Study on modeling and application of ultracapacitor

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***Abstract*—As a new energy storage device, ultracapacitor has the advantages of high capacity, high power density, long life of charging and discharging and stable temperature characteristic, which is rapidly developed. In this paper, firstly, the basic principle and classification of ultracapacitor are introduced. Secondly, the existing application models of ultracapacitor are analyzed. At last, the applications state and prospect of ultracapacitor are described.**

Keywords-ultracapacitor; battery; three-branch model; traffic application.

I. INTRODUCTION

As the most important form of energy conversion in human society, electric power is indispensable to complex systems of modern production and life. With the development of industry, energy crisis and environment pollution are prominent issues, therefore, it is imperative to develop an electric power storage device of high performance and green. Ultracapacitor is a new energy storage device, which has the advantages of high capacity, high power density, long life of charging and discharging and stable temperature characteristic [1].

Ultracapacitor is a new energy storage component between electrostatic capacitors and batteries, which combines higher power density than traditional physical capacitor and higher energy density than chemical batteries. Therefore, it always acts as power source for short-time output [2].

In recent years, ultracapacitor was rapidly developed. The advanced company in the world, such as Maxwell, NEC, Panasonic, have launched mature products, which are applied in the fields of hybrid vehicles, wind power, solar power, smart grid, industrial UPS, etc. What's more, other fields for ultracapacitor are also expanding actively, such as, electric rail, oil exploration, aerospace, etc.

In this paper, firstly, the basic principle and classification of ultracapacitor are introduced. Secondly, the existing application models of ultracapacitor are analyzed. At last, the applications state and prospect are described.

II. PRINCIPLE AND CLASSIFICATION OF ULTRACAPACITOR

A. *Woking princile*

The principle of ultracapacitor is based on the structure of the double layer capacitor. The typical ultracapacitor-cell is a symmetrical structure, which consists of porous electrodes, separators, current collectors, and electrolyte. Fig.1 shows the charging principle of ultracapacitor.

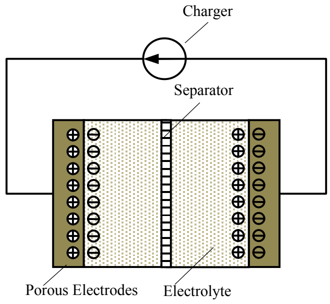

Figure 1. Structure and principle of typical ultracapacitor-cell

When the voltage applies on the porous electrodes of ultracapacitor, the same as the common capacitor, the positive charge are stored on positive electrode, and the negative charge are stored on negative electrode. In the effect of electric field caused by the charge on the porous electrodes, the opposite charge attaches on the interface of electrodes and electrolyte (Helmholtz layer), which balances the internal electric field in electrolyte. The positive charge and negative charge distribute on the different phases of the interface, and the distance between positive charge and negative charge is extremely close. Therefore, according to the capacitance equation as follow, we know that, the capacitance of ultracapacitor is very large.

$$C = \varepsilon\varepsilon_0 \frac{A}{d} \tag{1}$$

In which, A is the area of the electrode, d is the distance from ions to interface.

The structure feature of ultracapacitor is shown as follow:

1). The structure of ultracapacitor is double layer, which has more electrode area than conventional capacitor.

2). The porous electrodes of ultracapacitor provide much more surface, which could reach to $2000m^2/g$.

3). The distance between the positive charge and negative charge are much closer than the thickness of the film in conventional capacitor.

B. *Classification*

There are many methods for the classification of ultracapacitor.

According to the type of electrodes, ultracapacitor can be classified as follow:

1). Ultracapacitor with carbon-based electrodes. The electricity storage capacity is about $15\sim40\mu F/cm^2$ [3].

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2). Ultracapacitor with noble-metal oxides electrodes, such as RuO_2 and IrO_2, which has higher specific energy than with carbon electrodes.

3). Ultracapacitor with conductive polymer materials electrodes, which has higher charging and discharging performance than the two type described above.

According to the mechanism of electricity storage, ultracapacitor can be classified as follow:

1). Double layer capacitor, whose capacitance is based on the electric double layer capacitor caused by the charge separation between electrodes and electrolyte.

2). Faraday pseudo capacitor, the large capacitance exhibited by these systems was demonstrated to arise from a combination of the double-layer capacitance and pseudo-capacitance associated with surface redox-type reactions.

According to the structure of ultracapacitor and reacting direction, ultracapacitor can be classified as follow:

1). Symmetry type. The structure and reaction of electrodes of ultracapacitor are the same, but the reacting directions are opposite. Ultracapacitor with carbon-based electrodes noble-metal oxides electrodes, are belong to this type.

2). Asymmetry type. The structure and reaction of electrodes of ultracapacitor are not the same. Ultracapacitor with conductive polymer materials electrodes is this type, whose electrodes are N-type doped and P-type doped separately.

III. MODELING RESEARCH ON ULTRACAPACITOR

Recently, many researchers are studying modeling methods for ultracapacitor and useful and accurate model have obtained.

A. Modeling based on physical structure

As described in Section.2 and Fig.1, during the discharging process of ultracapacitor, the charge in capacitor will accumulate instantaneously. This phenomenon could be described as a polarization resistor, which is the charge transfer resistance in porous electrode of ultracapacitor [4]. The equivalent parallel resistance (EPR) describes the total leakage of electricity of ultracapacitor, which always affects the longtime energy storage.

Based on the symmetrical structure and the discharging principle of the ultracapacitor, we can get the equivalent model of ultracapacitor-cell, as shown in Fig. 2.

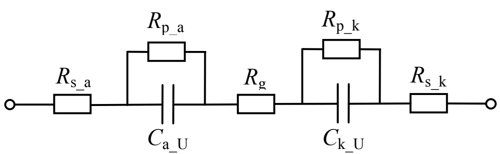

Figure 2. Simple equivalent model of ultracapacitor-cell

In Fig.2, R_{p_a} and R_{p_k} are polarization resistance, R_{s_a} and R_{s_k} are equivalent series resistance (ESR), R_g is resistance of separator, C_{a_U} and C_{k_U} are electric double layer capacitor between porous electrodes and electrolyte. Where,

$$\begin{cases} R_{s\_a} = R_{e\_a} + R_i \\ R_{s\_k} = R_{e\_k} + R_i \end{cases} \tag{2}$$

In which, R_i is resistance of electrolyte, R_{e_a} is resistance of anode and R_{e_k} is resistance of cathode.

The modeling method described above is based on the symmetrical physical structure, every parameter in which can present the particular physical characteristic of the ultracapacitor. However, this simple model couldn't describe the nonlinear characteristics of ultracapacitor in charging and discharging process.

B. Modeling based on electrical dynamic characteristics

In the practical application of ultracapacitor, the charge stored in ultracapacitor will redistribute after charging. The capacitance of ultracapacitor will be influenced by voltage and time, which means the capacitance of ultracapacitor is a dynamic physical quantity. Therefore, the model of ultracapacitor should describe the dynamic characteristic accurately.

The simplest equivalent model of ultracapacitor is the RC circuit model, but the accurate electrical dynamic characteristic of the ultracapacitor should be described by innumerous RC subcircuit, as shown in Fig.3.

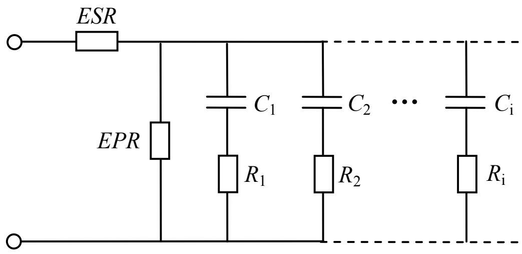

Figure 3. Accurate equivalent RC model of ultracapacitor

In Fig.3, the arrangement of RC subcircuit in the model is determined by the charging and discharging characteristic of the ultracapacitor. Each RC branch has the different time constant. The first branch has the maximum time constant, and the last branch has the minimum time constant. When the ultracapacitor is charging, the terminal voltage raises rapidly. When charging interrupts, the charge stored in ultracapacitor redistributes. It transfers from the branch of small time constant to the branch of large time constant, which leads the terminal voltage falling slowly [5].

The accurate equivalent model of ultracapacitor with innumerous RC subcircuits is an idealized model, which couldn't be used in practical application for the large calculation of parameter identification. Therefore, three-branch model are economic for practical application, as shown in Fig.4.

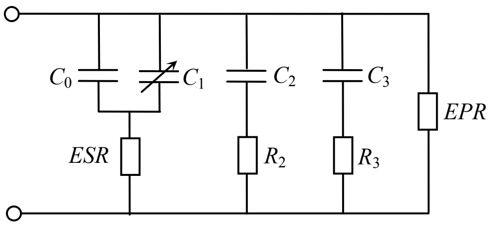

Figure 4. Three-branch model of ultracapacitor

The time constants of the three subcircuits in the model of ultracapacitor vary widely, which represent the external dynamic characteristics in different time period.

In the first subcircuit, the fixed capacitor is in parallel with the variable capacitor, which describes the linear relation between the capacitance and the voltage applied on ultracapacitor. The time constant of the first branch is much smaller than the others, therefore, the charges in the beginning period of charging are stored in the capacitors of the first subcircuit.

The second subcircuit and the third subcircuit describe the redistributing process of the internal charges in ultracapacitor. The second subcircuit is the branch of the short time constant, which describes the dynamic response of the ultracapacitor in one minute period after charging. The third subcircuit is the branch of the long time constant, which describes the dynamic response of the ultracapacitor in the period of ten minutes later after being charged.

The transfer function of the three-branch model can be is shown as follow [6]:

$$\frac{U(s)}{I(s)} = \frac{As^3 + Bs^2 + Cs + D}{s^3 + Es^2 + Fs + G} \tag{3}$$

With the modern method of pattern recognition, the parameters of the transfer function can be deduced. In most condition, the three-branch model can describe the external electrical characteristics of ultracapacitor.

IV. APPLICATION FIELD OF ULTRACAPACITOR

A. *Traffic Application*

The power resources of electric automobile include lead battery, NI-MH battery, lithium-ion battery and fuel cell. The common batteries have the advantages of high energy density and long driving distance. Compared with common batteries, ultracapacitor has the advantages of high power density and fast charging. Combined with common power batteries, ultracapacitor could be applied in electric automobile and hybrid automobile, which could supply high impulse power for the start-up and accelerative state. Moreover, with the advantage of fast charging, ultracapacitor could regenerate the braking energy rapidly. With ultracapacitor, the electric automobile could be powerful and energy-efficiency.

In urban rail traffic, for the short distance between stations, the train needs starting and braking frequently. Ultracapacitor can be applied in urban rail traffic for storing the braking energy. The energy produced by braking is equivalent to 30% of the pulling energy, which can be stored and released rapidly by ultracapacitor. When the train start-up again, the energy stored by ultracapacitor can be released for accelerating. With ultracapacitor, the starting current will reduce to 60% of its original level, which decrease the load level of the electricity grid. The MITRIC Energy Saver developed by Bombardier Company, is a typical application of ultracapacitor in urban rail traffic [7]. The MITRIC Energy Saver is applied in urban rail successfully, which has the following advantages:

1). The need for maximum power from catenary will decrease significantly.

2). The train could run for hundreds of meters under the condition of catenary systems not being disconnected.

3). Based on the charged energy storage device on the vehicle, the train could run on the rail without the catenary systems in the centre of the city.

B. *Renewable energy field*

In the wind power field, ultracapacitor could be applied for pitch angle controlling. The control system can change pitch, accordingly regulate the rotational speed and output power by adjusting blade incidence of wind-driven device. Under common wind condition, the electricity energy produced by wind turbine will charge continuously for the energy storage device based on ultracapacitor until the voltage raise to the nominal level. When the pitch of the wind turbine is need to change, the energy storage device based on ultracapacitor will output electricity power for pitch angle controlling [8]. Even under the condition of high wind speed, the pitch angle control system based on ultracapacitor will adjust the pitch angle, so that the output power of the wind turbine will not exceed the rated power.

In the photovoltaic technology field, the output power of photovoltaic cell is always disturbed by season and weather. As the assistant energy storage device, ultracapacitor has the following functions in photovoltaic technology field:

1). Store the electricity energy supplied by photovoltaic cell during the shiny day, and output electricity power to loads during the night and cloudy day.

2). Combined with photovoltaic cell, to supply steady and continuous electricity power to loads, and smooth the power delivery.

3). Combined with photovoltaic cell and control system, to realize the Maximum Power Point Tracking [9].

C. *Industry field*

In the field of heavy lifting equipment, ultracapacitor could supply high short-time power for the forklift and crane, which can make up the problem of power limitation and reduce carbon emission.

In the field that need high reliable power supply system, such as communication center, data center and network sever, the uninterruptible power supply (UPS) is an essential device for eliminating the grid faults, such as power outage, surge voltage, frequency oscillation. The energy storage element in common UPS is battery. When the electric source faults, the battery in UPS discharge instantaneously, but the output power is limited to a lower level. However, after applying ultracapacitor, the short-time output power of UPS promoted significantly, the lifetime extended, and the maintenance cost reduced.

V. SUMMARY AND OUTLOOK

Ultracapacitor is an electric energy device with high power density, which will change the supply and storage style of electric energy in future society. With the development of carbon material, more and more new material will applied in ultracapacitor, which will deduce the manufacture cost and enhance the power density of ultracapacitor. Meanwhile, we should pay more attention to the study of ultracapacitor modeling, which is helpful for reaching the full potential of ultracapacitor in its application. Other issues, such as environment temperature, charging rate, cut-off voltage will affect the life cycle of ultracapacitor. Therefore, the modeling research should consider external factors as more as possible.

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