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The Effect of Equivalent Series Resistance on the Charge Rate for Electric Double Layer Capacitor in an Energy Harvesting System

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ABSTRACT

The electric double layer capacitor (EDLC) has been applied mainly in the energy harvester storage system due to its efficiency in power density and long life cycle. The objective of this paper is to assess the effects of electrolyte properties in EDLC by comparing the different equivalent series resistance (ESR) for the same capacity EDLC. Three supercapacitors with different rated ESR were tested under a monitored working condition to study the relationship of ESR with the charge rate of EDLC. The results and measurements of the empirical study are presented and analyzed to illustrate the effect of rated ESR on the charge rate.

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INTRODUCTION

Renewable energy sources have given a great impact in research and are essential in view of fossil fuel exhaustion and environmental conservation. Various analytical models ranging from energy converters to energy storage system have been studied extensively with the aim of designing a robust energy harvester, maximising the output power of an energy harvester system.

In recent years, energy storage system incorporating an electric double layer capacitor (EDLC), also known as super capacitor, with power electronics has been developed extensively for renewable energy sources (Spyker and Nelms, 2000b; Zubieta and Bonert, 2000). The EDLC has been the main focus in the energy storage system for energy harvester due to its efficiency in power density and long life cycle. EDLCs are able to provide large energy density compared to conventional capacitors because of its carbon electrolytes which feature a huge surface area and thus large volumetric capacitance (Frackowiak, 2007; Zhang and Zhao, 2009). Furthermore, in comparison with the battery, it requires only a short duration for full charging and thus provides a larger power density. EDLCs have unlimited charging and discharging cycles due to its electromechanical properties that allow charges to be stored physically without any chemical alterations (Frackowiak, 2007; Zhang and Zhao, 2009; Zhang *et al*., 2009). Since EDLCs do not involve any chemical reactions, they are more environmental friendly compared to batteries.

The performance of EDLCs in terms of energy and power density is essentially dependent on its breakdown voltage by the electrolyte materials. Thus, the selection of an electrolyte with a high electromechanical potential is vital and generally preferred for the generation of high breakdown voltage (US Department of Energy, 2007). The selection of electrolyte materials also influences the capacitance of an EDLC. Furthermore, the design and material composition of EDLCs electrodes are also equally important in achieving high energy density. As most of the commercial EDLCs typically comprise of carbon structured electrodes, appropriate electrode designs such as pore distribution and pore size need to be optimised to ensure the electrode’s surface can be easily penetrated by the electrolyte ions.

Researchers found that the usage of smaller structured porous materials such as the electrode’s materials generally contain a larger surface area per unit volume and thus larger energy density (Cheng *et al*., 2008; Inagaki, 2009; Mao and Chen, 2007; Stein *et al*., 2009). Moreover, the advancement in nanotechnologies does make it possible for manufacturers to produce mesoporous materials, especially through an appropriate synthesis process.

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The selection of electrode and electrolyte materials strongly reflects the electrode conductivity and hence the value of equivalent series resistance (ESR) in the super capacitors. Since the power density of the EDLCs depends on the ESR, the choice of electrolyte should be optimised to suit the electrode materials. In other words, the best selection for electrode pore size will subject to the size of the ion in the electrolyte materials (Frackowiak and Beguin, 2001).

This paper studies the impact of the rated ESR of an EDLC and its relation in an energy storage system. By studying the variation of ESR, a proper selection of electrode and electrolyte materials can be done in determining the electrolyte breakdown voltage and its application for diverse ambient energy sources.

Edlc equivalent circuit:

The equivalent circuit of a double layer capacitor can be represented as a simple lumped parameter model consisting of a capacitance (C) with its equivalent parallel resistance (EPR) and an equivalent series resistance (ESR) (Spyker and Nelms, 2000a), as shown in Fig. 1.

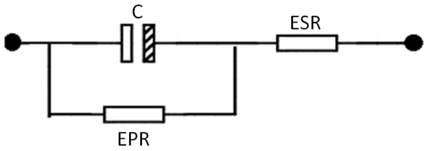


Fig. 1: Simple Lumped Parameter Model of EDLC Equivalent Circuit.

The calculation of EPR usually involves the process of charging and discharging a capacitor to its rated voltage over a substantial period of time. Since this empirical study involves only a short charging and discharging time up to the order of a few minutes, the EPR can be disregarded due to its large time constant of C. Thus, the equivalent circuit in this paper is assumed to comprise of only the capacitance and its ESR, which can be calculated based on the change in voltage, ΔV with respect to its current, ΔI during the charging process.

$$ESR = \frac{\Delta V}{\Delta I} \tag{1}$$

The value of ESR varies according to the operating temperature of an EDLC. As the operating temperature affects the breakdown voltage of the terminals and the porosity of carbon materials on the electrodes, the choice of electrolyte is also essential for the EDLC.

Methodology and design analysis:

The empirical design of the study involves the usage of a 10 W solar panel and three EDLC with different rated ESR. As the ESR is strongly dependent on the electrolyte conductivity of a capacitor, the selection of rated ESR is related to the porosity of the electrode material. Each of the EDLC selected has a maximum operating voltage of 5.5 Vdc and a nominal capacitance of 1.0 Farad (F). It is also observed that the selection of capacitance is strongly dependent on ESR. It is found that the value of ESR for the supercapacitor increases with the capacitance. The rated ESR of each supercapacitor selected is 35 Ω (Type A), 30 Ω (Type B) and 3.5 Ω (Type C) respectively.

The power source for this energy harvester is a 10 W solar panel working under a controlled condition with constant illumination. A voltage regulator circuit is applied into the system to ensure that the harvested output does not exceed 5.5 Vdc operating range of EDLC. The ESR value of the supercapacitor is altered overtime if the EDLC is operating above it rated voltage. The circuit for the charging and discharging process of the EDLC is as shown in Fig. 2 and Fig. 3 respectively.

Before the start of the charging process, each capacitor is discharged completely to remove any residual voltage. The capacitors are discharged in a closed circuit for 24 hours before they are used for this empirical study.

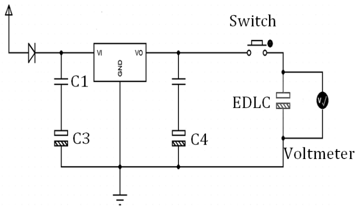


Fig. 2: Charging Circuit for Energy Storage System.

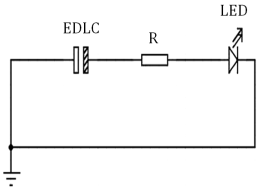


Fig. 3: Discharging Circuit for EDLC.

The energy storage process is carried out in an indoor workstation with the fluorescent light as the source of energy for the solar panel. This is to ensure that a constant source of current and voltage is received throughout the study. The initial conditions for the indoor charging are shown in Table 1. These conditions are monitored and maintained throughout the experiment.

For the charging process, each type of supercapacitor is charged up to a nominal voltage of 5.0 V before it is switched to the discharged circuit. The EDLC is then switched to discharge mode by connecting a resistor and a LED in a closed circuit, as shown in Fig. 3.

In order to further study the behaviour of its recharging process, the charging process is repeated after the EDLC has been discharged to 30% of its nominal voltage, which is at 1.5 V.

The selected capacitors are subjected to a series of charge and discharge cycles and the voltage and current are recorded for each cycle respectively. The variations of voltage and current for each charge and discharge cycle are recorded using a voltmeter and an ammeter throughout the experiment. From these voltage readings, the charge rate is calculated to compare the effect of the ESR selection in the energy storage system. The measured voltage is rewritten into charge, Q by using equation 2 to determine the charge rate for each EDLC.

$$Q = CV \tag{2}$$

Experimental Results And Discussion:

The response of the capacitor voltage to different charge and discharge cycles for the three types of EDLCs is measured and plotted against time, as shown in Fig. 4. In order to further relate the influence of ESR and hence electrode porosity on the charge rate of the EDLC, the measured voltage for the charge and discharge cycles is re-plotted with charge against time, as shown in Fig. 5.

For an improved visualisation, the measured results are plotted into three different phases. The first phase of the cycle involves the initial charging phase, where the EDLC is charged up from 0.1 V to 4.95 V, as shown in Fig. 5 (a). Fig. 5 (b) shows the second phase of the results which comprise of the discharge cycle for EDLC discharging from 4.85 V to 1.6 V. The final phase of the cycle involves analysing the recharging process, where the EDLC is charged up again from 1.6 V to 4.85 V, as shown in Fig. 5 (c).

Subsequently, the charge rate for each respective EDLC is calculated and tabulated in Table 2. Based on the data analysis of the graph and charge rate, the type A supercapacitor performs the best as it is able to charge up to 4.85 V in the shortest time duration and thus has the fastest charge rate. Since the power density is proportional to the rate of charge delivery, type A supercapacitor would have the highest power density compared to other EDLCs. For the discharge cycle, all the EDLCs appear to discharge in the same time duration. However, further calculation on the discharge rate shows that type C supercapacitor discharges at the slowest time duration as it is able to retain it charge in a longer period compared to the other EDLCs.

Conclusion:

Based on the empirical study, it is found that the EDLC with a higher rated ESR performs better in terms of charge rate for the solar energy storage system. However, due to the porosity of its electrode materials, the EDLC also loses it charge faster compared to other supercapacitors. Consequently, the selection of rated ESR which greatly depends on the choice of electrode and electrolyte materials does affect the charge and discharge rate in an energy storage system. Future work may be required to further optimise the effect of ESR of the supercapacitor, which may impact the output capacity and its charging and discharging effect in varied conditions.

Table 1: Initial Conditions for Solar Panel.

Temperature, T [°C]	Voltage, V [V]	Regulated Voltage, V [V]	Current, I [mA]	Power, P [mW]	Resistor, R [m Ω]
31	14.94	4.94	5.08	75.7	80

Table 2: Charge Rate for EDLC in 3 Phases.

Type of EDLC	Charge Rate [Coulombs/s]		
	Phase 1 (Charging)	Phase 2 (Discharging)	Phase 2 (Rcharging)
Type A	0.169	-0.361	0.231
Type B	0.110	-0.295	0.154
Type C	0.082	-0.271	0.147

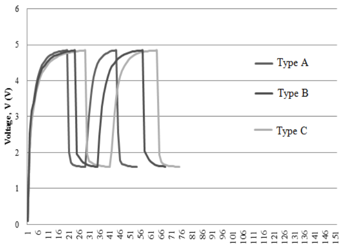
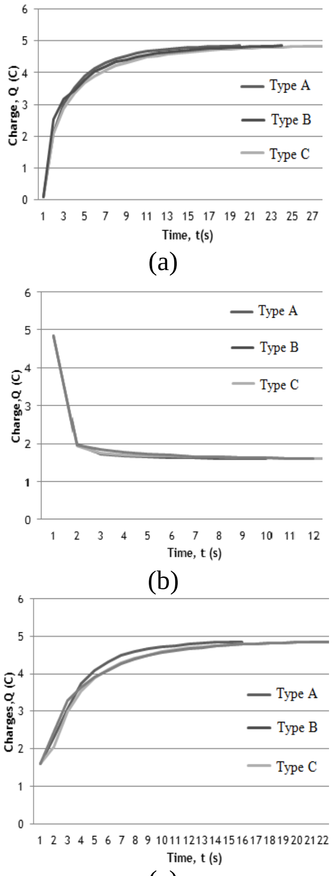


Fig. 4: Graph of Voltage, V versus Time, t for Three Types of EDLC.



(a)

(b)

(c)

Fig. 5: Graph of Charge, Q versus Time, t for 3 Types of EDLC (a) Initial Charging Phase (b) Discharging Phase (c) Re-Charging Phase.

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