STATIONARY ESS CONTROL ACCORDING TO TRAM TRAFFIC INTENSITY

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Abstract. In this paper the authors investigate how stationary supercapacitors (SCs) based energy storage system (ESS) control parameters affect the overall energy consumption of the public electric transport system. Optimal control parameters are found for different numbers of trams by the use of the simulation model of the tram system. The results show that the SC bank optimal discharge level has almost the same value for different numbers of trams.

Keywords: supercapacitors, energy storage system, control.

Introduction

Modern trams and trolleybuses in the braking mode operate as power generators, which recuperate the braking energy back into the feeding lines. In the cases when there are no other trams or trolleybuses within the area of the same substation feeding zone, the energy is dissipated in brake resistors.

Several technical solutions exist that allow utilizing the braking energy:

1. bidirectional substations [1; 2];
2. interconnection of sections of adjacent traction substations [3];
3. onboard ESS [4; 5];
4. stationary ESS [6; 7].

Since the supercapacitors based ESS technology is relatively new and expensive, it is important to maximize its efficiency, which would make it more economically viable. Many papers can be found on onboard ESS control, that optimizes its performance [8-11], however only several papers consider stationary ESS control [12; 13]. In this paper the authors investigate how the ESS control parameters influence the energy consumption from the substation for different numbers of trams. The parameters that are tested in this paper are the voltage that ESS stabilizes during charging and the SC bank discharge level. VESS is chosen as one of the control parameters, because it affects the energy amount that goes into ESS from the substation, due to a specific voltage-current curve, which is typical to traction substations found in Riga and other Eastern Europe cities. Experimentally measured tram power diagrams are used to achieve more reliable results.

Public electric transport system

In this study supercapacitors based ESS is examined in a public electric transport system which is shown in Fig. 1. For such an organization of tram feeding infrastructure it is said that it has “radial topology”, because multiple feeding cables come out of one feeding point.

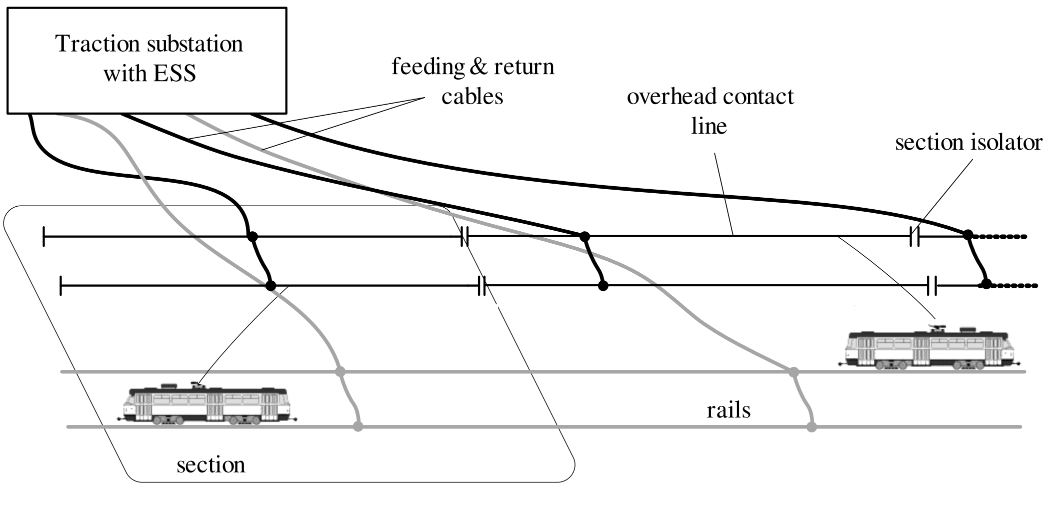

Fig. 1. **Tram system with “radial topology”**

The feeding area of one traction substation is divided in several sections, where each section has a separate feeding cable and contact lines, which are electrically isolated from contiguous section with a section isolator. The number of trams that are simultaneously within the area of one feeding substation usually varies from one to six.

Simulation model and input data

To carry out detailed simulations for such system, a model described in [14] could be used. This model is very advanced and allows simulation of contact lines with variable resistance values, which are synchronized to the tram location. If we add ESS to this model, then the simulation time step must be decreased to ensure stable operation of ESS control circuits. Decrease in the simulation time step leads to long lasting simulations, which is not suitable for the research, where the ESS control parameter influence on ESS performance is studied. Therefore, in this paper a simplified model is used.

Fig. 2 shows the block diagram of the mathematical model, which is used in this paper. The main elements in this diagram are: stationary ESS, substation, contact line resistance and tram.

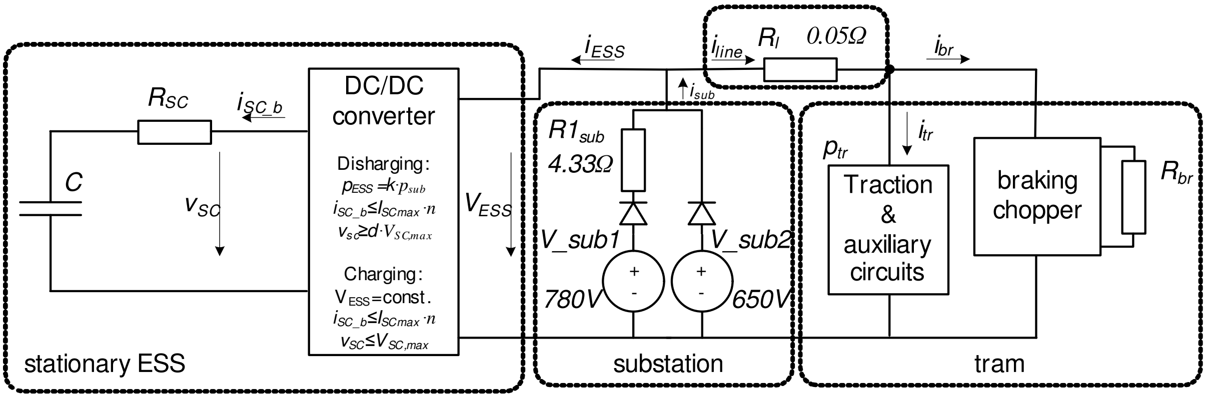

Fig. 2. **Block diagram of mathematical model for tram system with stationary ESS**

Constant line resistance (R_l) is substitute for feeding cables, overhead contact lines and rails, besides the value of R_l is 0.05 Ohm, which ensures similar energy transmission losses to those obtained by the advanced model.

Tram in this mathematical model contains two elements: traction and auxiliary circuits and braking chopper. The character of the tram is determined by its power (p_{tr}). If p_{tr} has positive values, the tram is in the running mode and is viewed as a load, whereas negative p_{tr} values determine that the tram operates as a power generator. If ESS is full, regenerated power is wasted in the braking resistor (R_{br}). Tram power profiles are based on experimentally measured power diagrams. Since this simplified system model contains only one tram, simulation of multiple trams is carried out with synthesized power profiles. The power profile for the case, when there are two trams within the area of one traction substation, is obtained as shown in Fig. 3. Energy losses in contact lines and feeding cables that occur when one tram consumes the regenerated power from the second tram are also taken into account. This is done by an assumption that energy from one tram to another is transferred via the contact line with 0.1 Ω resistance. Resistance of 0.1 Ω was determined in a similar way as it was done for R_l. Power profiles for a higher number of trams are obtained in a similar manner as shown in Fig. 3.

As can be seen in Fig. 2, the mathematical model of the traction substation includes two voltage sources (*V_sub*1, *V_sub*2), diodes and a resistor (*R_sub*1). Such combination of elements allows obtaining the approximated current-voltage curve, which is typical to traction substations with interphase transformers. In this paper an approximated current-voltage curve of the substation is used, as shown in Fig. 4, besides it is assumed that voltage never goes under 650 V, therefore, there is no resistor in series with *V_sub*2. Such current-voltage characteristic leads to partial ESS charging from the substation.

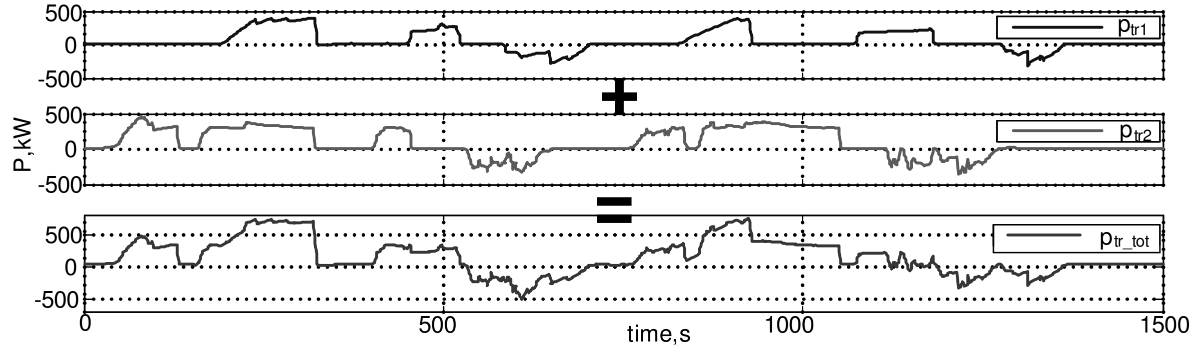

Fig. 3. **Synthesis of tram power profiles**

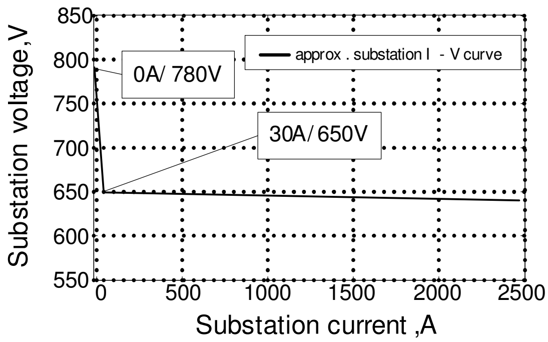

Fig. 4. **I-V curve of traction substation**

Stationary ESS contains a DC/DC converter and SC bank. Although the SC bank consists of n (n = 800) SC cells (3400F each), it is viewed as a single equivalent SC capacitance (C) and equivalent series resistance (R_{SC}). Particular number of SC cells in the SC bank is chosen based on the results in [15], where sizing of stationary ESS is carried out. In this paper the DC/DC power converter is viewed as an element that ensures the SC bank charging and discharging with certain control parameters and its losses are not considered. In the braking mode ESS has three operation modes:

- mode1– stationary ESS is in normal operation mode and stabilizes the input voltage of ESS (V_{ESS}) to some preset value;
- mode2 – the braking power of trams are too high and the SC bank charging current i_{SC_b} is limited to the value which corresponds to the maximum permissible single SC cell current value I_{SC_max}, which according to [15] is assumed to be 100 A;
- mode3 – the voltage over the SC cells reaches the maximum permissible value (V_{SC_max}) , therefore the SC bank current is limited to:

$$i_{SC\_b} = \frac{V_{SC,\max} - v_{SC}}{R_{SC}} \cdot n\,, \tag{1}$$

where R_{SC} – resistance of *single* SC cell (R_{SC} = 0.00022 Ω).

In the running mode of the tram, ESS has to discharge the energy it stores. The energy from ESS is discharged proportionally to the substation power p_{sub}. In the discharge state ESS has 2 operation modes:

- mode1 – ESS delivers the power to the trams according to equation:

$$p_{ESS} = k_P\, p_{sub}\,, \tag{2}$$

where k_P – proportionality coefficient, which is assumed to have the value 1;

- mode2 – tram power is higher than ESS can provide, therefore i_{SC_b} is limited to the maximum permissible value.

ESS exits the discharge state if p_{tr} becomes negative or the voltage in supercapacitors (v_{SC}) reaches the minimum value determined by equation:

$$v_{SC} = V_{SC\_\max} \cdot d\,, \tag{3}$$

where d – discharge level of the SC bank ($d = V_{SC\_min} \cdot V_{SC\_max}^{-1}$).

Simulation variables and simulation results

Supercapacitor discharge level is a variable which influences the ESS operation in the discharge and charge mode. Choosing low d values increases the energy capacity of ESS (E_{ESS}), but, on the other hand, it decreases the power capability of ESS (P_{ESS}):

$$E_{ESS} = \frac{V_{SC\_\max}^2 (1 - d^2) nC}{2}, \tag{4}$$

$$P_{ESS} = nV_{SC\_\max} d \cdot I_{SC\_max}\,. \tag{5}$$

If too high d values are chosen, then E_{ESS} is not sufficient to store the energy that the tram generates during braking, which means that ESS will enter the charging *mode3,* and the braking energy will be partly dissipated in brake resistors.

The second control parameter that was tested in these simulations was the input voltage of ESS (V_{ESS}). In the braking mode higher V_{ESS} values decrease the substation power that charges SCs and ensures that the power from braking tram is transferred to ESS via a higher voltage level, which means that resistive losses in R_l are decreased. On the other hand, too high V_{ESS} values lead to situations where not all braking energy is passed to ESS because the maximum power that can be transferred from the tram to ESS is limited by equivalent resistance of the contact lines and feeding cables:

$$P_{tr\_\max} = \frac{(V_{br\_\max} - V_{ESS}) V_{br\_\max}}{R_l}\,, \tag{6}$$

where V_{br_max} – braking chopper actuation voltage (780V).

In order to examine how the above mentioned ESS control parameters influence the energy consumption from the substation, numerous simulations where carried out for different numbers of trams, and the obtained results are depicted in Fig. 5.

Decrease in energy consumption from the substation is expressed in relative units:

$$E_r = \frac{E_{sub0} - E_{sub}}{E_{sub0}} \cdot 100\%, \tag{7}$$

where E_{sub} – energy consumption from substation with ESS;

E_{sub} – energy consumption from substation without ESS.

Four data points in Fig.5 for the case with 1 tram are highlighted to show how the E_r value changes when d and V_{ESS} are varied in a range between 0.7-0.9 and 700-765 respectively. As can be seen, the change in the value of V_{ESS} has no effect on E_r. This means that the difference of the energy amount that is charged in the SCs from the substation and the difference of the energy that is lost in R_l at different V_{ESS} values is negligible. V_{ESS} influences the value of E_r only if its value is increased over 765 V and the stored energy is affected by contact line resistance according to equation (6). Similar V_{ESS} effect on E_r can be observed also for a higher number of trams.

Fig. 5 also shows that E_r decreases as the number of trams increases. In the case of one tram maximum E_r is 18.2 % while in the case of 6 trams E_r is only 2.86 %. This is explained by the fact that the higher number of trams are running within the same feeding area of one substation, the higher is energy interchange between trams.

Fig. 5 gives an overall view for V_{ESS} and d effect on the relative energy consumption from the substation. More detailed d effect on E_r is shown in Fig. 6, where the energy consumption is analyzed for a fixed ESS input voltage value (V_{ESS} = 765 V).

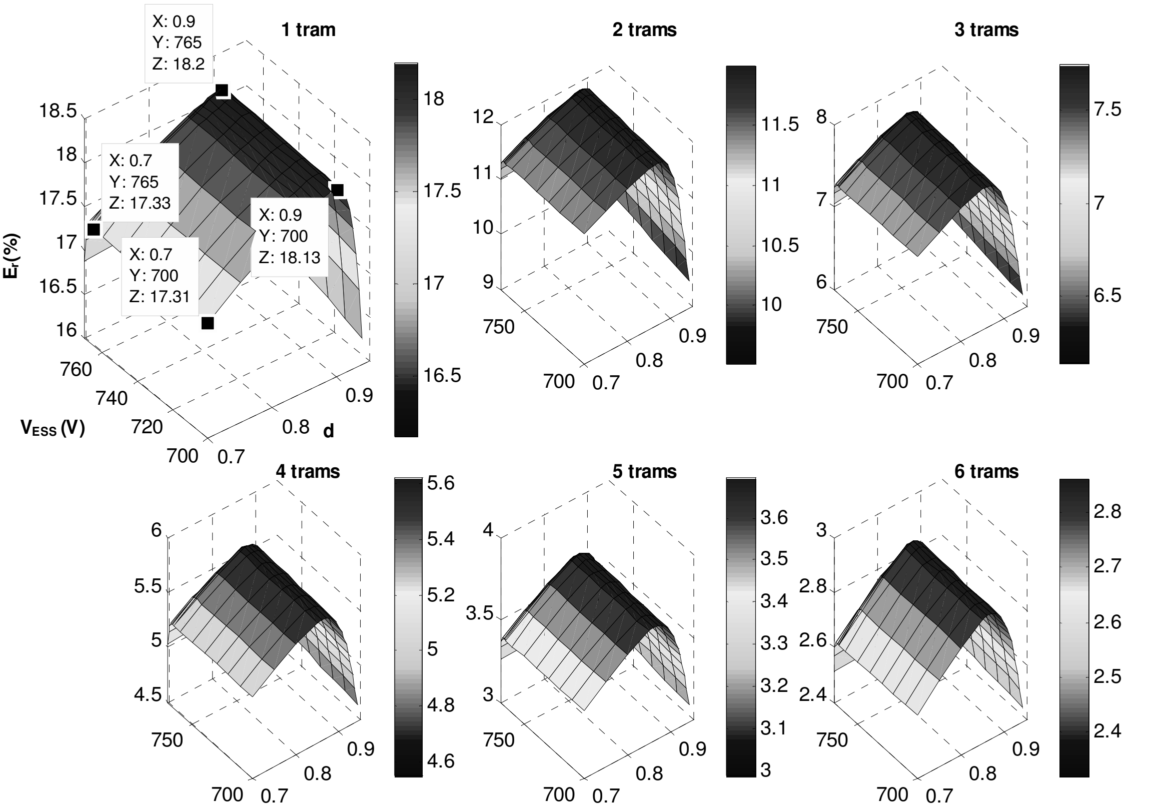

Fig. 5. **ESS control parameter influence on energy consumption from substation**

Analysis of Fig.6 leads to conclusion that the value of *d* for ESS can be hold constant for any number of trams and this value should be 0.86 or 0.87. Although this is not the optimum point for the case of 1 tram, the E_r difference is too small to be considered. The discharge level value that gives the best results does not match the value of 0.83, which was obtained in [15]. This can be explained by the additional energy losses ir R_1 and $R_{SC,}$ which were not taken into account in the above mentioned paper.

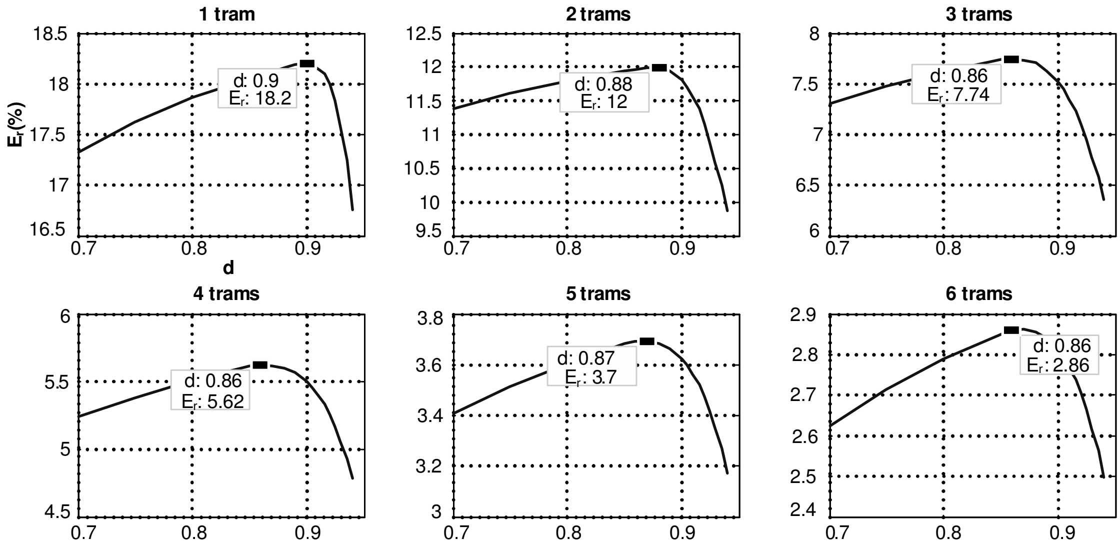

Fig. 5. **ESS discharge level effect on energy consumption from substation at V_{ESS} = 765 V**

Conclusions

1. ESS input voltage during the charging process should be held at a value which is in a range between 700-765 V. Higher input voltage values increase the energy consumption from the substation rapidly.

2. The SC bank discharge level should be approximately 0.87 for any number of trams.
3. Reduction of energy consumption from the substation varies in a range 18.2 % to 2.86 %. The higher the number of trams in the feeding area of one substation, the lower *Er*.

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