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Characterization, Analysis and Modeling of an Ultracapacitor

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Abstract

Ultracapacitors are potentially promising power-augmentation devices in hybrid powertrains. A commercial ultracapacitor module was characterized under standard procedures to assess its performance. Tests were carried out on a platform, with which ambient temperature can be regulated and charge/discharge procedures can be implemented. Key parameters of the ultracapacitor module obtained from tests were used to develop a control-oriented ultracapacitor model proposed in the paper. Simulation results of this model in a stable discharge procedure and in dynamic procedures (i.e. driving cycles) showed excellent agreement with results obtained from experiments, indicating that the ultracapacitor model is accurate enough to be used in further electric powertrain control simulation.

Keywords: ultracapacitor, coulometric efficiency, ESR, FreedomCAR, ultracapacitor model

1 Introduction

In order to meet future demands on low fuel consumptions and low exhaust emissions, hybrid powertrain system has played a more and more important role in recent years. Although there're different types of systems, such as hybrid electric powertrain and pure electric powertrain systems, energy storage devices are always the most critical components that will restrict the performance of systems. Therefore the selection of energy storage

devices should be carefully conducted, and the study of different energy storage devices' performance is required.

The ultracapacitor is a promising energy storage device with behavior somewhere between rechargeable battery and traditional capacitor. It can be charged and discharged quickly like a capacitor, but exhibits 20-200 times greater capacitance than conventional capacitors [1]. The ultracapacitor can supply the power needed during vehicle acceleration and capture energy during regenerative braking. At cruising speeds, a

fuel-efficient engine charges the ultracapacitor and provides the power needed for propulsion.

Compared to batteries, ultracapacitors normally hold rather high coulometric efficiency (i.e. charge/discharge efficiency) and energy efficiency. The power density of ultracapacitors is also higher than battery, while the energy density is lower. The difference is due to different mechanism of energy storage [1]. Batteries store energy by redox reactions in the bulk electrode, leading to high energy density but slow kinetics. The higher rate capability of ultracapacitors comes from the electrostatic storage of charge at the electrode surface. The transport of ions in the solution to the electrode surface is rapid, leading to fast charge and discharge capability. In contrast to batteries, no electron transfer takes place across the interface. Ultracapacitors can be fully charge or discharged within a few seconds without damaging the cell and thus are well suited for use in power-assistant applications in hybrid powertrain systems. The charging and discharging processes are highly reversible and do not require phase changes in the electrode. This should lead to high coulometric efficiency and increased cycle life. However, ultracapacitors' stand loss during self-discharge is higher than battery, limiting its use as single energy source in pure electric vehicle.

In order to compare performance of ultracapacitors from different manufacturers, standard testing procedures are needed. FreedomCAR team with the support of the U.S. Department of Energy established a general testing approach that intending to evaluate ultracapacitor performance [2]. The general approach in [2] is applied widely as guide in ultracapacitors' testing, including several major characterizing procedures such as reference

capacity testing, constant-current discharge/charge testing, constant-power discharge/charge testing, self-discharge testing, and hybrid pulse power characterization testing.

In this paper, key capacitor parameters of a commercial ultracapacitor module were obtained from characterization, including capacitance, capacity, energy, coulometric efficiency, energy efficiency, equivalent series resistance (ESR), stand loss, and so on. A control-oriented ultracapacitors model was proposed, the equivalent circuit and mathematical expression of the model are presented first, and the model was implemented in MATLAB/Simulink. Comparison between simulation and experiments was carried out under both stable and dynamic conditions.

2 Overview of Ultracapacitor Testing

The ultracapacitor module tested in this paper is based on 2.7-volt cells and incorporates proprietary balancing, monitoring and thermal management capabilities. Before all the tests, a reference capacity test is implemented in order to measure some reference parameters. They are important for other tests in the procedure determination and result analysis. Table 1 shows general technical data provided by manufacturer and data measured. Obviously, capacitance and delivered measured is a little lower than those given data, probably due to performance degradation over a long term.

Table 1: General technical data

	<i>Provided</i>	<i>Measured</i>
Manufacturer SN	BMOD0063F -P125-B01	
Device Weight(kg)	58	
Device Dimensions(mm)	762 * 425 *	
Device Volume(L)	85.82	
Capacitance(F)	63	61.64
Rated Voltage(V)	125	
Min Operating Volt.(V)	62.5	
Surge Voltage(V)	135	
Max Operating Curr.(A)	200	
Equivalent Series Resistance(mΩ)	18	
Energy(Wh)	101.7	100.18
Capacity(Ah)		1.066
5C rate(A)		5.33

One of the tests used to characterize the ultracapacitor module is the constant-current discharge/charge test, implemented by executing a sequence of discharge/charge cycles at increasing currents. The determined efficiency and equivalent series resistance (ESR) are used for modeling the behavior of ultracapacitors over a range of continuous discharge/charge conditions. Another test is the constant-power discharge/charge test, which is also implemented by executing a sequence of discharge/charge cycles, but at increasing powers. Unlike the constant-current test, the constant-power test is actually divided into two series. Discharge test consists of constant-power discharge and 5C rate current charge procedures, while charge test consists of reverse procedures. The major performance parameters determined by this test

are the specific energy and energy density, the specific power and power density.

Although not related to modeling of ultracapacitors, self-discharge test and hybrid pulse power characterization (HPPC) test are also regarded as important tests. Self-discharge test measures the time dependence of the self-dissipation of the capacitor, i.e. the rate of those internal processes that cause the capacitor to discharge when not connected to a load. The goal is to measure energy lost over the test interval and the decrease of the capacitor's voltage during the test. The calculated stand loss characterizes ultracapacitors' self-discharge loss. HPPC test determines dynamic power and energy capability over the capacitor's voltage range using a test profile that incorporates both discharge and regen pulse. Relationship between SOC and the discharge/charge power capability, between usable energy and usable power can be established. They are useful to evaluate ultracapacitors' performance in hybrid application.

All the tests were performed on an EVT 500-500-80 IGBT based test platform. A Heater with nominal power 1.6 kW is used to regulate the environmental temperature. EVT 500-500-80 IGBT can implement discharge/charge procedures with programmable set values including voltage, power and resistance. Software BTS-600 is used to control the platform, operate test procedures and record continuous measured data.

3 Characterization Results and Analysis

3.1 Constant-Current Discharge and Charge Test Results

Six current values were chosen as constant current, from 5C rate (5.33 A) to maximum operating current (200 A). Figure 1 shows ultracapacitors' working voltage versus charge removed curves at

each current. These curves are linear, in contrast to the lithium-ion batteries, which has a relatively flat voltage profile curve with sharp changes in voltage when the cell is in the fully charged or discharged condition. The difference is due to different mechanism of energy storage. Non-Faradic reaction occurs in ultracapacitors and leads to fast kinetics, while Faradic reaction occurs in batteries and leads to slower kinetics. Therefore SOC of ultracapacitor is linearly associated with its open voltage due to this characteristic, i.e. 125 V corresponding to SOC = 1 and 62.5 V corresponding to SOC = 0.

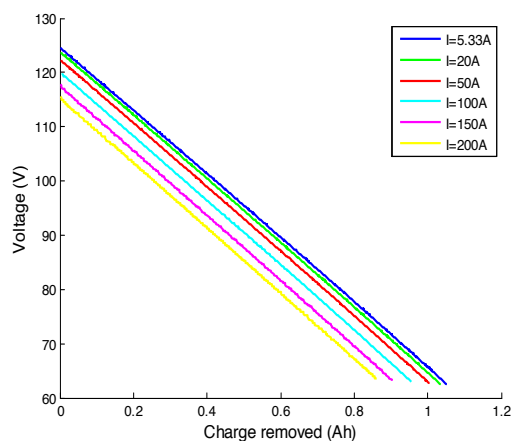


Figure 1: Voltage versus Charge removed plot

Figure 2 shows Coulometric Efficiency versus Current. Coulometric efficiency is the fraction of electrical charge stored in an energy storage device that is recoverable during discharging. It indicates device's Charge/Discharge reversible capability and lifespan as well. It can be observed from figure 2 that ultracapacitor holds very high coulometric efficiency (above 98%) along whole current range. When the current is large (above 50A), cycle period is very short, leading to very small leakage electrical charge and very high coulometric efficiency (near 100%). Coulometric efficiency above 100% (100.2%) appears in 50A, due to high coulometric efficiency of this

ultracapacitor and probably accumulated measurement error of the test facility.

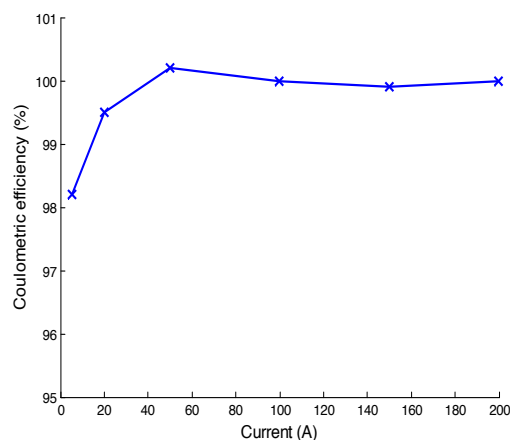


Figure 2: Coulometric efficiency versus current plot

Figure 3 shows Energy Efficiency versus Current. Energy efficiency indicates device's power capability. Energy efficiency decreases slightly (from 98% to 88%) when current increases. The Energy efficiency is determined by two factors: the leakage resistance and the ESR. The power of energy dissipation caused by leakage current is relatively constant. The power of energy dissipation caused by ESR is proportional to the square of the current. When the current is relatively small, the energy caused by leakage current is dominated, and the efficiency curve goes upside. When the current become large, the influence of the ESR is strengthened, and the curve goes downside.

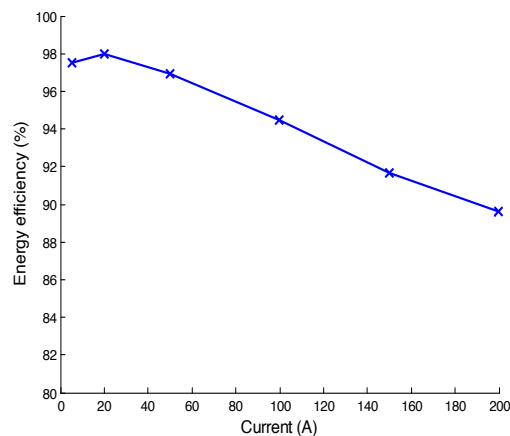


Figure 3: Energy efficiency versus current plot

Figure 4 shows Capacitance versus Current. The capacitance decreases as the current increases. The possible reason is that the temperature rises as the current increase due to self heating, the dielectric constant of double layer decreases, and heat diffusion becomes fiercer.

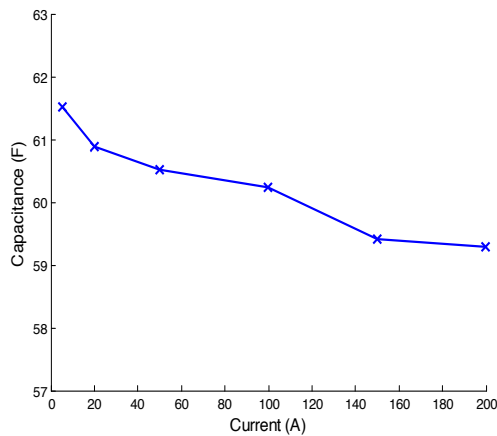


Figure 4: Capacitance versus current plot

Figure 5 shows ESR versus Current. Except at 5C rate, ESR of ultracapacitors is near 20mΩ, which is close to the value given by the manufacturer (18mΩ). In the test, ESR is calculated during an “instantaneous” period at the beginning (or end) of a constant-current charge or discharge step. The time interval is tester dependent, so the choice of this time interval may affect calculation results slightly. As $ESR = \Delta V / \Delta I$ and ΔI is much smaller at the smallest current (5.33 A) than that at any other current, uncertainty of results is larger, leading to the difference of ESR. On the other hand, the temperature of ultracapacitor increases at higher currents. The conductivity of the electrolyte increases, due to the rise of viscosity of solvent and the decrease of solubility of conducting salt. This is another reason why ESR is

smaller at higher currents than that at smallest current.

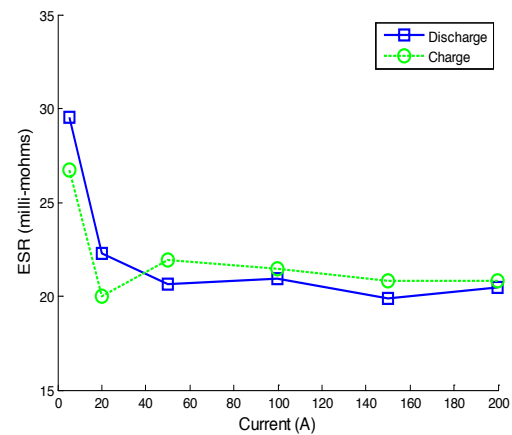


Figure 5: ESR (equivalent series resistance) versus current plot

3.2 Constant-Power Discharge and Charge Test Results

The power used in this test is determined by product of current and minimum operating voltage. Current is also chosen from 5C rate (5.33 A) to maximum operating current (200 A). Table 2 shows results of discharge test series and Table 3 shows results of charge test series.

From either of two tables, it can be learned that ultracapacitors hold high energy efficiency at all power (above 90%). Specific power of ultracapacitors can be very high with highest operating current allowed. This characteristic makes ultracapacitors especially suitable for application as instantaneous high power provider. Specific energy of ultracapacitors is relatively low, compared to around 80Wh/kg of lithium battery [3]. Therefore ultracapacitors are not suitable as single energy source in pure electric powertrain system.

Table 2: Specific power and energy from discharge test

Discharge Power (W)	Specific Power (W/kg)	Energy Removed (Wh)	Specific Energy (Wh/kg)	Energy Efficiency (%)
333	5.74	97.37	1.68	97.1
1250	21.55	97.40	1.68	98.1
3125	53.88	96.08	1.66	97.6
6250	107.76	93.57	1.61	96.6
12500	215.52	88.83	1.53	94.8

Table 3: Specific power and energy from charge test

Charge Power (W)	Specific Power (W/kg)	Energy Returned (Wh)	Specific Energy (Wh/kg)	Energy Efficiency (%)
333	5.74	100.8	1.74	97.2
1250	21.55	99.36	1.71	97.8
3125	53.88	98.29	1.69	97.3
6250	107.76	97.30	1.68	96.6
12500	215.52	96.12	1.66	94.6

Figure 6 visualizes the relationship between specific power and specific energy. Capacity of discharge energy (energy removed) drops a little faster with the increase of power used than capacity of charge energy (energy returned).

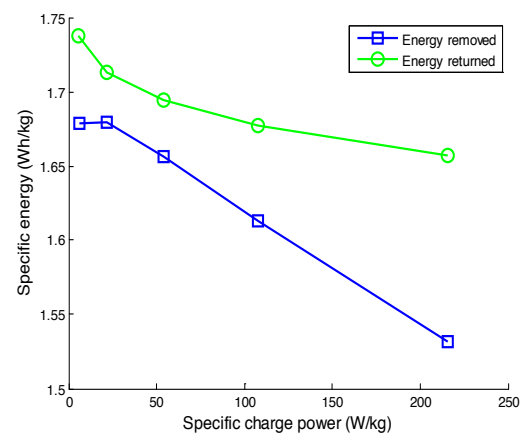


Figure 6: Specific energy versus specific power

3.3 Self-Discharge Test Results

Test starts from fully charged status of ultracapacitors, i.e. SOC = 1 and open circuit voltage (OCV) = 125V. Figure 7 shows OCV variation of ultracapacitors during whole 72 hours' stand time. Energy loss is calculated as the difference between the fully charged energy (obtained from pretest) and the energy in the partial discharges after self-discharge. Energy loss calculated was 15.23Wh, 15.5% of total energy. Another way to evaluate the energy loss is calculating SDLF (Self-discharge energy loss factor), which represents the fraction of the total theoretical energy of the device (down to zero voltage) that is lost as a function of time based on equation (1). It was 9.24% over 72 hours. Either assessment indicated that self-discharge loss of ultracapacitors over a long term is very large, and this will limit its application as single energy source in pure electric powertrain system, too.

$$SDLF(t) = 1 - (V(t)/V_0)^2 \quad (1)$$

V_0 is rated voltage (125V) here.

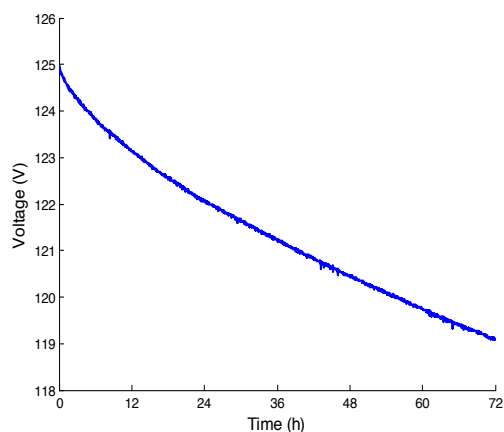


Figure 7: OCV (Open Circuit Voltage) of ultracapacitors versus time in the self-discharge test

3.4 HPPC Test Results

HPPC (Hybrid Pulse Power Characterization) test is implemented using test profile shown in figure 8. As ultracapacitors' performance differs between low current and high current, two representative discharge current values are chosen, 50A and 150A, which correspond to minimum and maximum HPPC test. Regen current is always 75% of discharge current. Both discharge and charge pulse duration are set to 5s, and voltage during test should be between 62.5V and 135V.

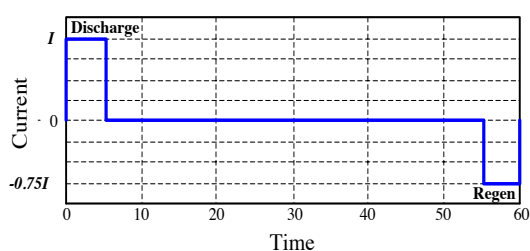


Figure 8: Ultracapacitor HPPC test profile

Figure 9 and 10 show pulse resistance versus SOC. The pulse resistance of ultracapacitors is around 105 milliohm and increases a little with the decrease of SOC. These values should not be compared to ESR obtained in constant-current test, because the test conditions are different. They are calculated based on the full pulse duration (5s)

rather than on an instantaneous voltage response to a step current change.

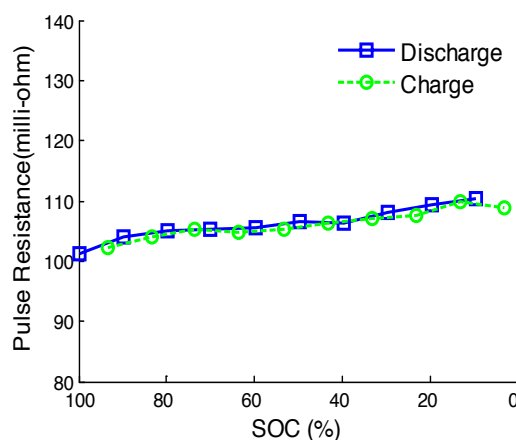


Figure 9: Pulse resistance versus SOC (Min HPPC)

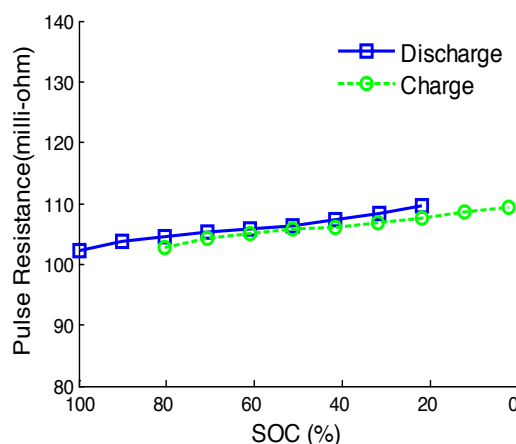


Figure 10: Pulse resistance versus SOC (Max HPPC)

Figure 11 and 12 show the relationship between pulse power capability and SOC. As SOC is associated with ultracapacitors energy, Figure 13 and 14 can be obtained, indicating the relationship between usable energy and pulse power capability. Pulse power capability is also known as usable power. When ultracapacitors are used as energy source in the powertrain system, it is convenient to get the corresponding usable power from target energy or get the corresponding usable energy from target pulse power.

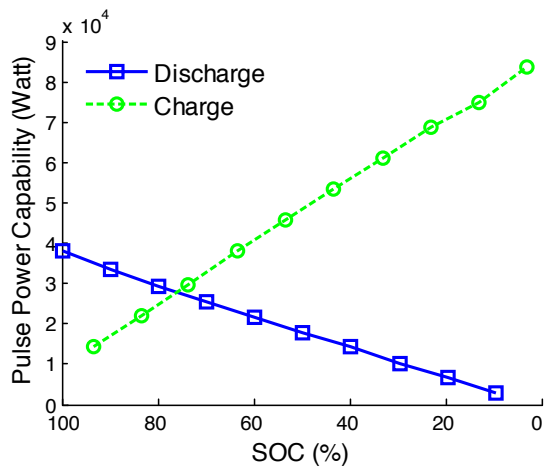


Figure 11: Pulse power capability versus SOC (Min HPPC)

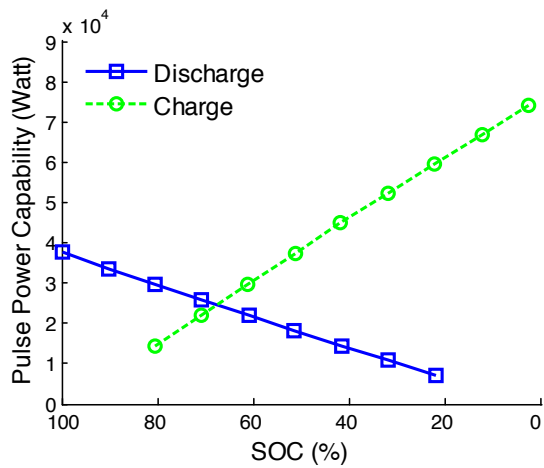


Figure 12: Pulse power capability versus SOC (Max HPPC)

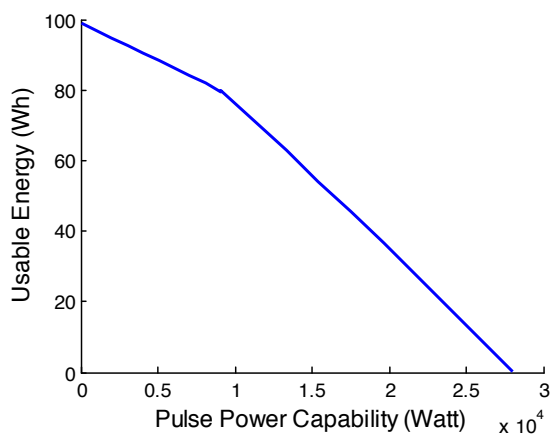


Figure 13: Usable energy versus pulse power capability

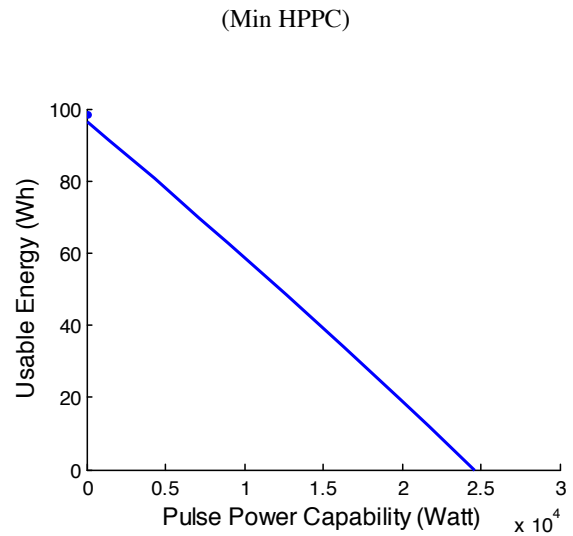


Figure 14: Usable energy versus pulse power capability (Max HPPC)

4 Modeling of the Ultracapacitor

4.1 Model Description

The ultracapacitor model proposed here is developed from a two-stage ladder model [4]. The RC equivalent circuit of the model is shown in Figure 15.

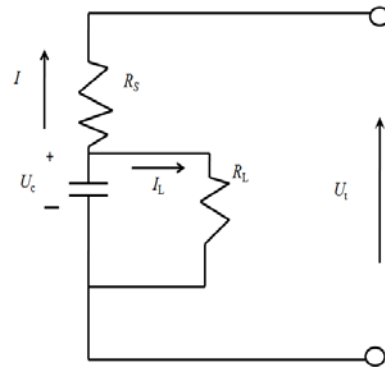


Figure 15: RC equivalent circuit of ultracapacitor model

The purpose of this model is to calculate ultracapacitor's SOC and working voltage according to the original open-circuit voltage and demand current of ultracapacitor.

4.1.1 Calculation of SOC

SOC is estimated by integrating ampere hour, as shown by following equations.

$$\text{SOC} = \text{SOC}_0 - \int_0^t \eta_c I / Q dt \quad (2)$$

$$\eta_c = \begin{cases} \eta_{c1}, I \geq 0 \\ \eta_{c2}, I < 0 \end{cases} \quad (3)$$

SOC_0 – initial value of SOC;

η_c – ampere hour efficiency of ultracapacitor;

η_{c1} – ampere hour efficiency of ultracapacitor during discharging;

η_{c2} – ampere hour efficiency of ultracapacitor during charging;

Q – electric quantity.

η_{c1} and η_{c2} are current depended. They are interpolated from data points obtained from current discharge and charge test. Q is obtained from formula $Q = C \times U$, C – Capacitance, U – Voltage.

4.1.2 Calculation of working voltage

Working voltage is calculated using equation below.

$$U_t = U_c - IR_s \quad (4)$$

U_t – working voltage;

U_c – open-circuit voltage;

I – demand current;

R_s – equivalent series resistance (ESR).

Similarly as η_{c1} and η_{c2} , R_s is interpolated from data points obtained from constant current discharge and charge test. Data points are divided into two resistance groups, i.e. charge and discharge resistance groups. U_c can be deduced from following differential equation, which describes the electric potential of ultracapacitor.

$$\frac{dU_c}{dt} = -\left(\frac{I + I_L}{C}\right) \quad (5)$$

C – Capacitance of ultracapacitor, obtained from Reference Capacity Test of ultracapacitor;

I_L – leakage current;

$$I_L = \frac{U_c}{R_L} \quad (6)$$

R_L – leakage resistance, obtained from Leakage-Current Test of ultracapacitor;

Combining equation (5) and (6) leads to equation (7).

$$\frac{dU_c}{dt} = -\frac{U_c}{CR_L} - \frac{I}{C} \quad (7)$$

(7) is a differential equation, its solution can be expressed as equation (8).

$$U_c = U_{c0} - \left[\int_0^T \frac{I}{C} e^{t/CR_L} dt \right] \cdot e^{-T/CR_L} \quad (8)$$

U_{c0} – initial value of open-circuit voltage;

T – time span from initial state to current state (corresponding to U_c)

Replace U_c in equation (4) with equation (8), working voltage can be obtained as follows.

$$U_t = U_{c0} - \left[\int_0^T \frac{I}{C} e^{t/CR_L} dt \right] \cdot e^{-T/CR_L} - IR_s \quad (9)$$

When this model is applied for the Ultracapacitor, leakage current I_L is so small that it can be omitted. Therefore, equation (5) ~ (9) can be converted to following equations.

$$\frac{dU_c}{dt} = -\frac{I}{C} \quad (10)$$

$$U_c = U_{c0} - \int_0^T \frac{I}{C} dt \quad (11)$$

$$U_t = U_{c0} - \int_0^T \frac{I}{C} dt - IR_s \quad (12)$$

Equation (11) shows one way to evaluate U_c and equation (12) is used to calculate working voltage of ultracapacitors.

However, as learned from HPPC Test of ultracapacitor, the relationship between open-circuit voltage and SOC is linear. It is possible that using SOC to deduce the open-circuit voltage value directly. This is another way to evaluate U_c and equation (4) is used to further calculate working voltage of ultracapacitors as equation (13), SOC is calculated using equation (2).

$$U_t = f(\text{SOC}) - IR_s \quad (13)$$

4.2 Model Validation

In order to validate the ultracapacitor model, comparison tests (different from characterization tests before) are carried out. Demand current values are input into both the ultracapacitor model and the test facility. Working voltage calculated by the model will be compared to the experimental results obtained from the test facility. Stable and dynamic tests are chosen so as to evaluate the ultracapacitor's performance under both conditions.

4.2.1 Stable Condition Test

Test is conducted under constant current (50A). The ultracapacitor device is discharged at 50A on test facility, working voltage data is recorded. In the meantime, 50A is used in the ultracapacitor model to calculate the same data. Figure 16 shows working voltage versus time comparison between test data and simulation results in stable condition test. The difference of working voltage is lower than 0.89%.

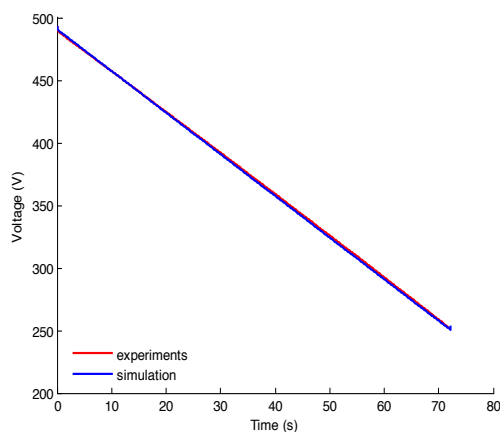


Figure 16: Working voltage versus time comparison in stable condition test

4.2.2 Dynamic Condition Test

In dynamic condition test, transient demand current values are input into the ultracapacitor

model and the test facility. These current values come from the power demand of the energy storage device used in a HEV bus under different drive cycles. Three typical cycles are used here, including Manhattan Cycle, China Suburban Cycle and China Urban Cycle.

Figure 17 shows the comparison between test data and simulation results of ultracapacitor working voltage over time in Manhattan Cycle. The maximum error in working voltage prediction is 0.94%.

Figure 18 shows the comparison between test data and simulation results of ultracapacitor working voltage over time in China Suburban Cycle. The maximum error in working voltage prediction is 1.62%.

Figure 19 shows working voltage versus time comparison between test data and simulation data in China Urban Cycle. The maximum error in working voltage prediction is 1.24%.

It is demonstrated that the developed ultracapacitor model has achieved satisfactory accuracy to predict the working voltage and SOC of the ultracapacitor.

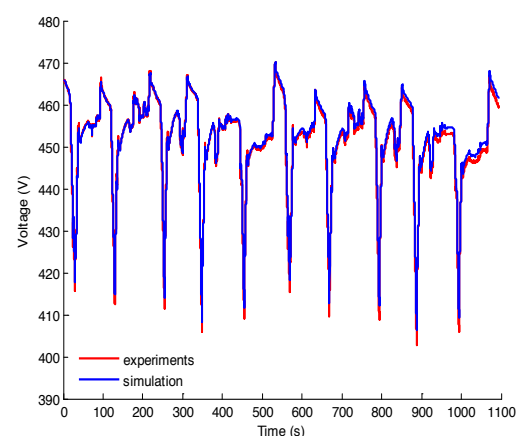


Figure 17: Working Voltage versus Time Comparison in Manhattan Cycle

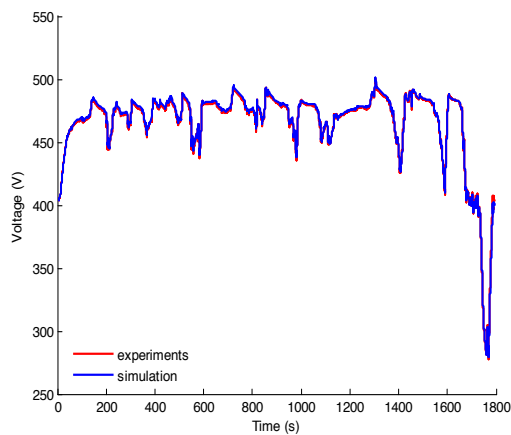


Figure 18: Working Voltage versus Time Comparison in China Suburban Cycle

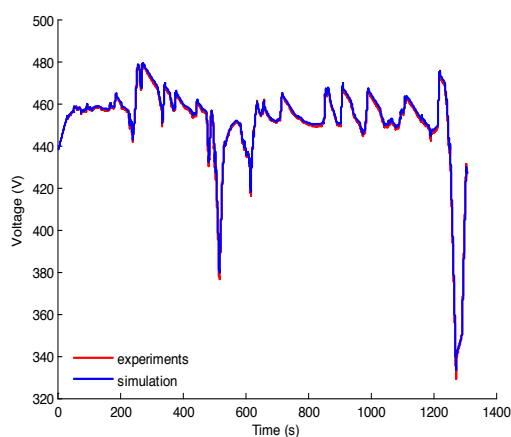


Figure 19: Working Voltage versus Time Comparison in China Urban Cycle

5 Conclusion

Commercial ultracapacitors have made great improvements in recent years. One type of Ultracapacitor module was characterized and analyzed in this report. It shows good and stable performance under all operating conditions during testing. Its coulometric efficiency is nearly 100% at all charge/discharge current, its energy efficiency is above 88%, and its specific power is relatively high compared to Lithium ion batteries. All these characteristics make ultracapacitors suitable for being used to compensate instantaneous power demand or absorb regenerated brake energy in electric powertrain

system application. However, the ultracapacitor module also showed some weakness, such as low energy density and high stand loss during self-discharge. Thus ultracapacitors should not be used as major energy source in a hybrid powertrain system.

Based on parameters obtained from characterization, a control-oriented ultracapacitor model was proposed and implemented in MATLAB/Simulink. Validation was made by comparing simulation results with experimental results from the test platform. The difference is no more than 2% under both stable and dynamic conditions, including Manhattan Cycle, China Suburban Cycle and China Urban Cycle. Therefore this ultracapacitor model is accurate enough to be used in further hybrid powertrain control simulation.

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