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ON-BOARD SUPERCAPACITOR ENERGY STORAGE: SIZING CONSIDERATIONS

L. Latkovskis, U. Sirmelis, L. Grigans

Institute of Physical Energetics,
21 Aizkraukles Str., Riga, LV 1006, LATVIA

The paper considers the problem of choosing the optimum size for on-board energy storage system (*ESS*) based on supercapacitors (*SC*s) taking into account both the braking energy and the braking power of an electrical vehicle. The authors have derived equations for calculation of the minimum *SC* number in the bank and the optimum depth of its discharge. The theory is exemplified by the Škoda 24Tr trolleybus. Besides, by simulation of the *ESS* mathematical model, the dependence of the saved braking energy *vs. SC* number at the optimum discharge depth has been studied. The research shows that a reduced number of *SC*s may be used as compromise solution between the *ESS* efficiency and its cost. It was found that in most cases the optimum discharge depth is much higher than 0.5 − the value recommended by SC manufacturers and often met in literature.

Key words: *on-board energy storage system, supercapacitors, discharge depth, braking energy and power.*

1. INTRODUCTION

Installation of the energy storage system (*ESS*) aboard the electrical vehicle is the most efficient way to save its regenerative braking energy. Only an on-board *ESS* provides the braking energy storage at the place of its generation and the direct use of stored energy at the place of its consumption. Besides, a serious advantage when using an on-board *ESS* is the autonomous vehicle traction for short distances. However, it is the most expensive way of braking energy saving as compared with the use of a stationary (way-side) *ESS* or reversible rectifiers at substations. Therefore, reducing the cost of *ESS* by its proper sizing is highly important. The case considered in the paper is for the *ESS* sized with regard only to the braking energy saving.

The most promising devices for energy storage in the *ESS* are supercapacitors (*SC*s). Their advantages are: large power capability, small weight, long life and the absence of moving parts. Because of voltage variation across a *SC* bank during charging and discharging, a power converter is needed for interfacing the supercapacitors and the *DC* overhead line. The converter and controller of *ESS* ensure a controllable bidirectional energy flow between the *SC* bank and the traction system or the overhead line. The controller performs four main tasks:

- charging of *SC* bank in the braking mode of a vehicle to store the braking energy as much as possible;
- limitation of *SC* current at the allowable level $\pm I_{C\max}$ for both *SC* and converter protection;

- discharging of *SC* bank in the acceleration mode of a vehicle (according to the accepted control strategy);
- prohibition of charging if the voltage on an *SC* bank reaches its maximum allowable value $V_{SC,\max}$, and prohibition of discharging if it reaches the value $d \cdot V_{SC,\max}$, where *d* is the discharge depth.

Examples of such controllers are described in [1, 2]. Their performance in the braking phase of a vehicle is based on the *ESS* input voltage control instead of the *SC* current control. The total braking energy can be utilized if the input voltage reference is set higher than the overhead voltage and lower than the braking chopper voltage threshold. As regards *SC* discharging, many different strategies exist. However, it is not a subject of this paper, so we will assume that at the braking the *SC* bank is always in the discharged state independently of the way it is done.

In the literature, variously sized on-board *ESS*s for different type electric vehicles are described. Most of them are sized for $d = 0.5$ [3–7], which is recommended by *SC* manufacturers and gives the maximum available useful energy (75% of the energy stored in an *SC*). This value of *d* is chosen taking into account only the energy requirements. However, at $d = 0.5$ the power capability of the *ESS* in the discharged state $P_{ESS} = I_{C\max} V_{SC,\max} \cdot d$ is only half that of a fully charged *ESS*. If the braking power exceeds P_{ESS}, a portion of the braking energy is lost, and the *ESS* energy capacity is not fully utilized. The situation can be improved by reducing the energy capacity and increasing the power capability if the discharge depth *d* is increased. Obviously, the optimum *d* value can be found for each braking process if the braking power profile is predictable. The necessity to take into account both the energy capacity and the power capability of the *ESS* in the stage of its sizing is accentuated in works [7, 8]. The authors of the former have chosen the stationary *ESS* with the energy capacity of 20.55 MJ at $d = 0.7$, while in [8] the *SC* discharge modes with a constant current & power are studied, with $d = 0.758$ matching the 90% energy efficiency. Our research is focused on the on-board *ESS* sizing taking into account both the energy capacity and the power capability of *ESS* when for this application a specific braking power profile is applied.

2. BRAKING ENERGY AND BRAKING POWER PROFILE

The vehicle braking energy E_{br} is defined as a recoverable portion of its kinetic energy released during deceleration from speed v_0 to standstill:

$$E_{br} = K_1 E_{kinetic} = K_1 \frac{m v_0^2}{2}, \tag{1}$$

where m is the vehicle mass,
K_1 is a coefficient which includes internal losses of a vehicle, the rolling resistance, the aerodynamic drag, *etc*. Its value can vary in the range 0.5–0.6 [6, 9].

Equation (1) is valid for flat surfaces. In the cases of inclined surfaces, the change in a vehicle's potential energy should be taken into account [9].

If a vehicle brakes with constant deceleration $a = -dv/dt = const$, its speed is $v = v_0 - at$ and the braking energy varies in time according to the expression:

$$e_{br}(t) = \frac{K_1 m}{2}(v_0^2 - 2v_0 at + a^2 t^2)\,. \quad (2)$$

In this case the braking power $p_{br}(t)$ has a linearly sloping down to zero profile:

$$p_{br}(t) = \frac{de_{br}(t)}{dt} = K_1 ma(v_0 - at)\,, \quad (3)$$

with its maximum at $t = 0$:

$$P_{br,\max} = p_{br}(0) = K_1 mav_0 = \frac{2E_{br}}{t_{br}}\,, \quad (4)$$

where $t_{br} = v_0/a$ is the braking time.

Such a braking power profile is essential for braking with constant deceleration and has been used by many authors for the *ESS* sizing or energy saving process simulation [3, 6, 9, 10]. The chosen profile can be fully defined by two of the three parameters: E_{br}, $P_{br,\max}$, and t_{br}. We will use E_{br} and $P_{br,\max}$ for this purpose.

As seen from (1) and (4), the braking energy E_{br} depends on the vehicle mass m and speed v_0 (before braking), while the maximum braking power $P_{br,\max}$ additionally depends on deceleration factor a. This provides a variety of the E_{br}, $P_{br,\max}$ parameters at different vehicle driving modes and complicates their choice for the on-board *ESS* sizing. As an example, Table 1 shows the E_{br}, $P_{br,\max}$ and t_{br} values for a Škoda 24Tr trolleybus calculated at $K_1 = 0.5$ for all combinations of the following driving conditions:

- empty mass, 11.5 t;
- fully loaded mass, 17 t;
- maximum vehicle speed, 65 km/h;
- maximum allowed speed in the city, 50 km/h;
- deceleration factor, –1.5 m/s^2;
- maximum allowed deceleration factor (excluding emergency situations), –2m/s^2.

Table 1

Braking parameters of Škoda 24Tr trolleybus at different driving conditions

Mass m, t	Speed v_0, km/h	$-a$, m/s^2	E_{br}, kJ	E_{br}, kWh	$-P_{br,\max}$, kW	t_{br}, s
11.5	50	1.5	554.6	0.154	119.8	9.3
		2	554.6	0.154	159.7	6.9
	65	1.5	937.3	0.260	155.7	12.0
		2	937.3	0.260	207.6	9.0
17	**50**	1.5	819.8	0.228	177.1	9.3
		2	819.8	**0.228**	**236.1**	6.9
	65	1.5	1385.5	0.385	230.2	12.0
		2	1385.5	0.385	306.9	9.0

In the literature, different approaches can be found for the choice of proper braking parameters of a vehicle for on-board *ESS* sizing. As an example, we will use the parameters of a fully loaded trolleybus braking at the speed of 50 km/h with the deceleration factor $a = -2$ m/s^2 (Table 1).

3. *ESS* OPERATION MODES

The block diagram of the electric vehicle equipped with an on-board *ESS* and operating in the braking mode is shown in Fig. 1. The DC/DC converter with defined efficiency η provides the controlled energy flow from the vehicle to supercapacitors and limits the *SC* bank current i_C and voltage v_{SC} to the threshold values $I_{C\max}$ and $V_{SC,\max}$ respectively.

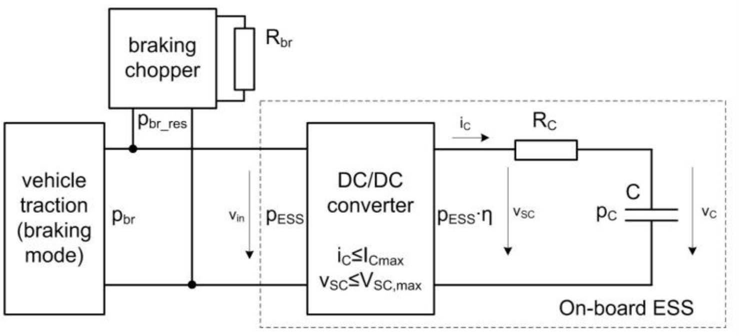

Fig. 1. The block diagram of an electric vehicle equipped with on-board *ESS* and operating in the braking mode.

The braking chopper with a relevant (braking) resistor is used to dissipate the energy not received by the *ESS* due to the *SC* bank voltage and current limitations. A simplified model of the *SC* containing linear capacitance C and internal series resistance R_C is used in Fig. 1. Such a model is accepted by many authors as a sufficiently accurate for calculation of the losses during a charge/discharge process [7, 8, 11, 12]. Only voltage v_{SC} may be measured by the *ESS* controller, while voltage v_C is not measurable and is used only for calculation of the energy stored in *SC* bank.

Figure 2 displays the operational diagrams for the case of a vehicle with braking power p_{br} which linearly decreases from $P_{br,\max}$ to 0 in the time interval $0 - t_{br}$. In general, three modes of the *ESS* operation can be distinguished:

− mode 1 takes place within the interval $0 - t_1$ when braking power p_{br} exceeds the *ESS* power capability restricted by current limitation. In this mode $i_C = I_{C\max}$, and a portion of p_{br} is dissipated in the braking resistors;

− mode 2 is a normal mode of *ESS* operation, when all the energy (excluding losses in DC/DC converter and supercapacitor series resistance R_C) is saved in supercapacitor bank C. Mode 2 starts at t_1 and ends at t_2 when voltage $v_{SC} = v_C +$ $+ i_C R_C$ reaches the maximum allowable value ($V_{SC,\max}$);

− mode 3 (called in [11] the *equalization step*) takes place within the interval $t_2 - t_3$ and is a mode of *SC* voltage stabilization at the level $v_{SC} = const = V_{SC,\max}$. The charging current is reduced to the $i_C = (V_{SC,\max} - v_C)/R_C$, and the excessive power is dissipated in the braking resistor.

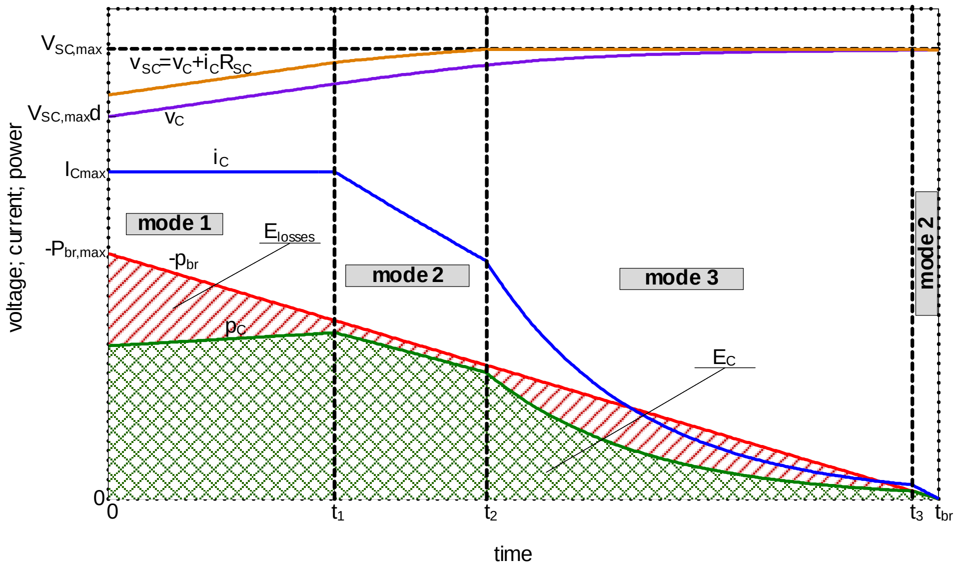

Fig. 2. Three possible operating modes of *ESS*.

At t_3 the p_{br} value decreases to the level when the current restrictions are released and the normal mode (i.e. mode 2) of *ESS* operation is again possible during the time interval t_3–t_{br}.

The highest energy losses are observed during time intervals 0–t_1 and t_2–t_3 when partial energy dissipation in braking resistors occurs. To avoid these losses it is necessary to correctly size the *SC* bank and select its discharge depth *d*.

4. *ESS* SIZING CONSIDERATIONS

The usable energy E_{ESS} of an *SC* bank with capacity *C* and allowable maximum voltage $V_{SC,\max}$ depends on the discharge depth $d=V_{SC,\min}/V_{SC,\max}$:

$$E_{ESS} = \frac{V_{SC,\max}^2 (1-d^2)C}{2}. \tag{5}$$

If an *ESS* battery contains *n* series- and *m* parallel-connected single supercapacitors with capacitance C_s and maximum allowable voltage $V_{s,\max}$, then $V_{SC,\max} = nV_{s,\max}$, $C = m/n\ C_s$ and

$$E_{ESS} = \frac{V_{s,\max}^2 (1-d^2)NC_s}{2}, \tag{6}$$

where $N=nm$ is the total number of supercapacitors.

The power capability of *ESS* in a discharged state is:

$$P_{ESS,discharged} = nV_{s,\max}d \cdot mI_{C\max} = NV_{s,\max}I_{C\max}d\,. \tag{7}$$

Note that both the usable energy and the power capability of such an *ESS* depend on the total number of supercapacitors *N* independently of their series or parallel arrangement.

To capture the total braking energy, the following inequalities should be satisfied:

$$E_{ESS} \geq E_{br}; \qquad P_{ESS,discharged} \geq P_{br,\max} . \tag{8}$$

Inserting (8) into (6) and (7) we can write the inequalities for determination of the required number of supercapacitors as

$$N \geq \frac{2E_{br}}{V_{s,\max}^2 C_s (1-d^2)} , \tag{9}$$

$$N \geq \frac{P_{br,\max}}{V_{s,\max} I_{C\max} d} . \tag{10}$$

Figure 3 exemplifies the required number N of supercapacitors *vs.* discharge depth d calculated according to (9) and (10) for E_{br} = 820 kJ, $P_{br,\max}$ = 236 kW, C_s = 3000 F and $V_{s,\max}$ = 2.5 V. The dashed line corresponds to (9) and shows the N value taking into account only the energy requirement. The minimum value (N = 117) is at d =0.5. However, to capture the total braking energy the maximum supercapacitor current (calculated according to (10)) should be 1614 A, which is not allowed.

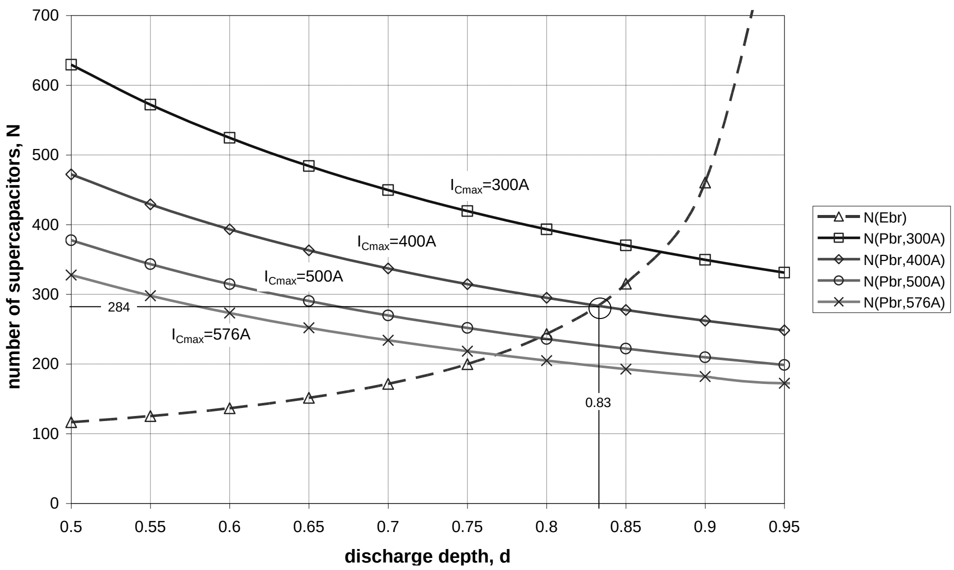

Fig. 3. The required number N of supercapacitors for E_{br} = 820 kJ (dashed line) and $P_{br,\max}$ = 236 kW (solid lines) at different $I_{C\max}$ values *vs.* discharge depth d.

The solid lines in Fig. 3 are calculated according to (10) for $I_{C\max}$ = 300; 400; 500; and 576 A, and show the necessary number of supercapacitors taking into account the power requirements. The last value ($I_{C\max}$ = 576 A) is chosen equal to 0.12 $I_{ShortCircuit}$ recommended in [4, 6, 9] as the maximum allowed for *SC*. The chosen N value should be located above both the energy and the power curves. The point of intersection gives the minimum N and the optimum d values meeting both the energy and the power requirements. These values can be calculated by the following equations (obtained by solving (9) and (10)) for N and d, correspondingly:

$$N = N_{\min} = \frac{E_{br}}{V_{s,\max}^2 C_s} + \sqrt{\left(\frac{E_{br}}{V_{s,\max}^2 C_s}\right)^2 + \left(\frac{P_{br,\max}}{V_{s,\max} I_{C\max}}\right)^2}\ , \qquad (11)$$

$$d = d_{opt} = \sqrt{\left(\frac{E_{br} I_{C\max}}{P_{br,\max} V_{s,\max} C_s}\right)^2 + 1} - \frac{E_{br} I_{C\max}}{P_{br,\max} V_{s,\max} C_s}\ . \qquad (12)$$

For the braking energy E_{br} = 820 kJ and power $P_{br,\max}$ = 236 kW and $I_{C\max}$ = = 400 A the calculated values are: $N_{\min}$ = 284 and d_{opt} = 0.83. As seen from Fig. 3, even at $I_{C\max}$ = 576 A the optimum discharge depth is greater than 0.75, which is far from the value d = 0.5 widely recommended in the literature.

The choice of $I_{C\max}$ depends on many factors: the vehicle driving cycle, the *ESS* discharge strategy, *SC* cooling conditions, the required *ESS* efficiency, *etc.*, which are beyond the scope of this article. However, the simulations made for the described above braking power profile and R_{sc} = 0.3 mΩ show that 90% of the overall *ESS* efficiency can be achieved at $I_{C\max}$ < 400 A. Therefore for our example the value $I_{C\max}$ = 400 A is chosen and will be used in further simulations. In more advanced *ESS*s the reference value for $I_{C\max}$ can be one of the output variables of an intelligent controller.

5. THE *ESS* MODEL AND SIMULATION RESULTS

The approach described above raises, however, several questions:

1. Since N_{min} and d_{opt} values have been calculated by Eqs. (11) and (12) ignoring the losses in an *SC*, how its real losses affect these values?
2. How critical is the calculated value d_{opt}? In other words: how d variations affect the amount of saved energy?
3. How a reduced size of *ESS* affects the amount of saved energy?

To find answers to these questions a simple mathematical model of the system shown in Fig. 1 was developed and relevant simulations performed. In compliance with this figure, the model is described by the following equations:

$$-p_{br}\eta = i_C^2 R_C + v_C i_C\,, \qquad (13)$$

$$v_C = \frac{1}{C}\int i_C dt + d \cdot V_{SC,\max}\ , \qquad (14)$$

$$v_{SC} = v_C + i_C R_C \qquad (15)$$

and the constraints: $i_C \le I_{C\max}$, $v_{SC} \le V_{SC,\max}$.

The *Matlab* algorithm of the model performs iterative calculations of Eqs. (13), (14), (15) with the iteration step of 0.01 s, and provides limitations on i_C and v_{SC} according to the constraints. The simulations were carried out for the braking power profile E_{br} = 820 kJ, $P_{br,\max}$ = 236 kW, t_{br} = 6.9 s and the *ESS* parameters: $I_{C\max}$ = 400 A, R_{sc} = 0.3 mΩ, converter efficiency η = 0.98.

Figure 4 shows the simulated saved energy (p.u.) as a function of d for three N values: 200; 250; 284.

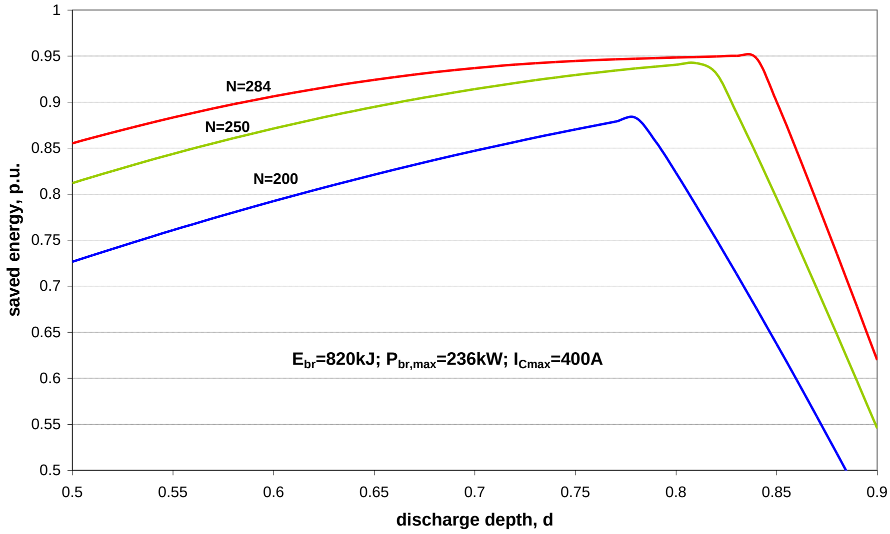

Fig. 4. Saved energy (p.u.) *vs.* discharge depth *d*.

For N = 284, mode 2 of the *ESS* operation is ensured in a comparatively wide range of d = 0.77–0.84 with the maximum energy saved at $d = d_{opt} = 0.84$. At $d < 0.77$, mode 1 occurs additionally at the start of braking. For $d > 0.84$, mode 3 takes place at the end of braking, and the saved energy falls dramatically with increasing d value. For the reduced number of cells: N = 250, N = 200, the d_{opt} values are 0.81 and 0.78, respectively. The amount of saved energy is smaller and more sensitive to the d variations. At a reduced number of cells either mode 1 (for $d < d_{opt}$) or mode 3 (for $d > d_{opt}$) is always present, and a portion of the braking energy is dissipated in the braking rheostat.

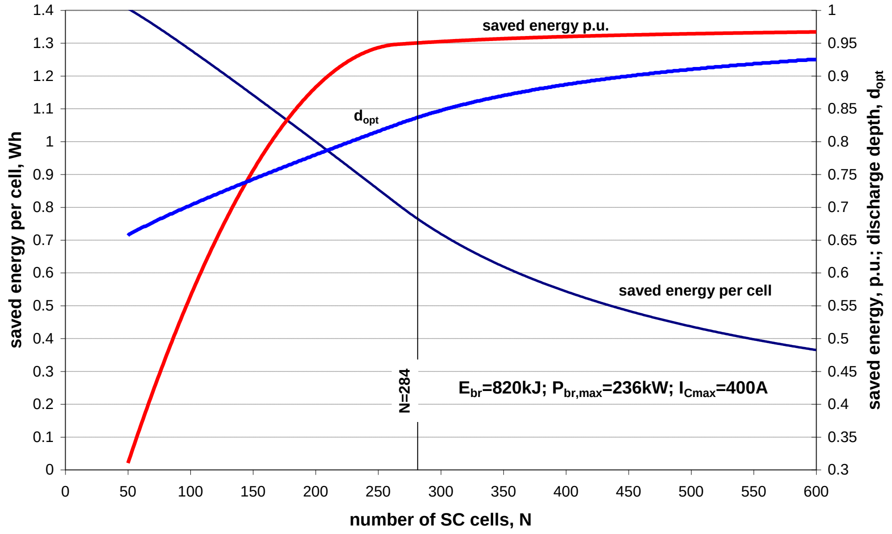

Fig. 5. Saved energy p.u., saved energy per cell and
the optimum discharge depth *vs.* the number of *SC* cells.

However, the reduced number of cells is of interest from the viewpoint of a compromise between the saved energy and the *ESS* cost. Figure 5 shows the saved energy per unit and per cell *vs.* the number of cells *N* calculated for the optimum value $d_{opt}(N)$. As seen in the figure, with *N* increasing above 284 the saved energy grows slightly as the *ESS* efficiency grows due to reduced *SC* current. At the same time, the saved energy per cell is small and decreases with *N* increasing. The cell number reduced below calculated $N_{\min}$ might be an option for the cases when the *ESS* payback time is more important than the amount of energy saved. Therefore, e.g., reducing *N* by 30% (i.e. choosing N = 200 instead of N = 284) gives only 6.7% less saved energy while per cell it will increase by 23%.

6. CONCLUSIONS

1. Sizing of the on-board *ESS* should be performed taking into account both the braking energy and the braking power of a vehicle.

2. The optimum discharge depth of supercapacitors in an on-board *ESS* in the most cases is in the range 0.75–0.85 instead of the widely recommended value 0.5.

3. The number of cells reduced below the calculated $N_{\min}$ could be proposed as a compromise solution in the cases when the payback time for *ESS* is more important than the amount of energy saved.

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MOBILO SUPERKONDENSATORU ENERĢIJAS UZKRĀJĒJU DIMENSIONĒŠANAS APSVĒRUMI

L. Latkovskis, U. Sirmelis, L. Grigāns

K o p s a v i l k u m s

Raksts veltīts elektriskajos transportlīdzekļos uzstādāmu superkondensatoru enerģijas uzkrājēju dimensionēšanai, ņemot vērā gan to bremzēšanas enerģiju, gan jaudu. Iegūtas izteiksmes minimālā superkondensatoru skaita un optimālās to izlādes pakāpes noteikšanai. Kā piemērs teorētiskie aprēķini pielietoti trolejbusa Škoda 24Tr enerģijas uzkrājēja dimensionēšanai. Pielietojot matemātisko modelēšanu, noteikta izmantotā bremzēšanas enerģija kā funkcija no superkondensatoru skaita pie optimālās to izlādes pakāpes. Šī sakarība dod iespēju meklēt kompromisa risinājumu starp enerģijas izmantošanas efektivitāti un uzkrājēja cenu. Katram superkondensatoru skaitam ir noteikta optimālā to izlādes pakāpe, kas nodrošina maksimālu bremzēšanas enerģijas izmantošanu. Atrasts, ka tā vairākumā gadījumu ir daudz lielāka par 0.5, kuru rekomendē superkondensatoru ražotāji un kas visbiežāk ir izvēlēta literatūrā aprakstītajos enerģijas uzkrājējos.

30.03.2012.