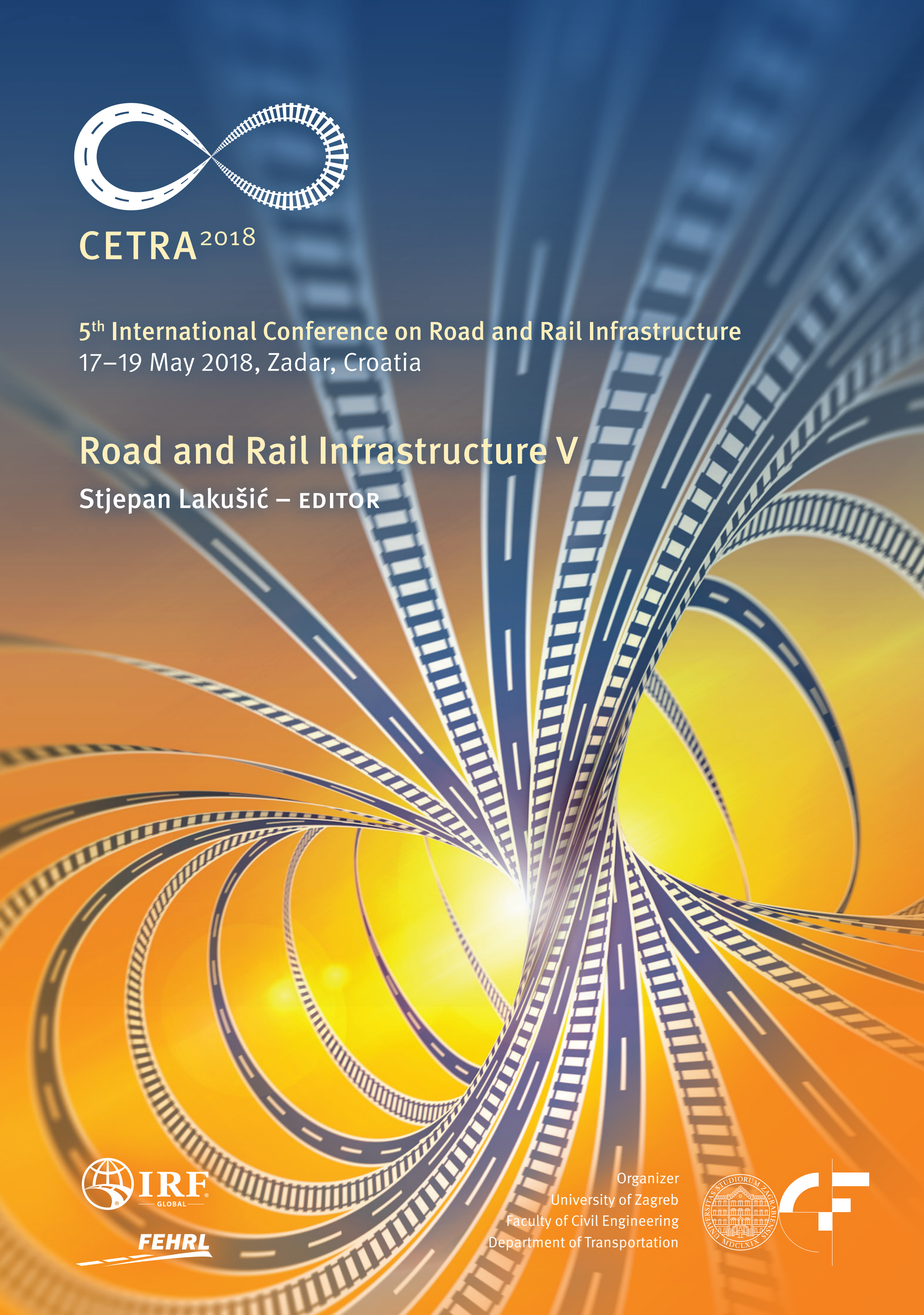

CETRA2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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CETRA^{2018}

5th International Conference on Road and Rail Infrastructure

17–19 May 2018, Zadar, Croatia

TITLE

Road and Rail Infrastructure V, Proceedings of the Conference CETRA 2018

EDITED BY

Stjepan Lakušić

ISSN

1848-9850

ISBN

978-953-8168-25-3

DOI

10.5592/CO/CETRA.2018

PUBLISHED BY

Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE

minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY

“Tiskara Zelina”, May 2018

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500

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THE OPTIMIZATION OF SUPERCAPACITOR MODULE PARAMETERS OF A STATIONARY ENERGY STORAGE SYSTEM IN DC POWER SUPPLY

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Abstract

The paper presents a method of optimization of nominal voltage and minimum state of charge (SoC) of a supercapacitor (SC) energy storage system (ESS) module dedicated for stationary traction application in a DC electrification system. The criteria of optimization include minimization of power losses during a charge-discharge cycle on one hand and maximization useful energy capacity on the other. The power losses are minimised by limitation of peak power values of SC cells and DC/DC converter elements. The optimization procedure is based on the simulation model of the SC module and DC/DC non-insulated converter. The purpose of the simulation model is power losses evaluation. The calculations of the annual energy and cost savings are carried out for the parameters of ESS obtained as a result of an optimization procedure.

1 Introduction

The significant part of railway industry operation constitutes the costs of traction energy. Furthermore, due to climate changes, energy efficiency has become an important issue approximately over the last decade. The issue plays an important part in the EU regulations, which demand the energy efficiency audits to be carried out in large companies. The environmental aspect of the energy efficiency is of utmost importance in Poland, where 97 % of electric energy is generated in coal power plants.

Most of the newly produced as well as modernized rolling stock in Europe is equipped with regenerative braking. The regenerative braking energy is effectively utilized under condition of catenary receptivity. The last is ensured when during the recuperation braking there are other trains drawing power remaining within the electric connection with the braking train via overhead catenary system (OCS). Otherwise, in order to ensure the OCS system receptivity additional equipment needs to be implemented. One of the measures applied for this purpose is stationary energy storage system (ESS). The trackside ESS in terms of the type of energy storage is mainly of three types: flywheels, supercapacitors (SC) and batteries. Due to optimistic tendency of price reduction observed for the last decade in case of SC energy storage devices, the growing attention of the researches is focused on them. Fig. 1 presents a general scheme of the stationary SC energy storage system installed in a traction substation. A significant number of analyses have been undertaken in order to investigate the efficiency of regenerative braking recovery by stationary SC ESS [1–6]. The number of research works investigated the influence of location of the ESSs as well as their parameters on the efficiency of regenerative energy recovery. Most of the analysed solutions focus on a 750 V DC electrification system for light transportation systems [4, 5, 7, 8].

DOI: https://doi.org/10.5592/CO/CETRA.2018.927

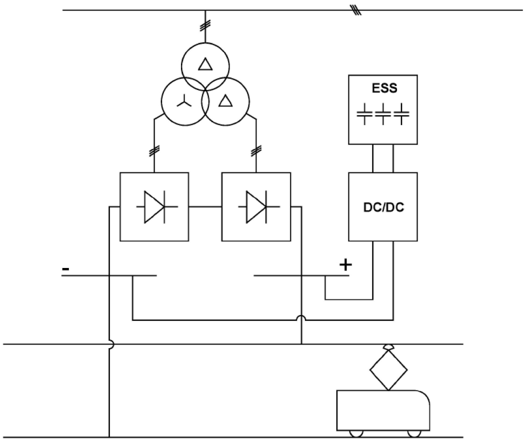

Figure 1 A general scheme of a stationary energy storage system connected to a traction substation with a 12-pulse transformer rectifier unit

The paper pays particular attention to optimization of SC pack parameters for a given location of ESS to ensure the maximum efficiency of regenerative energy recovery. The proposed solution is dedicated to all of the DC electrification systems. However, the investigation was carried out for a 3 kV DC system. The perspectives of SC ESS implementation in a 3 kV DC system are described in [9]. The efficiency models of the SC pack and the DC\DC converter were assumed based on the literature analysis.

2 Efficiency model of ESS with a supercapacitor.

For the investigation purpose the supercapacitor pack and DC/DC converter efficiency models were developed. The models are based on the literature analysis.

2.1 Model of a supercapacitor module

The model of a supercapacitor for efficiency calculations was taken from [10], where the SC cell consists of capacitance C and internal resistance ESR. The ESR value depends on the temperature inside the SC pack during its operation, however, for the purpose of the research, the constant value of ESR, declared by a manufacturer is assumed. In the SC pack the resistance of contacts between the adjacent SC cells R_C is assumed, Figure 2.

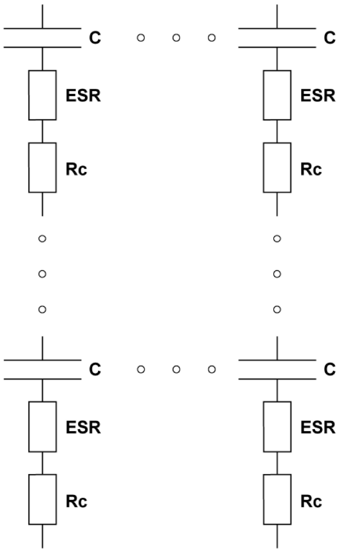

Figure 2 The assumed electrical model of a SC pack for efficiency calculations

Therefore, the resultant internal resistance of the SC pack is obtained according to (1):

$$ESR_P = \frac{n \cdot \left(ESR + R_C\right)}{m} \tag{1}$$

Where:
n – number of cells connected in serious;
m – number of cells connected in parallel.

2.2 Model of a DC/DC converter

There are known several types of DC/DC converters, which are generally divided into insulated and non – insulated converters [11, 12]. In the article the assumed type of a DC/DC converter is a non-insulated buck-boost converter. The general scheme of this converter is presented in Figure 3.

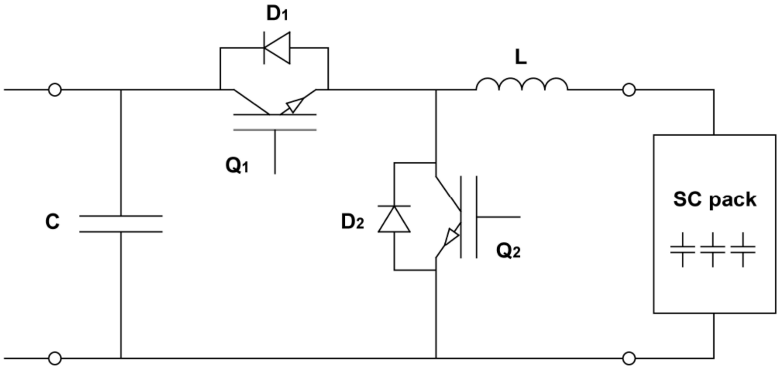

Figure 3 Bi-directional buck-boost converter connected to a battery pack

The efficiency model was developed in [7]. The efficiency model presented in [7] assumes replacing the electric power elements as well as L and C elements with equivalent resistances and switching losses of IGBT transistors. The efficiency of the converter in the buck mode is given by (2) [7]:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{U_2}{A_1 I_L + A_2 + \frac{A_3}{I_L}} \tag{2}$$

Where:

$$\begin{gathered} A_1 = K_{D1} + R_{on1} + \left(1 - K_{D1}\right) R_{D2} + R_L \\ A_2 = U_2 + \sqrt{\left(1 - K_{D1}\right)} U_{D2} \\ A_3 = \frac{R_{C2} U_2^2 \left(1 - K_{D1}\right)}{12 \left(f_s L\right)^2} + \frac{\left(E_{sw(on)} + E_{sw(off)}\right) \cdot f_s}{2} \end{gathered} \tag{3}$$

Whereas the efficiency of the converter in the boost mode is given by (4) [7]:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{U_1}{B_1 I_L + B_2 + \frac{B_3}{I_L}} \tag{4}$$

Where:

$$\begin{gathered} B_1 = \left(1 - K_{D2}\right) R_{on2} + K_{D2} R_{D1} + R_L \\ B_2 = U_1 + \sqrt{K_{D2}} U_{D1} \\ B_3 = \frac{\left(E_{sw(on)} + E_{sw(off)}\right) \cdot f_s}{2} \end{gathered} \tag{5}$$

Figures 4a and 4b show the losses in the converter assumed in the research as a function of current of the SC pack and duty cycle for boost and buck mode, respectively. Whereas Figure 4 c and d show the efficiency values as a function of SC pack current for the boost and buck mode, respectively, for the constant value of a duty cycle.

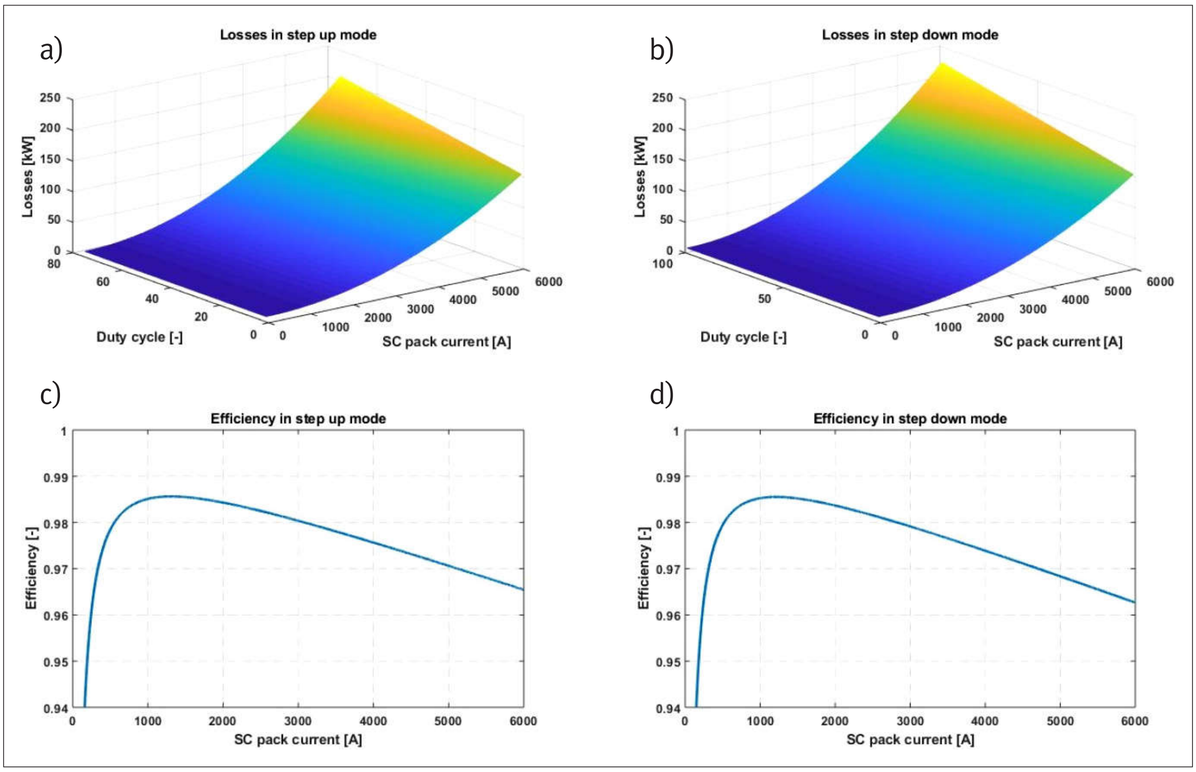

Figure 4 Power losses and efficiency of the buck-boost converter

3 Minimization of power losses in ESS

The mathematical models of the SC pack and DC/DC converter presented above were implemented in MATLAB. Based on both elements the simulation efficiency model of the whole SC ESS were developed. The efficiency model was investigated assuming the 24-hour power of the traction substation load where the ESS is assumed to be installed. The power load profile was obtained based on the simulation carried out on the electrified railway line simulation model developed in the Electric Traction Division of the Warsaw University of Technology. The power load includes positive values – the output DC power of a traction substation as well as negative values – regenerative power available in the traction substation due to the deficiency of overhead catenary receptivity.

The aim of the research is to minimise power losses. The losses in the DC/DC converter depend on the duty cycle and converter current (Figure 4). Whereas losses in the SC battery pack are the function of charge/discharge SC pack current I_{SC}.

$$\Delta P_{SC} = ESR_P \cdot I_{SC}^2 \tag{6}$$

Therefore, the total power losses are the sum of losses in the SC pack and in the DC/DC converter.

$$\Delta P_{ESS} = \Delta P_{SC} + P_{DC/DC} \tag{7}$$

The usable energy capacitance of the SC pack depends on the number and capacitance of the SC cells and the minimum state of charge (the depth of discharge). The typical assumed minimum state of charge in the literature is 50 % for stationary and vehicles applications [13]. For low state of charge available values, the usable energy capacitance is higher. However, on the other hand for low state of charge the operation of DC/DC converter is ineffective due to high values of the duty cycle in the boost mode, which leads to high values of losses in the converter and in the SC pack. Hence, the value of the SoC is a compromise solution between the available total energy capacitance maximum use and minimisation of power losses.

Figure 5 shows the losses in the whole energy storage system for two different minimum states of charge available in the strategy algorithm for the same ESS load. In Figure 5a, the minimum SoC assumed in ESS control algorithm is 0.5 U_n in Figure 5 b is 0.3 U_n.

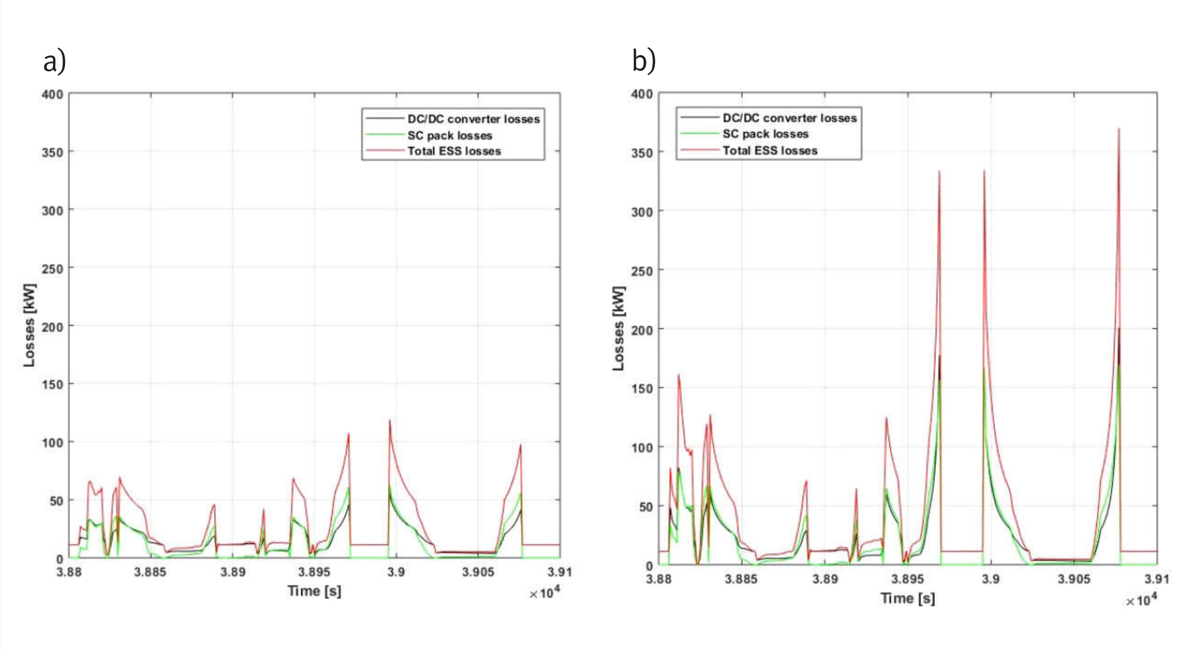

Figure 5 Power losses in the stationary ESS with a supercapacitor for different minimum states of charge (SoC) assumed in a control algorithm: a) 50 %, b) 30 %

In the research, it is assumed that the nominal power of the DC/DC converter is 1.2 MW and the useful energy capacitance of the number of SC cells in a pack is 3500. The parameters of the energy storage system were determined in the sizing process based on the economic analysis, description of which is omitted in the paper.

The proposed method of SC pack optimization includes simulation calculation of input energy of ESS, output ESS and total energy losses in ESS in a 24-hour cycle. The above parameters were calculated as a function of the minimum state of charge. The minimum state of charge is assumed between 30 % and 70 %. The investigation was carried out for different variants of a SC pack connection. The assumed variants of the SC pack connection are presented in Table 1. The results of simulation are presented in Figure 6.

Table 1 Variants of the battery pack configuration assumed for investigation: n – number of cells connected in serious, m – number of cells connected in parallel, U_n – nominal voltage of the SC pack.

	Pack 1	Pack 2	Pack 3	Pack 4	Pack 5	Pack 6
n	437	500	583	700	875	1167
m	8	7	6	5	4	3
m*n	3496	3500	3498	3500	3500	3501
U_n	1179,9	1350	1574,1	1890	2362,5	3150,9

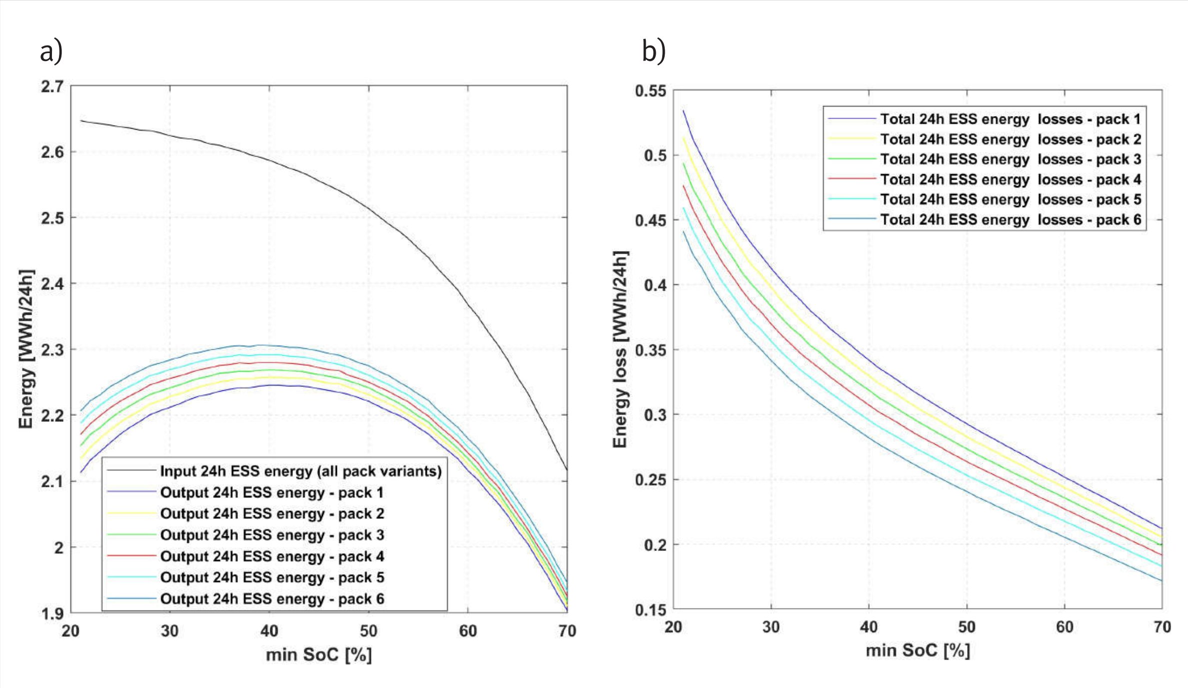

Figure 6 a) 24 h input energy of ESS for all of the variants of the pack and output 24 h energy of ESS as a function of a minimum state of charge, b) 24 h total ESS energy losses for the variants of the SC pack

4 Conclusion

The proposed method of optimization of an energy storage system SC pack allows finding the minimum state of charge, the most effective from the point of view of regenerative energy recovery for a given number of cells. The results show that the most effective minimum SoC is 39 %. The investigation carried out for the various configurations of the SC pack shows that the most effective from regenerative energy utilization efficiency is the variant with the largest number of cells connected in serious (pack 6). Current per single cell as well as the losses in the SC pack are comparable for the different variants of the SC pack. However, the losses in the DC/DC converter are lower in case has the nominal SC pack voltage is close to the no-load voltage of the substation busbar. The nominal voltage of the SC pack could not exceed the no-load voltage of the substation busbar; otherwise the full bridge topology of DC/DC converter is required.

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