RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Industrial Electronics and Electrical Engineering

Linards Grigans
Doctoral student in PhD study program "Computerized Control of Electrical Technologies"

RECUPERATED ELECTRIC ENERGY UTILIZATION IN URBAN ELECTRIC TRANSPORT BY APPLYING SUPERCAPACITORS

Summary of Doctoral Thesis

Scientific supervisor
Dr.sc.ing., asoc. Professor
L. LATKOVSKIS

Riga 2012

UDK 621.31(043)
Gr 530 r

Grigans L. Recuperated Electric Energy Utilization in Urban Electric Transport by Applying Supercapacitors. Summary of Doctoral Thesis.-R.:RTU, 2012. – 49 pages.

Printed in accordance with the decision No 61 of February 23, 2012 of the board of Institute of Industrial Electronics and Electrical Engineering.

EIROPAS SOCIĀLAIS FONDS

EIROPAS SAVIENĪBA

This work has been supported by the European Social Fund within the projects „Support for the implementation of doctoral studies at Riga Technical University" and "Scientific Group Supporting Latvian Activities of the European Strategic Energy Technology Plan", No.1DP/1.1.1.2.0./09/APIA/VIAA/027.

ISBN 978-9934-10-320-9

DOCTORAL THESIS SUBMITTED FOR THE DOCTORAL DEGREE OF ENGINEERING SCIENCE AT RIGA TECHNICAL UNIVERSITY

The defense of the thesis submitted for doctoral degree of engineering science will take place at an open session on July 25th, 2012 at 10:00 in Kronvalda blvd. 1, room 117, Riga Technical University, Faculty of Electrical and Power Engineering.

OFFICIAL REVIEWERS:

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Latvian University of Agriculture

APPROVAL

I confirm that I have developed this thesis submitted for the doctoral degree at Riga Technical University. This thesis has not been submitted for the doctoral degree in any other university.

Linards Grigans …………………………….(signature)

Date: ………………………

The doctoral thesis is written in Latvian and includes introduction, 5 chapters, and conclusions, bibliography list, 4 appendixes, 138 figures and illustrations, in total 132 pages. Bibliography contains 86 references.

THOPICALITY OF THE THEME

After the renewal of electric transport fleet of Riga city almost all trams and trolleybuses now are capable of recuperating braking energy back to the overhead supply line. However, due to the segmented power supply topology of the overhead supply network, and due to nonreversible rectifier feeding substations, not always the braking energy is used. If during the braking there is no other vehicle within the same overhead zone, which is consuming energy, then braking energy is still dissipated in brake rheostats.

AIM AND TASKS OF THE THESIS

The aim of this work is energy efficiency increase of urban electric transport by using of supercapacitor energy storage systems, thus reducing the amount of energy dissipated in brake rheostats. To meat the aim of the doctoral thesis following tasks were solved:

- To develop a methodology for estimation of the energy amount dissipated in brake rheostats;
- To develop a methodology for calculation of the saved energy as a function of energy storage parameters;
- To estimate the reserves of braking energy in the electric transport network of Riga;
- To study the properties of supercapacitors and application related problems;
- To develop onboard supercapacitor energy storage systems and their simulation models;
- To perform the analysis of the simulation results.

RESEARCH METHODS AND TOOLS

- Practical measurements to obtain power diagrams of substations and electric vehicles were performed in “Rigas Satiksme” Ltd. trams T3A and feeding substations.
- Data processing and development of algorithms is done using MATLAB software.
- Principles of probability theory (probability density function, convolution) are used in development of the methodologies for estimation the untapped recuperated energy amount.
- Development and modeling of onboard energy storage systems is done using PSIM and SIMULINK software tools.
- Experiments were carried out using technical facilities and laboratory equipment of the Power Electronics Laboratory at Institute of Physical Energetics.

SCIENTIFIC NOVELTY OF THE THESIS

- Methodology for estimation the untapped braking energy has been worked out.

- Methodology for estimation the recoverable energy amount as function of energy storage power capability and energy capacity has been worked out.
- Onboard energy storage with autonomous control system has been developed in PSIM software.
- Simulation models of energy storage systems with control link to vehicle control system have been developed in SIMULINK and PSIM software.
- Comparison of different control strategies for onboard energy storage systems have been carried out.
- Theoretical study of the effectiveness of the proposed capacitance balancing principle has been carried out.

PRACTICAL SIGNIFICANCE OF THE RESEARCH

- The developed power probability density methodology can be applied for the estimation of the untapped recuperated braking energy amount for electric transport networks with radial feeding topology.
- The developed stochastic modeling methodology can be applied for optimal sizing of energy storage.
- The developed models for energy storage systems with autonomous control system and models with control link to vehicle control system can be used as examples developing real devices.
- Capacitance balancing principle allows to increase the capacity of the supercapacitor battery and to save on the expense of balancing circuits.

DISSEMINATION OF RESULTS

The main results of the doctoral thesis were presented in the following scientific conferences:

1. 52nd Annual International Scientific Conference of Riga Technical University on “Power and Electrical Engineering”, Riga, Latvia, 13-15 October, 2011.
2. 14th European Conference on Power Electronics and Applications “EPE2011 ECCE Europe”, Birmingham, UK, August 30 – September 1, 2011.
3. 10th International Symposium “Topical Problems in the Field of Electrical and Power Engineering 2011”, Pärnu, Estonia, 10-15 January, 2011
4. 14th International Power Electronics and Motion Control Conference “EPE-PEMC 2010”, Ohrid, Macedonia, 6-8 September, 2010.
5. 13th European Conference on Power Electronics and Applications “EPE 09”, Barcelona, Spain, 8-10 September, 2009.
6. 4th International Conference on Intelligent Technologies in Logistics and Mechatronics Systems “ITELMS 2009”, Panevezys, Lithuania, 4-5 June, 2009.
7. 13th Power Electronics and Motion Control Conference “EPE-PEMC 2008”, Poznan, Poland, 1-3 September 2008.
8. 5th Conference of Young Scientists on Energy Issues “CYSENI 2008”, Kaunas, Lithuania, 29 May, 2008.

PUBLICATIONS

1. L. Latkovskis, L. Grigāns, “Pilsētas elektrotransportā neizmantotās rekuperētās enerģijas aprēķina metodika,” *Latvian Journal of Physics and Technical Sciences*, vol. 4, pp. 21-28, 2007.
2. L. Grigans and L. Latkovskis, “A Method for Estimation of the Untapped Regenerative Braking Energy in Urban Electric Transport,” in *5th Conference of Young Scientists on Energy Issues CYSENI 2008*, Kaunas, Lithuania, 2008, pp. 41-48.
3. L. Latkovskis and L. Grigans, “Estimation of the untapped regenerative braking energy in urban electric transportation network,” in *13th Power Electronics and Motion Control Conference EPE-PEMC 2008*, Poznan, Poland, 2008, pp. 2089-2093.
4. L. Latkovskis and L. Grigans, “Continuous PSIM Model of the Supercapacitor Energy Storage System for Simulation of Long Processes,” *Latvian Journal of Physics and Technical Sciences*, vol. 5, pp. 13-20, 2009.
5. V. Brazis, M. Gorobecs, L. Grigans, and A. Levcenkovs, “Optimization of Energy Consumption for Light Rail Electric Transport with Supercapacitor System Using Neural Network Controllers,” in *Intelligent Technologies in Logistics and Mechatronics Systems: ITELMS 2009: Proceedings of the 4th International Conference*, Lithuania, Panevezys, 2009, pp. 118-126.
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9. L. Latkovskis, V. Brazis, and L. Grigans, “Simulation of On-Board Supercapacitor Energy Storage System for Tatra T3A Type Tramcars,” in *Modelling Simulation and Optimization*, Gregorio Romero Rey and Luisa Martinez Muneta (Ed.)., InTech, 2010, pp. 307-330.
10. L. Grigans and L. Latkovskis, “Study of control strategies for energy storage system on board of urban electric vehicles,” in *14th International Power Electronics and Motion Control Conference EPE-PEMC 2010*, Macedonia, Ohrid, 2010, pp. T9-34-T9-38.
11. U. Sirmelis and L. Grigans, “Capacitance balancing for supercapacitive energy storage system,” in *10th International Symposium – Topical Problems in the Field of Electrical and Power Engineering*, Estonia, Pärnu, 2011.

12. U. Sirmelis, L. Grigans, and L. Latkovskis, “An analytic simulation model for a supercapacitor-based energy storage system,” in *EPE2011 ECCE Europe*, Birmingham, UK, 2011, p. 10.
13. V. Brazis, G. Zaleskis, L. Latkovskis, and L. Grigans, “Traction Drive Load Simulator,” in *Proceedings of the 52nd Annual International Scientific Conference of Riga Technical University on Power and Electrical Engineering*, Riga, Latvia, 2011, p. 6.
14. V. Brazis, G. Zaleskis, L. Latkovskis, L. Grigans, and U. Sirmelis, “Simulation of the Light Railway Traction Drive with Energy Storage System,” in *Proceedings of the 52nd Annual International Scientific Conference of Riga Technical University on Power and Electrical Engineering*, Riga, Latvia, 2011, p. 7.

CONTENTS OF THE DOCTORAL THESIS

INTRODUCTION

After the renewal of electric transport fleet of Riga city almost all trams and trolleybuses now are capable of recuperating braking energy back to the overhead supply line. However, due to the segmented power supply topology of the overhead supply network, and due to nonreversible rectifier feeding substations, not always the braking energy is used. If during the braking there is no other vehicle within the same overhead zone, which is consuming energy, then the recuperated braking energy is still dissipated in brake rheostats.

This energy amount wasted in brake rheostats is an energy reserve, which could be tapped, thus reducing overall energy consumption. Three basic solutions exist how to utilize this energy:

- modification of substations by replacing old rectifiers with reversible ones [4–6];
- installation of onboard energy storage devices on the electric vehicles [7–11];
- installation of stationary energy storages at substations or near the optimal connection points of the overhead power supply line [12–15].

This doctoral thesis is dedicated to the estimation of the energy amount wasted in the brake rheostats of trams and trolleybuses; and utilization of this energy by means of supercapacitor energy storage systems is studied.

1. RIGA ELECTRIC TRANSPORT AND ITS TRACTION DRIVE TYPES

In this chapter a short description of each electric transport traction drive type and an insight in current status and modernization dynamics of Riga electric transport fleet is given.

Fig. 1.1. shows the topicality of the recuperated braking energy utilization problem. If a couple of years ago this problem was relevant only for tram lines (and their feeding substations) then now, when the proportion of recuperation capable vehicles has significantly increased, this problem becomes relevant in all Riga electric transport network. There is no doubt that in couple of years the proportion of recuperation capable vehicles in Riga electric transport fleet will closely approach 100%.

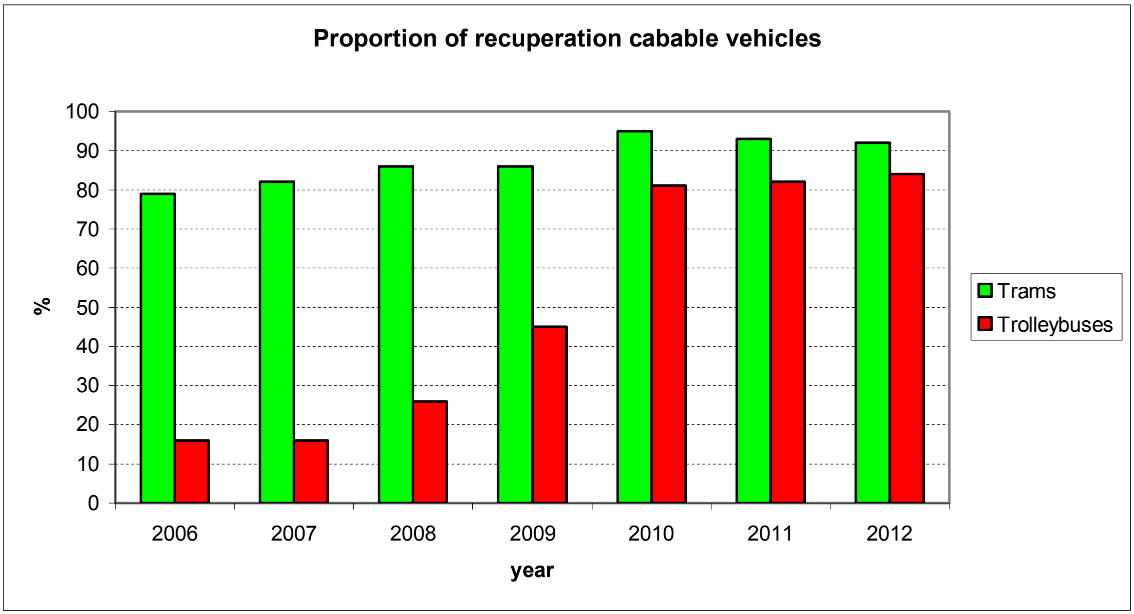

Fig. 1.1. Proportion of recuperation capable vehicles in the Riga electric transport fleet

For the further estimation of the recuperated braking energy amount it is assumed that all vehicles are recuperation capable, which corresponds to the situation of not so far future.

2. METHODOLOGY FOR ESTIMATION OF THE UNTAPPED RECUPERATIVE BRAKING ENERGY AND ITS APPLICATION

Estimation of the untapped recuperated braking energy in tram and trolleybus network is necessary for choosing the most economically justified way for reduction of energy consumption. For estimation the untapped energy reserves two different methodologies have been worked out in this work. The first one, called here “power probability density methodology” [19], [20], allows to estimate the energy amount dissipated in brake rheostats, while the second, called “stochastic modeling methodology” [21] besides the estimation of energy dissipated in brake rheostats allows also to estimate the energy amount saved by energy storage with a particular power capability and energy capacity.

In both methodologies different principles are used, however, as an input data both methodologies need vehicle power diagrams, which could be acquired in different ways [22–26]. In this work only experimentally measured power diagrams are used. Therefore in this chapter the concept “vehicle power” is defined. The literature review of different untapped recuperated braking energy estimation principles is presented in this chapter, followed by the description of both methodologies.

The untapped energy reserves are calculated for 18 of 34 feeding substations of Riga electric transport network and the results are presented at the end of this chapter [27].

Survey of the estimation principles for the untapped recuperated energy

The principles mentioned in literature for estimation the untapped braking energy could be divided into two groups. In the first group the simulation model of the electric transport system is built and used [23], [26], [28–34], while in the second group estimation is done indirectly using general transport system parameters such as average braking energy or power, power probability density functions, the overhead line receptivity, the average number of braking events during one day etc. [5], [7], [35–37].

The modeling of the electric transport system for estimation of the power flow is mentioned in numerous papers. As an input data it is necessary for the existing models to know the feeding topology of the overhead network, the parameters of the electric vehicles, the timetables, speed and track profiles, substation parameters and their location. Such simulation models are usually complicated and require large computation power. Therefore on personal computers such simulations are not run for whole day operation, but just diagrams of couple of minutes are simulated and the obtained results are recalculated for the time period of interest. Mainly the simulation models are used for demonstration the operation of the system with and without energy storage, as well as for energy storage sizing [15], [28], [29].

Several commercial software programs exist such as Sidytrac (Siemens), Elbas (Alstom), ECOtranz (Bombardier) and Fabel (Enotrac), which are designed for electric transport system simulation. The application of these programs is mentioned in paper [34], however detailed information about them is not freely available.

In the second group of recuperated energy estimation principles it is possible to partially include methods described in [7], [35], [36]. In these papers utilization of recuperated energy is investigated by introducing line receptivity concept. Use of such parameter allows significantly to simplify the overhead line model, thus increasing the simulation speed. In papers [35], [36] to obtain the line receptivity parameter simple vehicle power probability density functions are used, while in paper [7] line receptivity is freely assumed, which could be a cause for estimation error. It has to be mentioned that in the majority of papers the investigated electric transport system does not have isolated feeding zones. Therefore for modeling recuperated energy flow the line resistance has to be considered, otherwise all recuperated energy would always have a consumer.

The estimation of recuperated energy reserves for Riga electric transport network is described in [5], [37]. In these papers the method is based on average braking energy estimation, which subsequently is multiplied with the average number of daily braking events and chosen line receptivity coefficient. Such estimation method is very fast, though, because of many assumptions calculations could give significant error. Therefore, to increase the accuracy of this method, the adjustment of the assumed coefficients has to be done with a more precise method.

Acquisition of the electric vehicle power consumption diagrams

With a concept “vehicle power consumption diagram” we understand power $p_{tr}(t)$, which is consumed by vehicle or could be returned back to overhead line. It is assumed that power consumed from overhead line has „+” sign; this power is used for vehicle traction $p_{traction}(t)$ and for supply auxiliary equipment ($p_{aux}(t)$). In traction mode vehicle power is:

$$p_{tr}(t) = p_{in}(t) = p_{traction}(t) + p_{aux}(t) \tag{2.1}$$

In braking mode the generated power partly is used by auxiliary devices and the rest is sent back to overhead line with a „-” sign or is dissipated in brake rheostat ($p_{br}(t)$):

$$p_{tr}(t) = p_{traction}(t) + p_{aux}(t) = p_{in}(t) - p_{br}(t) \tag{2.2}$$

From (2.1) and (2.2) follows two methods how to experimentally measure the electric vehicle power $p_{tr}(t)$:

1. by measuring $p_{traction}(t)$ and $p_{aux}(t)$ and calculating $p_{tr}(t)$ from the expression

$$p_{tr}(t) = p_{traction}(t) + p_{aux}(t); \tag{2.3}$$

2. by measuring $p_{in}(t)$ and $p_{br}(t)$ and calculating $p_{tr}(t)$ from the expression

$$p_{tr}(t) = p_{in}(t) - p_{br}(t); \tag{2.4}$$

The choice of the method depends on the vehicle construction and the accessibility of its control signals. In this work as a main method is chosen the second one according to (2.4).

Power probability density methodology for estimation the power/energy dissipated in brake rheostats

Even though traffic in a section of overhead power supply line, that is fed from one substation, is taking place according to the electric transport timetable, and the nature of power diagrams is relatively predictable, however, at any freely chosen time moment the power consumed by the vehicle has a random nature. Like any random variable, this power can be characterized with a power probability density function (pdf), which allows determination of the probability for the power to be within a definite interval [38], [39].

We will assume that the power consumption $p_{tr}(t)$ of the vehicle for one section of overhead power supply line over a sufficiently long time interval T has been recorded. An exemplary fragment of a power-time diagram is shown in Fig. 2.1.

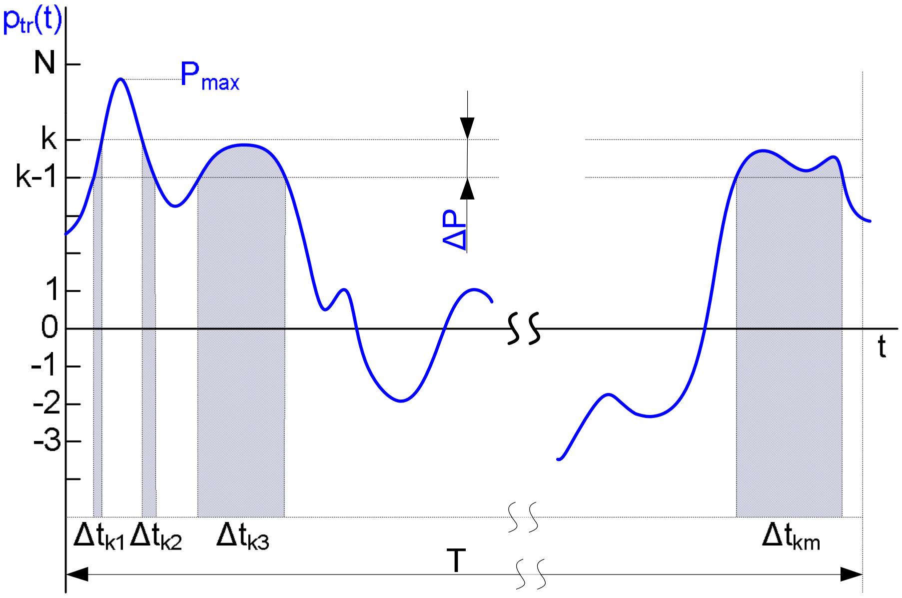

Fig. 2.1. Example of a power consumption diagram

We will choose the width of power interval equal to ΔP, dividing both the positive and the negative power ranges into N equal intervals so that $\Delta P \cdot N > \left|P_{max}; P_{min}\right|$. Assigning consecutive number k to each power interval, the probability that the power will be found within interval $\Delta P \cdot (k-1) < P_k < \Delta P \cdot k$ is:

$$p[k] = \frac{t_k}{T}, \tag{2.5}$$

where $t_k = \sum_{i=1}^{m} \Delta t_{ki}$ – total time when power $p_{tr}(t)$ lies in the k-th interval (Fig. 2.1.). Since power $p_{tr}(t)$ is practically recorded with a constant sample time ΔT, probability $p[k]$ can be calculated as:

$$p[k] = \frac{q_k}{Q}, \tag{2.6}$$

where: q_k - the number of samples when the power is in the k-th interval;

Q - the total number of samples.

The function $p[k]$, $k \in [-N;N]$ is a discrete vehicle power probability density function and its shape as an example can be as shown in Fig. 2.2.

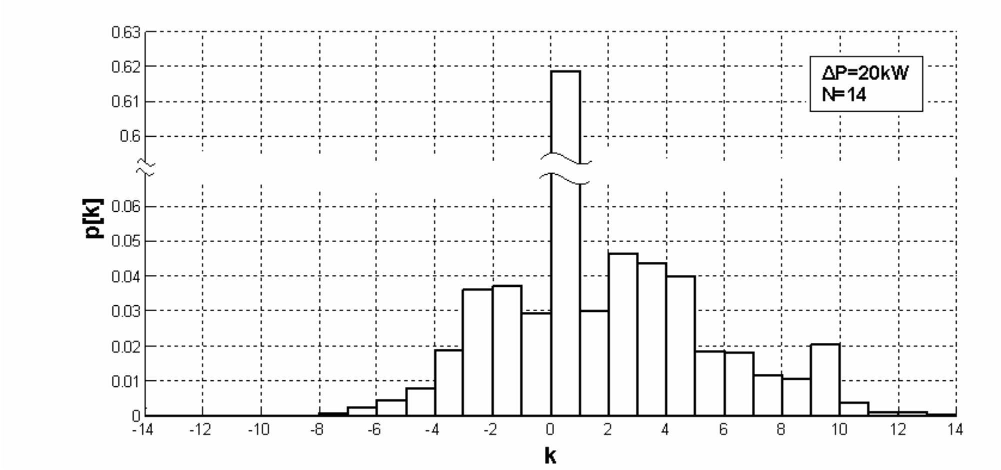

Fig. 2.2. Tram T3A power probability density function (example)

If in one section of the overhead power supply line there are simultaneously two vehicles of different electric drive types, e.g. type “A” and type “B”, then, assuming that their power consumption is random function and these are independent processes with power probability density functions p_A and p_B, respectively, the total power pdf p_{AB} can be calculated by using convolution [40], [41]. In the case of discrete power probability density functions with a number of power levels for “A” and “B” equal to N, the total power density function is expressed as

$$p_{AB}[k] = \sum_{m=\max(-N;k-N)}^{\min(N;k+N)} p_A[m] p_B[k-m], \qquad k \in [-2N;2N], \tag{2.7}$$

If there are simultaneously several vehicles of different types in one section of overhead power supply line, then the total power pdf is obtained step-by-step. For example, for l vehicles of type “A” and i vehicles of type “B” the power probability density functions p_{2A}, p_{3A},... p_{lA}, p_{2B}, p_{3B},... p_{iB} are consecutively calculated, and then the following total power pdf p_{lAiB}:

$$p_{lAiB}[k] = \sum_{m=\max(-(l+i)N;k-(l+i)N)}^{\min((l+i)N;k+(l+i)N)} p_{lA}[m] p_{iB}[k-m], \quad k \in [-(l+i)N;(l+i)N] \tag{2.8}$$

As an example power pdf for seven vehicles of the same type are shown in Fig. 2.3. It is assumed that all the vehicles have the same power pdf as shown in Fig. 2.2.

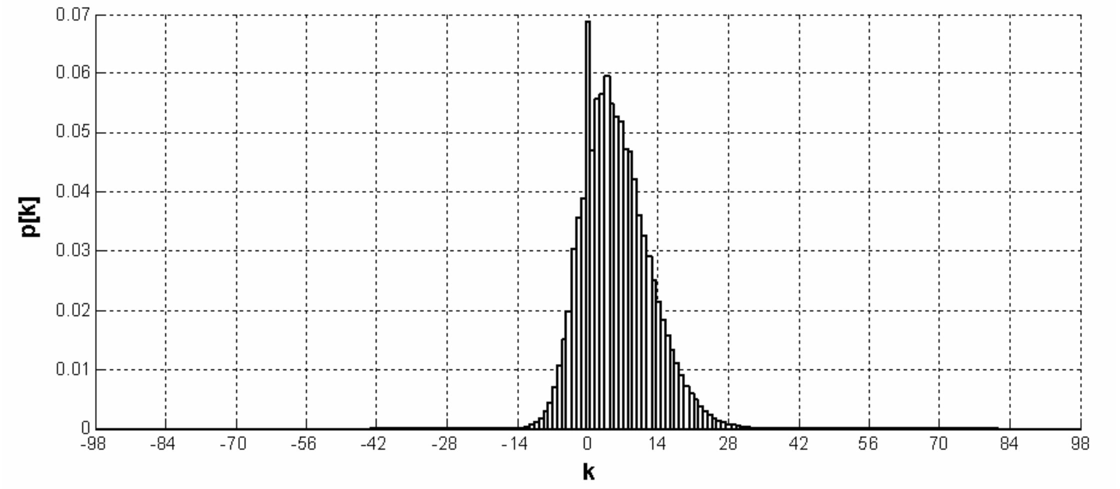

Fig. 2.3. Power pdf for 7 vehicles of the same type

The mean consumed power by a vehicle in time interval T is

$$P_{tr,av} = \frac{1}{T}\int_0^T p_{tr}(t)dt. \tag{2.9}$$

For the sampled function it is

$$P_{tr,av} \approx \frac{1}{T}\sum_{k=-N}^{N} P_k t_k = \frac{\Delta P}{T}\sum_{k=-N}^{N}(k-0.5)t_k, \tag{2.10}$$

where $P_k = \Delta P\frac{k+(k-1)}{2} = \Delta P(k-0.5)$ is the average power for level k and t_k is defined in expression (2.5). If we substitute t_k from expression (2.5) into expression (2.10) we obtain:

$$P_{tr,av} \approx \Delta P\sum_{k=-N}^{N}(k-0.5)p[k]. \tag{2.11}$$

The average probabilistic unutilized recuperative power $P_{j,av}$ for any possible number and type of vehicles can be calculated by applying expression (2.11) for the negative power region:

$$P_{j,av} = \Delta P\sum_{k=-\infty}^{0}(k-0.5)p_j[k], \tag{2.12}$$

while the total unutilized recuperative energy E is calculated as

$$E = \sum_j P_j\tau_j, \tag{2.13}$$

where τ_j – total time, when combination of vehicles of this type and number is within the feeding zone of one substation.

The methodology for estimation of the untapped recuperative energy can be summarized with the following steps:

1. Experimental registration of power consumption of the vehicles within the feeding zone of one substation.
2. Calculation of power pdf $p[k]$ for each type of vehicle.

3. Determination, according to the electric transport timetable, all j possible vehicle type and number combinations within a day and the total time, when each combination occurs within the limits of the section.
4. Calculation of $p_j[k]$ for each of the j combinations.
5. Calculation, using (2.12), of the average probabilistic power P_j for each combination.
6. Calculation of the total probabilistic unutilized recuperative energy E for the time period of interest.

Stochastic modeling methodology

As a second proposed approach for estimation the untapped recuperated braking energy is "stochastic modeling methodology". It besides the estimation of the untapped energy allows to obtain the energy amount that could be recovered by stationary energy storage with particular energy capacity and power capability. In the stochastic modeling methodology it is proposed to split the recorded power diagram into separate intervals from stop to stop (Fig. 2.4.)

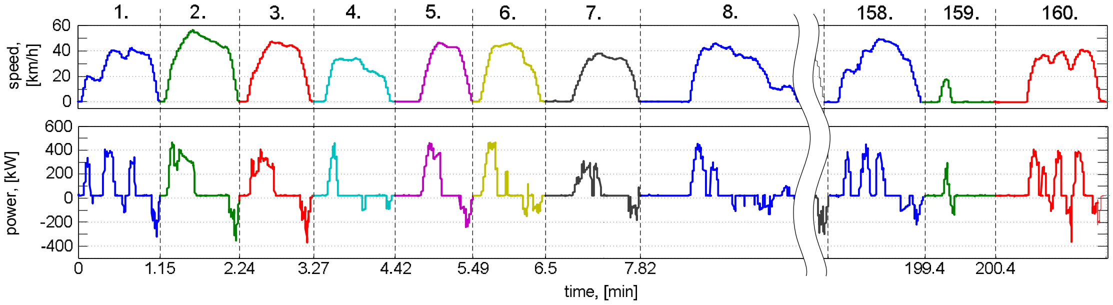

Fig. 2.4. Splitting of the tram power diagram into intervals

The power diagram for the second tram is obtained by randomly mixing the sequence of these intervals. In such a way several tram power diagrams are synthesized for calculating the total power for any number of trams. Fig. 2.5. shows an example of obtaining such a diagram for two trams.

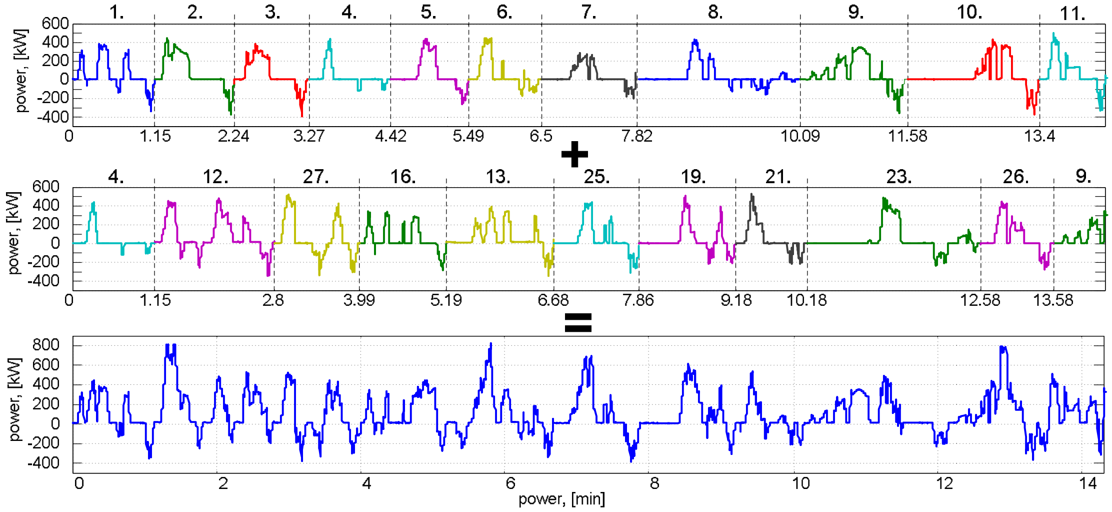

Fig. 2.5. An example of power diagram synthesis for two trams

The energy content of the ESS can be calculated as the integral of instantaneous power (see Fig. 2.6 a) – dashed green line). The negative energy represents the energy stored in ESS, therefore it cannot be positive. The energy stored in ESS and the energy returned to the overhead line is shown in Fig. 2.6. a) as the blue and red shaded areas, respectively. Fig. 2.6. b) demonstrates the same situation if the ESS has a limited power capability P_{max}, whereas Fig. 2.6. c) – if the ESS has a limited energy capacity E_{max}. In the same way calculations can be made if both limitations take place simultaneously (Fig. 2.6. d). In this case calculations consist of four steps: 1) limitation of the power diagram to the ESS power capability level P_{max}; 2) integration of the limited power diagram, considering that the energy content diagram cannot exceed zero; 3) differentiation of the energy content diagram to obtain the areas of the recoverable power (shaded blue areas); 4) determination of the average recoverable power $P_{av,recoverable}$ by averaging blue areas.

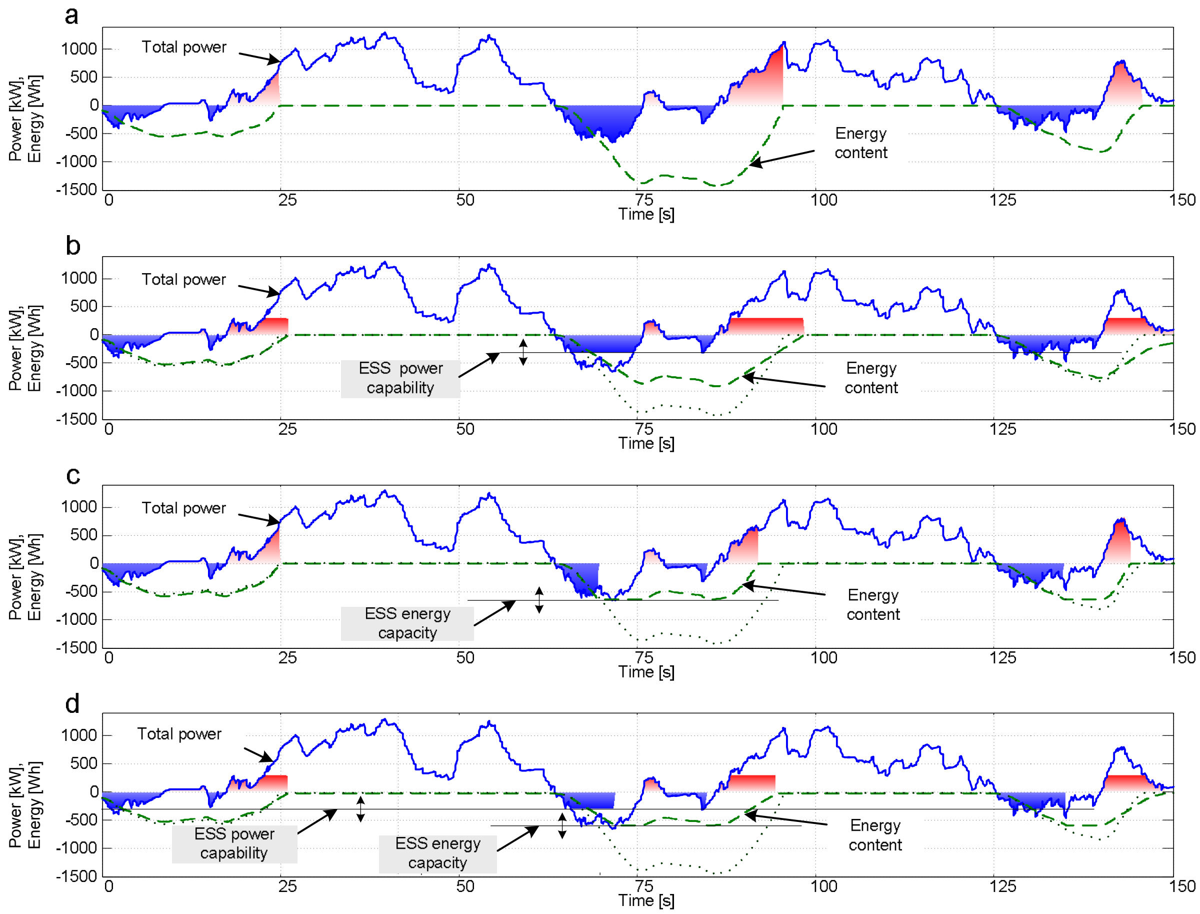

Fig. 2.6. Power and ESS energy content diagrams with: unlimited power capability and energy capacity of ESS (a); limited power capability P_{max}(b); limited energy capacity E_{max} (c); limited both – the power capability P_{max} and energy capacity E_{max} (d)

This way the average recoverable power $P_{av,recoverable}\left(P_{max};E_{max};j\right)$ for any number of trams j can be calculated. Daily recoverable energy for the particular P_{max} and E_{max} pair is calculated as:

$$E_{daily,recoverable}=\sum_{j=1}^{N}P_{av,recoverable}(P_{max};E_{max};j)\cdot T_{daily}(j), \tag{2.14}$$

where: N is the maximum number of trams simultaneously running in a substation feeding zone, $T_{daily}(j)$ is from the tram timetable calculated the duration of the situation when within a substation feeding zone there are j trams.

Untapped energy calculation results for 18 periphery substation of Riga

By applying power probability density or stochastic modeling methodology the untapped average power vs. number of trams and trolleybuses is obtained (Fig. 2.7.).

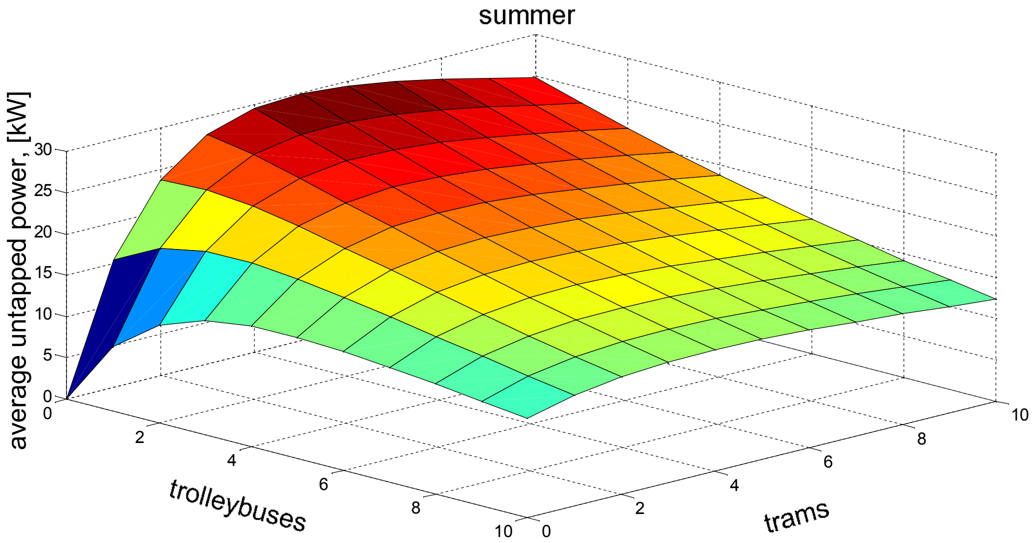

Fig. 2.7. Average untapped recuperated power vs. number of trolleybuses and trams running in the same feeding zone of one substation

From the timetables of trams and trolleybuses the number of simultaneously running vehicles is determined for each minute (Fig. 2.8.).

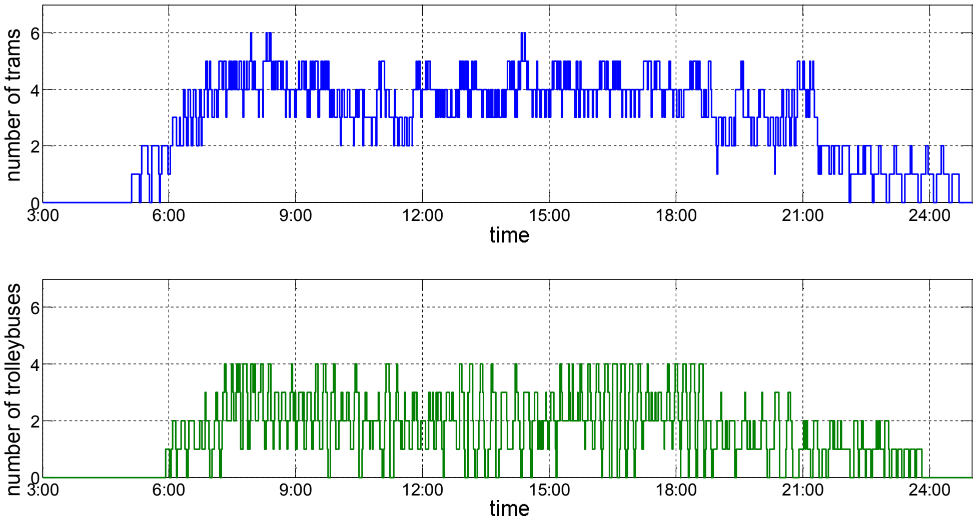

Fig. 2.8. Number of trams and trolleybuses running simultaneously within the feeding zone of the substation №10 during working days

Knowing the average untapped power for each number of trams and trolleybuses (Fig. 2.7.) it is possible to obtain the power diagram for one day (Fig. 2.9.).

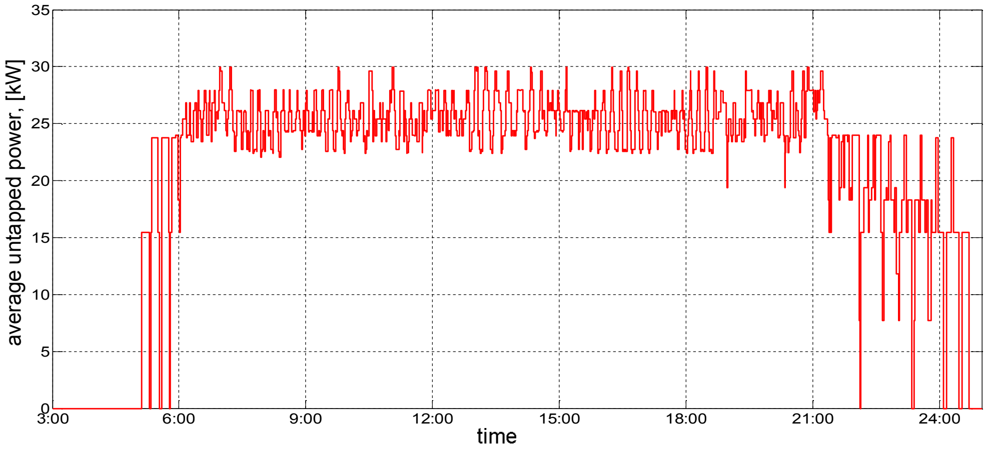

Fig. 2.9. Untapped power diagram for feeding zone of substation №10 during working days

For obtaining the energy amount wasted within the feeding zone of substation it is necessary to integrate the power diagram shown in Fig. 2.9. With these steps using the tram/trolleybus timetables for weekends as well as considering different power consumption diagrams for spring/autumn and winter seasons it is possible to obtain the untapped energy for each day in every season. By multiplying the obtained energies with corresponding number of days the annual untapped energy within the feeding zone of particular substation is obtained.

Calculations were performed for 18 of 34 feeding substations of Riga electric transport network. The results in are summarized in Table 2.1.

Table 2.1.

The results of the untapped energy calculations for the year 2010

Substation №	Tram routes	Trolleybus routes	E, kWh
10	3; 6	4; 16	118000
5	5; 9	3	113900
8	11	–	101300
16	4; 5	9; 25	98500
7	10	19; 24; 27	93300
30	2; 4	–	82200
12	5; 9	3	74800
13	3; 7; 9	15	66750
22	4	–	64200
27	2	–	62800
11	3; 7; 9	15	58800
17	3; 7; 9	15	57050
20	–	5; 11; 13; 22	54900
29	4	–	46300
33	–	16; 22	45550
32	–	16; 17; 22; 23	42850
18	–	11; 13; 16; 17; 18; 22; 23	40700
23	–	14; 18	38300
		Total:	1260200

3. SUPERCAPACITORS

In this chapter a description of supercapacitors as a one of the most suitable technology for recovering braking energy is given. Shortly the properties and equivalent circuits of supercapacitors are discussed. Voltage balancing problem between series connected capacitances is considered and a capacitance balancing principle is studied as a potential solution for eliminating the voltage disbalance.

Capacitance balancing

Capacitance balancing [72] can be used if for an application it is necessary to arrange supercapacitor cells not only in series but also in parallel to meet the required voltage and energy capacity. To be able to form modules of supercapacitors connected in parallel in a way that the capacitance distribution of these modules is significantly smaller than the capacitance distribution of individual supercapacitors, it is necessary to measure capacitance of each cell. Thus, connecting in series modules with small capacitance difference, the possibility of voltage disbalance is greatly reduced.

To study voltage disbalance an example for tram onboard ESS with 2x180 3000F SCs proposed in [61] is chosen. For theoretical analysis it is necessary to know SCs capacitance distribution. Maxwell for their BCAP3000 capacitors gives only capacitance tolerance -0%/+20%, however, distribution function is not provided. According to manufacturer research [73], SC capacitances for BCAP0008 (1800F, ±20%) are normally distributed with standard deviation σ = 1% of mean (μ = 1920F) value. Therefore, we assume that capacitances of BCAP3000 are also normally distributed (σ = 2%, μ = 3300F).

For analysis of voltage disbalance effect on ESS energy capacity, 360 capacitance values shown in Fig. 3.1. are generated using MATLAB randn function. The actual distribution mean value μ = 3304F and standard deviation σ = 2.05% is obtained.

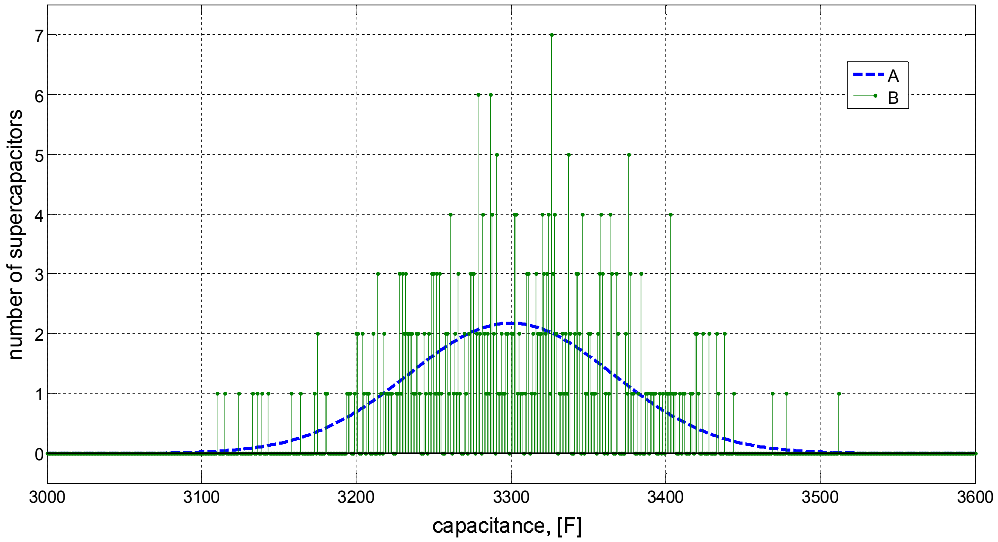

Fig. 3.1. . A – theoretical capacitance dispersion curve, B – randomly generated 360 capacitance values

Theoretical energy capacity of all these SCs can be calculated using (3.1) and is 1.03kWh.

$$W_{ESS} = \sum_{n=1}^{360} \frac{C_n \cdot V_{max}{}^2}{2} \tag{3.1}$$

where C_n – capacitance value of n-th SC;

V_{max} – maximum SC voltage (2.5V).

To match the application power and energy requirements, SC bank can be arranged either in series/parallel (Fig. 3.2., a) or parallel/series (Fig. 3.2., b).

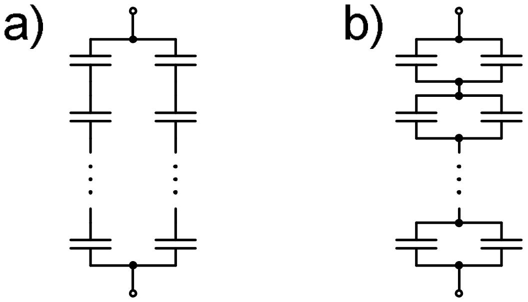

Fig. 3.2. Supercapacitor bank arrangement in series/parallel (a), parallel/series (b)

Previously generated 360 capacitances randomly arranging into series/parallel topology we obtain that the effective energy capacity of supercapacitor bank is less that theoretical maximum – 1.03kWh.

To evaluate the effect of random arrangement to the energy capacity of supercapacitor battery, the 360 supercapacitors (Fig. 3.1., b) were randomly arranged 100000 times into series/parallel and parallel/series topology. The results showed that the energy capacity of supercapacitor bank in series/parallel arrangement is from 0.905kWh to 0.925kWh, while in parallel/series – from 0.915kWh to 0.985kWh (Fig. 3.3.).

Arranging SCs in parallel/series connection reduces series connected capacitance dispersion. Theoretically standard deviation of these capacitances in comparison to standard deviation of individual cell capacitances is reduced by $\sqrt{2}$. Parallel/series connection on average gives larger effective energy capacity if compared to series/parallel connection. However, lower energy capacity may also occur. Therefore, to maximize effective energy capacity it is necessary to find optimal combination of SCs arrangement.

Simple way to achieve the best arrangement in most cases is by pairing the largest SC with the smallest, the second largest with the second smallest and so on. If SCs capacitances in SC bank were symmetrically distributed, then it would be possible to pair SCs in a way that the capacitances of series connected modules were equal and the total effective energy capacity would be 100%. Such supercapacitor pairing is called as capacitance balancing.

In Fig. 3.3. series/parallel, parallel/series and capacitance balancing method is compared. It is obvious that the capacitance balancing method gives significantly better results. If for the series/parallel the average effective energy capacity is 89% and 92% for the parallel/series connection then the capacitance balancing method gives 99%.

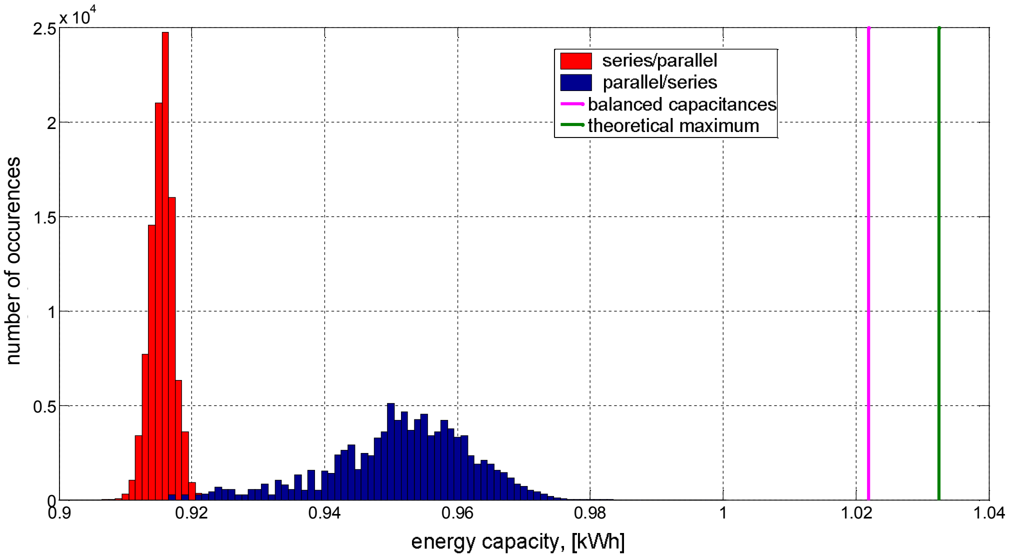

Fig. 3.3. Comparison of series/parallel, parallel/series and capacitance balancing method

It can be concluded that: 1) capacitance balancing in parallel/series connection significantly improves the effective energy capacity of SC bank; 2) the capacitance balancing method requires capacitance measurement, performed at identical conditions; 3) due to the degradation of SCs capacitance in operation life, to evaluate the efficiency of the capacitance balancing method, long-term experience with large number of SCs is needed.

4. UTILIZATION OF THE RECUPERATED ENERGY

In this chapter an overview of three basic solutions for utilization of the untapped recuperated energy is given. These three solutions are: 1) modification of the substations by replacing the old rectifiers with reversible ones; 2) installation of onboard energy storage devices on board the electric vehicles; 3) use of stationary energy storages. In this chapter an onboard energy storage system with an autonomous control system has been proposed. The proposed energy storage could be suited for installation onboard tram T3A. The power circuit, description of the control system, and analysis of simulation results is given. Energy storage systems with a control link to the vehicle control system are also considered. The developed models of energy storage are described and simulation results are given. To increase the simulation speed an average model for ESS power converter is developed and described. Several control strategies for ESS are investigated and their effect on energy consumption from the substation is studied.

By applying the stochastic modeling methodology the saved energy by stationary energy storage system installed in the substation is obtained as function of its power capability and energy capacity.

Retrofitting substations with reversible rectifiers

Feeding substations with non-reversible diode rectifiers are legacy from the beginning of the electric transport when a vehicle was only an energy consumer. Retrofitting substations with the reversible rectifiers is studied in several papers by authors from Riga Technical University [4], [5], [76]. This solution has several drawbacks:

- rectifier-inverter unit installed in substations has almost twice the price if compared to simple traction substation;
- simple reversible thyristor rectifiers have a low power factor and distorted line current;
- backup power has to be provided during the reconstruction time;
- failure of a reversible rectifier causes interruption of supply in the overhead power supply network;
- reversible rectifiers are not capable of leveling out the power consumed from the grid; on the contrary, with the opposite power flow they even increase power fluctuations in the grid;

Due to the mentioned drawbacks the conversion of non-reversible substations into reversible cannot compete with other two solutions for regenerative braking energy utilization. Even more, the trend of equipping even reversible substations with energy storage systems can be observed [6], [77].

Onboard energy storage systems

By installing energy storage system on board electric vehicle it is possible to utilize the braking energy in the most efficient way. This solution has the following advantages:

- the smallest energy losses;
- reduced overhead voltage fluctuations;

- possibility for autonomous traction for short distances without an overhead power supply.

Unfortunately this is also the most expensive solution, and due to the lack of space for energy storage on board the electric vehicles already in revenue service, the implementation is very complicated. For vehicles with the remaining lifetime less than 10 years the saved energy cannot cover the invested money. In Riga for onboard energy storage the most suitable are trolleybuses Skoda 24TR without the diesel generators.

Energy storage systems in feeding substations

This solution is an alternative to the previous. In comparison to that using reversible rectifier the stationary energy storage has following advantages:

- reduces power fluctuations in the AC grid; possibility to use the energy storage system for reducing the peak power demand charges;
- smaller energy losses;
- the stationary energy storage reduces the overhead line voltage fluctuations, thus improving the operation conditions for traction converters and auxiliary equipment.

Whereas in comparison with the onboard energy storage installation:

- considerably better operational conditions and therefore simpler and cheaper construction;
- the dissipated energy can be used for heating substations;
- the energy storage is more loaded, therefore fewer are needed and shorter payback time.

Autonomous operation energy storage for onboard tram application

For the tram Tatra T3A potential supercapacitive energy storage system following requirement was postulated. It has to store as much as possible regenerative energy, applying as simple as possible technical solutions. For this task a single-stage switching converter without intermediate DC conversion was chosen [78]. As the tram T3A lacks a speed sensor and the access to the traction and braking signal outputs are complicated, the control system of ESS has been developed independent of the tram controller.

The operation of the tram equipped with an onboard energy storage system was verified using simulation models in PSIM and MATLAB/SIMULINK environments. The simulations were carried out for different situations: single tram operation; two tram operation, where second tram is without ESS and autonomous operation without overhead power supply.

The PSIM model of the T3A tram traction drive with installed onboard ESS is shown in Fig. 4.1.

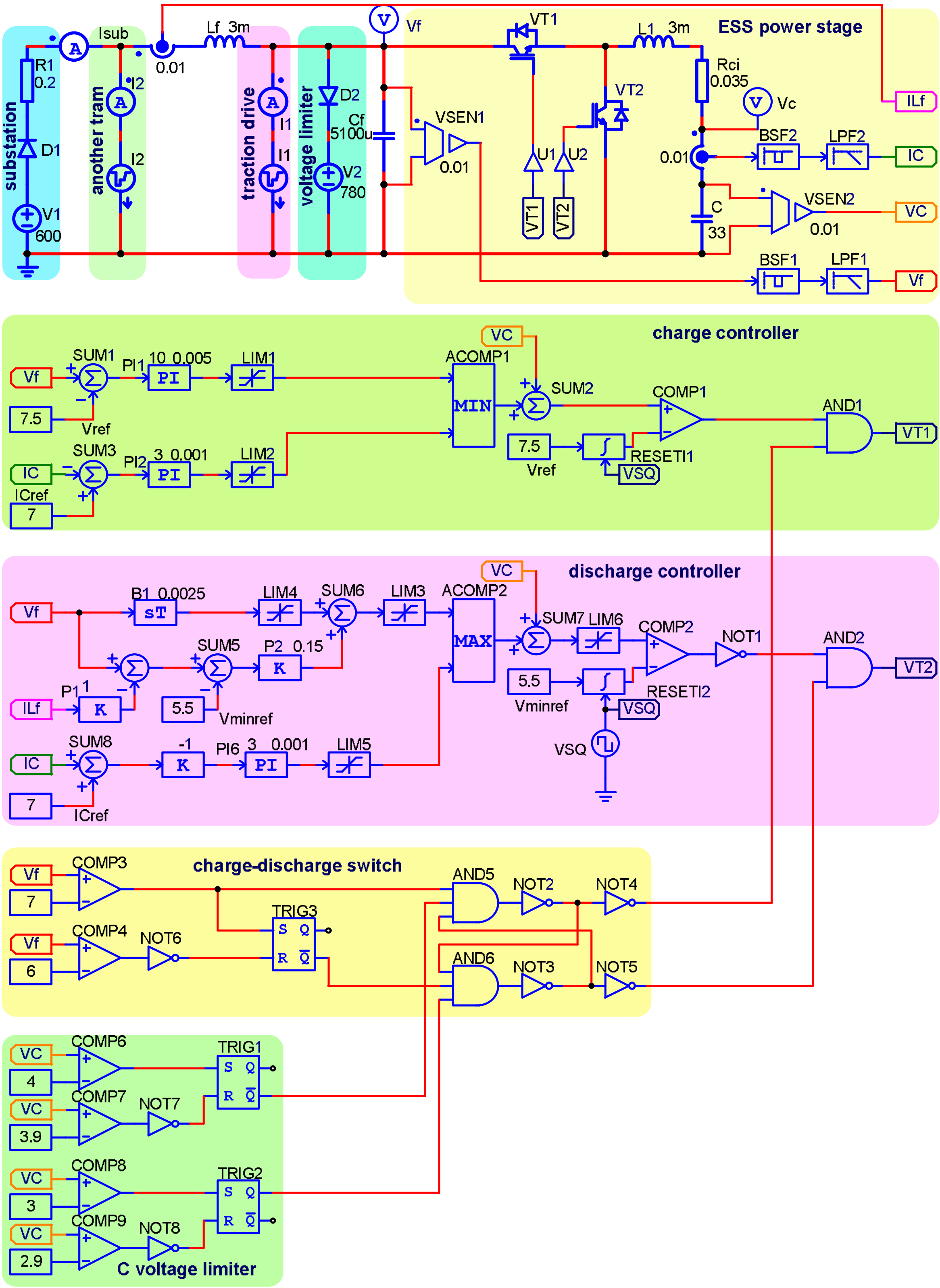

Fig. 4.1. The PSIM model of onboard ESS installed at T3A tram

ESS control system

The control system of the ESS (see Fig. 4.1.) contains a supercapacitor charge controller, a discharge controller, a charge-discharge mode switch and a supercapacitor voltage limiter.

The main task of the ESS controller is to store whole tramcar braking energy not allowing its dissipation in a braking rheostat. To store the energy, a capacitor must be discharged to voltage V_{Cmin} at the beginning of braking. As the braking energy depends on the tramcar speed, the processes of charging and discharging the supercapacitor may be controlled in compliance with the tramcar's real speed. Unfortunately, such a control principle could not be implemented in T3A tramcars due to the lack of a speed sensor.

The following two voltages and two currents are measured for the ESS control purposes: filter capacitor voltage v_f, supercapacitor voltage v_C, supercapacitor current i_C, and tram input filter current i_{Lf}. Since filter capacitor voltage v_f and supercapacitor current i_C have 1000Hz ripple with significant amplitude, the measured signals are filtered by 1000Hz band-stop filters BSF1, BSF2 and low-pass filters LPF1, LPF2 with the cut-off frequency of 800Hz.

One of the simulation tasks was to determine the optimal ESS energy capacity, which is dependant on the number supercapacitors connected in series and in parallel. However, the maximum number of in series connected supercapacitors is limited by the overhead voltage minimum, which is 450V.

Optimization of the control system parameters

The primary aim of the PSIM simulation was to find an optimal structure for the ESS control system and to optimize its feedback loop parameters in order to achieve its stable operation and transients without overshoots and oscillations.

The parameters of PI controllers were optimized by frequentative simulation of ESS at different modes of operation using the PSIM "parameter sweep" option. At a chosen gain of PI controller the time constant is varied. Then the time constant that gives the best transient is chosen, and the gain is varied. After multiple iterations the best gain-time constant combination is found. Optimal values for the control system parameters are shown in Fig. 4.1.

Simulation of the ESS operation modes

The PSIM/Simulink simulation has been performed for tramcar starting and braking processes in different situations, with and without another tram connected to the overhead line.

The results of PSIM simulation for a single tram with two values of ESS supercapacitor capacitance, 37.5F and 33.3F, are shown in Fig. 4.2.,a,b. Capacitance 33.3F absorbs more energy due to the higher maximum and minimum voltage settings, which allows more energy to be stored at the beginning of braking. In turn, this means a shorter time of current limitation when the regenerative energy is partially dissipated in a braking rheostat. The power peak shaving time (the time of supercapacitors discharge to the minimum allowed voltage) with a 33.3F supercapacitor is extended to 15.59s as compared with 13.72s for the 37.5F ESS capacitance. The total time of the current limitation at the 700A level is 4s for 37.5F ESS and 3s for 33.3F ESS. For further simulations a capacitance of 33.3F was chosen.

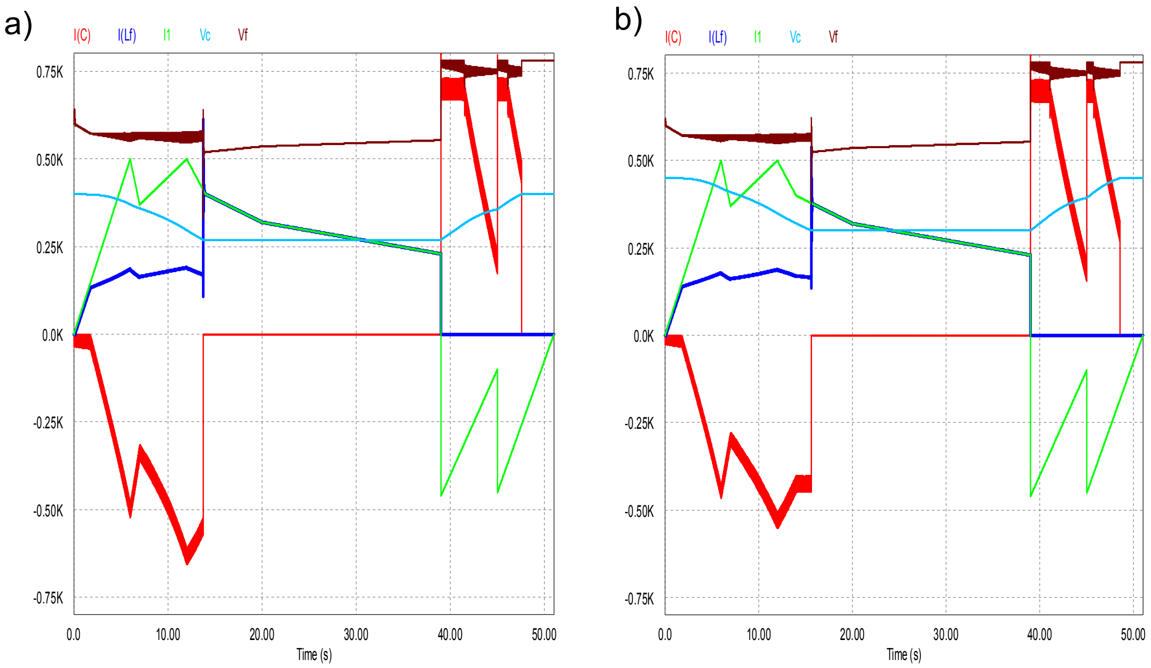

Fig. 4.2. PSIM simulation results of a single tram for two supercapacitor capacitances: a) 37.5F; b) and 33.3F (b)

Simulation results for the tram's autonomous operation are shown in Fig. 4.3. Due to the limited ESS capacity, the autonomous traction with the maximum traction current is possible within first 9s, when the supercapacitor voltage drops close to the lower limit and the filter capacitor voltage decreases to 500V. This corresponds to a vehicle's speed of about 27km/h.

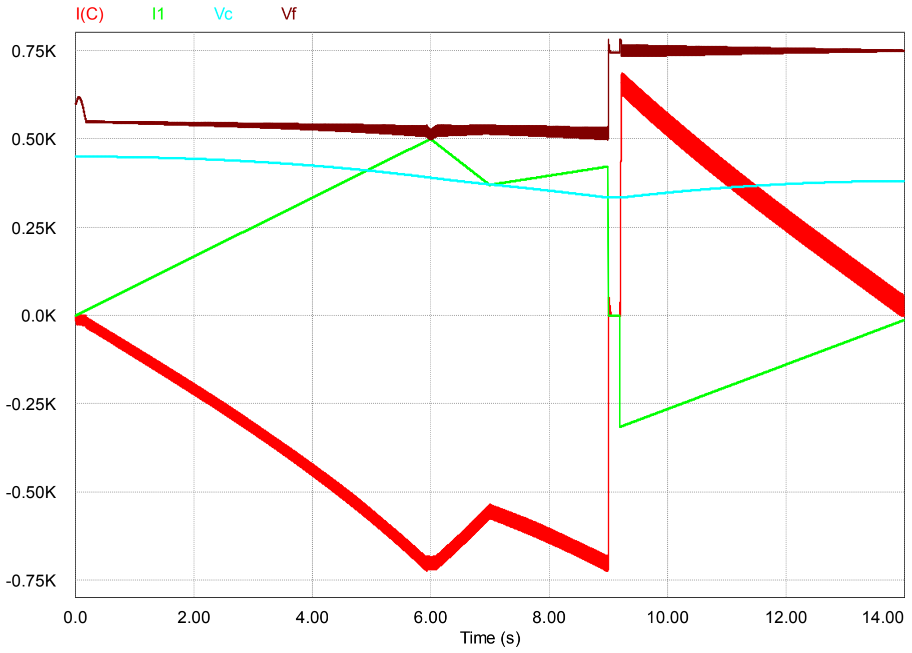

Fig. 4.3. PSIM simulation results of tram autonomous operation

Simulation has also been performed for overhead voltage failures at different stages of tram movement. Fig. 4.4. shows the case when an overhead voltage failure happened at the 42nd second, when tram was braking at full speed. From the Fig. 4.4. one can see that it did not disrupt the operation of tram equipment.

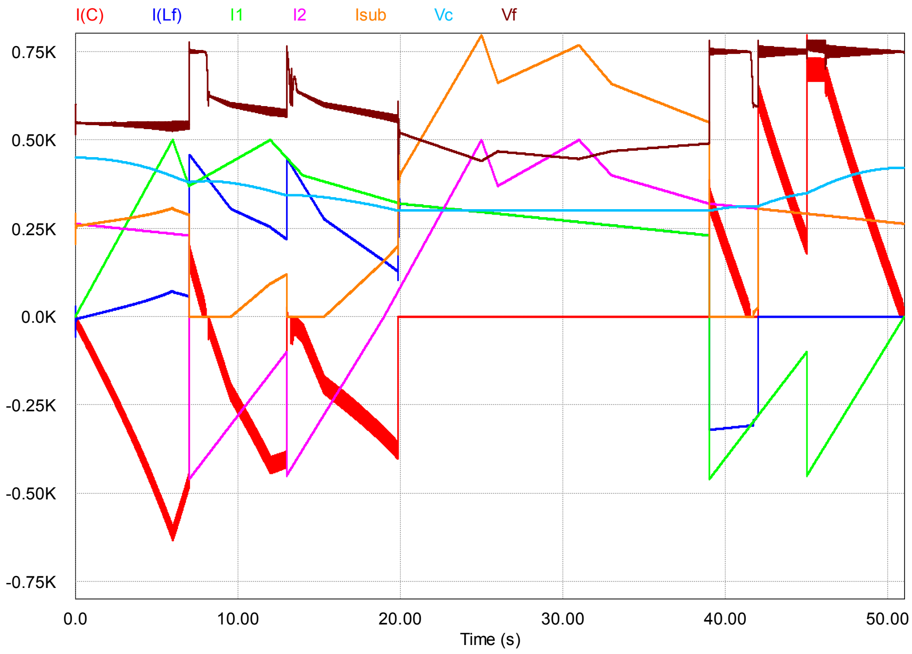

Fig. 4.4. Simulation of the overhead voltage failure at tram braking (42^{nd}s)

Based on a pulsed current PSIM model of DC PWM tram converter the stability of the ESS control system has been investigated in both synchronous and asynchronous operation modes of the tram converter and ESS current controller. In previous section, for faster and simpler simulation the tram's power scheme was replaced by a linear current source. In real situations, such a DC converter generates current pulses with 1000Hz frequency of almost constant amplitude and a variable pulse width. Filter capacitor Cf is common for both the tram's and ESS's converters. Owing to its relatively small capacitance (5100µF), current pulses cause a considerable voltage ripple of the capacitor, which can affect performance of the energy storage device. The aim of PSIM simulation was:

- to investigate how the interaction between the two converters affects performance of the voltage control loop;
- to optimize the parameters of PID control loops;
- to estimate the necessity to synchronize the action of both converters.

The situation for asynchronous operation mode with 1Hz (a) and 5Hz (b) difference in switching frequencies of both converters could be seen in Fig. 4.5. Fig. 4.5. c demonstrates autonomous traction with 1Hz difference in switching frequencies. The width of lines for voltage V_f and current I_C waveforms in Fig. 4.5. corresponds to their ripple amplitudes.

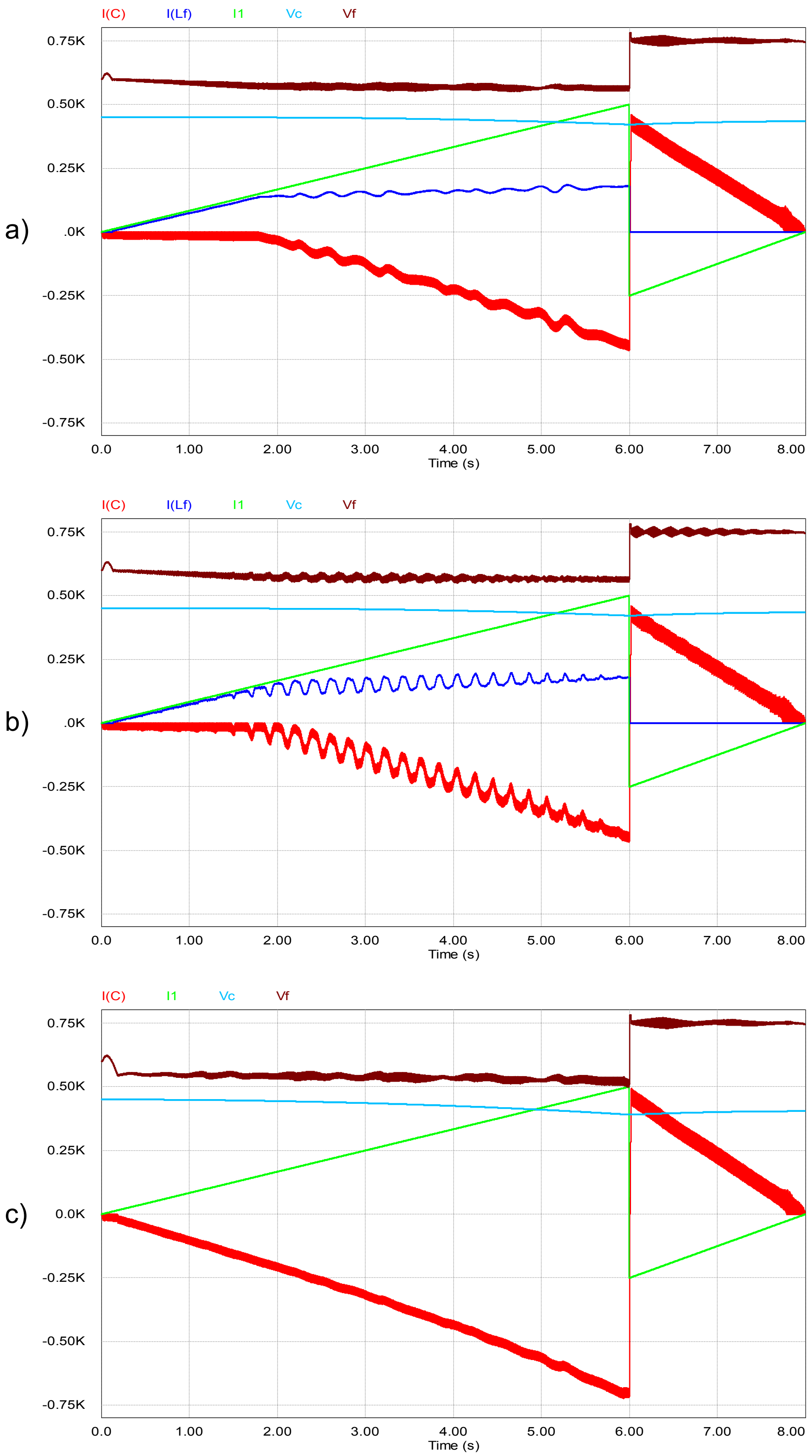

Fig. 4.5. Asynchronous operation mode with 1Hz (a) and 5Hz (b), and autonomous traction mode with 1Hz (c) switching frequency difference

From the results obtained in simulations with continuous and switching models it can be concluded that:

1. Installation of a supercapacitor in a T3A tramcar allows efficient storage of the total energy returned during the braking independently of other overhead connected consumers.
2. The complete braking energy storage is achieved if into the ESS controller the filter capacitor voltage feedback is introduced. To limit the supercapacitor current to an allowable level a current control loop is needed as well.
3. The dissimilarity between synchronous and asynchronous mode of converter operation is insignificant if the difference in switching frequencies of the tram DC chopper and ESS converter does not exceed 1Hz. Such a precision can easily be achieved if switching frequencies are quartz clocked; this means that synchronization of these frequencies is not needed.
4. The independent operation of the control systems of ESS and tram traction converters makes however the operation algorithms of ESS control system complicated, which reduces its stability margin.
5. For better performance of tram driving modes and oscillation dampening it is advisable to fit the ESS control system with a speed sensor. Synchronization of the ESS and traction converters is recommended if designing a new tramcar with onboard ESS. In this case a tram's control system and ESS controller should be linked.

Energy storage systems with link to electric vehicle control system

Designing a new tram or trolleybus it is obvious to link the ESS and electric vehicle control systems, thus making the implementation of different ESS control strategies possible. Therefore in this work models for ESS with control system linked with the vehicle control system are developed for a tram with a DC traction and for a trolleybus with an induction traction.

SIMULINK model of a feeding substation and a tram equipped with ESS is shown in Fig. 4.6.

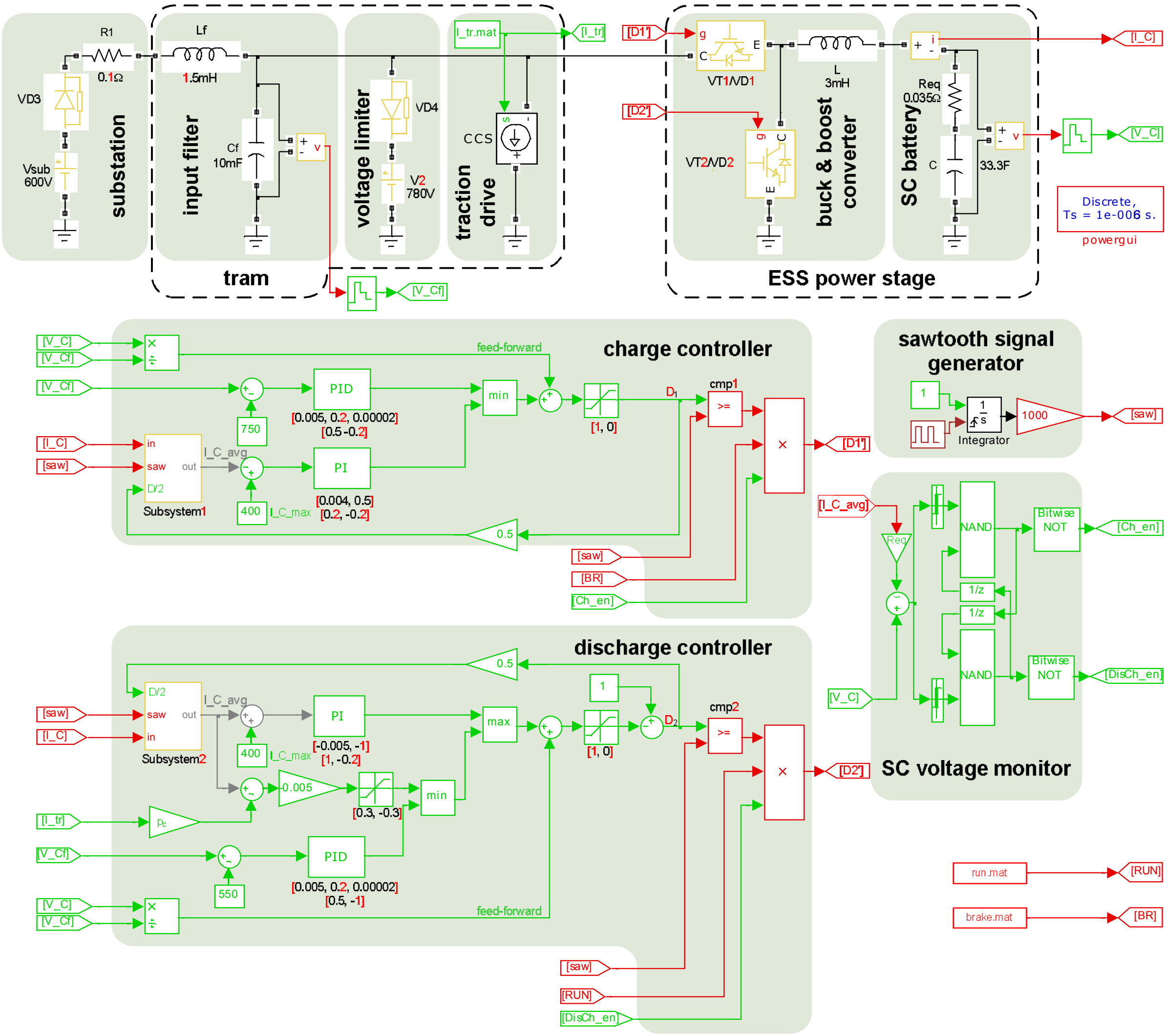

Fig. 4.6. SIMULINK model of a feeding substation and a tram equipped with ESS

A power stage of the trolleybus AC traction drive with a supercapacitor ESS is shown in Fig. 4.7. The power stage consists of two main parts – a traction AC drive connected through the overhead network to a substation and a supercapacitor ESS. Unlike the fully independent control system of a tram ESS, the ESS control system receives information from trolleybus control system about operation mode, thus improving ESS operation.

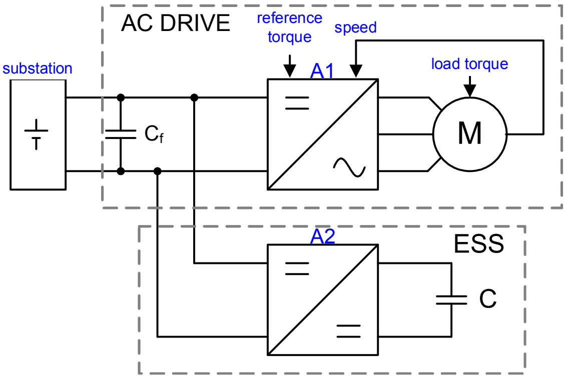

Fig. 4.7. The power stage of trolleybus AC traction drive with supercapacitor ESS

The traction AC converter of the trolleybus is simulated by a Matlab/Simulink direct torque control (DTC) drive model, and the supercapacitor ESS converter – by a PSIM-based continuous mode buck&boost converter. The both models are joined by a SimCoupler software tool (see Fig. 4.8.,Fig. 4.9.,Fig. 4.10.).

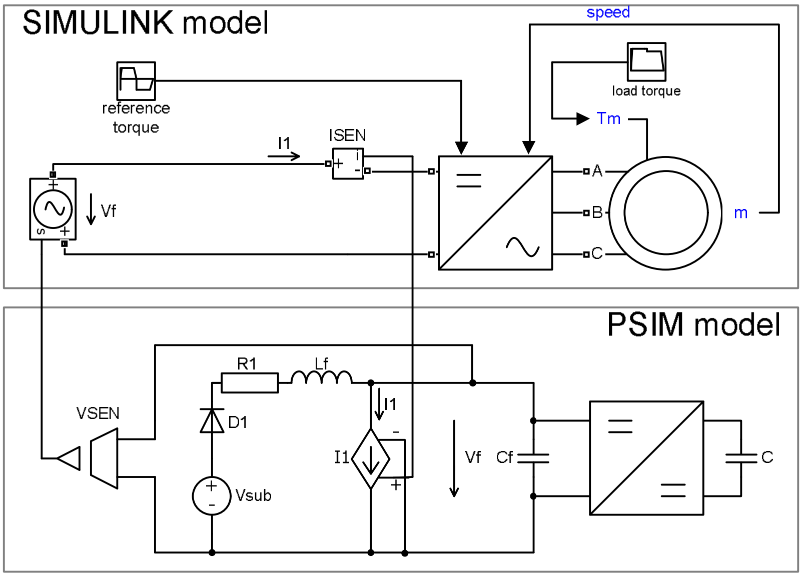

Fig. 4.8. Coupling of AC drive SIMULINK and ESS PSIM models

The trolleybus AC traction drive is replaced by Matlab/Simulink DTC drive model (Fig. 4.9.).

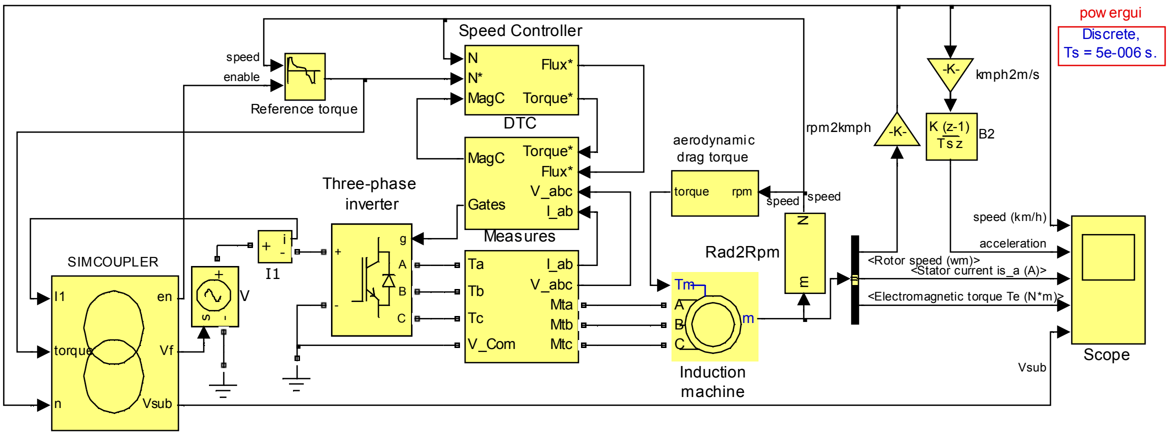

Fig. 4.9 AC drive Simulink model

The PSIM model of the installed on-board ESS is shown in Fig. 4.10. The switching mode buck&boost model of the ESS power converter is replaced with continuous one (subcircuit S1). This allows to increase the simulation time step and to decrease significantly the simulation time.

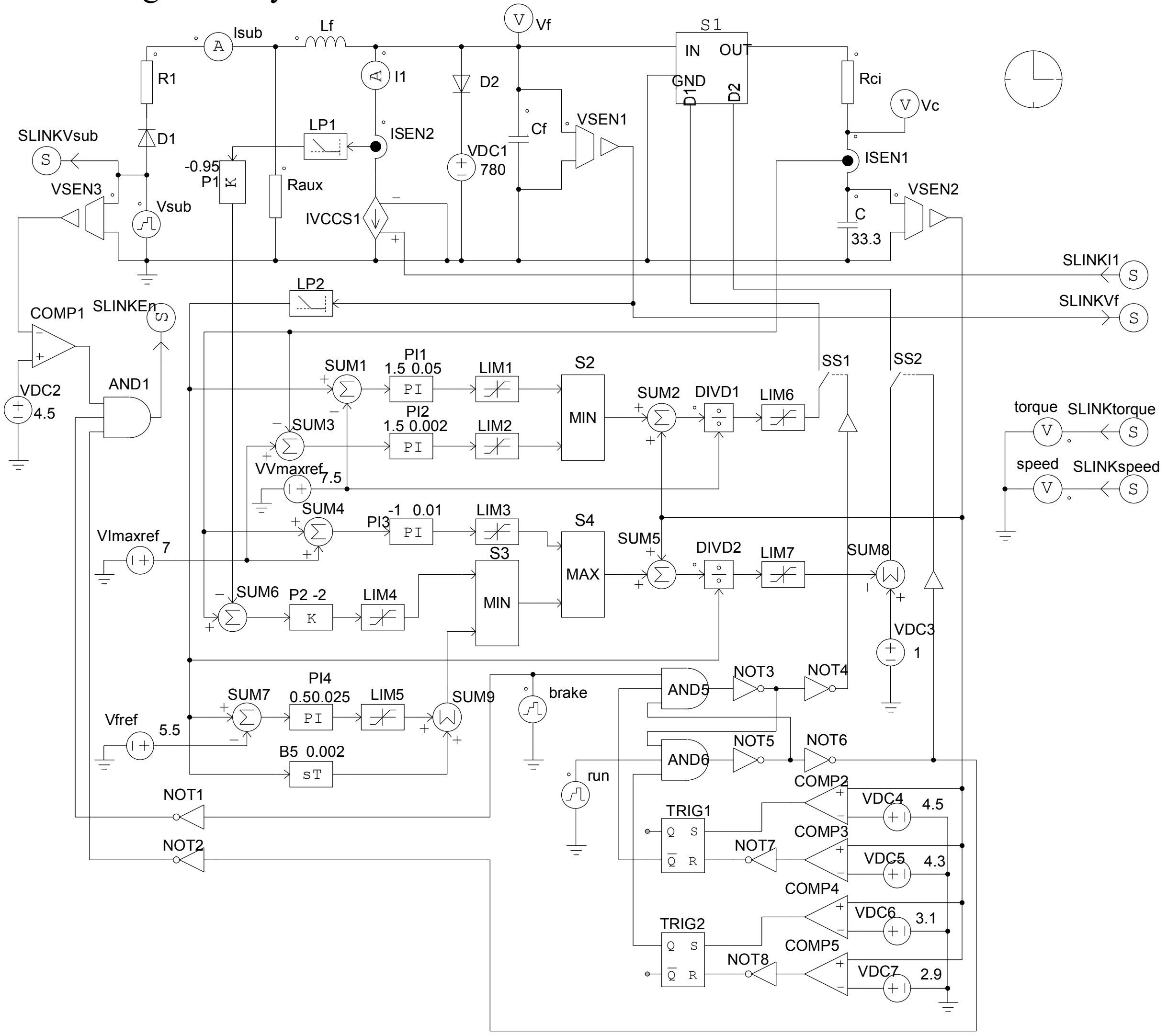

Fig. 4.10. PSIM model of ESS

Simulation results

The PSIM-MATLAB/SIMULINK simulations have been performed for a single trolleybus starting and braking processes in the overhead line voltage feeding and autonomous traction modes. The following typical supply variants were simulated:

- conventional overhead voltage supply (Fig. 4.11.);
- autonomous traction in the case of overhead line voltage unavailability;
- permanent loss of overhead voltage;
- temporary loss of overhead voltage.

As an example, simulation results at normal overhead voltage are shown in Fig. 4.11.

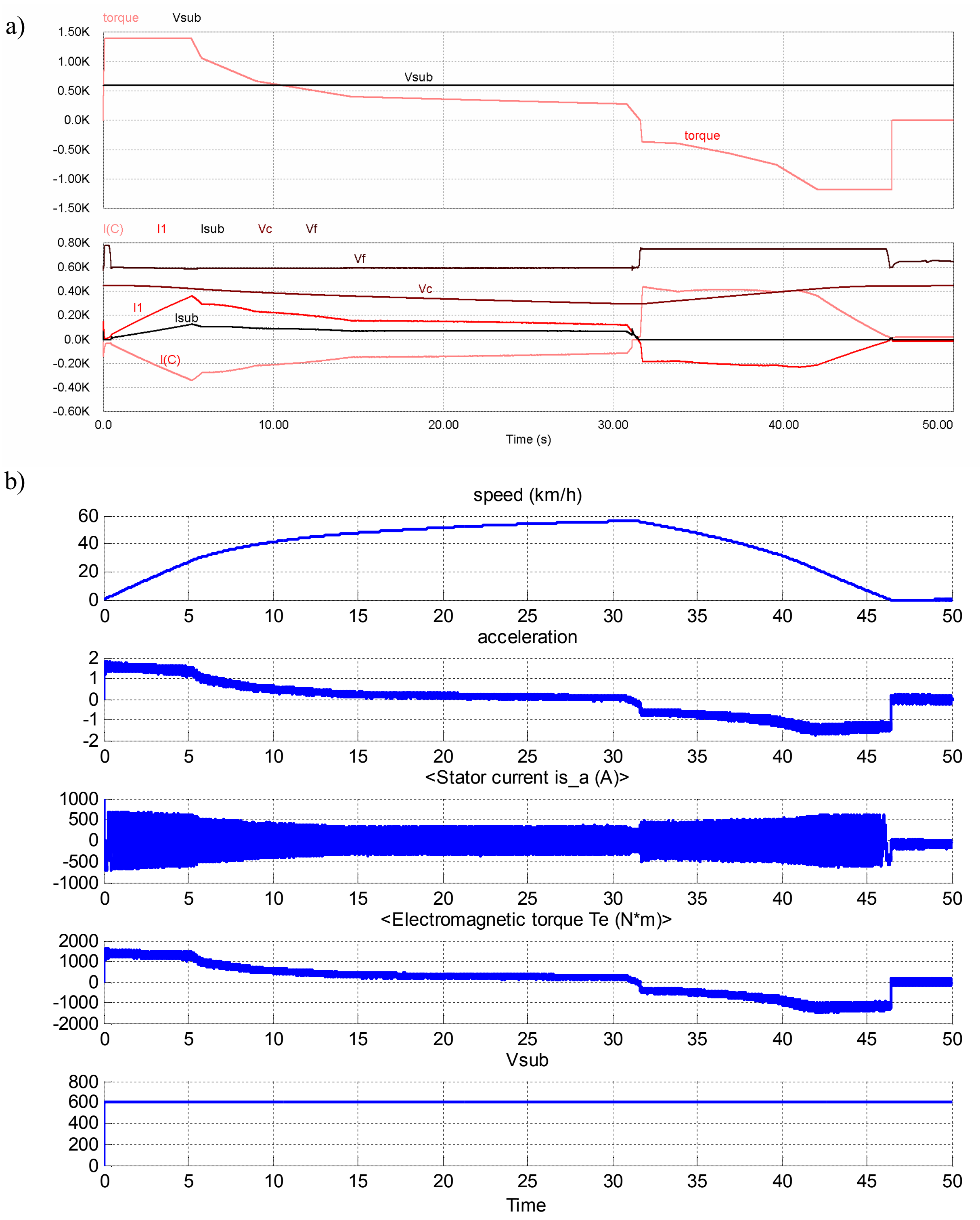

Fig. 4.11. Simulation results for trolleybus overhead operation mode:

a) PSIM; b) MATLAB/SIMULINK.

Conclusions

Simulation results show stability of the control system of the on-board ESS in all operation modes, and its ability to efficiently utilize the braking energy of a trolleybus.

The allowable simulation time step in the continuous model depends on the controller dynamic characteristics and the requirements for system response accuracy. A too large time step can cause oscillations in the system.

The ESS simulations using the continuous model have shown a six times reduction in the simulation time as compared with that for switching-mode model at 1000Hz switching frequency.

Control strategies for onboard ESS

In this work several ESS control strategies that could be named “mean”, “mean with prediction”, “peak shaving” and “proportional” were studied. The energy consumed from substation is calculated using MATLAB/SIMULINK model of the vehicle with onboard ESS and a particular control strategy applied. For calculations we used the power consumption profile of the vehicle experimentally recorded during one day on a tram route of the Riga city.

Table 4.1. shows the energy balance of the recorded power diagram. The energy loss in brake rheostats is calculated by integrating the power diagram over the negative power region.

Table 4.1.

Energy balance

	Energy, kWh	**Related energy,%**
Energy taken from the overhead contact line	1158.6kWh	93.9%
Energy returned to the overhead contact line	0kWh	0%
Energy dissipated in brake rheostats	230.1kWh	18.7%
Energy losses in the overhead contact line	75kWh	6.1%
Total energy taken from the substation	1233.6kWh	100%
Total energy losses	305.1kWh	24.8%
Theoretical energy maximum that could be saved	294.3kWh	23.9%

The theoretical energy maximum that could be saved is calculated for the case when a tram consumes constant power equal to its mean power (48.2 kW), and the fluctuating part of the power is covered by the ESS. In this case the overhead contact line wire losses are minimum, making up 0.9% of the total energy taken from the substation, i.e. overhead contact line losses can be reduced from 6.1% to 0.9%.

Mean power control strategy

Theoretical minimum in the energy consumption is achieved with an ideal ESS having a sufficiently large energy capacity and if from overhead contact line only constant power is consumed. However, such an ESS would be too large and expensive. In this work the energy consumption from the substation is studied as a function of ESS energy capacity and the power level, which ESS would try to stabilize at the tram input.

Fig. 4.12. shows SIMULINK model for calculation of the energy that would be taken from substation if the onboard ESS has energy capacity E_{max} and the mean control strategy is implemented. Typical behavior of the mean ESS controller when 100% of the mean power is taken from OCL ($c = 1$) is shown in Fig. 4.13. for an ideal ESS ($\eta = 1$).

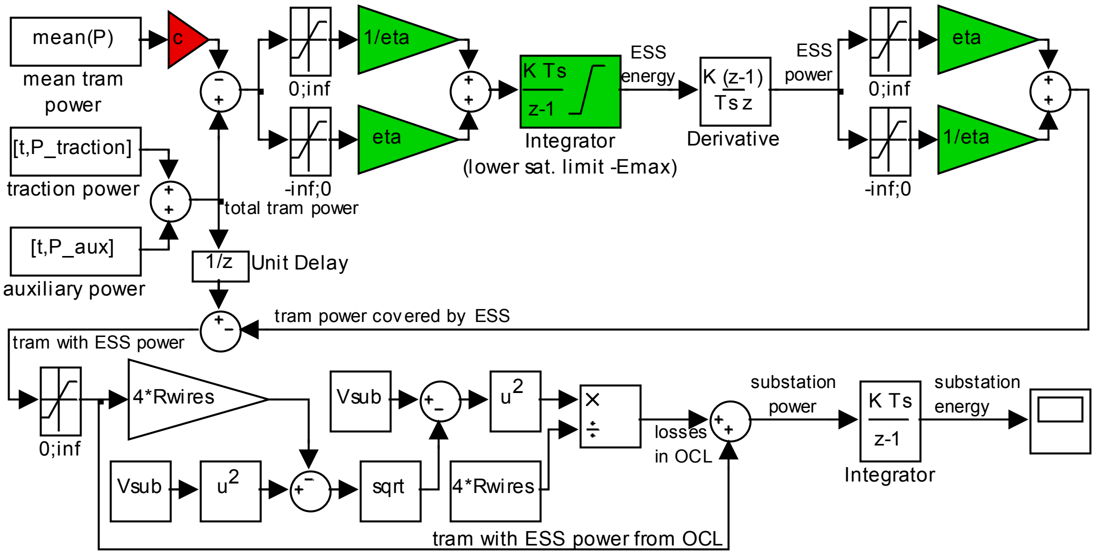

Fig. 4.12. SIMULINK model for calculating the energy consumed from substation for the ESS mean control strategy

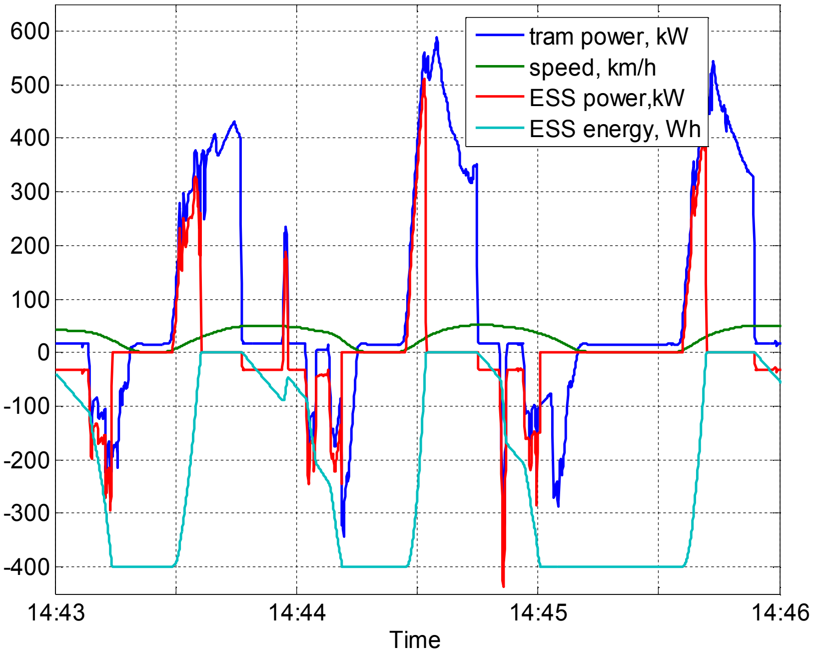

Fig. 4.13. Typical behavior of the mean power ESS controller

($E_{max} = 0.4$kWh, $\eta = 1$, $c = 1$)

Mean power control strategy with prediction

The tram mean power varies depending on the daytime and tram location on the route (the city center or periphery). Therefore, the strategy for control of mean power can be improved by the prediction of its value. This means that the control system tries to take from the overhead line the power that is not mean for the whole day but just for a couple of minutes.

Fig. 4.14. shows the comparison of the mean power control strategies without and with prediction. This latter is implemented quite theoretically, by averaging the power diagram over a 2 min time interval. The appreciable gain of prediction is apparent at the ESS capacities E_{max}>1kWh. As the benefit of approx. 1% of the saved energy takes place only for high ESS capacities, this strategy is impractical.

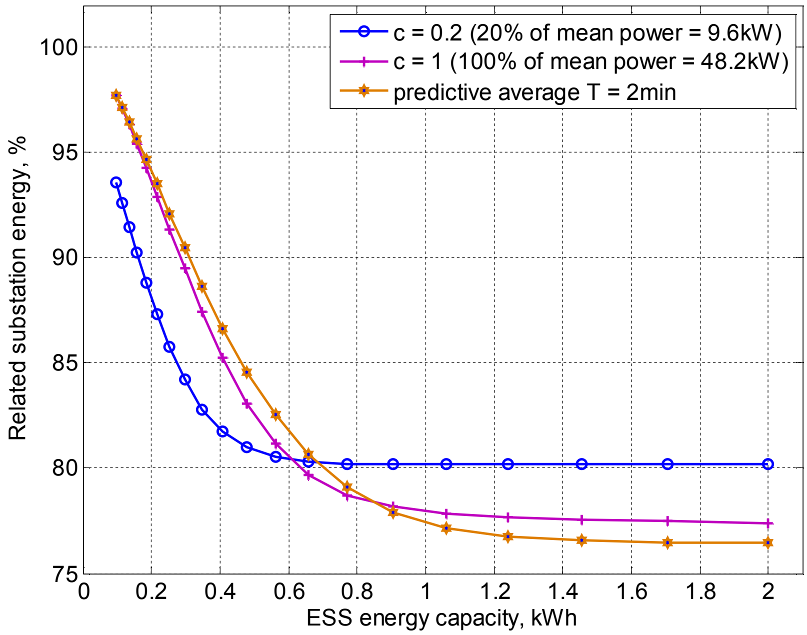

Fig. 4.14. Comparison of the mean power control strategies with and without prediction at η = 1

Peak shaving control strategy

The main idea of the peak shaving control strategy is to store braking energy and to discharge ESS only when the tram power is higher than the certain level $P_l = l \cdot P_{peak}$ (P_{peak} being the maximum tram peak power).

Proportional control strategy

The main idea of the proportional control strategy is to store braking energy and to discharge ESS with the power proportional to that of the tram traction.

Comparison of control strategies

The following best cases of each control strategy considered above were chosen for comparison:

- mean power at $c = 0.2$;
- mean predictive at averaging over time interval $T = 2$ min;
- peak shaving at $l = 0.25$;
- proportional at $k = 0.4$

For $\eta = 1$ these are shown in Fig. 4.15. For lower ESS capacities the proportional and the peak shaving strategies are comparable and show the best energy economy. For $E_{max} > 0.85$ kWh the mean power control strategy with prediction is the best.

As an ESS with efficiency η = 1 is not realizable, the influence of this parameter on the substation energy reduction is studied. Calculation results in the same cases of control strategies for η = 0.9 are shown in Fig. 4.16. It can be seen that the mean power control strategy with prediction is the worst, whereas the peak shaving strategy at $l = 0.25$ is the best, independently of the ESS capacity.

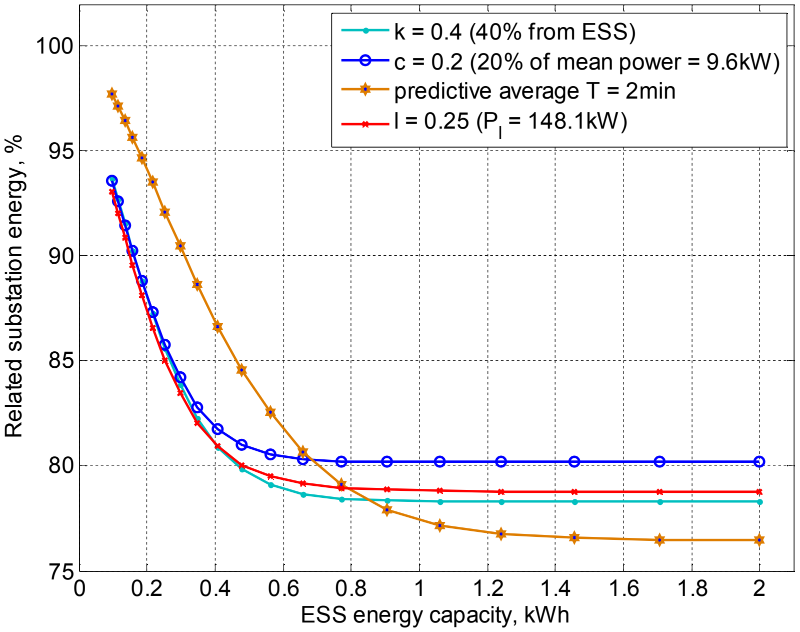

Fig. 4.15. Related substation energy for different control strategies vs. E_{max} at $\eta = 1$

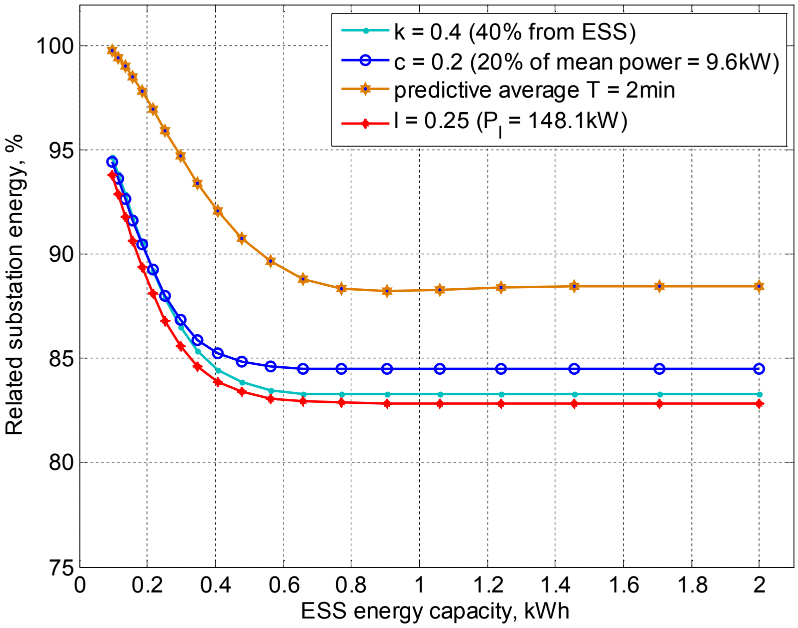

Fig. 4.16. Related substation energy for different control strategies *vs.* E_{max} at $\eta = 0.9$

It can be concluded that:

- The mean power control strategy has advantages over other strategies only at high ESS capacities, high wire resistances and for highly efficient ESSs.
- The peak shaving control strategy at η<0.95, l = 0.25 gives the best results as compared with other strategies independently of the ESS capacity.
- For $\eta < 0.95$ increase in the ESS capacity over 0.6kWh does not reduce the energy consumed from the substation.
- The results obtained cannot be generalized; they only apply to a particular route in Riga. Nevertheless, the method presented in the paper can be used for determination of the optimal (from the viewpoint of energy saving) control strategy of an ESS mounted on a vehicle that runs on the route(s) of a particular city.

Recovered energy dependence on energy storage parameters

The main task for stationary energy storage installed in substation is to reduce energy consumption, which means to reduce energy expenses. Choosing an oversized ESS it is possible that ESS during its service life won't save enough energy even to payback itself. Therefore very important is to choose ESS with an optimal energy capacity and power capability.

In this chapter applying previously described stochastic modeling methodology the recovered energy amount as a function of ESS energy capacity and power capability is studied. As an example the substation №10 is chosen. It was assumed that within its feeding zone only coupled T3A trams are running. The calculation results are shown in Fig. 4.17. as a 3D surface. These results can be used for selection ESS with economically justified parameters.

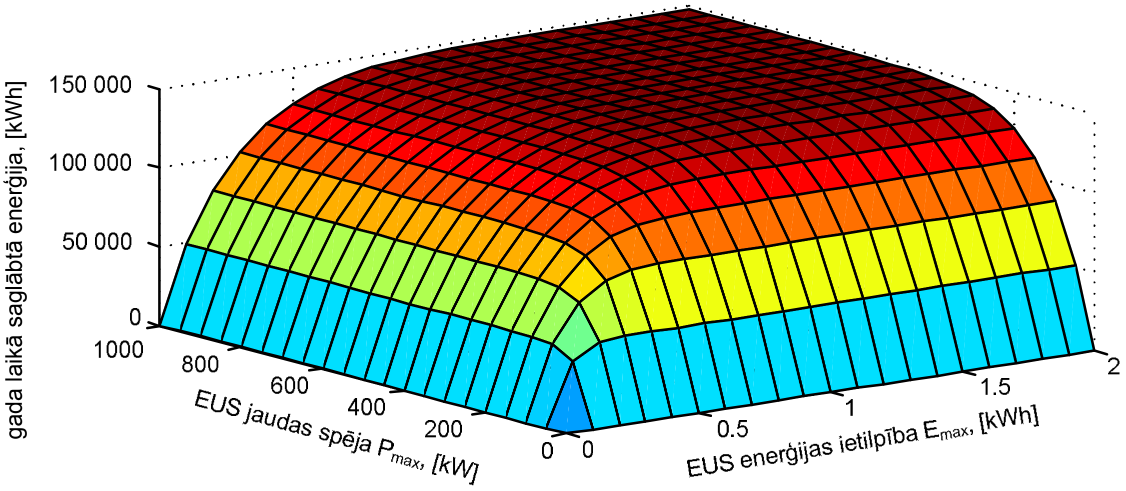

Fig. 4.17. Annual recovered energy for the substation №10 feeding zone as a function of ESS P_{max} and E_{max}

5. EXPERIMENTAL PART

In this chapter an experimental acquisition of the power diagrams for a tram T3A is described, as well as a description of supercapacitor capacitance measurement test bench is given and the analysis of the obtained results is provided.

Acquisition of T3A tram power consumption diagram

To obtain the tram power diagram, it is necessary to log signals of two voltage and three current sensors. The load resistors of the sensors are located on tram control cards VMT-1 and RT-1. The data logging was done with 16-bit multifunctional USB data acquisition module USB-4716. The connection of data logger to the sensor load resistors is shown in Fig. 5.1.

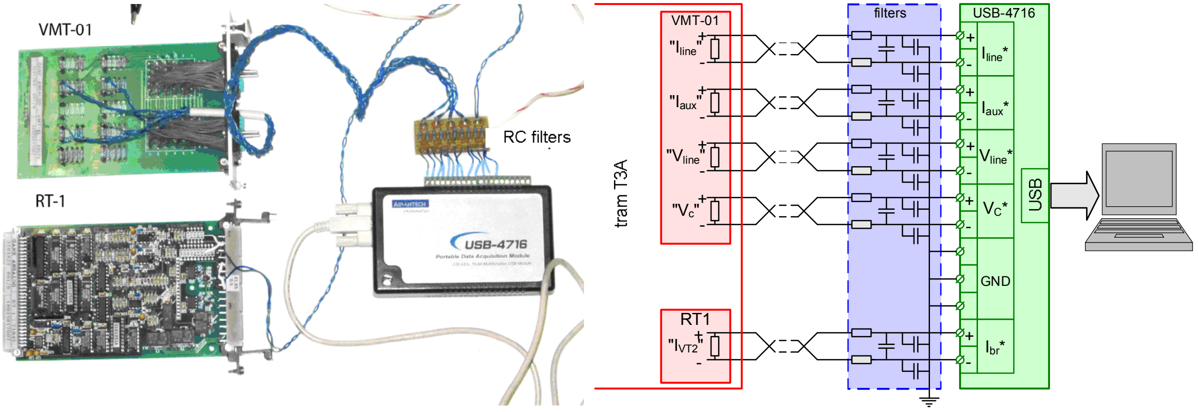

Fig. 5.1. The connection of data logger to the load resistors of voltage and current sensors

RC filter board is used for noise reduction and for averaging the pulsed with 1000Hz i_{VT2} current signal. Taking into account the gain values of the sensors, the tram power is obtained as follows:

$$p_{tr} = 200 v^*_{line}(200 i^*_{line} + 20 i^*_{aux}) - 12000 v^*_C i^*_{VT2}, \tag{5.1}$$

where $v^*_{line}, i^*_{line}, i^*_{aux}, v^*_C, i^*_{VT2}$ are measured signals of corresponding voltage and current sensors.

To extract the data for the feeding zone of the particular substation a GPS data logger i-Blue 747 was used. A fragment of the obtained data is shown in Fig. 5.2.

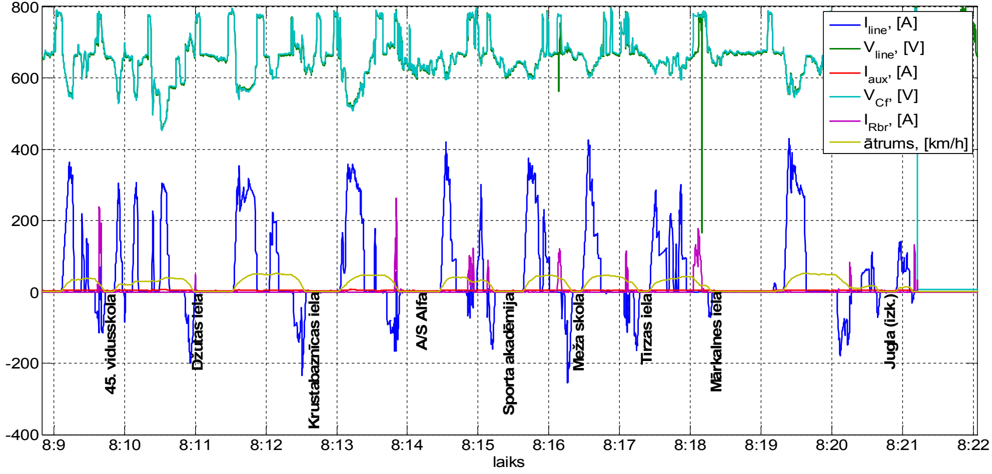

Fig. 5.2. An example of the registered tram T3A operation data

Supercapacitor capacitance measurement

For capacitance balancing principle it is necessary to measure the capacitances for each supercapacitor to be used in energy storage. Therefore, to study the capacitance measurement, a constant current charge and discharge test bench for capacitance measurement was built (Fig. 5.4.). The electric circuit of the test bench is shown in Fig. 5.3. The charge of the supercapacitors is done with 100A constant current laboratory power supply, while for the discharge a device (Fig. 5.4. 5.), which provides 100A constant current, was built.

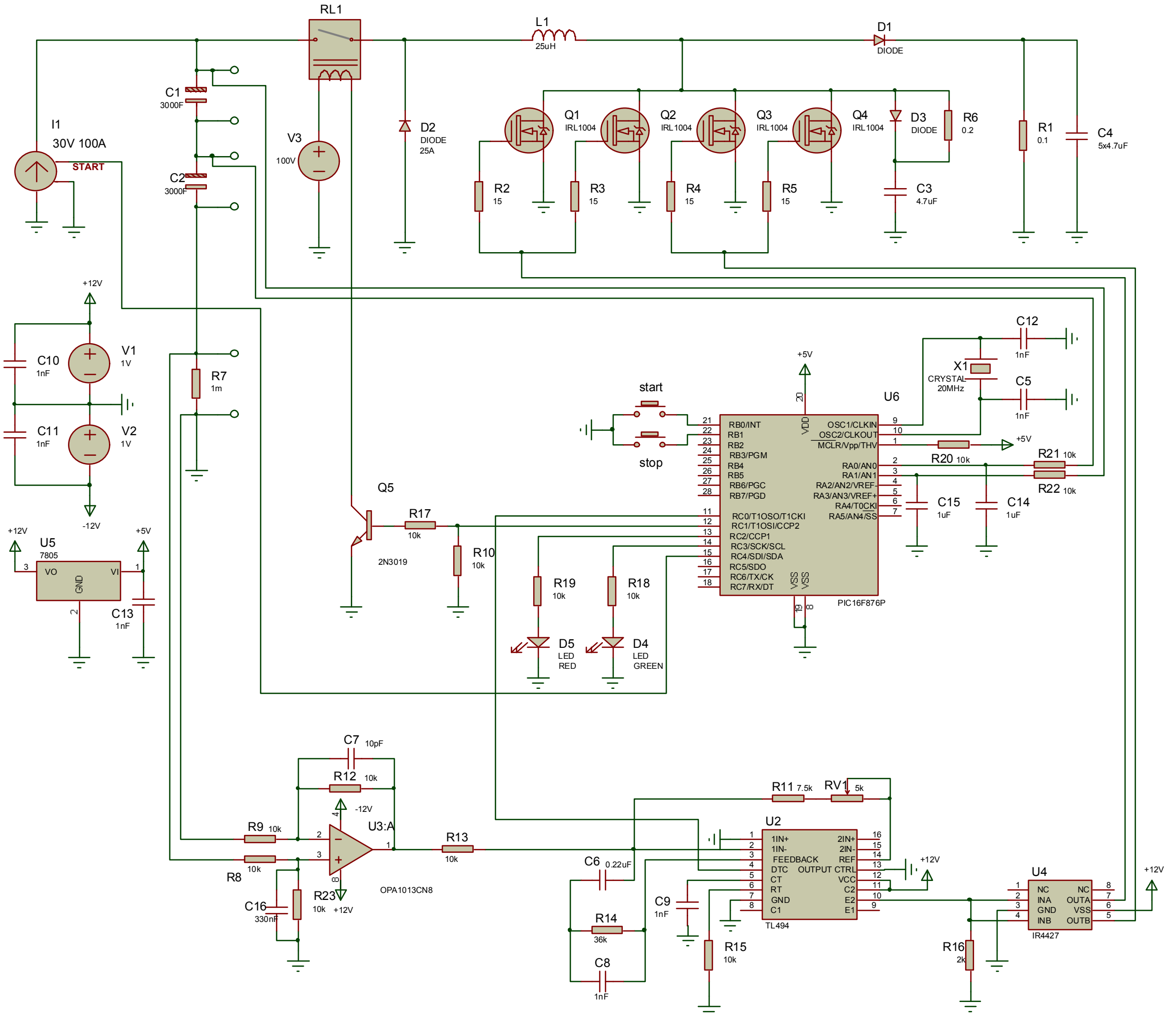

Fig. 5.3. Electric circuit of the supercapacitor charge/discharge test bench

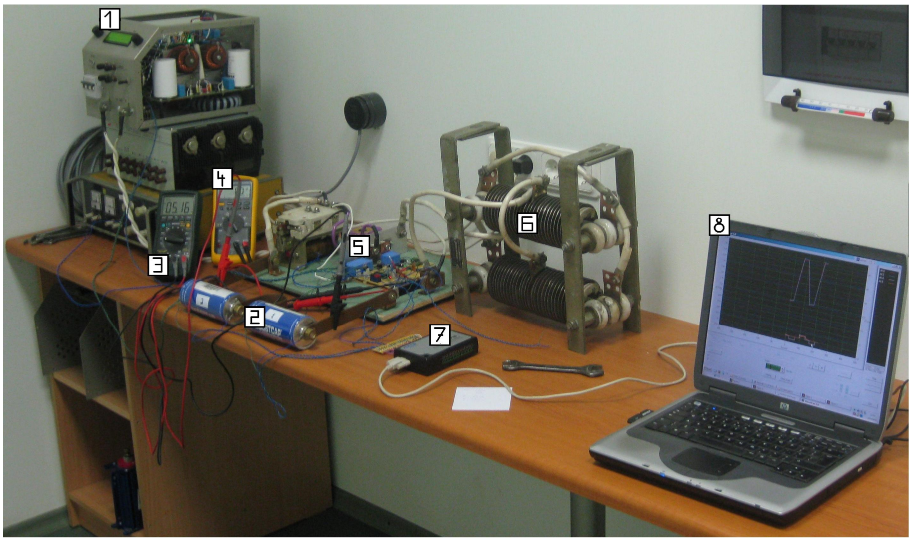

Fig. 5.4. 100A constant current supercapacitor charge/discharge test bench

(1. 100A current source; 2. SCs; 3. SC voltage indicator; 4. current indicator; 5. constant current discharger power circuit and controller; 6. load resistor; 7. USB-4716 16-bit ADC; 8. laptop with WaveScan 2.0 data logging software)

Charging a capacitor with constant current, the voltage drop on equivalent series resistance is constant and voltage increase on the supercapacitor terminals is directly proportional to the supplied charge and inversely proportional to capacitance. The capacitance is determined as follows:

$$C = \frac{I\Delta t}{\Delta V} \tag{5.2}$$

If interval Δt is sufficiently small, (5.2) expresses the dynamic capacitance, which could characterize the nonlinearity of the supercapacitor capacitance. In the test bench supercapacitors were charged from 1.25V to 2.5V. The change of the dynamic capacitance for one supercapacitor cell during four charge/discharge cycles is shown in Fig. 5.5.

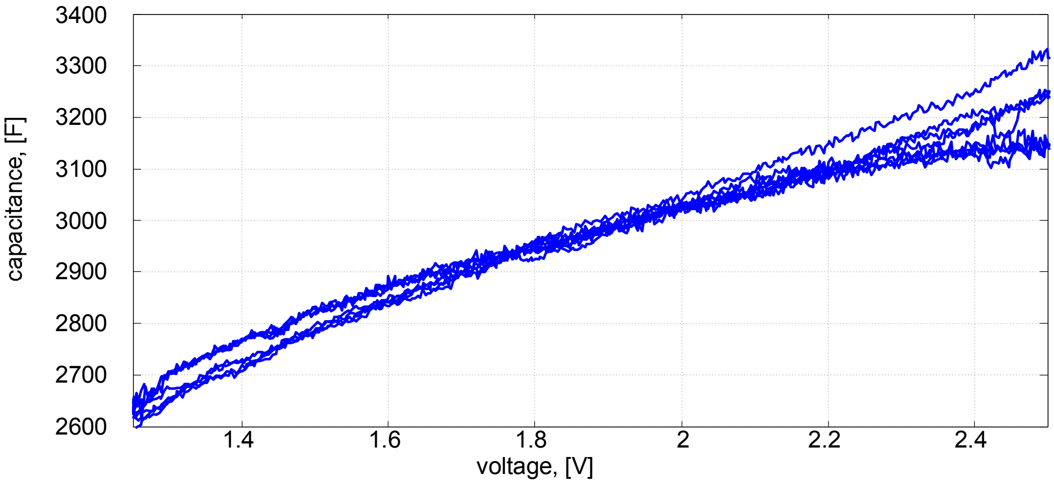

Fig. 5.5. The dynamic capacitance of the supercapacitor

For the experiments 8 supercapacitor cells were available. Their measured capacitance values at 2.1V are shown in Table 5.1. It can be seen that the largest capacitance difference is 210F.

Table 5.1.

Supercapacitor capacitance measured at 2.1V

Supercapacitor №	capacitance
1.	3075F
2.	3000F
3.	3000F
4.	2990F
5.	3200F
6.	3150F
7.	3180F
8.	3075F

Eight supercapacitors can be arranged into 4 pairs according to (5.3) in 105 different ways.

$$N = \frac{n!}{\left(\frac{n}{2}\right)! \cdot 2^{\frac{n}{2}}}, \tag{5.3}$$

where n – number of supercapacitors ($n = 8$).

Calculation results of energy capacity of all 105 arrangements are shown in Fig. 5.6.

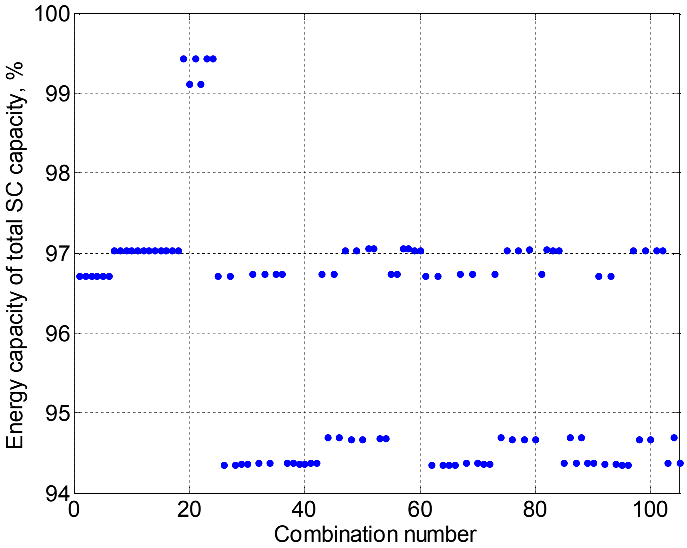

Fig. 5.6. Eight SCs effective energy capacity in different parallel/series arrangements

The arrangements that give the best effective energy capacity are shown in Table 5.2.

Table 5.2.

Balanced capacitances

arrangement		capacitance
1.+8.	1.+8.	6150F
2.+5.	2.+6.	6200F
3.+6.	3.+5.	6150F
4.+7.	4.+7.	6170F

After pairing, the maximum capacitance difference is reduced to 50 F.

CONCLUSIONS

Efficient use of recuperated braking energy has become more important now when the ratio of the recuperation capable vehicles has approached 100%.

The proposed power probability density methodology allows quick estimation of the untapped recuperated energy amount in urban electric transport using tram and trolleybus timetables and power diagrams as an input data.

The second developed stochastic modeling methodology besides the estimation of untapped braking energy allows to obtain the saved energy amount as a function of the energy storage power capability and energy capacity.

Both the methods make it possible to estimate the economical aspects of the regenerative braking energy utilization not only for the current situation but also for the future in view of the plans concerning renovation of the transport fleet and changes in the traffic organization.

The annual untapped recuperated braking energy for 18 periphery substations of Riga electric transport network by applying power probability methodology is estimated to be 1.26GWh.

Stationary or mobile energy storage systems allow the energy consumption and power fluctuation in AC grid to be reduced. As well as energy storage can operate as a power limiter.

Onboard energy storage would give the largest energy savings; however, there is no space for energy storage on board the electrical vehicles already in revenue service (except Skoda 24TR trolleybuses without installed diesel generator). Therefore, in Riga the most appropriate method for recovering braking energy is installation of stationary energy storage systems in feeding substations.

Simulation results of the developed simulation models of onboard supercapacitor energy storage systems demonstrate stable operation of the system and efficient storage and utilization of the braking energy.

From the compared onboard energy storage system control strategies the most efficient is “peak shaving” strategy.

The proposed capacitance balancing principle can be applied for elimination the voltage disbalance in supercapacitor battery between series connected capacitances; however, for verification the effectiveness of the capacitance balancing principle further extended experiments on large number of supercapacitors have to be performed.

Funding has to be found for the development and installation of the first energy storage for experimental verification of the theoretical research.

In the first order stationary energy storage systems has to be installed in substations №: 5; 7; 8; 10; 11; 12; 13; 16; 17; 20; 22; 27; 29; 30, which would give approximately 800MWh annual energy savings. The efficiency of energy storage in substations of city centre has to be studied separately.

For each substation individual calculations has to be done for optimal energy storage sizing considering current and perspective traffic organization.

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