Stationary energy storage system in a 3 kV DC – the conception comparison

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Abstract. The paper presents the research results of a few different conception of stationary energy storage system in a 3 kV DC system. The most attention is focused on the comparison between two topologies of the ESS: energy storage system with supercapacitor and with supercapacitor and LFP battery. The variants are compared in terms of energy saving and peak power demand reduction. The implementation of ESS with SC results the decrease of active energy drawn from traction substation. Meanwhile the implementation of ESS with SC and LFP battery leads to achieving of two aims - decreasing of active energy consumption by maximization of regenerative energy utilization and reduction of 15 - min. peak power demand of traction substation.

1 Introduction

The significant part of the railway industry operation are the costs of traction energy. The traction energy costs in railway mainly consist of the active energy component and the peak power demand component costs.

Besides due to climate changes the energy efficiency has become an important problem for the last two decades. The issue takes an important part in EU regulations, which demand the energy efficiency audits to be carried out in a large companies. The environmental aspect of the energy efficiency is of utmost importance in Poland, where 97% of the electric energy is generated in coal power plants.

At the same time the growing number of the rolling stock in Polish railway is equipped with the regenerative braking, which gives the new opportunities of energy saving. In this case the use of regenerative energy depends in the main degree on the receptivity of overhead catenary system (OCS). The overhead catenary is receptive if during regenerative braking of the train if there is the load on the same supply section able to drawn and utilise the regenerative power. If there are no any trains in start up or constant speed mode the energy could be saved in the trackside energy storage system (ESS). The track-side ESS apart from energy savings could contribute to reduction of peak power demand as well as improvement of pantograph voltage conditions in specific situations [1, 2]. Depending on the purpose of the ESS implementation it could be fixed in traction substation or in other place along the track. The general scheme of the ESS connected with 12-pulse transformer rectifier unit in 3 kV DC traction substation is presented in Fig.1.

The problem of stationary energy storage system sizing and location optimization has been undertaken by the range of authors [3-6]. The literature analyse the ESS with supercapacitors and different types of batteries [7].

Not much attention of researchers is dedicated to the problem of energy management strategy in trackside ESS. In [8] the optimization method of energy management based on the genetic algorithm is presented.

The paper presents the analysis of two variants of trackside ESS: with supercapacitor and hybrid ESS with supercapacitor and LFP battery. The analysis covers the comparison among different energy management strategies in both ESS configurations. The deterministic rule based strategies are developed for the specific ESS applications. In order to estimate the effects of energy storage system operation the indication parameters are defined and proposed.

2 ESS operation indicators

As mentioned many researchers focus their attention on the conception of improvement of pantograph voltage conditions by implementation of ESS trackside. The aim could be achieved in railway lines with the big headway times of train operation, where the traction substation could be replaced by stationary ESS. However the paper is focused on the option of ESS

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implementation in the existing substation in 3 kV DC system in order to maximise the regenerative energy utilization and minimise 15-min power demand. In order to estimate the value of ESS operation effects the below parameters are proposed:

- 24 -hour efficiency of energy recovery (1)

$$\gamma_E = \frac{\int_{t=0}^{24h} P_{Dis}(t)dt}{\int_{t=0}^{24h} P_{\mathrm{Re}c}(t)dt} \cdot 100\% \tag{1}$$

where:
$P_{Dis}(t)$ - power of ESS discharge at the point of connection of ESS to the catenary,
$P_{\mathrm{Re}c}(t)$ - regenerative power possible to utilize due to the deficiency of OCS receptivity;

- maximum 15-min power drawn by traction substation.

The indicators of ESS presented above are used to compare the effects of ESS operation for the different option of ESS structure, energy management strategies, locations and size parameters. The first indicator specifies the ratio between the energy recovered by the energy storage system and the energy available to recover due to the deficiency of overhead catenary receptivity. The second indicator specifies the maximum average 15 minute power, among 15 minutes period during 24 hours. The parameter is important due to the power demand fee which refers to the 15 min. average power.

3 ESS with supercapacitor

The general scheme of ESS with supercapacitor is presented in Fig 1. The most important parameters of ESS with supercapacitor are:

- number of cells connected in module in parallel and serious,
- power of DC/DC converter,
- minimum state of charge (depth of discharge).

In the investigation the equivalent RC model of supercapacitor is used . The equivalent scheme is shown in Fig. 2. The assumed model of supercapacitor is widely approved and used [9].

The supercapacitor current could be expressed by (2)

$$i_2(t) = \frac{u_1(t)}{u_2(t)} \cdot i_1(t) \cdot \eta_{DC/DC} \tag{2}$$

where:

$$u_2(t) = u_{ESR}(t) + u_{SC}(t) \tag{3}$$

and

$$u_{SC}(t) = \frac{1}{C}\int_{t_0}^{t_1} i_2(t)dt + u_{SC}(t_0) \tag{4}$$

where:
$u_{ESR}(t)$ - voltage drop on the internal resistance of the SC pack,
$u_{SC}(t)$- state of charge of SC module,
$u_{SC}(t_0)$- initial state of charge of SC module
C - SC capacitance.

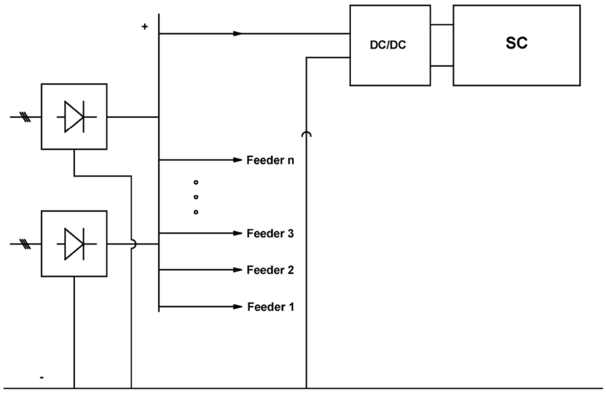

Fig. 1. The scheme of the ESS with supercapacitor connected in to 12-pulse transformer rectifier unit in 3 kV DC traction substation.

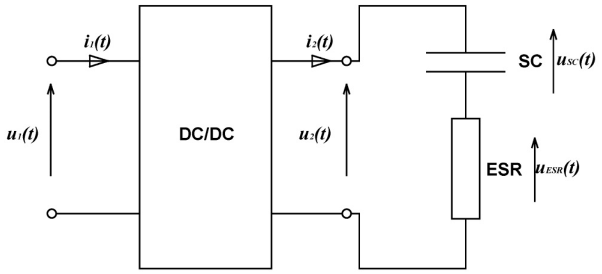

Fig. 2. The equivalent circuit of the supercapacitor ESS.

The module of the supercapacitor cells in proposed solution consists of 500 cells connected in series. The number of branches connected in parallel depends on the capacity of the converter needed in the specific location. The number of cells connected in serious and parallel branches determines the nominal voltage, the resultant capacitance as well as the resultant internal resistance of the SC module.

In Table 1 the parameters of supercapacitor cells used in the module 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

The investigation has been made based on the power demand of substation on the specified location. The power demand of substation including the regenerative power $P_{\mathrm{Re}\,c}(t)$ available is obtained from the simulation model of electric railway line. In the model the real timetable and infrastructure parameters has been implemented. The simulation has been carried out for the substation location on the railway line with the relatively large number of trains operating (115 trains/24h/direction). Three train types operates in the modelled railway line (suburban electric multiple units, long distance multiple units and locomotive passenger trains). For the suburban electric multiple units the average number of stops is 3 per 10 km. The 24-hours energy consumption on the analysed substation is 24,85 MWh, the regenerative energy available during 24-hourse period is 3,56 MWh.

For the given power demand the investigation of the influence of main ESS parameters (usage energy and power of DC/DC converter) under different energy management strategies has been carried out. For the ESS three deterministic strategies was taken into account. The algorithm of the strategies are presented in Fig 3. The purpose of the strategies is minimisation of the energy consumption and minimisation of 15-min. power demand.

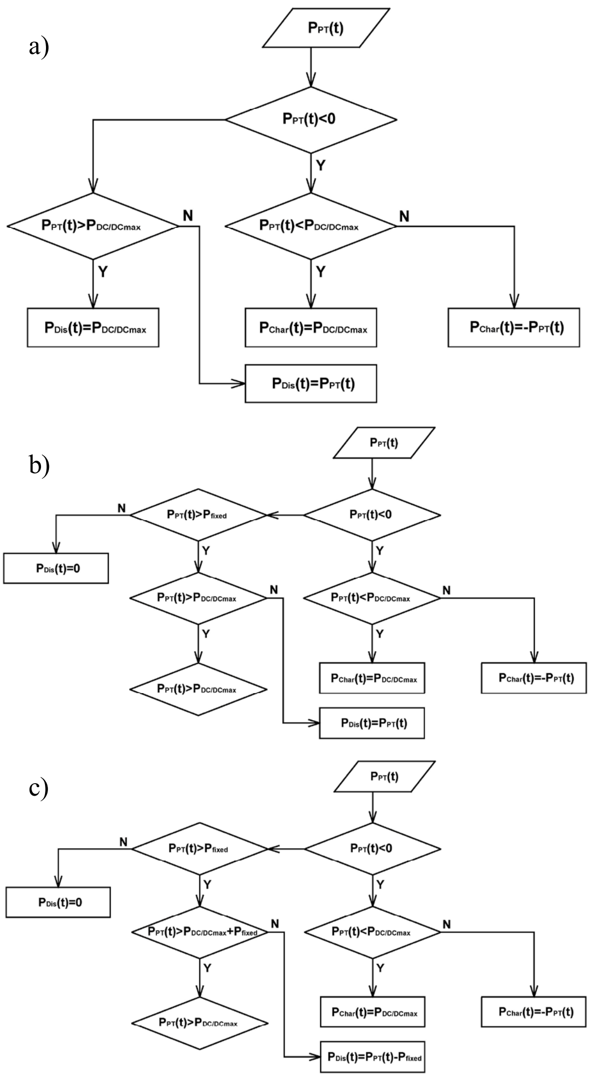

Fig. 3. The algorithms of the investigated energy management strategies for ESS with ultracapacitor.

Strategy *a* is the most effective from the point of view of energy consumption. The part of regenerative energy recovered γ_E is limited by the ESS and DC/DC converter features. Fig. 4 presents the instant power against time of ESS charge and discharge at the point of its connection to DC busbar of traction substation and regenerative power available at the same point. The figure shows, that part of the available regenerative power is beyond the power of ESS DC/DC converter (blue).

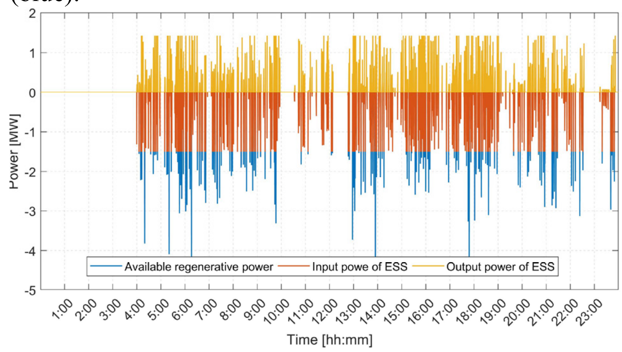

Fig. 4. The instantaneous power of charge and discharge of SC ESS at the point of connection to the DC busbar of traction substation and regenerative power available at the same point in 24-hourse time period.

The further investigation present the influence of the ESS parameters on its operation features. Fig. 5 presents the value of the 24 hour efficiency of energy recovery γ_E (1) for strategy *a* as the function of ESS capacitance and DC/DC converter.

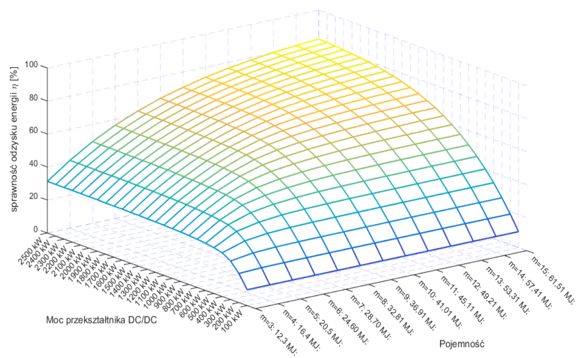

Fig. 5. The value of γ_E parameter (1) as the function of ESS capacitance and DC/DC converter.

The results show that the strategy *a* is effective from the point of view of energy efficiency. Fig. 5 presents the comparison between the histogram of 15-min power occurrence for strategy *a*. The result show that in terms of the maximum 15-min power drawn from traction substation the ESS system with SC and the investigate strategy doesn't give any improvement.

The strategy *b* and *c* are the modifications of strategy *a*. In strategies *b* and *c* the discharge takes place in case if the instant power of traction substation exceeds the assumed power P_{fixed}. The results of the proposed strategies implementation, presented in Table 2 show that the strategies *b* and *c* don't reduce the 15 min power demand.

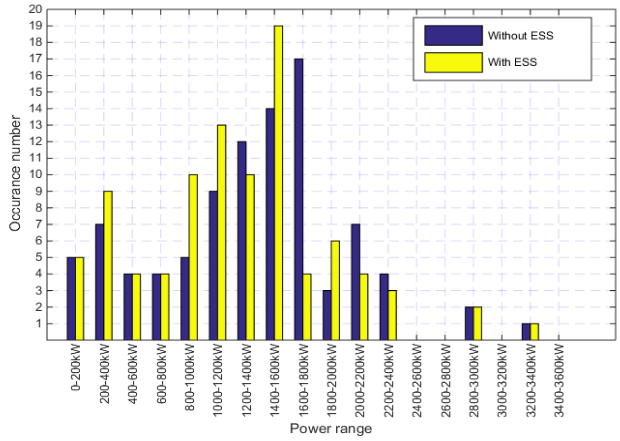

Fig. 6. The histogram of 15-min power demand of traction substation with ESS with SC and without it.

Table 2. The comparison of the ESS operation parameters for investigated strategies.

Parameter	Strategy a	Strategy b	Strategy c
γ_E	75,48 %	71,03 %	67,56 %
P_{15max}	3,335 MW	3,32 MW	3,32 MW
E_{24_PT}	22,16 MWh	22,32 MWh	22,44 MWh

In Table 2 the last row shows the 24 hour energy E_{24_PT} consumed by traction substation. The 24 hour energy consumption on the analysed substation without ESS is 24,85 MWh.

4 ESS with supercapacitor and LFP battery

The scheme of the hybrid energy storage system connected to the 12-pulse transformer rectifier unit in a 3 kV DC system is presented in Fig 7. Among the range of batteries types the LFP batteries was chosen according to its most appropriate parameters in terms of the specific demands.

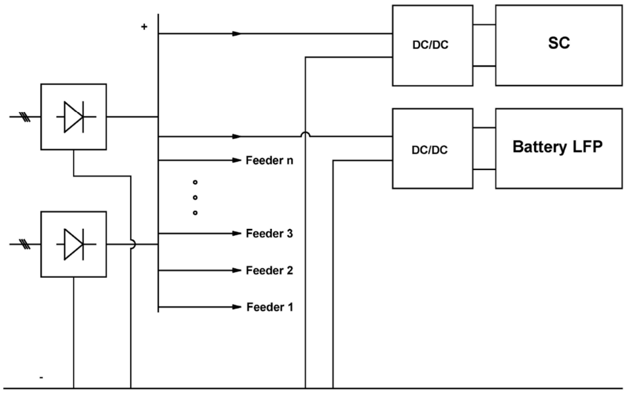

Fig. 7. The scheme of the ESS with supercapacitor and LFP battery connected in to 12-pulse transformer rectifier unit in 3 kV DC traction substation.

The operation effects of that type of energy storage have been analysed. The parameters of its operation have been compared with the corresponding parameters of SC ESS operation.

Fig. 8 presents the histogram of 15-min power demand of traction substation for variant with ESS and without it. The results show that the maximum 15-min current could be limited significantly comparing to the SC ESS. The 24 hour energy consumed by the assumed traction substation with the proposed ESS is 22,59 MWh.

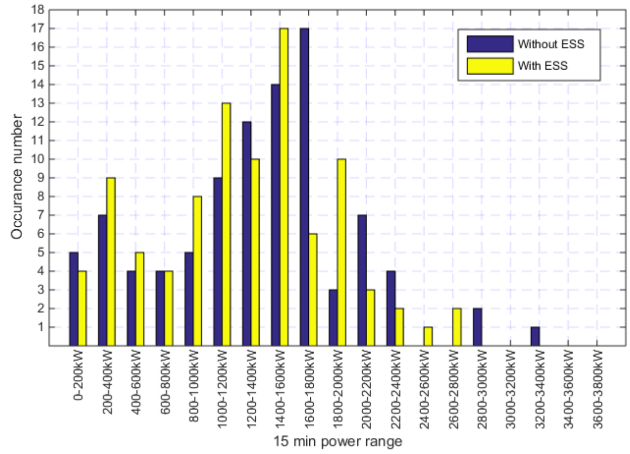

Fig. 8. The histogram of 15-min power demand of traction substation with ESS with SC and LFP battery and without it.

In Fig. 9 the rolling 15-min power drawn from the traction substation for variants with and without ESS. On the figure the operation way of the ESS is shown on the example of 15-min power. The battery discharge and compensation of the 15-min power is recognisable during the peak of the power drawn by the traction substation. After which the charge battery occurs, which lead to the increase to the rolling 15-min power demand.

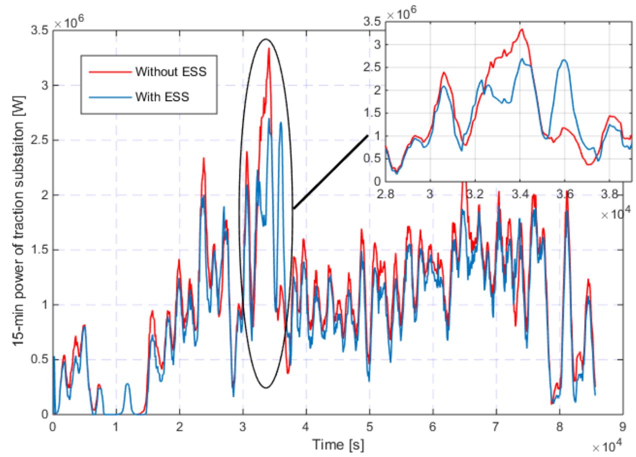

Fig. 9. Rolling 15-min power of traction substation with and without ESS with SC and LFP battery during 24 h period.

In Table 3 the values of the operation parameters are compared for the variant with and without hybrid ESS on the traction substation. The result show the significant improvement of all of the investigated parameters of the ESS operation effect. The value γ_E for this type of strategy is not to be found.

Table 3. The comparison of the ESS operation parameters between the case without ESS and the hybrid ESS.

Parameter	Without ESS	ESS with SC and LFP battery
γ_E	0	-
P_{15max}	3,34 MW	2,7 MW
E_{24_PT}	24,85 MWh	22,59 MWh

5 Conclusions

The paper presents the comparison analysis between two conceptions of ESS in the 3 kV DC electrification system. Both conceptions covers the solution of implementation of the ESS in the existing traction substation. The first is ESS with supercapacitor, the second is ESS with supercapacitor and LFP battery. The aim of the study is finding the solution of ESS which allows to achieve the following aims:

- maximise the utilization of the regenerative energy
- minimise the 15-min power demand of the traction substation

The solution with the SC is effective in terms of the first criteria. It allows to utilise the most significant part of the regenerative energy available in the point of ESS connection, as it is shown in Table 2. The part of the regenerative energy which could be utilized by using of this type of ESS if limited practically only by DC/DC and charge/discharge cycle efficiencies.

However the ESS with SC is inefficient in terms of minimising of 15-min power demand due to the insufficient energy capacitance. The energy capacitance of the ESS with SC, which is sufficient from the point of view of regenerative energy utilization is one order of magnitude smaller than needed for decreasing the 15-min power.

The proposed solution of HESS with SC and LFP battery meets both above mentioned criteria. The value of 15-min. power reduction influence the number of charge/discharge cycles and the discharge current, hence the live cycle of the LFP battery.

There is demanded to insure the high level of reliability for HESS in order to avoid 15-min demand power exceedance. In case of demand power exceedance, the penalty fees are to be paid according to the agreement between DNOs and the energy regulator office guidelines.

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