verified the validity of the model.

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II. THE TIME DOMAIN MODEL OF UC

In order to model the behaviour of UC, certain requirements are set before formulation of equivalent circuit model of UC. For that the model should be as simple as possible, model should describe the behavior of UC accurately & parameters should be determined by using UC terminal measurements. As UC has complex physical nature, it is very much preferable to do analysis of UC based of distributed parameter system. UCs are modeled based on three physical aspects: (1) electro-chemistry of two different materials interfaced in different phases, which is modeled as an RC circuit. The resistive element depends on the resistance of electrode materials, resistance of electrolytic solvent, pores width membrane porosity, quality of the connection electrode-collector. (2) Based on the theory of the interfaced tension in the double layer, the capacitance of the UC varies linearly with the capacitor terminal voltage (3) Double layer charge distribution shows certain self-discharge.

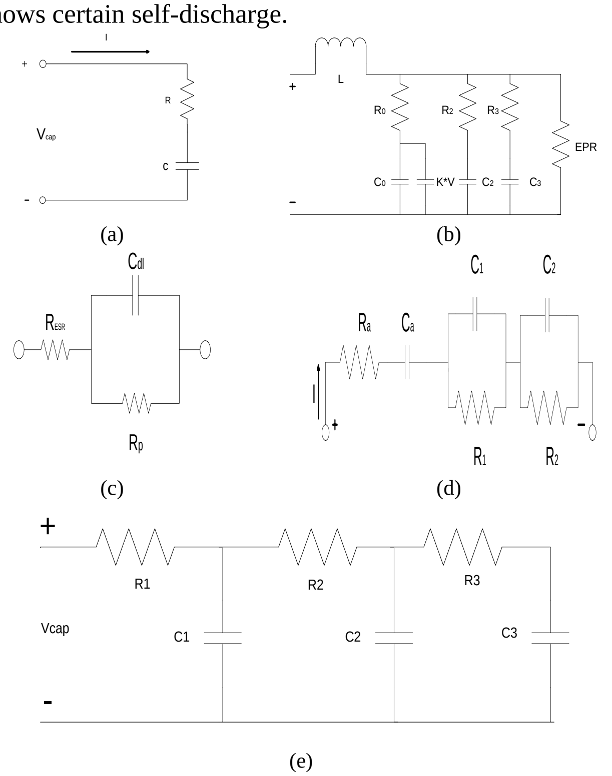


Fig. 1. (a) Simple UC Model (b) RC parallel branch model (c)UC Model with ESR and Rp (d) RC Branch Series – Parallel Model (e)Transmission line model

Various time domain model of UC have been proposed by different authors to study its electrical behaviour under various operating condition [3], [4]. Model in Fig. 1(a), (c) and (d) are incomplete to describe the behaviour of UC under various operating conditions. Therefore, more efficient ultra capacitor models have been proposed recently by many authors are shown in Fig.1(b) and (e), but many of them have ignored the temperature dependency of UC dynamics. The model used in this paper as shown in fig1(b) takes in to account temperature effect and it fits in various operating conditions more accurately. Here, the identification process is much simpler and it does not require very sophisticated instrumentation.

III. UC-RC –PARALLEL BRANCH MODEL PARAMETER IDENTIFICATION

The no. of RC circuits of the equivalent circuit model depends on the time span of the transient response to be covered. It is recommended that with three distinct R-C branches as shown in Fig. 1(b), the desired time span of the transient response is covered. Each branch has distinct time constant. With the assumption that, the first branch that is, "Fast Branch" is mainly responsible for the storage, the model first branch is identified as fast or immediate branch with the element Ro = TCF * ESR , Co & voltage dependent capacitor C_v=K*V in (f/v) and used to represent immediate behaviour of ultracapacitor in time range of seconds. This assumption has been verified in zubieta-bonert model [4].The second branch comprise of R2, C2 with charging response in the time range of minutes .Third long term branch with parameters R3,C3 determines the behaviour of UC in longer time range .The self-discharge property of UC is represented in terms of leakage resistor parallel to the terminal of UC modelled as equivalent parallel resistor (EPR) [5]. This is an important factor for determining the duration of time to store energy under open circuit. A series inductor may be added for fast charging load condition, but measurement shows that inductance is too small & it can be neglected in most applications [6],[7].

3.1 *Identification of fast branch parameter*

To start with the procedure, values of parameters of "Fast Branch" will be found out first. The resistance ESR can be calculated as:

$$ESR = \Delta V/I \qquad (1)$$

Here ΔV is the potential difference between terminals of ultracapacitor during the first charge moment and "I" is the corresponding charging current.

3.2 The Effects of Temperature on UC Dynamics

In order to develop an accurate UC model compatible with vehicular applications, it is necessary to study its thermal behaviour in its operational environment [8]. UC dynamics are strongly affected by temperature changes in all operating conditions. The experimental studies realized by Maxwell point out that the UC capacity is not affected by temperature changes, while the value of UC series resistance(ESR) changes with respect to operating temperature range, as shown in Fig 2. Especially low temperature values have reasonable impacts on ESR. Many other studies realized by different authors also prove the dependency of ESR on temperature changes [9]. Thus, a temperature correction factor (TCF) can be used to define the effects of temperature changes on ESR. The equation of TCF deducted from the resistance relative performance curve [9] can be defined as:

$$TCF = -3.5*10^{-7}\, T^3 + 7.7*10^{-5}\, T^2 -0.0054*\, T^3 + 1.1 \qquad (2)$$

Where T is the temperature of UC under operation.

ThenR_0 as a function of temperature can be defined as:

$$R_0 = TCF * ESR \qquad (3)$$

Now, next task is to determine the values of two parallel capacitances C_0 and K *V. This parallel combination can be defined as:

$$C_1 = C_0 + K \cdot V \quad (4)$$

For initial charging current i, the equation will become:

$$i = C_1 \, dv/dt \quad (5)$$

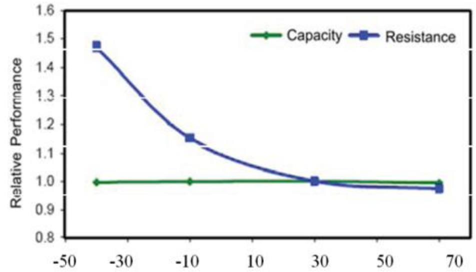


Fig. 2. Relative UC performance over operating temperature range

From equation (4) and (5) after integration it can be written that:

$$t = C_0 V/I + k V^2/2 I \quad (6)$$

As the current I is known, calculation for C_0 and K will become very simple by using two points of the charging curve as shown by Jubieta Bonert. The method shown there is two point method but here it has been modified by taking such sets of two points and then taking average of these calculations to reduce deviation of the experimental and simulated model.

3.3 Identification of intermediate branch parameters

After the identification of "Fast Branch" parameters the next task is to determine the parameters of intermediate branch. For that the time constant τ_1 is considered as 200 seconds. To approximate the value of time constant τ_1 many time constants were considered to validate the model and finally it is concluded as 200 seconds to get good accuracy. Hence,

$$\tau_1 = R_2 C_2 = 200 \text{ seconds} \quad (7)$$

As the value of I and τ_1 are known, with the measurement of the terminal voltage V_2 at the time equal to three times of $\tau_1$that is nearly 10 minutes so that the charging process transfers from intermediate branch to slow branch. So, now C_1 and C_2 are at the same voltage level. Therefore,

$$I T = (C_2 + C_0) V_2 + K (V_2)^2 /2 \quad (8)$$

Now, it is easy to calculate C_2 from (8) and once the C_2 is known R_2 can be calculated as:

$$R_2 = \tau_1 / C_2 \quad (9)$$

3.4 Identification of Slow Branch Parameters

Similarly, values of slow branch parameters C_3 and R_3 can be calculated by considering τ_2 as 600 seconds and then taking readings for voltage at 3 times τ_2 that is at 30 minutes so that the values of R_3 and C_3 can be determined.

Equivalent series resistance is important during charging and discharging because it is a loss term that will cause internal heating in the capacitor. It also reduce terminal voltage during discharge into a small load resistance due to the resistive divider effect.

3.5 Calculation of effective parallel resistance (EPR)

Equivalent parallel resistance will impact long term storage performance because it is basically a leakage effect . EPR measured during open circuit discharge: 150F capacitor EPR=4.8 kΩ, 350F capacitor EPR = 2.7 kΩ. Thus the two most important parameters of the double layer capacitor are its equivalent series resistance and its capacitance. Equivalent Parallel Resistance (EPR) IS be measured by taking the ratio of voltage and current during discharge process.

IV. Experimental Setup

Based on the physical reasoning mentioned in the previous discussion, physical model of UC is proposed. Proposed model with 8 parameters have unlimited possible solutions. Therefore the measurement procedure can be considered arbitrary to a certain degree. Experimental setup is shown in Fig.3. System is equipped with UC, a constant current source, current voltage data logger & PC. Total duration of test is 1800 sec. All the data are captured at 1 second time interval & stored in the memory of data logger. Then through USB port connectivity it is transferred to the PC.

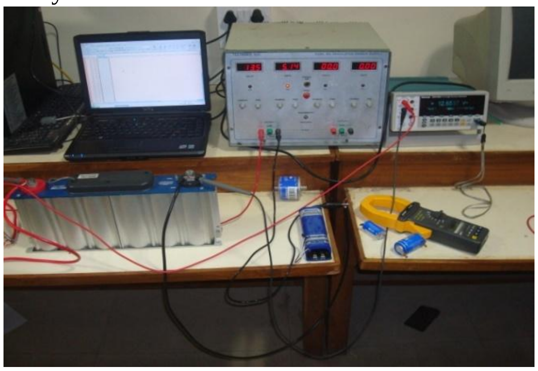


Fig. 3. Experimental Setup

4.1Model Validation

An experiment for charging of UC was performed with 150 F and 350 F ultracapacitors manufactured by MAXELL. Both ultracapacitors under testing were charged by constant current of 5A.With the help of experimental data, a third order equivalent circuit model parameters are calculated using above mentioned method of identification of branch parameters. The parameters of selected equivalent model of UCs are shown in table II. Fig. 4 shows MATLAB/SIMULINK equivalent circuit model of UC. Behaviour of UC under constant current charging is tested with Simple RC model in MATLAB/Simulink and compared with experimental results as shown Fig. 5(a). Simulation results are deviating from experimental results. Experimental results shows that behaviour of UC is non-linear as soon as charging stops, such behaviour cannot be predicated with simple RC model.

TABLE II. ELECTRICAL PARAMETERS FOR UCS

Parameter	***350 F UC***	***150 F UC***
R_0	0.004732	0.009873
C_0	237.128	118.771
K_v[F/V]	91.357	39.035
R_2	1.7839	2.85424
C_2	112.11	70.0711
R_3	2.4326	3.9123
C_3	246.642	154.130
EPR	2700 Ω	4800Ω

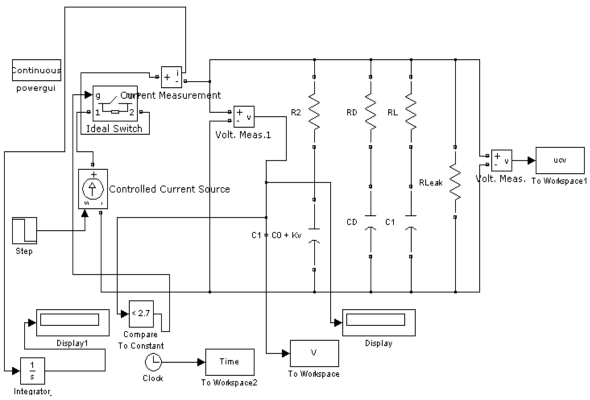


Fig. 4. MATLAB/Simulink model for both UC

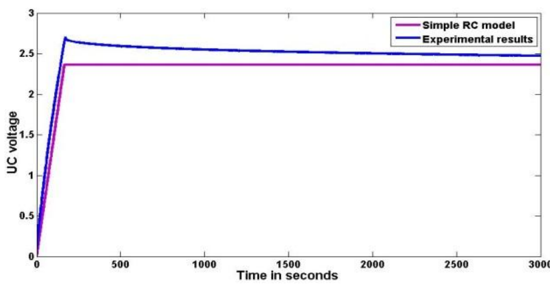


Fig. 5 (a)

Fig. 5.(a) Experimental and simulated results with simple R-C branch model for BCAP 350F with constant current 5A

Fig. 5(b) shows the charging of 350 F and 150 F with constant current of 5 A. Simulated and experimental results follow the same course. Fig. 6(a) and 6(b) shows the behaviour of UC after charging is stopped. The charge redistribution and self-discharge of UCs after charging stops in simulation environment are matching with experimental results.

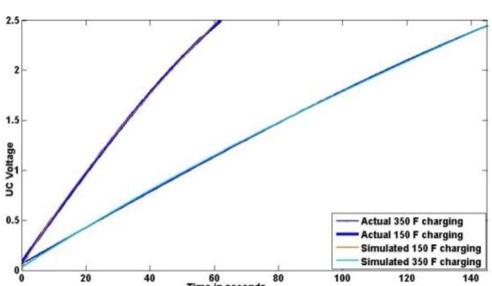
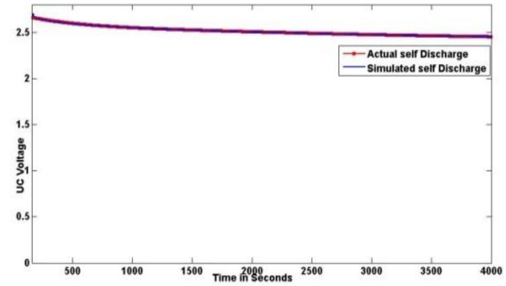


Fig.5(b)

Fig. 5. (b) Experimental and simulated results for charging mode operation with model under study for BCAP 150f and BCAP 350F with constant current of 5A.



(a)

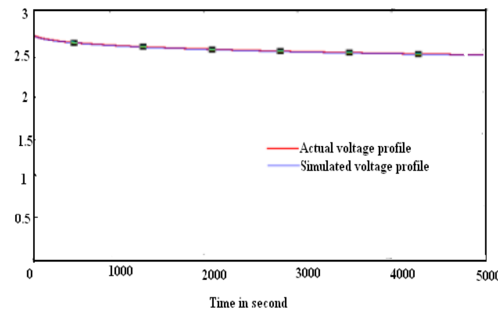


Fig.6 (b)

Fig. 6. (a) Experimental and simulated results with proposed model for BCAP 350F with constant current 5 A, (b) Experimental and simulated results with proposed model for BCAP 150F with constant current 5A (charge redistribution)

V. APPLICATIONS OF UC

Low power applications of ultracapacitors are: These capacitors are extensively used as power back-up for memory functions in a wide range of consumer products such as mobile phones, laptops and radio tuners used in pulsed applications to share the load and for providing peak power assistance to reduce the duty cycle on the battery to prolong battery life in products or devices using mechanical actuators such as digital cameras. Also used for energy storage for solar panels, and motor starters.

One of the prominent applications of ultracapacitor is its integration with FACTS devices like STATCOM to enhance real power flow. FACTS device like STATCOM can provide reactive power and can mitigate voltage fluctuations dynamically but cannot provide real power to the system to large extent. UC are enhancing this capability to deliver real power to the system when integrated with STATCOM.

The ultracapacitors are unsuitable as primary power source for EV and HEV applications however their advantages make them ideal for temporary energy storage for capturing and storing the energy from regenerative braking and for providing a booster charge in response to sudden power demands. Since the capacitor is normally connected in parallel with the battery in these applications, it can only be charged up to the battery upper voltage level and it can only be discharged down to the battery lower discharge level, leaving considerable unusable charge in the capacitor, thus limiting its effective or useful energy storage capacity.

Using ultracapacitors in EVs and HEVs to facilitate regenerative braking can add 15% to 25% to the range of the vehicle. At the same time, ultracapacitors can be used as energy storage devices such that it can provide an effective short duration peak power boost allowing the prime battery to be downsized. Ultracapacitors are also used to provide fast acting short term power back up for UPS applications. By combining a capacitor with a battery-based uninterruptible power supply system, the life of the batteries can be extended.

VI. CONCLUSION

Among several attempts for estimation of equivalent circuit parameters of UC which involves precise voltage and current measurements in time domain as well as analysis of frequency spectrum of UC in frequency domain, the proposed method offers simpler approach. The calculation is based on precise measurement of UC terminal voltage at time interval of 20ms during charging and 1s after charging is stopped. Proposed time domain model of UC consists of third order RC model. While calculating the fast branch parameter values the averaging point method is more accurate than two point method, capacitance in this branch is selected as voltage dependant parameter. The proposed model of UC is intended for use in applications like vehicle traction and power quality control. These applications utilize UCs for shorter period of time, hence branches which have time constant in range hours and days have been neglected. The models reproduce the internal charge redistribution and self-discharge accurately during a certain time span. The ultracapacitors were tested for constant current of 5A. The Simulated results matches with actual results which validate the proposed model can be used for modelling of UC for analysis during its application development like EV, HEV and STATCOM.

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