Optimal Supercapacitive Energy Storage Sizing for Mobile Application

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***Abstract*-The paper presents a method for sizing a supercapacitor (SC) energy storage system (ESS) for installation in trams. The sizing method is intended for trams running on little-used lines where it is assumed that regenerated braking energy cannot be transferred to and used by other trams. In such a situation all regenerated braking energy is dissipated in brake resistors. Onboard SC ESS could be used to reduce the amount of energy wasted; however, the cost of retrofitting a tram with an ESS in some cases may even exceed the value of recovered braking energy. Therefore, while sizing ESS it is important to consider the economics and choose the ESS parameters in a way to maximize the return on investment over the ESS service life and not to shorten SC lifetime. In this paper the proposed ESS sizing method is demonstrated for Tatra T3A type tram.**

I. INTRODUCTION

Most recently trams have the ability while braking to operate the traction motors in generator mode and recover the vehicle kinetic energy converting it to electricity. A small portion of regenerated energy is used by the vehicle auxiliaries, while largest part could be returned to the overhead line, where it could be used by other nearby trams, if they at that moment are accelerating and consuming energy. Since typical traction substations are not reversible, the surplus regenerated energy cannot be returned to the AC grid and therefore has to be dissipated in the tram brake resistors. If the traffic intensity is low, then most of the regenerated energy is wasted in the brake resistors. To make use of braking energy, there are several options: 1) to equip trams with energy storage; 2) to rebuild traction substations into reversible ones; 3) to install stationary energy storage; 4) to connect adjacent feeding zones of traction substations [1].

The scope of this work is on the first option, where tram with an onboard supercapacitive energy storage system (ESS) is considered. Supercapacitor (SC) as a storage technology is chosen due to its high power capability and high cycle life. In this work a method for sizing SC battery to maximize return on investment is proposed. The proposed method is intended for trams running on lines with low traffic intensity where the regenerated energy exchange between vehicles does not occur.

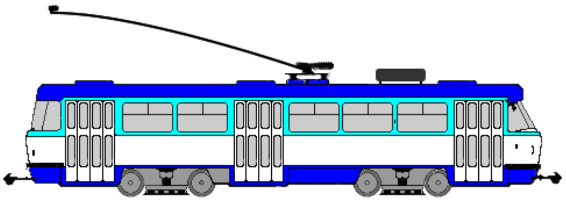
The available literature on the trams fitted with onboard energy storage either does not cover the economical feasibility [2],[3],[4], or shows negative return on investment [5], or considers other benefits of onboard energy storage such as ability of operation without overhead power supply [6] or reduction of power peak demand [2].

In this article, the proposed ESS sizing method allows to choose number of SC cells and discharge coefficient so that ESS over its lifetime gives the greatest return on investment. The method is explained and demonstrated as an ESS sizing example for a specific tram.

II. RECOVERABLE ENERGY ESTIMATION

A. *Case Study*

Tatra T3A is for this study selected tram that could be equipped with an onboard energy storage. Picture of the tram and its specification is shown in Fig. 1. The tram power diagram was recorded experimentally in Riga on route №6 on 15.10.2009. The power diagram was obtained as described in [7] by recording voltage and current signals from the sensors used by tram control system. Tram speed was recorded using GPS logger. As shown in Fig. 2 the maximum tram speed was below 60 km/h and the maximum power taken from overhead line was 296 kW while maximum surplus regenerated power was 238 kW. The length of the diagram is 19 h. A detailed energy and power balance of this diagram is summarized in TABLE I. As can be seen from the table the theoretical maximum for energy consumption reduction that could be obtained with a lossless ESS is 19.9%.



Tatra T3A specification	
Voltage	600 V±30 %
Weight	17200 kg
Capacity	162 passengers
Traction system	4×40 kW
Maximum speed	70 km/h

Fig. 1. Tatra T3A tram and its specification.

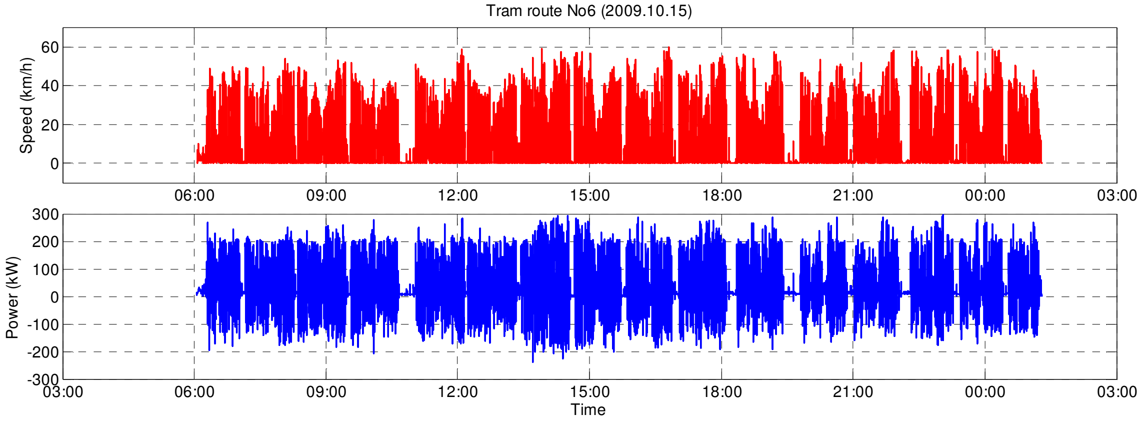


Fig. 2. Experimentally recorded tram Tatra T3A power diagram in Riga on route №6.

TABLE I
Energy balance for the recorded tram power diagram

Name	**Energy, kWh**	**Energy %**	**Average power, kW**
Energy taken from overhead line	579 kWh	100%	30 kW
Energy used for traction	430 kWh	75.4%	22 kW
Energy consumed by auxiliaries	173.7 kWh	30.5%	9 kW
Regenerated braking energy	139.7 kWh	24.5%	7.3 kW
Regenerated energy used by auxiliaries	24.7 kWh	4.3%	1.3 kW
Energy that could be recovered by onboard storage	115 kWh	19.9%	6 kW

To get a more accurate picture of the situation in the example, the recorded tram power diagram was analyzed according to energy per braking event and duration between braking events. As a braking event here a cycle of theoretical energy storage charge with consecutive discharge is considered. The energy content diagram of this theoretical energy storage is obtained by integrating tram power diagram. Since regenerated power is negative, then also the energy stored is negative and cannot be larger that zero (Fig. 3). In total 1103 intervals were obtained, and for each interval the recoverable energy and the duration was estimated. The obtained results are depicted in Fig. 4 and Fig. 5 respectively. As can be seen from Fig. 4 recoverable energy per braking does not exceed 0.4 kWh, while average energy is around 0.15 kWh. And the average duration between braking events is around 50 s (Fig. 5).

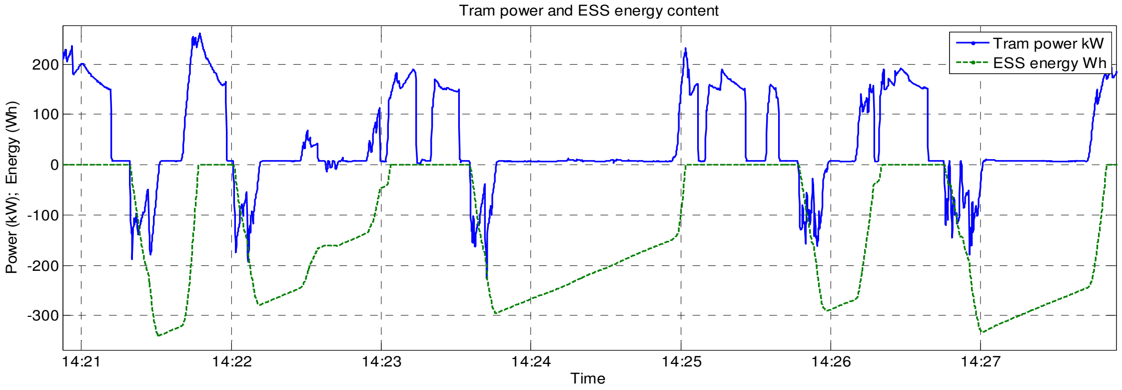


Fig. 3. Tram power diagram and ESS energy content diagram.

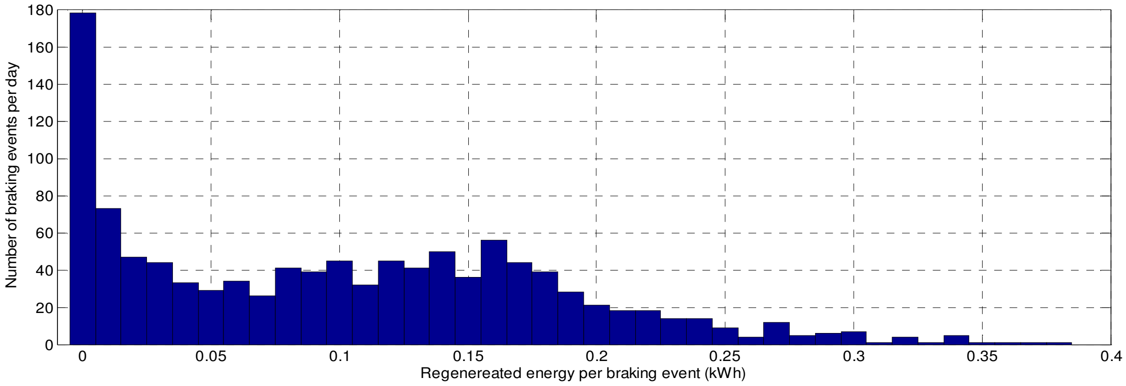


Fig. 4. Distribution of braking events vs. regenerated energy.

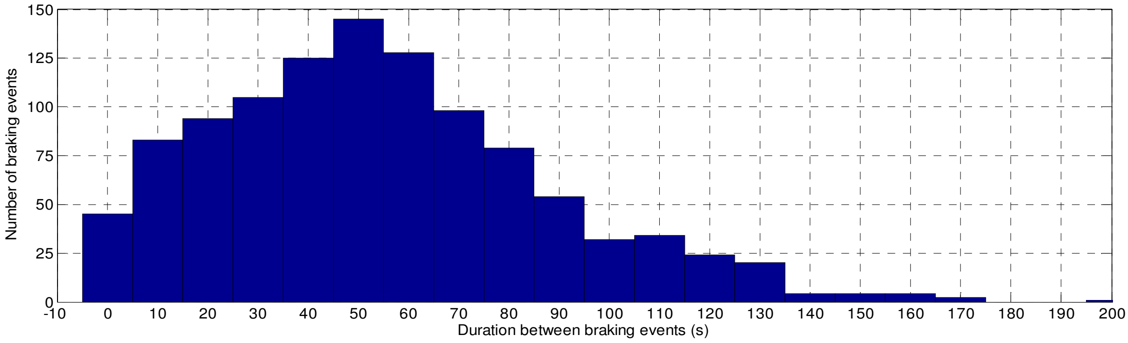


Fig. 5. Distribution of braking events vs. duration between the events.

B. Recoverable Energy vs. Power Capability and Energy Capacity

To get an idea of how ESS power capability (P_{max}) and energy capacity (E_{max}) affects the amount of recoverable energy, the recorded tram power diagram has to be processes as described in [8] for each ESS P_{max} and E_{max} combination. Shortly, the algorithm for obtaining the recoverable regenerated energy as a function of ESS power capability and energy capacity is as follows: 1) tram power diagram has to be trimmed to particular power capability (P_{max}); 2) the trimmed power diagram has to be integrated taking into account that integral cannot be positive or its absolute value cannot exceed the ESS energy capacity (E_{max}); 3) the integral diagram, which represents ESS state of charge diagram, has to be derived to obtain the ESS power diagram; 4) the ESS power diagram positive values has to be integrated to obtain daily recoverable energy for particular E_{max} and P_{max}; 5) the daily recoverable energy for particular E_{max} and P_{max} has to be normalized by dividing it by daily regenerated energy.

The obtained recoverable energy diagram is shown in Fig. 6. As can be seen from this diagram, the ESS with energy capacity of 0.22 kWh and power capability of 120 kW can recover more than 95% of all regenerated energy.

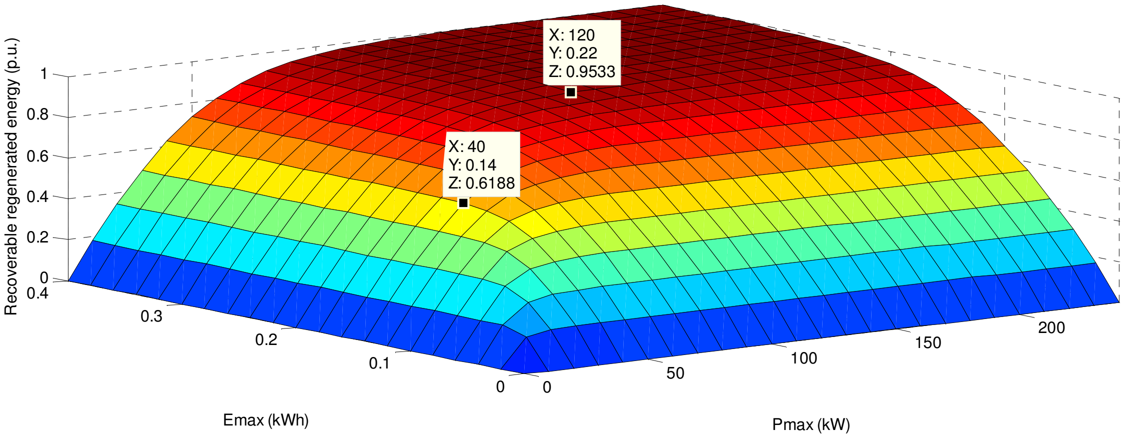


Fig. 6. Recoverable regenerated energy (p.u.) vs. ESS energy capacity and power capability

III. SUPERCAPACITOR BATTERY SIZING

In this sizing example it is assumed that SC lifetime is 10 years. Such an assumption is based on the SC manufacturers technical literature [9],[10],[11]. Cycling of supercapacitors with high current values leads to rapid decrease of their capacitance and increase in series resistance, and the end of SCs lifetime can be reached in several days [12]. Therefore, to ensure that the lifetime of SCs is at least 10 years, the maximum SC charge/discharge current in this paper is limited to 100 A. For more reasonable choice of SC maximum current, advanced SC aging model is required, which considers continuous values of SC current, voltage and temperature. Such a model is not provided by SC manufactures, but SC aging models analyzed in various scientific papers are incomplete and give questionable results for wider SC temperature and voltage range[12],[13],[14],[15].

A. ESS Cost Estimation

To find the optimal values for ESS power capability P_{max} and energy capacity E_{max}, it is not enough if we have the diagram of recoverable energy (Fig. 6). Also the ESS cost as a function of its parameters E_{max} and P_{max} is needed.

The ESS cost includes the price of IGBT transistors and their drivers, filter capacitors, inductors, cooling system, mounting enclosure, control system, SC voltage balancing and monitoring system, current sensors, contactors, cables, busbars, other assembly materials, development, production and installation costs. Since the price of ESS forming components are highly dependent on the volume, manufacturer, or distributor, it is impossible to clearly evaluate the total costs. However, an approximate ESS price estimation can be made by assuming that the total ESS price is proportional to the number of SCs. It is assumed that the price of SCs is half of the ESS price, similar assumption is done also in [1]. Thus it is necessary to find for each P_{max} and E_{max} combination corresponding number of SCs. This number can be derived from the ESS energy capacity and power capability expressions. The ESS energy capacity can be calculated as follows:

$$E_{max} = N \cdot \frac{C \cdot V_{max}^2}{2} \cdot \left(1 - d^2\right), \tag{1}$$

where: N – number of SCs;
C – capacitance of single SC cell, [F];
V_{max} – single SC cell maximum voltage, [V];
d – SC discharge coeficient.

The ESS power capability is calculated as follows:

$$P_{max} = N \cdot d \cdot V_{max} \cdot I_{max}, \tag{2}$$

where I_{max} is the chosen maximum current for single SC cell.
From (1) and (2) the minimal number of SCs N and SC discharge coefficient d can be obtained as:

$$N = \frac{E_{max}}{V_{max}^2 \cdot C} + \sqrt{\left(\frac{E_{max}}{V_{max}^2 \cdot C}\right)^2 + \left(\frac{P_{max}}{V_{max} \cdot I_{max}}\right)^2}, \tag{3}$$

$$d = \sqrt{\left(\frac{E_{max} \cdot I_{max}}{P_{max} \cdot V_{max} \cdot C}\right)^2 + 1} - \frac{E_{max} \cdot \mathrm{I}_{max}}{P_{max} \cdot V_{max} \cdot C}. \tag{4}$$

To find optimal SC discharge depth and number of SC cells as a function of ESS parameters, calculations using (3) and (4) were carried out for previously discussed P_{max} and E_{max} values. In this case we assumed that V_{max}=2.85 V and C=3400 F, which corresponds to the technical data of Maxwell K2 3400 supercapacitors.

Fig. 7 shows the number of SCs and discharge coefficients as the functions of ESS power capability and energy capacity. It can be seen that number of SCs surface gradient in the E_{max} axis direction is much lower than gradient of P_{max} axis, which means that SCs power capability is the dominating parameter that determines the number of SCs in ESS.

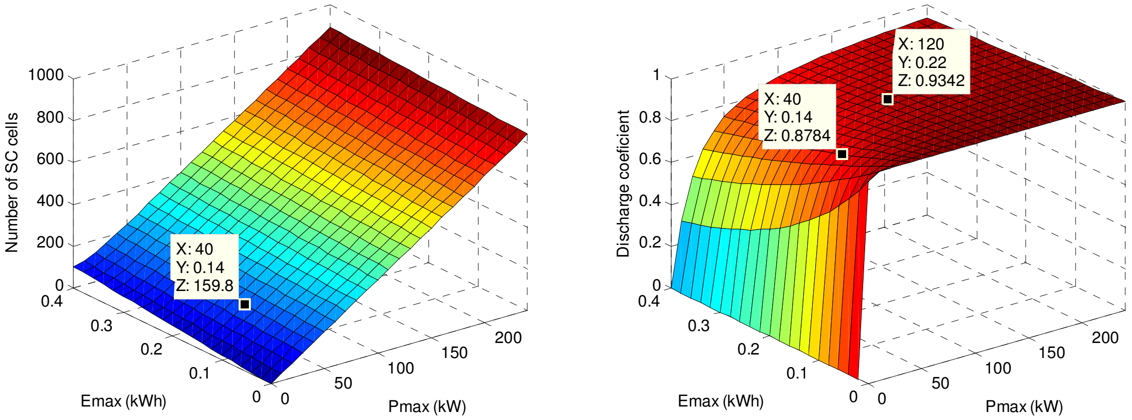


Fig. 7. Optimal number of SC cell and discharge coefficient for different E_{max} and P_{max}.

The approximate ESS cost as a function of ESS power capability P_{max} and energy capacity E_{max} is obtained by multiplying the number of SCs cells with the price for one Maxwell K2 3400F cell (based on Mouser and Digikey electronic catalogues here this price is assumed to be €50) and then multiplying by two. The obtained ESS cost diagram is shown in Fig. 8.

Fig. 8 leads to a similar conclusion that was made from Fig. 7 analysis – the price of ESS is mainly determined by its power capability rather than energy capacity.

Profit Estimation

Since typical lifetime for SCs according to manufactures is 10 years, then consequently, this could be a period during which the amount of recoverable energy will determine the ESS optimal parameters. If we assume the electricity price for 1 kWh to be €0.10, and the discount rate for the investments to be 5%, then the present value of recoverable energy over ten years period is calculated according to (5) and the results are shown in Fig. 8.

$$PV_{recovrable\ energy}\left(i,n\right)=\sum_{t=0}^{n}\frac{E_{recoverable}\left(E_{max},P_{max}\right)\cdot 365}{\left(1+i\right)^{t}}, \tag{5}$$

where: $PV_{recoverable\ energy}(i,n)$ – present value of in ten years recoverable energy [€];
i – discount rate;
n – SC lifetime [years];
$E_{recoverable}(E_{max},P_{max})$ – daily recoverable energy value [€];
t – the time of the cash flow [years];

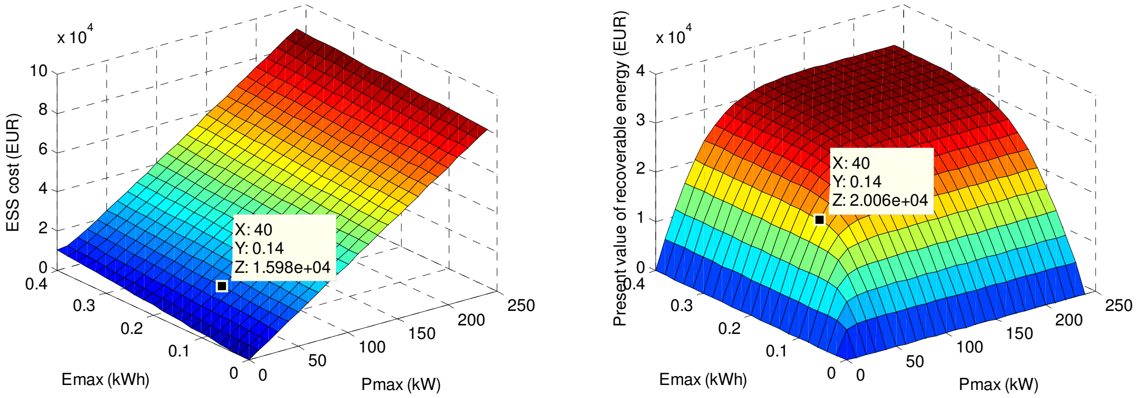


Fig. 8. ESS cost in Euros for different E_{max} and P_{max} and present value of recoverable braking energy in 10 years.

Then by subtracting the ESS cost diagram from this recoverable energy present value diagram (Fig. 8), the diagram of net present value of the ESS investment is obtained (Fig. 9).

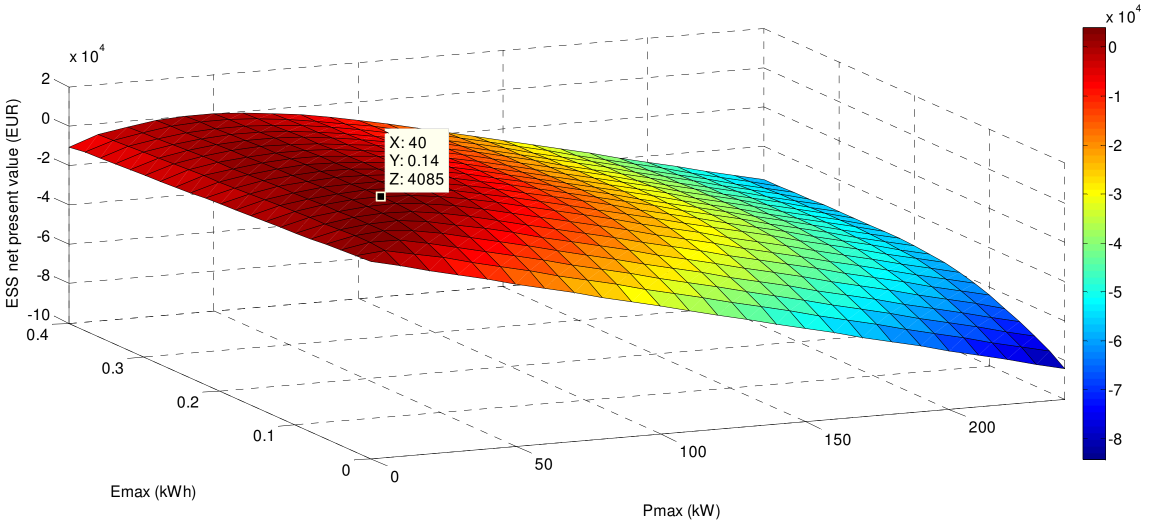


Fig. 9. ESS net present value considering energy savings over ESS lifetime.

The ESS power capability P_{max} =40 kW and energy capacity E_{max} =0.14 kWh values, which in Fig. 9 give the maximum return on investment of €4085, are the optimal ESS parameters. According to Fig. 7 ESS would be formed of 160 cells with discharge coefficient d equal to 0.87. Initial investments for such a system is approximately €16 000 and it would recover in ten years energy worth of €20 060.

In the proposed method the ESS power capability is assumed to be constant, however, in practical implementation maximum current is constant and power capability depends on SC state of charge. Therefore, a diagram of net present value of the ESS as a function of number of SC cells and discharge coefficient is obtained (Fig. 10) taking into account also the losses due to SC internal resistance and the constant maximum current. As can be seen from the diagram a point of 160 cells and discharge coefficient 0.87 gives just by €22 less ESS net present value than maximum point with 150 cells and the same discharge coefficient. From that we can conclude that the optimum (160 cells and discharge coefficient 0.87) obtained with the proposed method practically gives maximum return on investment.

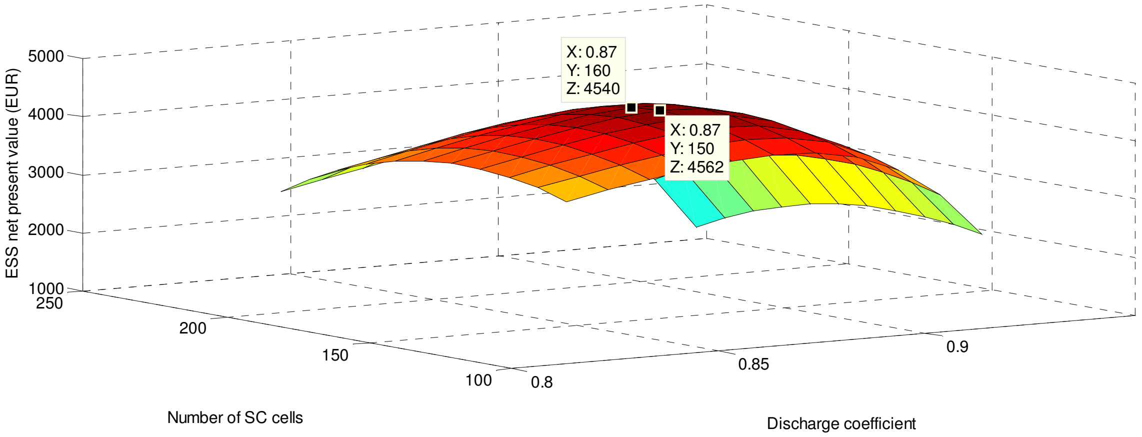


Fig. 10. ESS net present value considering energy savings over ESS lifetime vs. number of SC cells and discharge coefficient.

IV. DISCUSSION

Excluding previously mentioned discussions on SC lifetime, losses in system and ESS price, three other factors that may influence the accuracy of the proposed method can be discussed: (1) change of discount rate, (2) electricity price increase, (3) changes in tram power consumption over different seasons.

V. CONCLUSIONS

The ESS sizing method presented in this paper shows that it is more profitable to choose ESS with power and energy capacity parameters that do not provide recovery off all regenerated energy. For the Tatra T3A tram, only 62% of the energy currently wasted in brake resistors could be recovered by using ESS that is sized with the proposed method.

Optimal SC discharge coefficient is much higher than 0.5 that is usually mentioned in literature, which means that theoretical ESS energy capacity is not fully utilized. In the case studied in this paper optimum discharge depth is 0.87.

Although SCs are traditionally viewed as energy sources that have very high power capability, but limited energy capacity, this research shows that number of SCs needed to ensure optimal sized ESS is mainly determined by SCs power capability.

REFERENCES

[1] H. Hõimoja, "Energy Efficiency Estimation and Energy Storage Calculation Methods for Urban Electric Transportation," PhD Thesis, TTU, Tallin, Estonia, 2009.

[2] D. Iannuzzi and P. Tricoli, "Speed-Based State-of-Charge Tracking Control for Metro Trains With Onboard Supercapacitors," *IEEE Trans. Power Electron.*, vol. 27, no. 4, pp. 2129–2140, Apr. 2012.

[3] F. Ciccarelli, D. Iannuzzi, and P. Tricoli, "Control of metro-trains equipped with onboard supercapacitors for energy saving and reduction of power peak demand," *Transp. Res. Part C Emerg. Technol.*, vol. 24, pp. 36–49, Oct. 2012.

[4] R. Barrero, X. Tackoen, and J. Van Mierlo, "Analysis and configuration of supercapacitor based energy storage system on-board light rail vehicles," in *Power Electronics and Motion Control Conference, 2008. EPE-PEMC 2008. 13th*, 2008, pp. 1512–1517.

[5] R. Barrero and X. Tackoen, "New Technologies (Supercapacitors) for Energy Storage and Energy Recuperation for a Higher Efficiency of the Brussels Public Transportation Company Vehicles," IRSIB/IWOIB, Sep. 2008.

[6] J.-P. Moskowitz and J.-L. Cohuau, "STEEM: ALSTOM and RATP experience of supercapacitors in tramway operation," in *2010 IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2010, pp. 1–5.

[7] L. Latkovskis and L. Grigāns, "Estimation of the untapped regenerative braking energy in urban electric transportation network," in *13th Power Electronics and Motion Control Conference EPE-PEMC 2008*, Poznan, Poland, 2008, pp. 2089–2093.

[8] L. Grigans and L. Latkovskis, "Estimation of the power and energy requirements for trackside energy storage systems," in *13th European Conference on Power Electronics and Applications EPE 09*, Spain, Barcelona, 2009, pp. P1–P7.

[9] "Product Guide - BOOSTCAP Ultracapacitors - Doc. No. 1014627.1," Maxwell Technologies, Inc., 2009.

[10] "K2 2.85V/3400F Cell Datasheet." [Online] - Available: http://www.maxwell.com.

[11] "iCAP 3000F 2.7V Cell Datasheet." [Online] - Available: http://www.ioxus.com.

[12] P. Kreczanik, P. Venet, A. Hijazi, and G. Clerc, "Study of Supercapacitor Aging and Lifetime Estimation According to Voltage, Temperature, and RMS Current," *IEEE Trans. Ind. Electron.*, vol. 61, no. 9, pp. 4895–4902, Sep. 2014.

[13] "UltraCap Double Layer Capacitors, A New Energy Storage Device for Peak Power Applications." EPCOS, Product Profile-2001.

[14] D. Linzen, S. Buller, E. Karden, and R. W. De Doncker, "Analysis and evaluation of charge-balancing circuits on performance, reliability, and lifetime of supercapacitor systems," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1135–1141, 2005.

[15] T. Kovaltchouk, B. Multon, H. Ben Ahmed, J. Aubry, and P. Venet, "Enhanced Aging Model for Supercapacitors taking into account Power Cycling: Application to the Sizing of an Energy Storage System in a Direct Wave Energy Converter," *IEEE Trans. Ind. Appl.*, vol. PP, no. 99, pp. 1–1, 2014.

[16] H. Hõimoja, "Energy Efficiency Estimation and Energy Storage Calculation Methods for Urban Electric Transportation," Phd Thesis, Tallinn University of Technology, Tallin, Estonia, 2009.