Temperature Dependent Charging Algorithm of Supercapacitor Module

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Abstract—In order to increase energy efficiency in distributed energy generation systems, energy storage systems are used. Supercapacitors are one type of energy storage elements whose characteristics include high power density, long cycle life and low energy density. Since they are better suited for usage in high power applications, it is important to consider their temperature in order to avoid overheating and cause irreversible damage. This paper presents a supercapacitor charging algorithm that takes into account its temperature in order to increase energy efficiency. The algorithm is part of a regenerative braking system integrated within an electric railway vehicle. The foundation of the temperature dependent charging algorithm is the supercapacitor’s electro-thermal model, which includes forced air-cooling, and its development within MATLAB. The electro-thermal model consists of a supercapacitor’s electrical model and thermal model: the electric model’s rheostatic loss is the input for the thermal model, which outputs the supercapacitor’s temperature. The resulting algorithm outputs the maximum allowed charging/discharging current depending on the supercapacitor temperature, and results in an increase in energy savings, as well as lowering the impact of the light electric railway vehicle’s accelerating and braking on the power grid concerning current and voltage peak values.

Keywords—supercapacitor modeling, charging algorithm, supercapacitor temperature, electric railway vehicle, energy savings

I. INTRODUCTION

Reducing greenhouse gas emissions, increasing the efficiency of electricity use and increasing the share of renewable sources necessarily requires the development and application of energy storage systems (ESS). One type of ESS are supercapacitor modules, which are characterized by high charging and discharging power, and a larger number of cycles, but also lower energy density compared to batteries. Supercapacitors are suitable for applications in which a fast cycling of large amounts of power is required, e.g. in electric vehicles, and for covering peak power demands in distributed power generation networks. In electric railway vehicles, supercapacitors allow the storage of braking energy if there is no possibility of returning energy to the power grid. The stored energy is used to accelerate the vehicle, and can act as an additional energy source during peak load periods. The consequences are energy savings in the power supply grid of rail vehicles, and indirectly, savings in the distributed generation grid and stabilization of the power grid's voltage.

The operation of supercapacitors at high power makes them susceptible to overheating. Prolonged operation at elevated temperatures accelerates the aging of supercapacitors [1-5]. Increasing their temperature above 65 °C, the process of accelerated decomposition of electrolytes and complete destruction of supercapacitors begins. It follows that supercapacitor temperature control is one of the essential requirements to increase efficiency and preserve the declared cycle life. For this purpose, it is necessary to measure the temperature and use it as an additional control variable in the charging and discharging algorithm in order to regulate the current flow depending on the highest cell temperature. At lower temperatures, higher charging currents can be used, increasing the system efficiency. At higher temperatures, the charging/discharging current is limited, extending the cycle life of the supercapacitor. During the design phase of the regenerative braking system, and primarily in the optimization phase of the charging and discharging algorithm, it is necessary to know the ESS temperature. For this purpose, it is possible to use different electro-thermal models of supercapacitors. In the electrical part of the supercapacitor model, power dissipation is calculated, and in the thermal system model, the temperature due to dissipation. The electrical model of a supercapacitor is most often represented by a series connection of a resistance (equivalent series resistance - ESR) and a capacitance. More complex electrical models with multiple different RC combinations are used to model the dynamic behavior of supercapacitors [6-9]. The model of the thermal system of supercapacitors is modeled by electrical RC networks of different complexity, in which the electrical resistances and capacities are analogous to the thermal resistances and capacities [10-13]. The current source within these networks is analogous to dissipation, i.e. the heat dissipated at the equivalent series resistance of a supercapacitor. The voltage response of the
RC network is analogous to the temperature of a certain point inside the supercapacitor module. More complex models of the thermal system give more accurate estimates of temperature, but the process of determining the values of individual elements is not trivial and it is also necessary to know the structure of the supercapacitor construction. In this paper, for the purposes of estimating the temperature of the supercapacitor module in the phase of optimizing the charging and discharging algorithm, a relatively simple and sufficiently accurate model of the thermal system of the supercapacitor module taken from [14] will be used. The temperature estimated using this model is used as an additional input variable to the simulation model of the rail vehicle braking energy storage system to design and optimize the temperature-dependent charging and discharging algorithm of the supercapacitor module. A description of the thermal system model is given in the second chapter of the paper. The third chapter presents the integration of the electro-thermal model of a supercapacitor module into a system that simulates the operation of a temperature-dependent module charging algorithm. The results of the simulation are given in the fourth chapter, and the conclusion in the fifth.

II. ELECTRO-THERMAL MODEL OF A SUPERCAPACITOR MODULE

A. Electro-thermal model of a supercapacitor cell

The electro-thermal model of a supercapacitor cell consists of an electrical model and a thermal model, fig. 1. In the electrical model, losses are calculated, and in the thermal system model, the cell temperature is calculated as a consequence of losses occurring in the electrical part of the model. The electrical model of the supercapacitor cell is composed of an equivalent series resistance $R$ and capacitance $C$, fig. 1 a). The model of the thermal system of a supercapacitor cell consists of a current source $P_{loss}$, which is analogous to dissipated power, i.e. the heat developed at the equivalent series resistance of the cell, and resistance and capacitance analogous to thermal resistances and capacitances, fig. 1 b).

![Fig. 1. Electro-thermal model of a supercapacitor cell; a) electrical model, b) thermal model.](image)

Resistance $R_{cond}$ represents the thermal resistance due to heat conduction between the core and the surface of the supercapacitor, $R_{conv}$ represents the thermal resistance due to convection between the supercapacitor and the environment. The capacity $C_{th,dc}$ is the thermal capacitance of the supercapacitor cell. The environment of the cell is represented by the ideal voltage source $T_{ambient}$, the amount of which corresponds to the current ambient temperature.

B. Supercapacitor module thermal modeling

Using the model from fig. 1, a model of a supercapacitor module is constructed that takes into account the spatial arrangement of the cells and the action of the air inside the module. Fig. 2 a) shows a model of one part of a supercapacitor module taken from the literature [14]. Fig. 2 b) shows the spatial arrangement of cells within the considered module. In [14], the influence of the air inside the module on the heat flow is simplified, i.e. the turbulence of the air and the effect of the module casing on the air temperature inside the module are neglected. Depending on the module casing temperature, which should be equal to the ambient temperature, the housing acts as a heat source or a heat sink.

According to fig. 2, it is clear that developing the model within a graphical programming environment (simulation tools such as PLECS) presents a difficulty due to the large number of cells. For this reason, in this paper, the whole system is formulated in state space, using the MATLAB software tool, according to (1):

$$\frac{dT}{dt} = \left[ A_{cond} + A_{conv} + A_{trans} \right] T + q_{gen}$$

(1)

The conductivity matrix $A_{cond}$ contains conduction resistances between the cell center and the cell surface. The conduction resistance value can be calculated if the cell structure and the materials of which it is composed are known [12]. A simpler way is to measure the temperature of the center, i.e. the cell terminals, and the surface of the cell [14]. The thermal resistance of the conduction $R_{cond}$ is calculated from the difference between the temperature of the center and the cell surface along with knowing the value of the dissipated power within the cell.

The $A_{conv}$ matrix contains convection resistances that thermally connect the cell surface with the ambient air flow and the casing surface with the ambient air flow within the module. Most often, the amount of this resistance is determined based on measurements or using empirical equations. The convection resistance $R_{conv}$ that connects the air flow to the casing surface is calculated from the equation:

$$R_{conv} = \frac{1}{nhS}$$

(2)

where $S$ is the value of the cell’s surface, $h$ is the heat transfer coefficient. The heat transfer coefficient is calculated from an empirical equation, using the air flow velocity inside the module casing $v$:

$$h = 12.12 - 1.16v + 11.6v^{0.5}$$

(3)
The matrix \( A_{\text{trans}} \) contains air mass transfer elements. For two nodes in a row, \( n-1 \) and \( n \), the value of the \( P_{\text{air}} \) source in node \( n \) is calculated from the following equation:

\[
P_{\text{air}}(n) = \dot{m}_{(n-1,n)} C_p(T_{n-1} - T_n)
\]

where \( C_p \) is the specific heat capacity of the air, \( T_n \) is the air temperature at node \( n \), and \( \dot{m}_{(n-1,n)} \) is the mass flow of air from node \( n-1 \) to node \( n \). Determining the mass flow between nodes is trivial if the cell arrangement is in-line; the flow in node \( n \) has the same mass flow as the previous flow node \( n-1 \). If the cell arrangement is staggered, as shown in fig. 2 b), the manner in which the air flow is distributed in the nodes should be considered. It is assumed that the air does not slow down as a result of the pressure drop in the zones between the cells. The determination of the flow in the following air zones is based on the preservation of the initial air flow. Fig. 3 shows the distribution of air flow between cells [14].

The air flow is divided based on the ratio of the surface cross-section of the entrance to the next zone over the total cross-section area of the entrance to the next zones. For example, the contribution of air flow from zone 1 to zone 2, according to fig. 3, amounts to:

\[
\dot{m}_2 = \dot{m}_1 \frac{S_1}{S_1 + S_2}
\]

The matrix \( q_{\text{gen}} \) contains the losses occurring in cells (current sources \( P_{\text{loss}} \)) which are equal to \( i^2(t)R \) where \( i(t) \) is the instantaneous value of the current flowing through the cell, and \( R \) is the value of the equivalent series resistance in the cell.

The vector \( C_{\text{th}} \) contains the thermal capacitances of matrices \( A_{\text{cond}}, A_{\text{conv}} \) and \( A_{\text{trans}} \). The thermal capacitance of cells is found in their manufacturer’s datasheets. The thermal capacity of air zones is calculated from the following equation:

\[
C_{\text{th-air}} = \rho V C_p
\]

where \( \rho \) is the air density, and \( V \) is the volume of air within the zone.

### III. INTEGRATION OF THE TEMPERATURE AS AN ADDITIONAL CONTROL VARIABLE INTO THE ENERGY FLOW CONTROL ALGORITHM

Before you begin to format your paper, first write and save the content as a separate text file. Complete all content and organizational editing before formatting. Please note sections A-D below for more information on proofreading, spelling and grammar.

The model of the thermal system of the supercapacitor module, described in the previous chapter, is integrated into the simulation model of the regenerative braking system for an electric railway vehicle developed in [15], fig. 4. The goal is to upgrade the control system in such a way that the temperature of the supercapacitor module influences the decision to charge or discharge the ESS. In this way, in the phase of developing the
charging and discharging algorithm, the possibility of increasing the efficiency of the regenerative braking system by exceeding the recommended amount of charging current given for the maximum allowed module temperature, as well as the possibility of extending the life of the supercapacitor module.

The electro-thermal model of the supercapacitor module, composed of the electrical and thermal model, outputs the voltage of the supercapacitor and losses caused by equivalent series resistance in the electric model, and the thermal model outputs the temperature of cells and air zones, fig. 5.

The thermal model of the supercapacitor module is integrated using the \textit{Simulink} block \textit{Descriptor State-Space}, fig. 6.

The vector of the state variable (x) consists of the temperature of the center of each cell and the temperature of the air zones. Matrix E contains the heat capacitances of cells and air zones (\(C_{\text{th-sc}}\) and \(C_{\text{th-air}}\)). Matrix A is the sum of matrices \(A_{\text{cond}}\), \(A_{\text{conv}}\) and \(A_{\text{trans}}\), and contains elements of thermal resistances \(R_{\text{cond}}\) and \(R_{\text{conv}}\) as well as equations for calculating the heat flow of an individual air zone. Matrix B is a square matrix containing ones in diagonals only in rows pertaining to supercapacitor cells, while the input vector (u) contains the squared value of the current flowing through a single cell (since all cells are connected in series, it is the same current) multiplied by equivalent series resistance of that cell. Matrix C is unitary, and matrix D is empty, which means that the vector (y) is equal to the vector of state variables.

The energy flow control algorithm controls the maximum current value that flows in the supercapacitor using the temperature of the hottest cell as a variable, shown in the following expression:

\[
i_{\text{sc_ref_MAX}} = \frac{240 \cdot 65}{T} \tag{7}\]

The maximum current of the supercapacitor module can be higher than the nominal one if the temperature of the hottest cell of the module is lower than the maximum allowed temperature of the cell. The amount of the coefficient \(240 \cdot 65\) was chosen also for the temperature of 65 ° C the maximum reference current of the supercapacitor is 240 A, which is the nominal charging/discharging current of the considered supercapacitor module.

IV. SIMULATION RESULTS

The simulation was performed using the measured speed of the electric tramway TMK 2200 K, manufactured by Končar Elektroindustrija Zagreb d.d. and TZV Gredelj d.o.o., fig. 7. The vehicle speed was measured during 2500 s of driving on the Zagreb tramway line 11 (Dubec-Crnomoře-Dubec) which doesn't have any significant changes in altitude, i.e. the influence of gravitational force during acceleration and braking of the vehicle is negligible.

The rated voltage of the simulated power grid is 600 V. The simulated ESS consists of seven series-connected modules, each containing 25 cells. The arrangement of the cells is shown in fig. 8. Due to the serial connection of all cells, the charging current is the same for each module, i.e. for each cell. Therefore, it is sufficient to analyze the phenomena for one module.

![Fig. 4 Simulation model of energy flow control algorithm with electro-thermal model of supercapacitor module](image1)

![Fig. 5 Simulation model of electro-thermal model of supercapacitor](image2)

![Fig. 6 Supercondacitor thermal model representation in \textit{Simulink}](image3)

![Fig. 7 Tramway speed profile on the Zagreb tram line no. 11](image4)

![Fig. 8 Cell positions within a module](image5)
The simulation results of the influence of the ESS and the use of the braking energy of the rail vehicle on the voltage and current of the power grid with and without the electro-thermal model of the supercapacitor are shown in fig. 9 and 10. From the figures, it is possible to clearly see the savings, i.e. reducing the amount of current taken from the power grid and stabilizing the grid’s voltage by using the highest cell temperature as an additional control variable in the charging and discharging algorithm of the supercapacitor module.

Fig. 9 Influence of the algorithm on the power grid voltage: a) during the complete period, b) enlarged display

Fig. 10 Influence of the algorithm on the power grid current: a) during the complete period, b) enlarged display

The consequence of using the algorithm that uses the highest cell temperature as a variable is the decrease of the number of peak currents and voltage in the power grid, Table I. The peaks of the power grid voltage above 610 V and below 590 V and peak power grid currents below -400 A and above 600 A are observed.

<table>
<thead>
<tr>
<th>Energy flow control algorithm</th>
<th>Without temperature as variable</th>
<th>With temperature as variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of peak voltage</td>
<td>451</td>
<td>405</td>
</tr>
<tr>
<td>occurrences</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of peak current</td>
<td>158</td>
<td>134</td>
</tr>
<tr>
<td>occurrences</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The use of an energy flow control algorithm that takes into account the temperature of the supercapacitor module reduces the number of voltage peaks by 10.2% and the number of current peaks by 15.2% compared to an energy flow control algorithm that does not use ESS temperature as a variable, which improves the stability of the power supply network. Fig. 11 shows the total energy stored during the tramway drive.

Fig. 11 Total energy stored during the tramway drive

TABLE I. COMPARISON OF THE POWER GRID PEAK VOLTAGES AND CURRENTS
Using temperature as an additional input variable to the energy flow control algorithm increases energy savings by 66%. The reason for this is that the allowable maximum value of the supercapacitor current can be higher than the rated one, thus allowing a larger amount of energy to be stored.

![Figure 12: Supercapacitor module's hottest cell temperature during the tramway drive](image)

Fig. 12 shows the temperature of the hottest cell inside the supercapacitor module during the tramway drive. Using this temperature as a variable within the energy flow control algorithm increases the cell's temperature by 7 °C. The reason for this is that, according to (7), the maximum current of the module increases, and by increasing the current of the module, the power dissipation at its equivalent series resistance also increases.

V. CONCLUSION

This paper describes a simulation model of the energy flow control algorithm in regenerative braking of an electric railway vehicle that takes into account the temperature of the supercapacitor module as an additional control variable. For the purpose of supercapacitor temperature estimation, an electro-thermal model of the supercapacitor module with forced air-cooling was developed. The model is based on the electro-thermal model of the cell and its thermal interaction with the surrounding air. The influence of the module casing on the air inside the module is also taken into account. For a simpler description of the simulation model of a module with a large number of cells, a state-space mathematical model is used. The simulation model of the entire regenerative braking system is implemented within the MATLAB software tool. Using the developed model and measurements obtained during a tramway ride, a simulation experiment was performed to test the influence of the algorithm using the hottest cell temperature as an additional control variable on the stabilization of the power grid, as well as on the energy efficiency of the power grid. It has been shown that using that temperature as a variable within the energy management algorithm achieves a greater stability in the power grid, reducing the number of voltage peaks by 10.2% and current peaks by 15.2%, and increasing the stored energy by 66%, all while using the same number of cycles. Consequently, the impact of electric railway vehicles on the distributed generation power grid is reduced, to the benefit of other grid participants. Additional improvements can be achieved by using a more complex control algorithm, and by introducing the possibility of controlling the air flow rate within the module, which would achieve a greater grid stability and ESS efficiency.

REFERENCES