Case study of stationary energy storage device in a 3 kV DC traction system

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Abstract. The paper presents the results of economic study of energy storage system (ESS) implemented in 3 kV DC power supply system. Two conceptions of ESS have been investigated: ESS with supercapacitor (SC) and hybrid ESS (HESS) with SC and LFP battery. The investigated locations of energy storage systems are considered among existing traction substations in two railway lines with different density of train operation. The considered aims of energy storage system implementation are decreasing of energy consumption by maximum regenerative energy utilization and reduction of peak 15-min power demand of traction substation. The paper presents a method of regenerative power estimation depending on the location of the considered ESS implementation point. Also the method of optimal location selection of ESS in terms of minimization of Simple Payback Time (SPBT) of investment is presented. Besides the influence of initial cost value as well as energy price on the SPBT value are investigated. The results are compared between two railway lines with different number of trains operating.

1 Introduction

Energy efficiency is increasingly gaining in importance, due to the climate changes and global grow of CO_2 emission. In Poland the issue is highly important due to the structure of electric energy generation sector, where 97% of electric energy is generated by coal power plants. Annual traction energy consumption in Polish railways is 2,4 TWh, which is 1,5% of the whole electric energy consumed in Poland. Meanwhile due to the rolling stock modernization the and replacing programs in perspective of the next years the absolute majority of the rolling stock is going to be equipped with regenerative braking. That condition gives the opportunity of braking power utilization, which in the case of a large number of stops enables to save between 10 % and 30 % of traction energy [1-4].

The regenerative power can be utilized in case if overhead catenary system (OCS) is receptive. In other case in DC systems the additional means of regenerative power utilization need to be introduces. One of them is stationary energy storage device. Apart from energy saving ESS could be used as the mean of 15-min power reduction as well as the pantograph voltage condition improvement [5]. In this paper the conception of ESS implementation in the existing traction substation is considered, which would enable satisfying the first two criteria. The voltage conditions could be improved only in case of substation outage under condition of appropriate ESS parameters and state of charge. The general scheme of the ESS in the 3 kV DC traction substation is presented in Fig. 1.

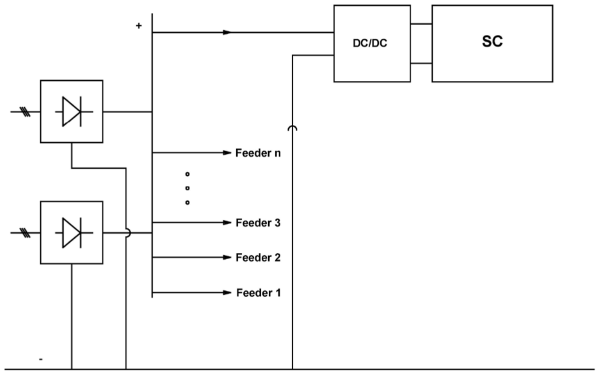

Fig. 1. The scheme of the ESS in the 3 kV DC traction substation with 12 pulse transformer rectifier unit.

Considering the given railway line the significant influence on regenerative energy utilization has the location of the ESS. According to the variable number of train stops and vertical profile along the track the regenerative energy which potentially could be recovered is variable as well. From the point of view of OCS receptivity the number of trains in the specified locations and timetable are important. Thus the factors has also influence on the variation of regenerative energy along the railway track.

In the paper two topologies of the ESS are considered: ESS with supercapacitor (SC) and ESS with SC and LFP battery. In the second topology the SC is used for the utilization of regenerative energy, while the

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LFP battery is used to compensate the 15-min. power demand of the substation in order to reduce power demand charge. The stored energy of the LFP battery is much higher than SC. The LFP battery is charged by transformer rectifier unit. The appropriate energy management strategy has been used for the ESS with SC and LFP battery. For the implemented ESS the rule based deterministic strategy has been used. The energy management strategies have been mainly developed for ESS systems for autonomous electric vehicles, the range of strategies has been developed for the variable purposes [6].

The economic effect of the ESS implementation on traction substation depends on the substation location, the ESS topology, its sizing and the energy management strategy. In the paper the economic analysis has been carried out for the variants with different substation load character. The case study for specific railway line is carried out.

2 Model of the electrified railway line (ERL)

Due to the necessity of taking into account the number of factors important from the point of view of regenerative power availability along the railway track the appropriate simulation model needs to be used. The model of ERL used in the research consists of two parts: the train performance calculation (TPC) algorithm and power flow (PF) algorithm.

The TPC model covers the movement modelling of each train given in the forecasted or current timetable. The train movement parameters could be determined by (1) according to the Newton's second law of motion.

$$\begin{bmatrix} \frac{dx_i}{dt} \\ \frac{dv_i}{dt} \end{bmatrix} = \begin{bmatrix} v_i \\ \frac{F_i(v_i,U_i) - W(v_i,x_i)}{m_i(1+\eta_i)} \end{bmatrix} \tag{1}$$

where:
x_i, v_i, F_i, m_i, η_i, U_i - respectively, i-th train location, speed, tractive effort, mass, rotation mass coefficient, pantograph voltage. The rolling resistance is expressed by (2):

$$W(v_i,x_i) = a_i v_i^2 + b_i v_i + c_i + W_{hor} + W_{ver} \tag{2}$$

Where:
W_{hor} – rolling resistance from hirisontal profile
W_{ver} – rolling resistance from vertical profile

The algorithm determines the acceleration, speed, location, tractive effort and power of each train in each time step of simulation. The power values of train are positive or negative, depending of the mode of train operation and drive cycle phase. The current drawn by each train and pantograph voltage are determined in the power flow algorithm with use of mesh method of circuit analysis and superposition method. Trains are modelled as non-linear current sources, hence the iterative method is used for equivalent circuit analysis. The methodology of power flow calculations has been developed by range of authors [7-9] whose results and descriptions were the source of model development.

3 ESS with supercapacitor

The simulation research of ESS with supercapacitor has been carried out on the SC model based on the equivalent RC model. The mathematical model is based on the capacitor equation. In Table 1 the basic parameters of the used capacitor cells are presented.

Table 1. Supercapacitor cell parameters.

Type	BCAP
Mass	510 g
Nominal voltage	2,7 V
Capacitance	3000 F
Internal resistance	0,29 mΩ
Specific power	5,9 kW/kg
Cost	60 $
Nominal cycle life	1000000

[Source: http://www.maxwell.com]

The price model of the ESS with SC implementation could be obtained based on the formula [10] (3)

$$C_{ESS\_SC} = C_{const} + c\_u_{DCDC} \cdot P_{DCDC\_C} + 1.4 m_C \cdot n_C \cdot c_{sc\_cell}$$
(3)

where:
C_{onst} – constant cost of ESS installation [USD], $c\_u_{DC/DC}$ – unit cost of DC/DC converter [USD/kW], P_{DC/DC_C} – power of DC/DC converter [kW], m_C – number of cells connected in series, n_c – number of cells connected in parallel, c_{sc_cell} – price of the single SC cell.

The profit due to the energy savings is dependent on the tariff group of traction substation. The general active energy cost is calculated according to (4)

$$C_E = \sum_{i=1}^{n} c_i \cdot E_i \tag{4}$$

where c_i is energy price for the specific time zone, and E_i is the energy consumed in the specific time zone, n - number of time zones. The SPBT is calculated according to (5)

$$SPBT = \frac{C_{ESS\_SC}}{365 \cdot C_{E\_24h}} \tag{5}$$

The simulation study has been carried out for two railway lines, with relatively low and high density of train operation. The basic parameters of the investigated railway lines are presented in table 2.

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Table 2. The basic parameters of the investigated railway lines.

	Line 1	Line 2
Length [km]	95	50
Number of substations	7	4
Number of trains/24 h/direction	26	115
Nr of train stops	16	15
Average nr of train stops per 10 km	1,68	3
Average distance between substations [km]	13,57	12,5

Fig. 2 shows the graphic timetables of the trains operation in the investigated railway line 1 (a) and 2 (b) for 24 hours cycle. In the figure the locations of train stops as well as the substations and section cabins (red lines) are marked. The substations considered as the possible locations of ESS implementation have been marked in circles.

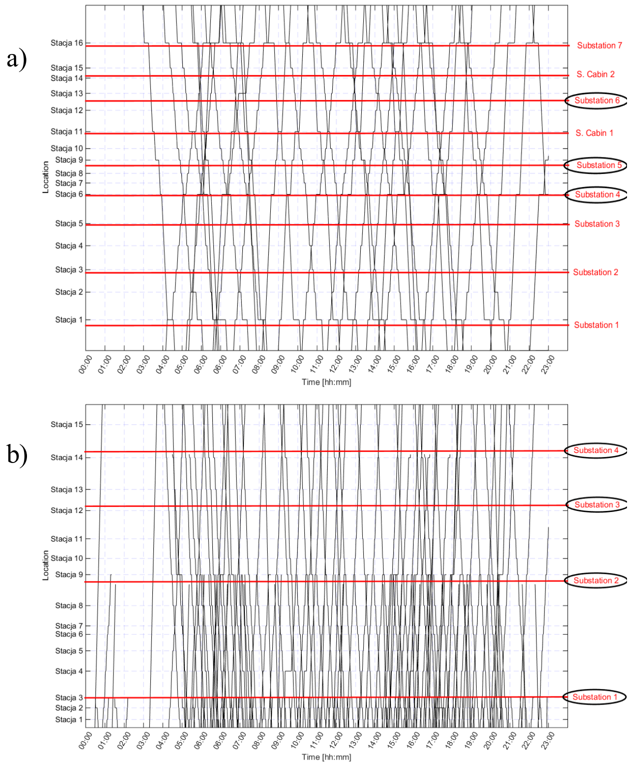

Fig. 2. The graphic representation of timetable of train operation in railway line 1 (a) and 2 (b), investigated in the study.

In railway line nr 1 (Fig. 2 a) two types of rolling stock operates - the 5 cars multiple units and locomotive passenger trains, in railway line nr 2 - 5 cars electric multiple units, locomotive passenger trains, and long distance electric multiple units.

Fig. 3 shows the values of the regenerative energy available in the substations, considered as the possible locations for ESS implementation. The results show that the available regenerative energy is higher in the railway line with the larger number of trains operating, however the difference is not as significant as the difference between number of trains operating.

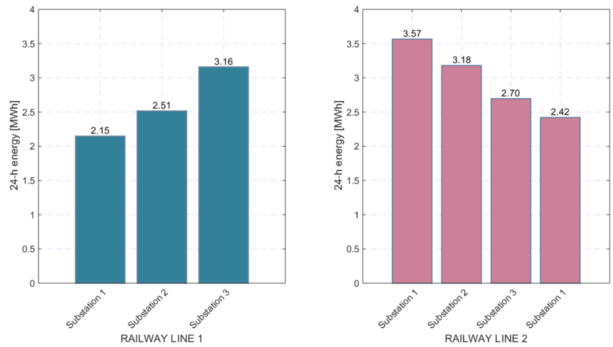

Fig. 3. The values of regenerative energy available on the different locations of the analysed railway lines.

The values of the investment efficiency parameters have been calculated for the ESS implementation, especially simple payback period time (SPBT). The basic assumptions for the calculations are presented in Table 3.

Table 3. The basic assumptions for the cost calculations.

Energy price	80,95 $/MWh
SC cell cost	60 $
DC/DC converter unit cost	130 $/kW
Constant cost C_{const}	100.000 $
LFP cell cost	21 $

The assumptions for the cost model presented in Table 3 for Energy price, SC cell cost, LFP cell cost have been taken from the energy tariff and manufacturers catalogues subsequently. The rest of the parameters - DC/DC converter unit cost and constant cost are difficult to evaluate due to a lack of appropriate information. The application of DC/DC converters in 3 kV DC with the energy storage system is prototype and the prices are not established in the market.

The value of C_{const} (3) depends on the cost of all component of equipment necessary for the ESS implementation at traction substation. The most important elements of the facilities are:

- building extension or separate container usage ventilation system adjustment and development,
- DC switchgear extension,
- protection relay and switching equipment installation,
- cable laying.

Cost of each component can vary depending on the substation location and its specific conditions.

Fig. 4 presents the values of the 24-hour energy utilized by the ESS with SC as the function of DC/DC converter power and SC module capacitance for the location of substation 1 in the railway line 2. The energy shown in Fig. 4 is the part of regenerative energy available in the point of substation 1 connection to the overhead catenary. The SC module consists of number of SC cells connected in series, creating branches. The number of parallel branches in ESS module of SC is integer, hence the possible values of SC module capacitance are strictly specified and shown in Fig. 4. In the analysis the assumed number of SC cells connected in series is 500.

Using the formulas (3),(4) and (5) and parameters from table 3, the SPBT was calculated. The SPBT values as the function of DC/DC converter power and SC module capacitance are shown in Fig. 5.

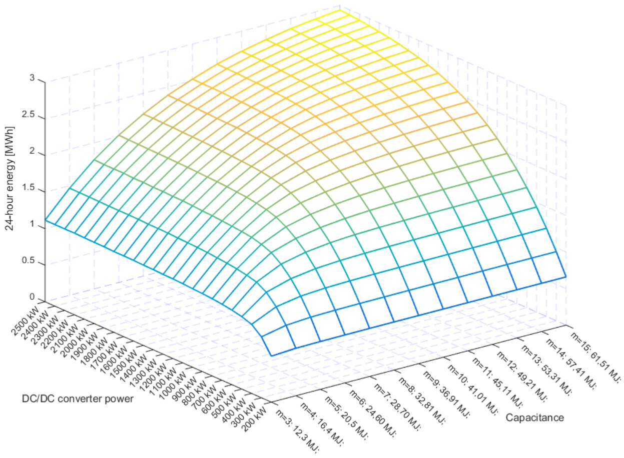

Fig. 4. Energy saving as the function of SC pack capacitance and DC/DC converter for substation 4.

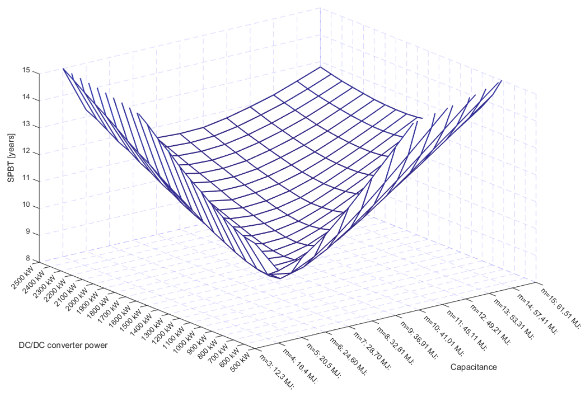

Fig. 5. The value of SPBT for the ESS with SC as the function of ESS capacity and DC/DC converter for substation 4 of railway line 2.

Among the values of the SPBT given as the function of inverter power and SC module for each capacity the minimum value of the SPBT could be found. Fig. 5 shows the minimum values of SPBT for the investigated locations of the railway lines. The results are shown as the minimum values for the specific ESS capacity. Fig. 8 shows that the min. value of SPBT depends on the location of ESS implementation. Comparing the minimum values of SPBT with the values of energy available in the specific points of possible ESS connection, it could be claimed that the SPBT values depend on the energy, however relationship between them is not linear. SPBT depends on the value of 24-hour energy and the shape of the instant regenerative power transient.

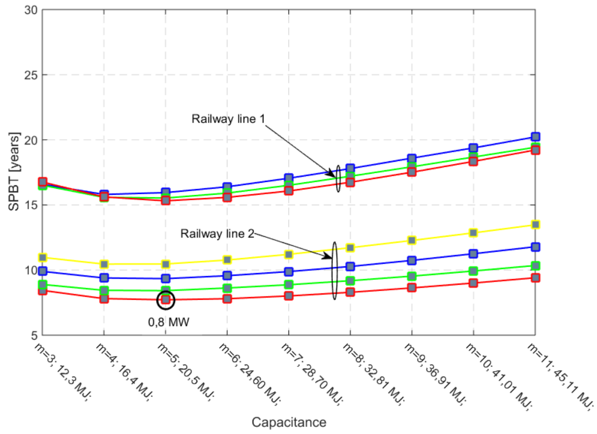

Fig. 6. The minimum values of SPBT for the railway lines and locations.

Fig 7 shows the minimum values of SPBT for the different prices of electric energy, as well as for the current energy price taken from the DNO tariff. The price level of the electric energy is not a constant value, the growth is being observed in the prices. The analysis including the forecast for the energy prices is not included in the scope of the study. The results of the parameter analysis is presented in Fig. 7, where the most reasonable variation of energy price for the perspective of 5-10 years is considered.

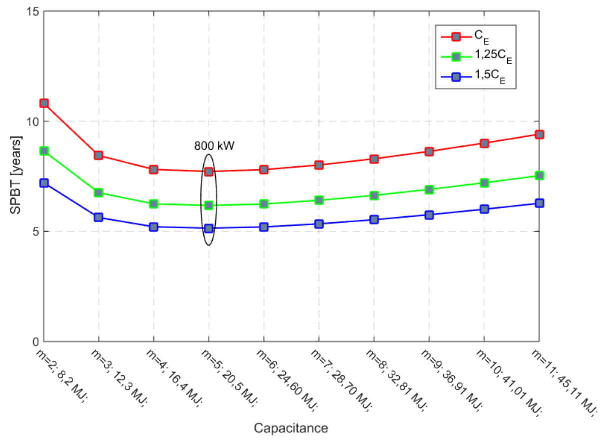

Fig. 7. The minimum values of SPBT for the different values of initial constant cost energy price C_E.

Fig. 8 presents the minimum values of SPBT for the different values of initial constant cost. The initial constant cost could vary depending on the specific substation conditions for implementation of ESS.

Fig. 8 shows that the initial constant cost influence not only the minimum value of SPBT, but as well the parameters of the ESS which are the most beneficial. In the figure values of module capacitance and DC/DC converter power are presented for the different values of initial cost, where the value of SPBT is minimal.

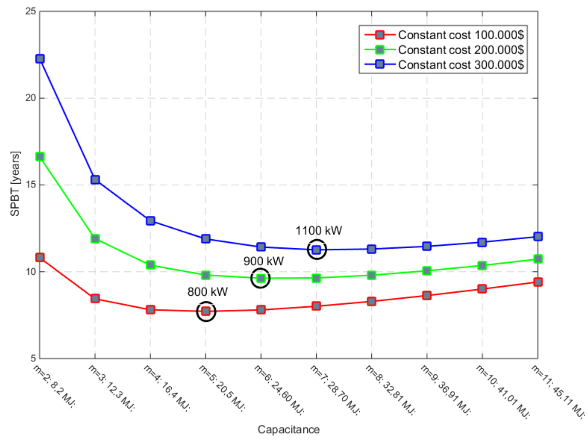

Fig. 8. The minimal values of SPBT for the different values of initial constant cost C_{const}.

4 ESS with supercapacitor and LFP battery

The scheme of the ESS with supercapacitor and LFP battery in traction substation is presented in Fig. 9. The aim of this energy storage system implementation is regenerative energy utilization (mainly by SC part) and 15-min power demand minimization in order to decrease the power demand fee.

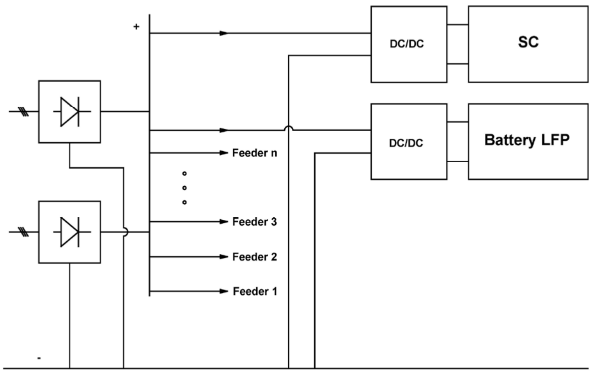

Fig. 9. The scheme of the ESS with SC and LFP battery in the 3 kV DC traction substation with 12 pulse transformer rectifier unit.

The LFP battery remains charged during the most of operation time. The energy of battery is used only during the time when the rolling average power for the last specified period of time excides the specific power. LFP battery could supply the traction load directly and/or charge the supercapacitor. In that way LFP battery compensates 15 min power demand of traction load. The frequency of LFP battery usage, hence the live cycle depends on the difference between the energy demand, which needs to be obtained.

The total cost of energy storage system implementation has been calculated according to next formula [10]:

$$C_{ESS\_SC\_LFP} = C_{const} + c\_u_{DCDC} \cdot (P_{DCDC\_C} + P_{DCDC\_LFP}) + \ldots$$
$$+ \ldots C_{ESS\_SCp} + C_{ESS\_LFPp} \quad (6)$$

where:

$$C_{ESS\_SC\_cell} = 1.4 \cdot m_C \cdot n_C \cdot c_{sc\_cell} \quad (7)$$

$$C_{ESS\_LFP\_cell} = 1.4 \cdot m_{LFP} \cdot n_{LFP} \cdot c_{LFP\_cell} \quad (8)$$

where:

P_{DCDC_LFP} – power of DC/DC converter connected to the LFP battery, C_{ESS_SCp} – price of the SC pack, C_{ESS_LFPp} – price of the LFP battery pack, m_{LFP} – number of LFP cells connected in series, n_{LFP} – number of LFP cells connected in parallel, $c_{LFP\ cell}$ – price of the single SC cell.

Fig. 10 shows the values of fee components for the active energy and the power demand for two variants of railway lines and for two variants of ESS implemented in the traction substation. The results show that connecting of LFP battery to the supercapacitor ESS leads to increasing of the energy fee component and decreasing of demand power fee component. The effect is more significant in the substation of less loaded railway line. The calculations of fees has been carried out based on the data taken from DNO tariff. The assumed energy price is 80,95 $/MWh, and demand power fee 32983,61 $/MW/year.

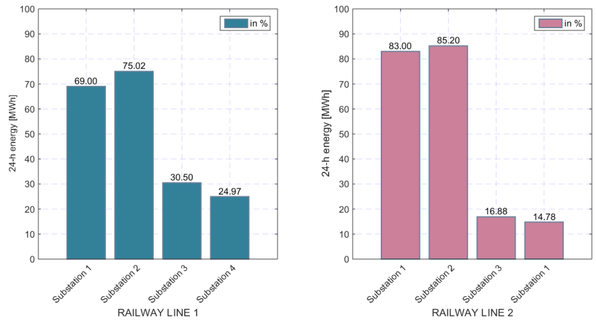

Fig. 10. The comparison of energy and power fee between two differently loaded traction substation and for the different variant of ESS (with SC and LFP battery).

Fig. 11 shows the SPBT value for two investigated railway lines, for two variants of ESS: with SC and with SC and LFP battery. The results show that for both railway lines implementation of LFP battery causes decrease of SPBT values, however the effect is more significant in less loaded railway line, where the power demand fee ratio is higher than in highly loaded railway line.

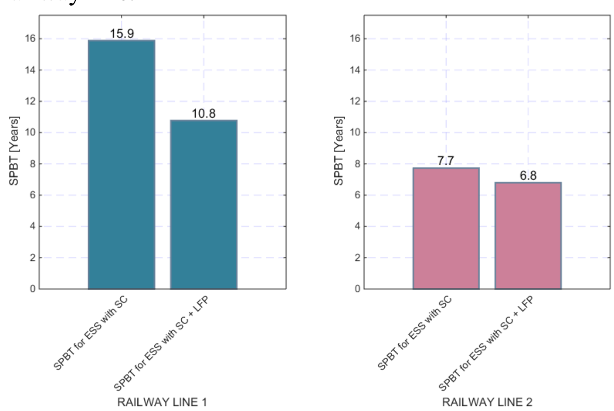

Fig. 11. The value of SPBT for two differently loaded substations and two variants of ESS.

5 Conclusions

The results presented in the paper show that the regenerative energy available in the point of potential ESS system connection depends on its location. The available energy depends on one hand on the number of trains operating and the number of stops , where trains brake with recuperation, but on the other hand also on the overhead receptivity [11-12]. The actual amount of energy which could be utilized could be calculated with use of simulation tools, modelling the electrified railway line. The results show that between two cases of railway line the bigger amount of energy is available in the traction substation of more loaded railway line with larger number of stops, however the difference is not significant.

The SPBT values for the ESS with SC are higher in the railway line with the higher trains operation density, however the relationship between the energy and minimum SPBT is not linear.

The significant influence on the investment effectiveness has the initial constant cost C_{const}. It influence not only the minimum SPBT value, but also the parameters of the ESS with supercapacitors for which the SPBT is minimal.

The conception of HESS with SC and LFP battery is presented in terms of investment effectiveness. The results show that the fee for the power demand could be significantly decreased thanks to the implementation of HESS with SC and LFP battery. Comparing with the ESS with SC, the minimal SPBT values are lower for the HESS with SC and LFP battery. For two investigated examples the implementation of HESS is more reasonable in the railway lines with less number of trains operating.

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