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AN INVESTIGATION OF THE CHARGE-DISCHARGE CHARACTERISTICS OF AN ULTRACAPACITOR IN COMPARISON WITH CONVENTIONAL BATTERIES USING PSCAD-1D

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Abstract: The charging and discharging of ultra-capacitors have been studied in this research. An equivalent circuit was used to describe the electrical behavior of the ultra-capacitors. The equivalent circuit was implemented in Power System Computer Aided Design (PSCAD-1D) software for simulations. Maxwell 350F ultra-capacitors were used in the basic model. Simulation results of this model in a stable charge/discharge procedure showed excellent agreement with results obtained from experiments. The charging of the ultra-capacitor took approximately 50 seconds. The ultra-capacitor shows a nearly constant energy storage capacity. Also, the time constant for the full charging phase is 63% while the discharge phase is 37%. The graph of the discharge phase is exponential. A discharge efficiency of 85% at all charge/discharge current was determined and its specific power is relatively high.

Keywords: ultra-capacitor, charging, discharging, efficiency and power

INTRODUCTION

The ultra-capacitor is a promising energy storage device with behavior between traditional capacitor and rechargeable battery. The ultra-capacitor possesses outstanding unique features that could possibly give it an edge over the existing energy storage system. It can be charged and discharged quickly like a capacitor, but still exhibits 20-200 times greater capacitance than conventional capacitors (Conway B.E., 1999). The full charging and discharging time can take only few seconds without damaging the cell. Ultra-capacitors are also known as super-capacitors. Ultra-capacitors with capacitances ranged from several hundreds to over a thousand Farads are produced on large scale for transportation applications [(Kim Y., 2003), (Pay, S. and Y. Baghzouz, 2003)].

The charging and discharging processes of ultra-capacitors are highly reversible and does not require any intermediate stages. Also, the power density of ultra-capacitors is higher than those of normal batteries, although the energy density is lower. The difference is due to different mechanism of energy storage (Conway B.E., 1999). These unique features of ultra-capacitors

allow its use in a wide variety of applications in the backup power sources, auxiliary sources, for instantaneous power compensation, for peak power or simply as energy storage element. Although, super-capacitors have clear advantages over conventional use of batteries as energy storage medium, there are still obstacles to its wider use such as low energy density and a very high discharging rate.

This study aims at studying the intricacies of the charging and discharging mechanisms of the super-capacitors with a view to providing insight to the dynamics of its operation. This will be achieved through the modelling and simulation of the model using PSCAD-1D software.

DEVICE STRUCTURE AND MODELING

Ultra-capacitors store energy electrostatically through a process known as non-faradaic electrical energy storage. Testing any simulation program involves an initial building of a model. Some models have been developed in literatures which permit the determination of some of the super-capacitors parameters [Conway B.E., 1999 and Camara, M., 2007].

The ultra-capacitor cell modeled in this paper was based on 2.7V cell. A series of measures for Maxwell 350F super-capacitor was tested in this study. The basic model used for this study is shown in figure 1 and the analyses given below.

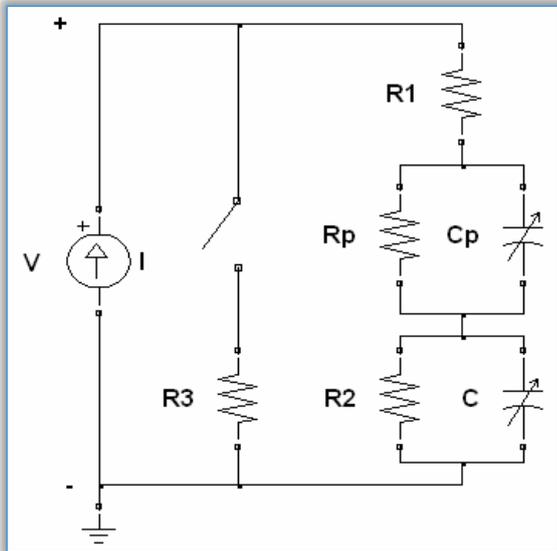


Figure 1: The basic circuit model of the Maxwell 350F super-capacitor

Figure 1 above shows a super-capacitor modelled containing standard circuit components. A similar circuit design was presented in the data sheet for the super-capacitor from European Phase Change Ovonic Science (EPCOS) (Data Sheet, EPCOS). This circuit consists of the essential parts used in the basic model.

Table 1: General technical data provided by the manufacturer (Product guide, 1.2)

Product	BCAP0350
Dimensions	L = 61.5mm D = 33.3
Mass	60g
Rated capacitance	350F
Minimum capacitance	350F
Maximum ESR	3.2mΩ
Rated voltage	2.70V
Maximum voltage	2.85V
Maximum current	170A
Specific energy	5.9Wh/kg
Stored energy	0.35Wh

The two variable capacitors are nonlinearly varying with the voltage that is applied across the circuit, according to the relation found in the measurement data. The capacitance C is responsible for the control of the charging processes of the super-capacitor. The capacitance value determines the amount of energy stored and the rate of energy level variations. The capacitance C determines amount of energy stored and Cp is taken as one thirteenth of C, as its impact is very small.

The self-discharge effect is handled by resistance R2 that is connected in parallel with the capacitor while the R1 connected in series resistance signifies the losses during charging and discharging processes. These losses are presumed to occur since the connection is not ideal and therefore the conducting element in the super-capacitor has a resistance.

The resistance R3 offers excess voltage protection. The switch next to R3 prevents damage that could occur to the capacitor elements by balancing the voltage levels. This difference in voltage can occur if a cell has a smaller capacitance than the other, which is reflected in the amount of stored energy [6]. Resistance Rp and R2 are included in the circuit to show the fast-dynamic processes in the behavior of the super-capacitor.

The values of the circuit component used in the implementation of the model in the PSCAD software are: R1 = 6 mΩ, R2 = 18 kΩ, R3 = 52Ω, Rp = 3mΩ, C = 350F, Cp = 27F. The technical data of the ultra-capacitor used for the model as specified by the manufacturer is given in table 1.

RESULTS AND DISCUSSION

» Charging Stage

The values of all the components are varied to optimize the circuit to a practical model. To characterize this ultra-capacitor, a constant current discharge/recharge test was used. The charging phase shows the following variations of voltage with time as shown in figure 2.



Figure 2: Voltage variation with time

The precise current control of ultra-capacitor is not required for the simulation since, it can accept a wide range of charging current. Thus, the criterion for terminating charging is the maximum rated voltage of the ultra-capacitor (Marco et. al., 2015). In this work, the ultra-capacitor used is fully charged to its rated value in approximately 50 seconds.

Figure 2 shows that the charging voltage is approximately 2.8V which is in agreement with the value of the technical data used.

This gives it a better advantage over the conventional batteries that takes several minutes to hours to charge. In addition to this, the charging can start from 0V without any damage to the ultra-capacitor. It has a very long term time constant of approximately one second. The available charges at any time is a function of the output voltage. Thus, when the charging current is varied, the ultra-capacitor shows a nearly constant energy storage capacity.

For an ultra-capacitor, experimental results reveal that the energy storage capacity is nearly constant under different rates of charging. In practical situations, a voltage comparator is employed for charging termination of the ultra-capacitor as soon as it reaches its rated value (Marco et. al., 2015).

» Discharging Stage

The time constant of ultra-capacitors is approximately one second (Ultra-capacitor Product guide 1.2). For the ultra-capacitor under consideration, the time constant is given as $\tau = R_s C = 0.90$. R_s is the ultra-capacitor internal resistance and C is the capacitance.

The time constant for the full charging phase is 63% while the discharge phase is 37% (figure 3). This is in agreement with BCAP0350 specification data.



Figure 3: Current variation with time

The discharge phase was determined from the values of current with their corresponding time interval from the PSCAD software used for the simulation of the super-capacitor. Microsoft Excel Program was used to plot the graph of the data obtained from the simulator as shown in the Figure 4.

The test starts from fully charged status with an open circuit voltage (OCV) = 2.8V. The following observations were deduced from the simulation as shown in the graph of figure 4. The discharge phase is exponential (figure 4). Hence, a non-purely resistive short term behaviour during the first few seconds.

In practical applications, direct short circuit is not a problem. This gives it a better advantage over conventional batteries.

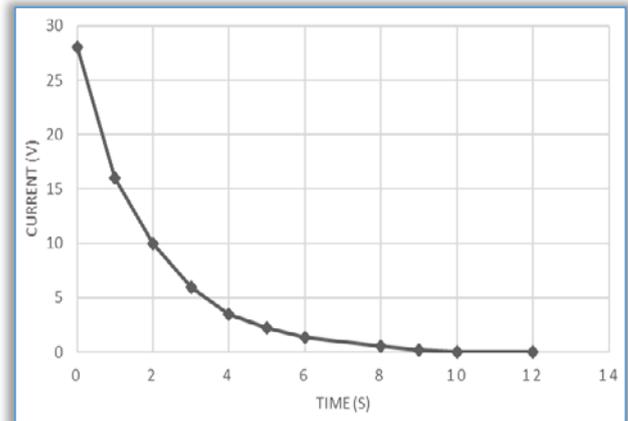


Figure 4: Current-time graph of the discharge phase

» Discharge Efficiency (η_d)

The discharged efficiency η_d of the BCAP0350 is determined from the time constant τ as follows.

$$\eta_d = 1 - 2 \left(\frac{\tau}{T_d} \right) \quad (1)$$

The constant total current discharge time T_d to fully deplete the stored energy in the ultracapacitor is 12 seconds (figure 4). Therefore, the discharge efficiency of the ultra-capacitors is approximately 85%. The graph of figure 4 shows that ultra-capacitors exhibit non-linear behavior as soon as the charging stops.

CONCLUSIONS

A dynamic modelling technique for power conversion is important in terms of domestic and commercial needs for a fast storage, conversion and supply of a quantity of energy.

Ultra-capacitor module of (350F) was characterized and analyzed in this report. It shows good and stable performance under all operating conditions during testing.

Its efficiency is about 85% at all charge/discharge current and its specific power is relatively high compared to Lithium ion batteries. It is however recommended that the optimization of the model can improve the model performance.

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