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Measurement of Specifications of Ultracapacitor

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Abstract:- This paper proposes a Digital meter for measuring specifications of Ultracapacitor using Charge-discharge method. Ultracapacitors have large energy density, high power density, high capacitance ranging from few farads to thousands of farads, low Equivalent Series Resistance (ESR) and low rated voltages. Standard measurement devices like LCR meters, etc., are not suitable for measurement of Capacitance and ESR of Ultracapacitor, as their measurement ranges are not adequate for measurement of parameters of Ultracapacitors.

Keywords— Ultracapacitors, Charge-Discharge Method, Window Comparator, DAC, Operational Amplifier, Digital Meter, Capacitance Measurement, ESR Measurement.

I. Introduction

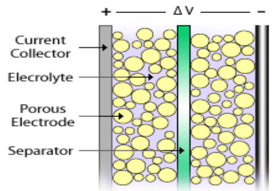
In the current world demand for efficient energy repository is increasing day by day. Like many of electronic appliances & gadgets Uninterrupted Power Supplies, etc., have pushed up the need for efficient energy storage. Main Criteria for energy storage requirements include higher power density, higher energy density, better operating performance, lower Installation/ maintenance costs, and reliability.

From previous experiences, it is evident that one single device is not adequate to support complete energy storage requirements. New approach in Energy Management is to review energy storage from two aspects viz., Average power requirements and peak power requirements. Thus, finalizing the requirements on both these aspects is a more effective approach for electrical energy requirements [3].

Presently for average power requirements of different applications we are widely using Batteries and fuel cells. Capacitors with higher power capability are used for satisfying peak power requirements. With more and more advancement in gadgets, pulse duration of peak power has gone up significantly. Conventional capacitors are not suitable for the enhanced pulse duration of peak power [4],[6]. Search for a better device delivering high power coupled with large storage capability of energy led to invention of Ultracapacitors.

II. Ultracapacitors

Ultracapacitors also called as electrochemical Double Layer Capacitors or Super Capacitors having very high energy density and power density than conventional capacitors [4]. Ultracapacitors consist of two electrodes, a separator, and an electrolyte filling the space inside the device. Here the electrodes consist of highly conducting metallic current collectors with activated carbon part having porous structure. The porous structure of activated carbon increases the contact surface significantly between the electrodes [2].



Due to above construction, these capacitors offer reliability, and high power density, increased cycle-life than normal batteries. They have very high capacitance values and low Equivalent Series Resistance (ESR) values with low rated voltages.

III. Applications of Ultracapacitors

The performance benefits of Ultracapacitors come into play most effectively when a large spike in power consumption or a large-scale, repeated charging cycle is required.

These have less charging cycle and longer shelf life than batteries. These are attractive for varieties of applications of Energy storage.

The prominent applications using Ultracapacitors are Transport applications, viz., hybrid vehicles, electric buses, and Motor racing cars, Rails and Trams, Railway Locomotives. Industrial apps like Cranes, Forklifts, Tractors, industrial power management, & other applications viz., Toys, Medical, Wind Power applications, etc. [6] [10]

IV. Measurement of Specifications of Ultracapacitors

Measurement of Specifications of UC is necessary for the quality of UC and suitability for particular application. Standard measurement devices viz., LCR meters, etc., are found inadequate for measuring the characteristics of an Ultracapacitor.

The range of measuring capacitance values from standard LCR meters is much narrower than the ranges of capacitance values of Ultracapacitors. Further, these devices are mostly battery powered and hence have limited energy [4]. Therefore, these devices are not suitable for measuring characteristics of Ultracapacitor. Hence, there is need for a devising a new method for measuring capacitance and ESR of an Ultracapacitor.

To develop a new meter for measuring Capacitance of an Ultracapacitor, it is essential that the method is capable of applying large DC current signals across an UC at low rated voltage. Charging/Discharging method is one of the most suitable ways for this application.

For measuring Capacitance of UC by charging/ discharging method, time taken to charge from lower preset voltage to higher preset voltage or discharge from higher preset voltage to lower preset voltage, is determined[1]. From this, Capacitance of Ultracapacitor can be arrived using formulae described below.

In addition, there is a need for digital data acquisition, measurement and display system in a Digital platform for achieving higher accuracy and resolution.

To understand charging/discharging circuit and to arrive at formulae for Capacitance C, let us consider a simple charging circuit as given in Figure 1 below, having a power supply with voltage Vi, a Switch, a Resistance R and an Ultracapacitor. Voltage across UC is VC.

Let t1 be the time taken for the Ultracapacitor to get charged to voltage level V1 and t2 is time taken to get charged to Voltage level V2. The voltage across the Ultracapacitor at time t1 is given by

$$V_1 = V_i(1 - e^{-t_1/RC}) \qquad (1)$$

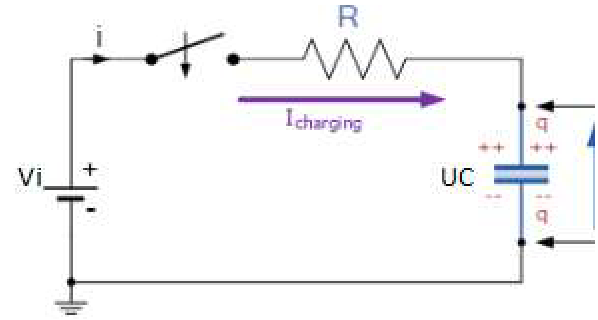


Fig.1: Charging Circuit of UC.

Where Vi is the supply voltage and RC is the time constant. Similarly, the voltage across the Ultracapacitor at time t2 is given by

$$V_2 = V_i(1 - e^{-t_2/RC}) \qquad (2)$$

From the above equations (1) and (2),

$$\frac{t_1}{RC} = -ln(1 - \frac{V_1}{V_i}) \qquad (3)$$

$$\frac{t_2}{RC} = -ln(1 - \frac{V_2}{V_i}) \qquad (4)$$

From the above equations (3) and (4), Capacitance of Ultracapacitor during charging cycle can be derived by the following formula.

$$C = \frac{t_2 - t_1}{R\left[ln\left(1 - \frac{V_1}{V_i}\right) - ln\left(1 - \frac{V_2}{V_i}\right)\right]} \qquad (5)$$

In the above equation (5), t2-t1 is the pulse width measured in seconds through the circuit. All other values V2, V1 and Rare known and hence C can be arrived.The above concept has been implemented for measurement of capacitance using Charge/Discharge circuit, DAC and Window Comparator.

ESR is a measure of the total lossless of a capacitor including in-phase AC resistance of the dielectric, plate material, electrolytic solution, and terminal leads at a particular frequency. A theoretically perfect capacitor would be lossless with Nil ESR i.e. no in-phase AC resistance.

To measure ESR of UC, the capacitor is charged to a specified voltage and then allowed to discharge through opening of a switch. When the Capacitor is allowed to discharge, an instantaneous drop in voltage is observed at the commencement of discharge. Since Capacitors do not react to sudden changes, it can be understood that this sudden drop in voltage is not due to capacitance of Ultracapacitor. Therefore, this sudden drop in voltage is due to ESR of Ultracapacitor. After this initial drop in voltage, actual capacitive action of UC starts leading to discharge in exponential fashion.Measurement of this voltage drop will lead to measure of ESR of Ultracapacitor.

V. Circuit Implementation

By using RC charging circuit UC has been charged with applied voltage Vi without exceeding the voltage rating of the Ultracapacitor. Current requirement for the charging of UC is very high. Hence an electronic switch ADG 1401 has been selected for the design maximum current of 400 mA. To measure the time taken for charging of UC from V1 to V2, a window comparator has been used. A window comparator has a pair of voltage comparators. Both comparators trigger on detection

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of upper and lower voltage threshold level V2 and V1 respectively. The voltage levels between these two reference voltages is called 'window'.

In this circuit, both the comparators of window comparator are in inverting mode. Reference voltage is applied to the non- inverting input and Voltage across the capacitor is applied to the inverting input. Whenever, the voltage across the capacitor goes above set voltage (V1 or V2), the output of the comparator becomes low [7]. The pulse is obtained from V1 to V2 by using NOT & AND gates. Pulse output illustrating t2-t1 from window comparator is directly proportional to the Capacitance Value. This Pulse output can be observed in DSO and also is fed to a microcontroller for calculating capacitance value. To get clear output from comparator quietly, a positive feedback is provided around the comparator. The use of this implies that once the output is triggered into saturation at either level, there must be a significant change to the input signal Vi before the output switches back to the original saturation point. This difference between two switching points is called hysteresis, and the circuit is generally known as Schmitt trigger circuit [7].

In the design commercial voltage comparators LM311 with low input bias current of around 250 nA has been used. The outputs of voltage comparators are open collector outputs. A pull-up resistor is used at the output of the comparator to provide an output voltage signal to the input of another device. This concept of window comparator with hysteresis and pull up resistor is deployed while designing Digital meter.

For improving the resolution of measurement, AD7541, a 12 bit multiplying Digital to Analog Converter (DAC) has been used in the circuit for accurate setting of reference voltage levels. These are" Multiplying DACs" or MDACs where the analog output is the product of the analog input and the digital code [7]. It gives a high resolution of 1/4096 (0.244 mV) of reference voltage. Hardware is made on a PCB and tested.

For measurement of ESR, first the Ultracapacitor is allowed to charge to a specified voltage level and then allowed to discharge. For taking the Voltage to peak and discharging, a Peak detector is used for detecting and holding the most positive value. This voltage is attained by the input signal prior to the time when the switch is open. Conventional Peak detectors will discharge in milliseconds so these are not suitable.

For holding peak voltage of Ultracapacitor DAC is used. Block diagram of the circuit is given in Figure 2.

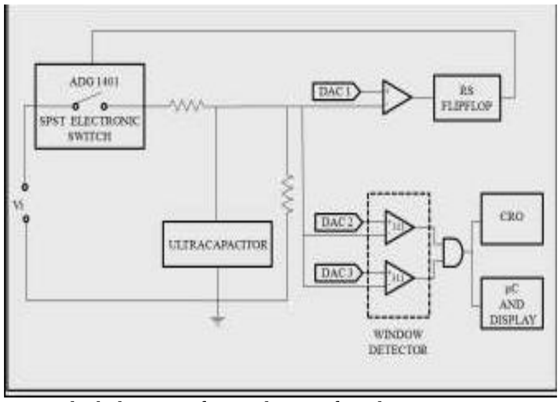

Fig.2: Block diagram of Digital Meter for Ultracapacitor

At first switch is closed and capacitor is allowed to charge. After it reaches the particular set voltage, the switch is opened allowing for discharge. To achieve this, a comparator has been used. DAC output is given to non-inverting input of comparator. Voltage across capacitor is given to inverting input of comparator.

As long as capacitor voltage is less than the preset voltage, comparator output is high. This comparator is given to RS flip-flop and output of flip-flop is given to control input of switch. As long as the switch is closed, capacitor continues to charge.

Once capacitor voltage reaches the set voltage, comparator output moved to LOW by making flip-flop output in turn to LOW. This LOW output of RS Flip Flop leads to opening of the switch, allowing the capacitor to commence discharge. At the time of start of discharge, sudden drop in voltage is observed, which a measure of ESR of Ultracapacitor.

As capacitor continues to discharge, time taken for discharge from V2 to V1 has been observed using DSO and it is used to calculate capacitance. The below Equation(6) gives capacitance value while discharging. The final equation for capacitance measurement during discharge cycle is given by

$$C = \frac{t_2 - t_1}{R * \ln V_2 / V_1} \qquad (6)$$

Where, t2-t1 is the time taken for discharging from Set voltage V2 to set voltage V1.

VI. Hardware testing & results

The block diagram given in Figure 2 was implemented in hardware and tested. The actual pictures of the hardware are included below in Figure 3 and Figure 4 and the waveform observed in DSO is included as Figure 5.

Figure 3 below shows display of capacitance waveform in DSO while testing. Figure 5 shows

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the sudden drop in voltage at the instant of opening of Switch and thereafter waveform of exponential discharge of UC and Figure 6 shows the display of Capacitance value in LCD.

Using this circuit, readings were taken while charging for different values of Ultracapacitors with capacitance ranging from 3F to 350 F and these readings were plotted in a graph.
Graph given in Figure 7 clearly describes linearity between capacitance and pulse width. Readings are also taken while discharging. ESR measurement is carried out during discharge.

First abrupt drop in voltage due to 3F capacitor alone at the instant of starting of discharge is observed on DSO and it is found to be 0.04V. Subsequently, a 1 ohm resistor has been connected in series with 3F Ultracapacitor and the sudden drop in voltage at the instant of starting of discharge has been observed on DSO and it is found to be 0.12 V.

ESR of 3F Ultracapacitor is arrived at by dividing the initial reading with the final reading. For a 3F Ultracapacitor, ESR is measured to be 333mΩ (0.04/0.12) and the above graph is obtained by carrying out measurements of Ultracapacitors of known values viz., 3 Farads, 25 Farads,50 Farads, 75 Farads, 100 Farads and 350 Farads using the Digital Meter.

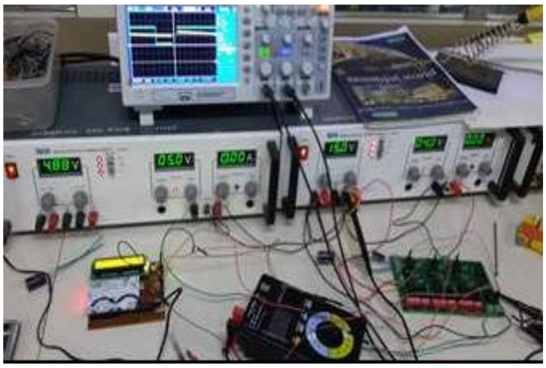

Fig.3: Testing of Circuit with display of waveform

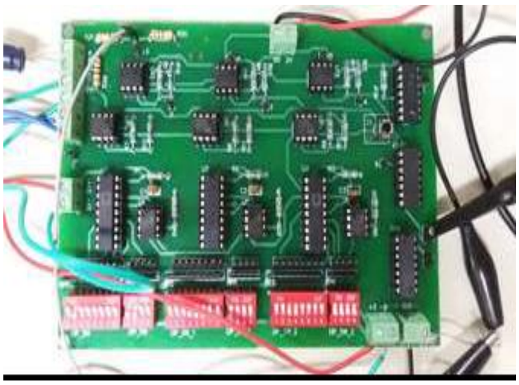

Fig.4: Hardware implementation in PCB

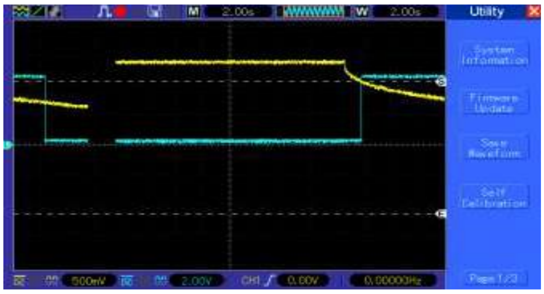

Fig.5: Waveform showing sudden drop due to ESR and Pulse for Capacitance measurement.

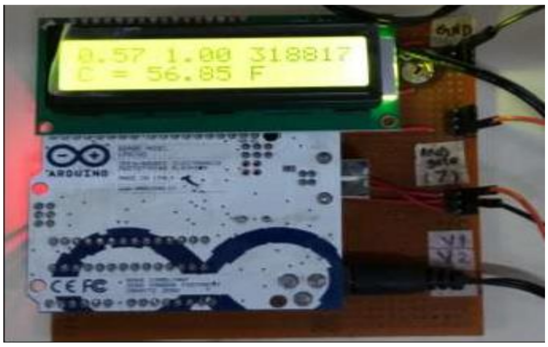

Fig.6: Display in LCD

VII. Validation of results

As per the product specification sheets of Ultracapacitors, it was observed that 3 F, 25 F and 50 F have capacitance tolerance of -20% to +20%. 100 F has a tolerance of -10% to +10%.350 F Ultracapacitor has a tolerance of 0% to 20% tolerance.

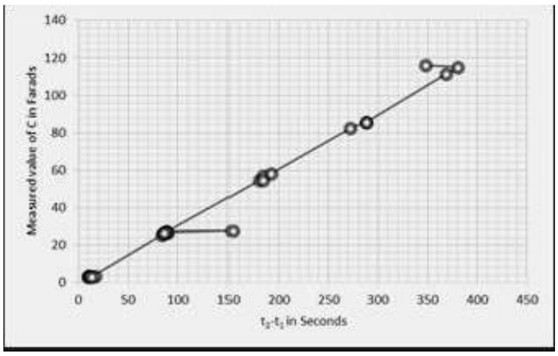

Fig.7: Graph showing Measured Value of C in Farads Vs t2-t1 in seconds

All the results obtained while testing are well within the tolerance limits given in the product specification sheets.

VIII. Conclusion & way forward

Based upon review of various research papers, it was found that there is scope in developing measurement technique for measuring Capacitance and ESR of Ultracapacitors, which

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requires high resolution measurement. Further study was carried out on Ultracapacitors to understand the construction, parameters and Operating characteristics of Ultracapacitors. Based on the understanding of the same, a suitable procedure for measuring Capacitance and ESR was developed and circuit was designed and circuit was implemented using various components. The Circuit was tested and got good results.

A dedicated Analog to Digital converter and display system can be developed for ESR measurement. After the measurement of specifications of Ultracapacitor, detailed research can be undertaken for energy storage applications in Rural and remote areas so as to provide Urban facilities in Rural Areas. This would bring good change in the standard of living for those living in villages and in turn give a boost to the development of the Mankind.

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