ESS SIZING CONSIDERATIONS ACCORDING TO CONTROL STARTEGY

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Abstract. In this paper the sizing problem of supercapacitive mobile energy storage system (ESS) is considered by comparing two ESS control strategies, besides experimentally measured power diagrams of the tram Tatra T3A running in Riga city are used. Both control strategies discharge supercapacitor (SC) bank with a power that is proportional to the tram power, however, the choice of a discharge proportionality coefficient and discharge depth of SC bank for these strategies differs. Sizing is carried out by numerous simulations using the Matlab model of the system that includes the tram, ESS, substation and contact lines. The research shows that one control strategy ensures higher energy consumption decrease from the substation; however, it shortens the life expectancy of the SC bank.

Keywords: mobile energy storage, supercapacitors, ESS control strategy.

Introduction

Modern public electric transport is capable of recuperating the braking energy back to the feeding lines. If there are no other vehicles nearby, all the recuperated energy is wasted in brake resistors.

To recover the energy that is dissipated in brake resistors, it is useful to equip trams and trolleybuses or traction feeding substations with energy storage systems. ESSs installed in substations are more commercially viable than on-borad ESSs, because they serve for several vehicles simultaneously. On the other hand, since on-board ESSs do not lose a part of the braking energy in overhead contact lines, they are more efficient. In addition, mobile ESSs also provide an opportunity to carry out short sections of road with no external power source.

To decrease the cost of mobile ESS implementation, it is very important to pay additional attention to correct sizing of ESS. Since supercapacitors are widely recognized as very promising technology for braking energy recovery systems, then ESS sizing in this case means the choice of optimum number of SCs and parameters of ESS control strategy.

In literature many authors use triangle shaped vehicle power profiles or standard drive cycles for ESS sizing or energy saving process simulation [1-5], however, such approach may be far from reality. Therefore, in this paper ESS sizing is based on experimentally measured tram power diagrams. The sizing problem is considered by comparing the ESS efficiency with two control strategies.

System with on-board ESS

The block diagram of the system examined in this paper is shown in Fig. 1. The system consists of a substation (*V_sub*), contact lines (*R_l*) and a tram equipped with mobile ESS. In such a simplified system *V_sub* can be viewed as a constant 660 VDC source that provides power only in one direction, substation – tram. *R_l* include electrical resistance of overhead contact lines, rails and feeding cables. Since trams are continuously in motion, the value of *R_l* is alternating; however for simplification it is assumed that the average value of *R_l* is 0.05 Ω. 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. On-board ESS contains the DC/DC power converter and SC bank. Although the SC bank consists of n_{SC} series connected SC cells (3000F), it is viewed as a single equivalent SC capacitance (C) and equivalent series resistance (R_{SC}). In the braking mode ESS has the same operation modes as described in [1]:

- mode 1 – the braking power of the tram exceeds the power capability of ESS and the SC charging current i_{SC} is limited to maximum permissible value $I_{SC,max}$;
- mode 2 – the voltage over the SC bank (v_{SC}) reaches the maximum permissible value ($V_{SC,max}$), therefore the SC current is limited to:

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

where R_{SC} – total resistance of n_{SC} series connected SC cells, where each has a resistance of 0.00029Ω;

- mode 3 – ESS is in normal operation mode and all the braking energy is stored in C, excluding the losses in the DC/DC converter and R_{SC}.

In the running mode of the tram, ESS has to discharge the energy it stores. The energy from ESS is discharged proportionally to the tram power. The choice of the proportional discharge strategy is based on the results obtained in [6]. In the discharge state ESS has 2 operation modes:

- mode 1 – ESS delivers the power to the tram according to equation:

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

where k_P- proportionality coefficient.

The rest of the energy required by the tram is taken from the substation;

- mode 2 – requested power from ESS exceeds its power capability and again i_{SC} is limited to $I_{SC,max}$.

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

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

where d – discharge depth of the SC bank ($d = V_{SC,min} \cdot V_{SC,max}^{-1}$).

The braking chopper and braking resistor (R_{br}) dissipate the energy that ESS is not capable to receive due to mode1 or mode2 in the charging state. The braking chopper in the braking mode stabilizes the tram input voltage (v_{in}) to the value of 780V.

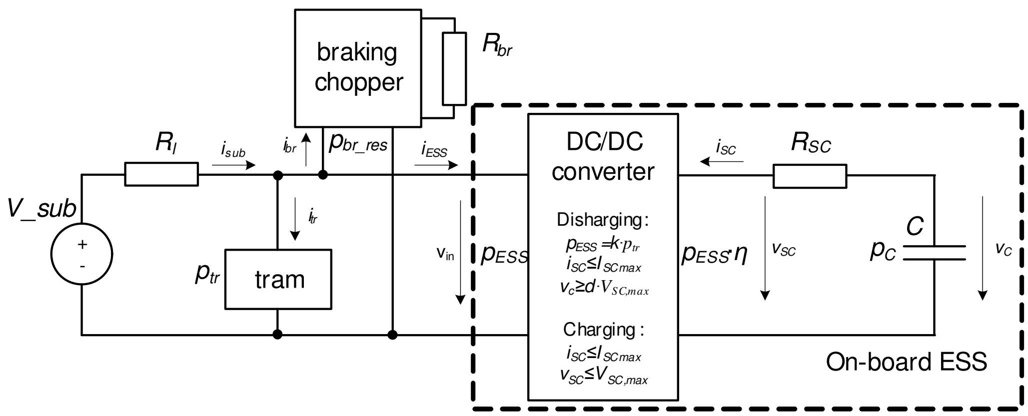

Fig. 1. **Block diagram of electric transport feeding system and tram equipped with ESS**

Input data and control strategies

The vehicle power profile can be considered as the most important factor that must be taken into account when sizing of mobile ESS is carried out. Besides, the more realistic power profile is used for ESS sizing, the more proper ESS will be for the particular case. Therefore, in this paper the experimentally measured tram Tatra T3A power diagram is used to compare variously sized ESS utilization efficiency. The diagram is obtained from a tram running in Riga city in route 11 and is about 19 hours long. A part of this diagram is shown in Fig. 2.

Another factor that has to be considered for proper ESS sizing is its control strategy. The first ESS control strategy that is analysed is a basically proportional strategy described in [6]. ESS with proportional control strategy is charged and discharged with a power proportional to the tram power. Unlike the ESS used in [6], which has only energy capacity constraint, the ESS used in this paper has additional limitation regarding its power capability. The parameters that allow affecting the power capability and energy capacity for ESS with defined number of supercapacitors are k_p and the discharge depth of the SC bank. Therefore, by choosing different k_p and d values, optimal combination that gives the highest decrease of energy consumption from the substation can be found. In the first control method the chosen combination of k_p and d remains constant for the whole power diagram.

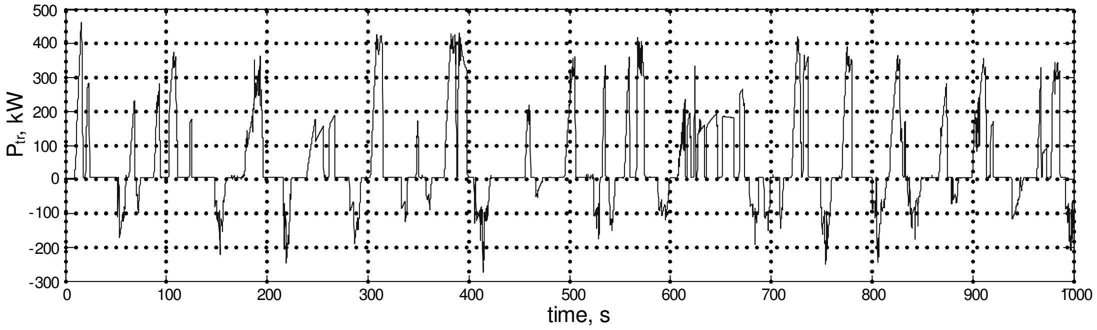

Fig. 2. **Experimentally measured tram power diagram**

To reduce the amount of energy that is wasted in brake resistors when ESS operates in mode1 or mode2 (charging state), the SC bank before every braking should be discharged to the level which allows to store exactly the amount of energy that will be recuperated. This means that maximum power capability and sufficient energy capacity of ESS for particular braking profile will be provided. To carry out sizing of ESS with such control, the tram power diagram must be divided into sections, where the length of each section is determined by the time that the tram is in motion. The section starts when the tram starts to accelerate and ends when the speed of the tram decreases to 0 km/h. An example of the tram power profile in one such section is depicted in Fig. 3.

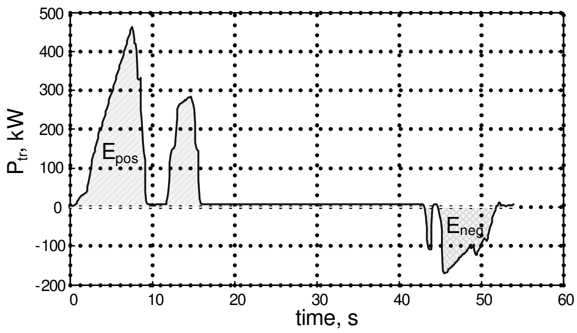

Fig. 3. **Tram power diagram between two stops**

Since the energy amount that the tram will consume (E_{pos}) and recuperate (E_{neg}) in each power section is known, it is possible to calculate the discharge depth of the SC bank and the coefficient of discharge power according to equations:

$$d = \frac{\sqrt{V_{SC,\max}^2 - \frac{2E_{neg}}{C}}}{V_{SC,\max}^2}, \tag{4}$$

$$k_P = \frac{E_{neg}}{E_{pos}}. \tag{5}$$

Despite it is impossible to implement the second control strategy for ESS in real application; it can be used for comparative evaluation of the first control strategy.

Simulation model and results

To carry out sizing of ESS, the mathematical model of the system shown in Fig. 1 was developed. The model is realized in Matlab and its charging state is based on equations (1) and:

$$p_{tr}\eta = i_{SC}^2 R_{SC} + v_C i_{SC}, \tag{6}$$

$$v_C = \frac{1}{C}\int i_{SC}dt \,, \tag{7}$$

with following limitations: $i_{SC} \leq I_{SC,\max}$, $v_{SC} \leq V_{SC,\max} = n_{SC}V_{SC,\max}$,
where η – efficiency of DC/DC converter.

In the discharging mode ESS simulation requires additional equations:

$$i_{sub}V_{sub} = i_{sub}^2 R_l + p_{tr}(1 - k_P) \,, \tag{8}$$

$$v_{in} = V_{sub} - i_{sub}R_l \,, \tag{9}$$

$$i_{ESS} = \frac{p_{tr}}{v_{in}} - i_{sub} \,, \tag{10}$$

$$i_{SC}v_C = i_{SC}^2 R_{SC} + \frac{i_{ESS}v_{in}}{\eta} \,, \tag{11}$$

where i_{sub} – substation current, A
v_{in} – voltage on tram input, V
i_{ESS} – ESS current, A.

ESS operation with Matlab model was calculated with 0.1s time step, which is equal to the sample length of the measured tram power.

Fig. 4, a exemplifies how changing of k_P reduces the energy consumption from the substation (E_{saved}) for various sized ESS with the first control strategy. The maximum SC permissible current was set to 400 A and by numerous simulations the optimal discharge depth for every k_P was found. As it can be seen, changing the k_P value from 0.3 to 1 leaves no significant effect on the saved energy. However, if the k_P value is set lower than 0.3, E_{saved} starts to drop rapidly. For example, if we take 300 SCs and change the value of k_P from 0.3 to 1, the value of E_{saved} decreases by 0.8 %, but if k_P is set to 0.2, E_{saved} will decrease by 5 %.

The simulation results depicted in Fig. 4, a also show how E_{saved} is affected by the size of the SC bank. As it can be seen, to choose ESS with n_{SC} higher than 300 is not necessary because it has a very little effort on E_{saved}. Changing n_{SC} from 300 to 600 increases E_{saved} only by 0.7 %.

Fig. 4, b shows how the discharge depth influences E_{saved} of various sized SC bank. The higher n_{SC} is chosen, the higher d value gives the best result. Choosing d under its optimum value increases the losses due to mode1 of the charging controller, while larger d values lead to losses caused by mode2.

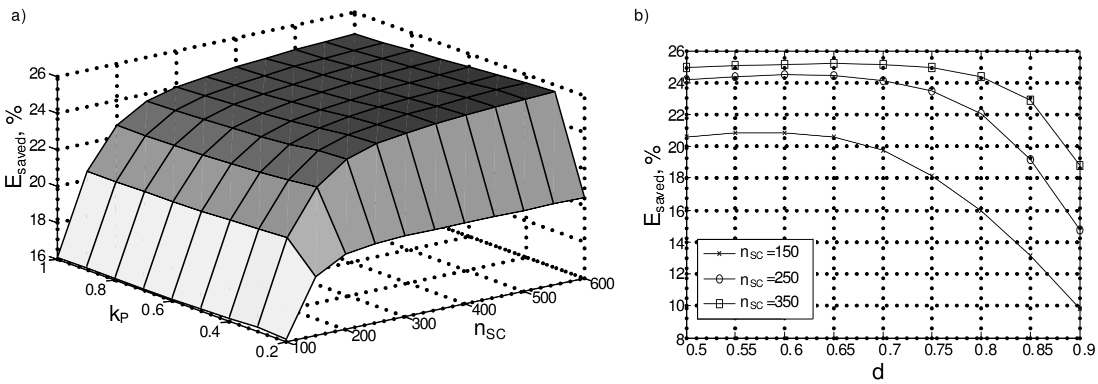

Fig. 4. **ESS control parameter effect on its efficiency**

To evaluate the efficiency of relatively simple first control strategy, it was compared with the second strategy, and the results are shown in Fig. 5. The second control method on average gives 0.5 % increase in E_{saved} for the n_{SC} range (200-300), where the choice of ESS size would be done. These results may also lead to the conclusion that strategy 2 allows to achieve the same E_{saved} value with lower number of supercapacitors. For example, in Fig. 5, b we can see that n_{SC} = 260 for the strategy 2 gives the same results as $n_{SC} = 340$ with the first strategy. If $n_{SC} = 260$ is chosen for strategy1, about 0.5 % decrease in E_{saved} can be observed.

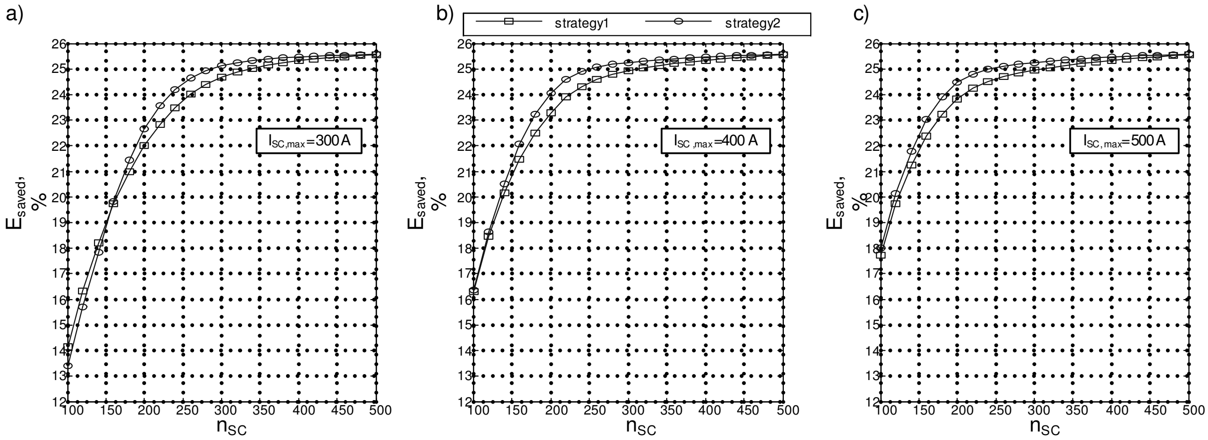

Fig. 5. **Comparison of ESS efficiency with different control strategies**

Fig. 6 shows the temperature and voltage diagrams of the SC bank (n_{SC} = 260) for both strategies. Maximum SC current here is set to 400 A, k_P and d values for strategy1 are set to 0.3 and 0.6 respectively. In Fig. 6, a the SC bank voltage of ESS with the first control strategy is shown. Averaging of this diagram over whole 19 hours gives 2 V voltage per SC cell. If the same averaging is done for the diagram in Fig. 6, b, where the SC bank voltage of ESS with the second control strategy is shown, the average voltage per SC cell has the value of 2.4 V. In Fig. 6, c rise of SC bank temperatures (Δt_{SC}) for both strategies is compared. Strategy1 on average gives 6.2 ºC rise of SC temperature while strategy2 leads to Δt_{SC} = 5.1 ºC. According to [7], the rise of average SC voltage by 0.1 V shortens its expected life by half while lowering the SC temperature by 10 ºC doubles its life expectancy. This allows concluding that ESS controlled with the second control strategy is expected to have shorter lifetime.

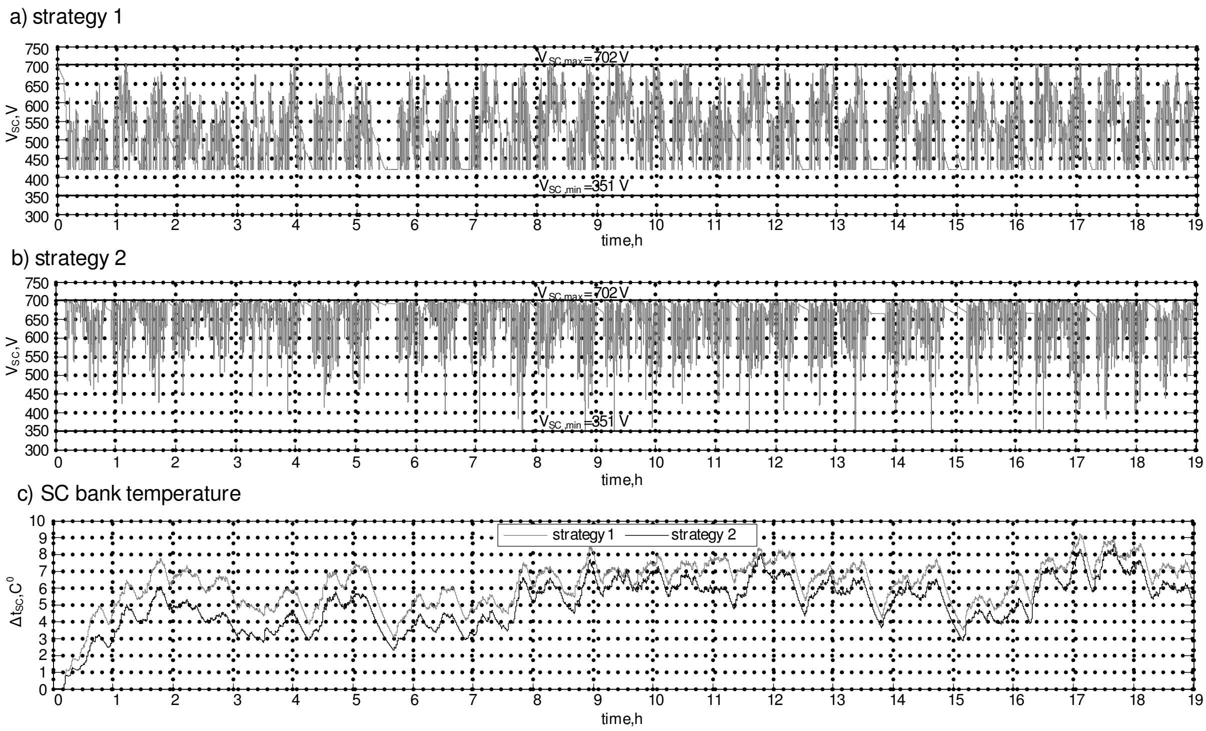

Fig. 6. **SC bank voltage and temperature diagrams**

Conclusions

1. If ESS is discharged proportionally to the tram power, the best results can be obtained if the proportionality coefficient is 0.3 while, depending on the SC bank size, the optimum discharge depth varies from 0.5 to 0.75.
2. If ESS control parameters (discharge depth and power proportionality coefficient) are calculated for each braking, the consumed energy from the substation on average decreases by 0.5 % if compared to the results obtained by ESS with constant control parameters.
3. The ESS control strategy, where control parameters are calculated for each braking, leads to faster degradation of supercapacitors.

References

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