Methodology for Investigation of Supercapacitor Equivalent Distributed Resistance in Pulse Modes

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***Abstract* — the publication examines the behavior of supercapacitors when discharging with high pulse currents with a duration of less than 10ms. The declared values of supercapacitor electrical parameters from the manufacturers cannot be applied and are not valid in the tested pulse modes. The study presents the behavior of a supercapacitor when a pulsed current flows through it by estimating the equivalent distributed resistance parameter – EDR. A method for its experimental determination by using a current pulse with a strictly linear leading edge and a constant plateau is proposed. Results from the application of the methodology are presented in the current paper.**

Keywords — supercapacitors; equivalent distributed resistance EDR; equivalent series resistance (*ESR*); specific current pulse; strictly linear front pulse; pulse mode

I. INTRODUCTION

Supercapacitors, originally called "dual layer capacitors", were based on *Helmholtz's* discovery in 1853, but have only been commercially available for about 40 years. During this period, they received a strong development, which continues to grow significantly in recent years. The first patent for supercapacitors was filed in 1957, but so far a high degree of commercialization has not been achieved due to low energy density and high cost. Currently, several companies produce supercapacitors with different sizes, parameters, capacity over *10 kF*, designed for various applications. Supercapacitors still have a small relative share compared to other electricity storage technologies – less than 2%. New applications of supercapacitors have been developed worldwide, and scientific research in this direction is constantly evolving. There is a constant demand for new applications of supercapacitors such as hybrid vehicles, rail, wind and solar generators. Supercapacitors are still considered relatively new energy storage devices, but they still play an important role in modern life. Many companies constantly working to improve the performance of supercapacitors in order to find new applications.

There are two main reasons for the entry of supercapacitors in many areas:

1. Applications requiring high power - thanks to their high power, supercapacitors find new opportunities in converter technology, where short time high power are required.

2. Application requiring a large number of cycles and long life - in low power applications, the batteries have maintenance problems or insufficient performance. Applications of electrochemical capacitors include transportation (electric vehicles [EV], hybrid EVs [HEVs], automotive subsystems, energy saving, regenerative braking, traction systems), consumer electronics, uninterruptible power supplies, renewable energy, etc. [1, 2].

Compared to conventional capacitors, supercapacitors have a higher specific capacity and the ability to store more energy per unit volume and unit weight, fast charge/discharge capability (within seconds). These properties are the basis for the expanding application in transport and power engineering. The parameters and behavior of supercapacitors depend on temperature, state of charge, charge and discharge intensity, frequency and other variables. Frequency domain analysis shows that a typical supercapacitor shows different behavior in several different frequency bands. The operation of supercapacitors in power electronic devices is limited by the low working frequency [3, 4, 5].

It is well known that the operation of supercapacitors in power electronic devices is limited by the low frequency at which they can operate [6].

According to *Musolino* et.al the dynamic behavior of the supercapacitor is related to the ions mobility of the electrolyte used and the degree of electrodes porosity. Depending on the technology, the capacity starts to decrease from 0.1 to 0.2 Hz and becomes zero at frequencies of a few hundred hertz or a few kilohertz. The real part of the impedance of the supercapacitor decreases with increasing frequency. This decrease in capacity with increasing charge/discharge frequency is the result of ionic processes (ion inertia). Thus, in practice it is impossible to use the full capacity of the device at high frequencies [7].

The literature presents studies on the electrical characteristics of supercapacitors and presents models that refer to periodic operational modes with a frequency of several hertz [8, 9, 10].

In the available literature there is no data on the parameters of supercapacitors under load of short duration and high currents.

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World famous manufacturers (*Cornell Dubilier*) offer a methodology, according to which, the determination of capacitance and equivalent series resistance (ESR) should not be based on measurements in the interval less than 10ms after switching on [11].

The aim of the present work is to propose a methodology for determining the equivalent distributed resistance *EDR*, according to which: the parameters of a supercapacitor operating in a pulsed load mode are determined by measuring with a powerful current pulse with a strictly linear steep front and a sharp transition to a constant plateau.

II. METODOLOGY

The supercapacitors charging and discharging processes are related and determined by the movement of charge carriers (ions) in the electrolyte, which makes a connection between the electrodes. A highly developed porous structure of the electrodes also plays a special role. The interaction between the electrolyte and the electrode materials also plays an important role in the supercapacitor performance. The behaviour of supercapacitors in the considered pulse regimes is determined by the transient processes of ionic currents in the electrolytes.

The equivalent series resistance (*ESR*) of the electrochemical supercapacitor is directly related to the ionic conductivity of the electrolyte and can have a strong influence on the power density. In addition, interactions between the ion and the solvent, and between the electrolyte and the electrode material can affect the life and self-discharge [12].

Figure 1 shows a supercapacitor equivalent circuit that is valid for short-term loads [1, 3]. The characteristic element in this equivalent electric circuit is the *EDR* (equivalent distributed resistance). It characterizes the transient electrochemical processes in the electrolyte volume of supercapacitors. The quality of supercapacitors is usually determined by its capacitance – *C*, equivalent series resistance - *ESR*, equivalent distributed resistance - *EDR* and impedance.

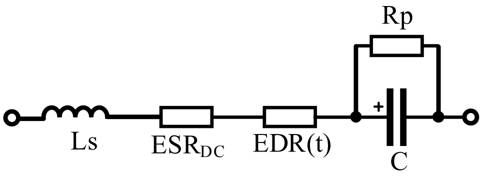

Fig. 1. Equivalent supercapacitor electric circuit.

To reflect the influence of the equivalent distributed resistance parameter, another *EDR(t)* is added in the equivalent electric circuit, which reflects the internal losses of the supercapacitor. It has been experimentally established that the change in the value of equivalent distributed resistance after switching on decreases over time, i.e. *EDR* is a time function - *EDR(t).*

The other elements of the equivalent electric circuit are analogous to those of ordinary capacitors: *Ls* - inductance; *ESR*- equivalent series resistance, measured at direct current, sometimes referred to as ESR_{DC} as well as *Ri*; *C* - supercapacitor capacity; *Rp* - resistance due to leakage current flow.

In the company catalogues for supercapacitors, inductance data *Ls*, equivalent series resistance at constant current ESR_{DC} and capacitance *C* are reported, but data on equivalent distributed resistance *EDR* are missing. Therefore, the problem to be solved in this article is to determine the parameter equivalent distributed resistance *EDR(t).*

The methodology is based on electrical measurements and the supercapacitors electrical parameters known by the manufacturers– ESR_{DC} и L_S.

The purpose of this paper is to propose a methodology for the experimental determination of the value of time dependent equivalent distributed resistance *EDR(t).*

To implement the proposed methodology, it is necessary to perform a number of measurements to determine the equivalent distributed resistance *EDR(t).*

Commonly used methods for supercapacitors testing are: galvanostatic cycling with potential limitations, cycling voltammetry, impedance spectroscopy, and accelerated aging. All those methods are based on observation of current and voltage during forced charging/discharging of the supercapacitor at selected bias conditions and requires measurement set-up [13].

The *idea* is to offer and use a specific current pulse with a strictly linear front, i.e. we have a steady increase in di/dt. Using this pulse type, in the period of pulse increase we can differentiate the components of the U_L voltage on the inductance and on the two resistances of the equivalent series resistance ESR_{DC} and *EDR*.

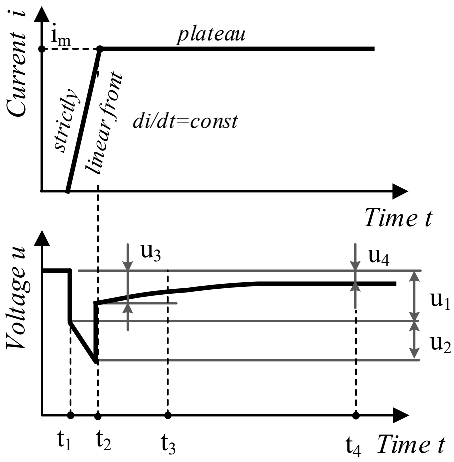

Fig. 2. Voltage and current waveforms at supercapacitor loaded with strictly linear front pulsed current.

The studied supercapacitor is loaded with a current pulse with a strictly linear front, i.e. *di/dt = const* and a certain value of the maximum current – i_m, Figure 2. After reaching the maximum value of the current, the current pulse must be with a time-constant plateau, as shown in Figure 2. The same figure shows the voltage waveform on a supercapacitor loaded with the required current pulse.

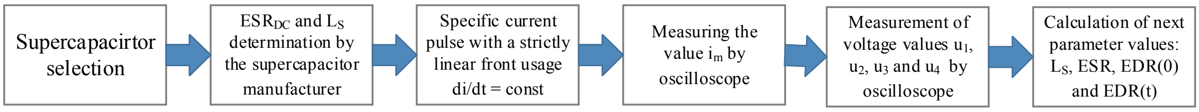

Fig. 3. Block diagram representing the sequence of work for determining the equivalent distributed resistance *EDR(t)*, that depends on time.

The methodology involves measuring of four typical values of voltage - u_1, u_2, u_3 and u_4 as shown on Figure 2, i.e. the developed methodology includes measurement of electrical voltages at certain points in time:

- at moment t_1, which coincides with the beginning of the current pulse, voltage u_1 is measured
- at moment t_2, which coincides with the end of the steep edge of the pulse and the transition to a set current value, the voltages u_2 and u_3 are measured;
- after the beginning of the current pulse and the establishment of the voltage on the supercapacitor, at a time sufficiently distant in time, the voltage u_4 is measured;
- measurement of a series of values *u(t)* in the interval after the moment t_2 and until the fixed value of the supercapacitor voltage is reached;

The voltage values measured in this way are used for further calculations set in the methodology.

The next step is to determine the parameter values of the equivalent electric circuit using the following dependencies:

Supercapacitor inductance - L_S:

$$L_S = u_1/(di/dt) \quad (1)$$

Equivalent series resistance - *ESR*:

$$ESR = u_4/Im \quad (2)$$

Equivalent distributed resistance – *EDR(0)* at the initial moment of switching on in pulse mode:

$$EDR(0) = (u_2/Im) - ESR \quad (3)$$

Equivalent distributed resistance EDR(0) at the initial moment of switching on in pulse mode:

$$EDR(0) = (u_3/Im) - ESR \quad (4)$$

Equivalent distributed resistance *EDR(t)* as a function of time *t – EDR(t)*:

$$EDR(t) = u(t)/Im \quad (5)$$

The initial value of equivalent distributed resistance *EDR(0)* i.e. at the initial moment of switching on the supercapacitor, can be determined both by equation (3) for the established mode and by equation (4) - for the transient mode of loading. It can be expected that the values of the voltages u_2 and u_3 will be very close to each other.

In the case of a current pulse with a sharp transition from the strictly linear front to the plateau, the measurement of the two voltages u_2 and u_3 is practically carried out simultaneously.

To determine the change in resistance *EDR(t)* over time, equation (5) must be used.

The sequence of the developed methodology is shown on Figure 3.

III. MEASUREMENT RESULTS AND DISCUSSION

The developed methodology for determining the parameters of the equivalent electric circuit at short-term loads is used on a battery composed from several supercapacitors manufactured by Maxwell Technologies, Inc., USA. Measurement set-up was tested with commercially available supercapacitors. The measurements have been done on a Maxwell Technologies *BCAP3400 P300 K04* supercapacitor, with a nominal capacitance of *3400 F*, rated voltage of 3.0 V, leakage current – *12mA*, for temperatures between *−40* and *65 °C* and for voltages between 0 and *3.0 V*.

The total capacity of the composite battery is 1700F. Two groups connected in parallel are realized, each group consisting of 4 series-connected supercapacitors.

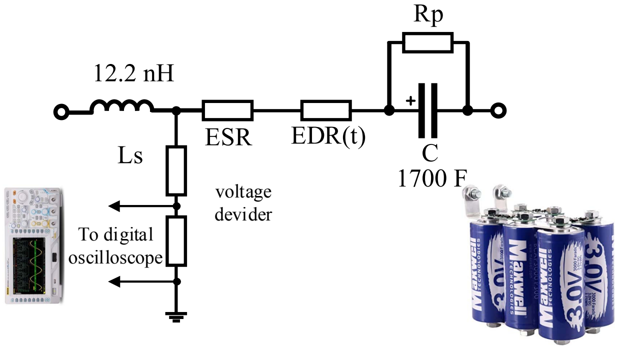

Fig. 4. Equivalent electric circuit with rated values.

The implementation of the developed methodology can be demonstrated by the following experiment and shown in Figure 5 current and voltage oscillogram.

The above-mentioned composite battery is discharged with a current pulse with a front with a derivative *di/dt=200 A/µs* and a measured maximum value of the plateau – current *Im = 670A*.

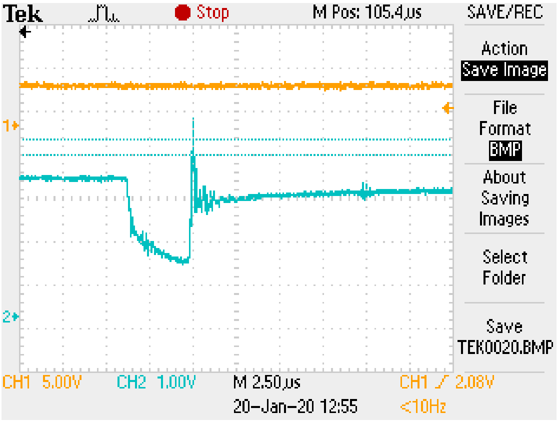

Fig. 5. Experimentally recorded oscillogram used to determine determining the change of current flowing through the supercapacitor.

In order to be able to make voltage measurements at different time intervals, it is necessary to use an oscilloscope and a voltage divider. A voltage divider with a ratio of *2/1* is used, Figure 4. The measured voltages at the indicated characteristic points are as follows:

u_1 = 2 x 1,22V; u_2 = 2 x 0,75V;

u_3 = 2 x 0,76V; u_4 = 2 x 0,18V.

By formula (1) the value of the inductance of the supercapacitor Ls is calculated:

$$L_S = 12.2 \text{ nH}$$

According to expression (2) the value of equivalent series resistance of the supercapacitor is calculated:

$$ESR = 0.53 \text{ m}\Omega$$

Expression (4) is used to calculate the value of the supercapacitor equivalent distributed resistance at the initial moment of switching on in transient load mode.

$$EDR(0) = 1.72 \text{ m}\Omega$$

A series of capacitors were tested, and in all cases it was found that the initial value of EDR (0) exceeds the value of equivalent series resistance ESR 3.24 times at direct current flow. This significant difference in the resistance values turns out to be too substantial when using both pulse modes with steep fronts and high current values.

For all tested capacitors, it was experimentally proven that the measured values for the supercapacitor inductance Ls and the equivalent series resistance in steady state ESR (R_{DC}) match the company data. In all performed experiments, the decay time of the equivalent distributed resistance did not exceed *1ms*.

In fact, this coincidence of values with company data confirms that the methodology is correct and can be successfully applied.

CONCLUSIONS

A methodology for experimental determination of the equivalent distributed resistance *EDR* of a supercapacitor in pulsed mode has been developed and proposed.

The study of the change in the value of the equivalent distributed resistance can provide guidelines for the introduction of additional measures to compensate for the current drop in very short time intervals.

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