Energy recovery effectiveness in trolleybus transport

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A B S T R A C T
Nowadays the issue of electric energy saving in public transport is becoming a key area of interest which is connected both with a growth in environmental awareness of the society and an increase in the prices of fuel and electricity. One of the possibilities to reduce energy consumption in urban public transport is to increase the extent of regenerative braking energy utilization. This can be achieved by its accumulation in the supercapacitors or a change in the topology of the power supply system in order to facilitate its flow. The article presents an analysis of applying these two options for increasing recovery energy usage on the example of the trolleybus network in the Polish city of Gdynia. For the purpose of the analysis there was used a simulation model of trolleybus traction power system based on the Monte Carlo simulation method. The research results and findings can be applied in other similar trolley or tram networks.

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1. Introduction

One of the distinctive features of electrical vehicles is their capacity to return electricity to the traction network, which is called energy recuperation. Recuperation reduces energy consumption in transport through energy re-use. In recent years, the issues related to increasing the efficiency of regenerative braking have been assuming growing importance. This is caused by the increased number of vehicles equipped with the recuperation module and the necessity of curbing electricity consumption due to environmental and financial factors. Energy storage devices, which allow the storage of recovered energy, are increasingly used. They include supercapacitors and flywheels. Today, a vast number of such storage devices are already applied in undergrounds, trams, and trolleybuses. As a result, the optimization of recuperation energy storage devices is growing in significance [1–6].

Energy storage devices can be divided into two groups: the on-board devices placed in vehicles and off-board devices installed in traction substations or other power supply system units. There are two main lines of research related to increasing the energy efficiency of urban traction systems which can be found in the literature: vehicle storage devices for light electrical vehicles (LEV) [7–9] and lowering energy consumption in heavy electrical vehicles (HEV) such as railway, suburban railway, and underground [10–13]. There is a clear shortage of publications on stationary energy storage devices or on energy consumption reduction in light electrical vehicles (LEV) and urban transport systems.

In Europe, tram and trolleybus transportation is still developing. Over the last decade, many new trams and trolleybus systems have been launched. This creates a need for research on increasing the efficiency of urban traction power supply systems, which could be possible by e.g. using stationary energy storage devices.

Moreover, attention should be paid to another deficiency in the current areas of research: the issues of design, construction, and control of energy storage devices. Although they are often the subject of studies [5,8,9,14,15], these studies are usually limited to the accumulation of electricity in the storage devices alone. There is no literature on the methods of increasing the scale of recuperation energy re-use from the global perspective, i.e. with regard to re-using such energy by auxiliaries and other electrical vehicles. Research on the analysis of the full recuperation energy balance are...
relatively rare, e.g. a riveting research paper is presented in [16], but it concerns the underground power system and its results cannot be applied to the trolleybus traction.

The article contains an analysis of raising the efficiency of regenerative braking in the trolleybus network in the city of Gdynia. The aim is to determine potential energy savings in the power supply system of the trolleybus traction network. The use of a stationary supercapacitor energy storage device and the reconfiguration of the power system was compared. Section 2 presents the research subject, and Sections 3 and 4 describe the developed model of trolleybus power supply system based on the Monte Carlo method. The experimental verification of the model is presented in Section 5. Sections 6 and 7 constitute the summary of research.

2. The subject of research

Gdynia is the city with more than 250,000 inhabitants, placed on the north side of the Poland by the Baltic Sea. At the moment there are 85 trolleybuses exploited in the city of Gdynia trolleybus network, out of which 50% of them is equipped with recuperation brake systems. Energy saving, which is the effect of recuperation in these vehicles, is at the level of 20%. In the nearest future it is being planned to purchase new rolling stock units fitted with brake recovery systems. The result of this – quite the contrary – may be the drop in recuperation effectiveness [17–21].

Investment realized in 2009–2013 years was a modernization of a power supply system of Gdynia trolleybuses aiming at reduction of voltage drops in the traction network and ensuring energetic redundancy. The scope of this investment involved the construction of 5 single unit traction substations, which had an influence on reducing brake recovery effectiveness due to division of the traction network into a bigger number of galvanically separated power supply areas.

The increase of the number of trolleybuses equipped with brake recovery systems causes the necessity to modernize the existing power supply systems in order to ensure optimal recuperation energy usage. It becomes necessary to take measures so as to prevent worsening of brake recovery conditions. The article hereby presents the analysis of possibilities to boost energy recovery effectiveness, which has been conducted for a fragment of Gdynia trolleybus network and has been based on Monte Carlo statistical modelling method. Two variants have been applied for the analysis: an installation of supercapacitors and introduction of bilateral power supply to the traction network [22–25].

The subject of analysis presented in the article hereby is the power supply area of existing substation Chwarszczyńska located in the mountainous part of Gdynia. It was launched in 1989 and it supplied power to six power supply sections at the length of 1.5 km each (Fig. 1). This substation is powered with two 15 kV lines from public energy network and fitted with two rectifier units. The cross-section of the feeders is 625 mm² Al and the cross-section of traction network wires is 100 mm² Cu.

Currently in Gdynia there are only 12-metre trolleybuses in use, majority of this rolling stock fleet (about 70%) is still equipped with drive systems with resistor steering.

In 2010 in the framework of Gdynia power supply system modernization there was built a new single unit traction substation Wielkopolska, which took over power supply to Wajdeloty section (Fig. 2). A basic objective of this investment is to boost power supply to Wajdeloty section which, before modernization, had been powered by two feeders of 3.1 and 4.1 km length from Chwarszczyńska substation.

Undoubtedly the construction of this substation will improve voltage stability in the traction network and increase power supply system redundancy. However, separating power supply area of Chwarszczyńska substation into two galvanically isolated parts will worsen conditions for recuperative braking. With regard to mountainous character of analyzed power supply area predestining it to energy recovery it becomes necessary to prevent expected deterioration of energy recuperation conditions. Two ways of reaching this aim are considered, namely:

1) the installation of energy supercapacitors on both substations in order to accumulate energy created during recuperation,
2) the introduction to exploitation of bilateral power supply of Wajdeloty and Żródło Marii sections by their mutual connection, which will enable recuperation energy flow.

These two variants were presented in Fig. 2.

In connection with the above for the analyzed area it is possible to highlight four power supply systems, i.e.:

1) a current power supply system, i.e. powering the subject traction network fragment from one traction substation Chwarszczyńska,
2) a basic variant created after the power supply system modernization as a result of which powering of the traction network is conducted by means of two galvanically separated substations, without them being equipped with any energy supercapacitors,
3) a variant with bilateral power supply to traction network created also as a result of a power supply system modernization, which operates through bilateral powering of Wajdeloty and Żródło Marii network sections from two substations, realized through a short circuit of section insulators between these sections,
4) a variant with energy supercapacitors that has also emerged from the power supply system modernization, as a result of which powering of the analyzed area is conducted by two substations – separated from each other and fitted with supercapacitors.

A further analysis will contain only the variants of traction network powering arising from power supply system modernization, i.e. the variants 2, 3 and 4. Moreover, an assumption was accepted that all vehicles will be fitted with recovery brake recovery systems and that this braking will be exploited. The analysis will be carried out on the basis of the Monte Carlo method.

3. The Monte Carlo method

Solution for many computational problems bases on an algorithm (list of actions), that leads to finding the value $f$, either precisely or with a specified error. Shall we label with $f_1, f_2, \ldots, f_n$ results of subsequent accumulation ns of an algorithm, then

$$f = \lim_{n \to \infty} f_n$$

Process performs a limited number of iterations before it is stopped. This process is strictly determined: every algorithm results in an identical solution.

There are problems for which it is complicated to define such an algorithm. In such situation the task is modified, basing on the law of large numbers (LLN) from the probability theory. Utilizing the stochastic analysis related to multiple random samples evaluations $f_1, f_2, \ldots, f_n$ of the searched variable are obtained. This requires the random variable $f_n$ to be stochastically convergent to the searched value $f$. Therefore it is valid for any $\varepsilon > 0$:

$$\lim_{n \to \infty} P(|f - f_n| < \varepsilon) = 1$$

where $P$ stands for probability of the given event. Choice of the variable $f$ depends on each problem’s specifics. Frequently the searched variable is considered as an occurrence of a particular event. Such
A trolleybus, as opposed to rail vehicles, does not have dedicated lanes and moves along the road with other road vehicles. Hence, a factor determining a trolleybus movement is the impact of other road users. Moreover, the number of speed limits on the road is greater than in the case of rail traction. A frequent method applied by trolleybus drivers is repeating the starting and coasting phases several times during one ride cycle (Fig. 3b), which can be called travelling with quasi-constant speed.

In many cases, delicate braking between subsequent starting phases is also applied, particularly when driving in heavy traffic – there is a need to slow down due to the movement of other vehicles which are in front of a trolleybus. This way of travelling is difficult to present via simulation modelling due to the randomness of

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**Fig. 1.** Diagram of power supply area of Chwaszczyńska substation in Gdynia before supply system reconstruction with the scheme of DC switchboard of substation. The bold lines mean trolleybus catenary, the fine dashed lines-feeders, each supply sector is marked by different colours.

**Substation Chwaszczyńska**

**Fig. 2.** Diagram of power supply area of Chwaszczyńska and Wielkopolska substations in Gdynia before supply system reconstruction, the proposed changes was marked: (1) connection between supply sectors, (2) supercapacitor bank.
transitioning from driving to coasting and vice versa, the effect of which is that the power consumption from the trolleybus power system also has a stochastic nature. As a result, it is reasonable to treat a trolleybus power system as a stochastic object and use the Monte Carlo method for modelling the work of a trolleybus power system.

The two main factors describing the condition of a power supply system is the location of vehicles and the currents consumed by individual vehicles. Given the described influence of the traffic congestion, it can be concluded that these two variables are random in nature and can be treated as random input variables of the Monte Carlo method. In this case, it is possible to describe the condition of a trolleybus power supply system in accordance with the Eq. (1) as the function \( f \), which is defined as two random variables: the location of vehicles and vehicles currents. These variables are described by the probability density distributions.

In other words, vehicles location estimators and current consumption are considered as the input whereas the currents flows across the network at a random point in time are the event. Probability density distributions of currents and potentials in the power supply system. A general scheme of the traction power supply network simulation model is presented in Fig. 4. In each iteration vehicles locations and currents, which are used to calculate power supply system's parameters, are randomly set. Probability density distributions of currents and potentials in the power supply system are determined after all the steps are completed [28,29].

![Fig. 3. A typical ride cycle of: (a) rail traction vehicle; (b) trolleybus (* ride with quasi constant speed), \( t \) – time, \( v \) – velocity.](image)

### 4. Simulation model

The main feature of the model is to implement the random nature of the load supply. This aim achieved by a stochastic method of determining random current of vehicles (Section 4.2) and their positions (Section 4.3).

#### 4.1. The main model’s structure

Simulation calculations are based on the repetition of the iteration loop, the result of which are histograms of the probability distribution of currents and voltages in the power supply system. The model's main tenet is treating a power supply system as a stochastic object based on two random variables: the vehicle positions and currents. In each iteration cycle, there is the random determination of the positions and currents of vehicles on the basis of the histogram distributions set in the block of initial calculations. This allows modelling the influence of random factors on the work of a power system.

The main elements of each iteration loop include the random determination of the values of vehicles' positions and currents (Fig. 3). It takes place in a random way based on the density distributions of positions and currents, which are set during the preparatory phase of the calculations. Section 4.3 presents the algorithm for the random determination of vehicle positions, while Section 4.4 describes the method of randomly determining the vehicle currents.

The elaborated simulation model using the Monte Carlo method and enabling calculations of characteristic parameters of the traction power supply system consists of three main components:

- module of initial calculations that runs only once in order to prepare the necessary input data,
- iteration loop in which calculations based on random factors, like differences in drivers driving techniques and delays, are performed,
- final calculations module that determines the density distributions of currents and potentials in the power supply system.

The block of initial calculations provides the following data necessary for the iteration loops that follow it:

- set of values for the inverse function of the vehicle location distribution probability, that is used for objects placement,
- distribution of trolleybuses delays,
- distribution of vehicles' current consumption.

The iteration loop consists of the following calculation blocks (Fig. 5):

![Fig. 4. General scheme of the traction power supply system simulation model using the Monte Carlo method.](image)
Fig. 5. Iteration loop schema. Items marked as “Preliminary calculation block” are realized only one time, at the beginning of the calculations. Others calculation are repeated in each iteration loop.

- random assignment of the simulated trolleybuses across the power supply sections basing on the provided schedule intervals and probabilities’ distribution density. The latter is based on historical data sets of vehicles punctuality,
- determining trolleybuses’ location basing on the given profile of velocity in time,
- current consumption calculations. The velocity characteristics are used to determine particular steps of the journey: accelerating, running, retarding and stop and that is then combined with trolleybuses type and relevant current consumption profile,
- power supply systems’ parameters calculation,
- correction of current flow of the trolleybuses depending on the power supply network voltage and the retarding currents limitations,
- calculations of the power supply system parameters taking under the account the corrected trolleybuses current consumptions.

The distinctive features of vehicles’ movement are described by the speed profile \( \nu(s) \), which is the basis for the random determination of vehicles and their currents. The speed profile characteristics \( \nu(s) \) presents the relationship between trolleybuses locations \( s \) and their speeds \( \nu \) and it is assumed to be the same for all the vehicles. It is based on schedules, local speed limits and vehicles’ technical limitations.

The calculations are carried out using the node potential method, the outcome of which are the values of currents and voltages in different parts of the power supply system.

### 4.2. Variability of the power supply system’s parameters

Each step of iteration entails the random determination of currents and positions of vehicles, which is the basis for calculating the distribution of currents and voltages in the entire system. It should be noted that the vehicles’ currents are set based on the traction characteristics referred to the nominal voltage of the vehicle power system. Changes in the power supply voltage caused by voltage drops in the traction network create the need to consider their impact on:

- the shape of traction characteristics;
- the change in the parameters of regenerative braking.

In each simulation cycle the voltage of trolleybuses’ pickup is evaluated. If it differs from the nominal value above the given margin, the following trolleybuses current values are modified:

- its consumption while starting and cruising at the constant speed,
- its value during the regenerative braking.

The correction of the trolleybus load currents is followed by the recalculation of the power supply system parameters. That process is repeated until the convergence condition is met for the model of the simulated power supply system, as given:

\[
\max_{i=1:n}(V_i^k - V_i^{k-1}) < \Delta V_{\text{max}}
\]  

(3)
where the $V_{i}^{k}$ is the potential of the $i$th junction/node of the model in $k$th step; $\Delta V_{\text{max}}$ stands for the convergence condition threshold where $n$ represents the number of junctions/nodes. Shall the condition is not met an error message is returned.

4.2.1. Changes in traction characteristics

Another essential element is considering the influence of changes in the power supply voltage on the shape of the vehicles’ traction characteristics.

The relationship between the starting current and the power supply voltage is based on the assumption that trolleybuses propulsion works with constant torque. In order to eradicate voltage oscillations in the power supply system, the power of the trolleybus propulsion systems is reduced when there occurs an excessive voltage drop in the power system. It involves power reduction which is proportional to the value of voltage drop. Depending on the pickup voltage $U_{t}$ vehicles currents estimated for the nominal voltage $U_{n}$, are modified as according to the pattern (4).

$$
\begin{align*}
U_{t} \geq U_{0} & \rightarrow I_{t} = I_{n} \cdot \frac{U_{n}}{U_{t}} \\
U_{t} < U_{0} & \rightarrow I_{t} = I_{n} \cdot \frac{U_{n}}{U_{0}}
\end{align*}
$$

(4)

where $I_{t}$ – trolleybus current value referred to $U_{t}$, $U_{0}$ – value of voltage with involve start of regenerative braking.

4.2.2. Changes in the current of regenerative braking

Energy gained from braking may be returned to the power supply system when decreasing speed or when running downhill with braking engaged. During regenerative braking the trolleybuses are modelled as current–voltage sources depending on the value of the traction voltage on pickup $U_{t}$ and the maximal recuperation voltage $U_{h,\text{max}}$.

The state of regenerative braking is simulated in the following way:

1) in the first phase a trolleybus is treated as a current source of with a current value indicated on the basis of its traction characteristic,
2) if the value of voltage on receivers exceeds the permissible level of voltage for regenerative braking (in Gdynia it is 750 V), which means the lack of a possibility to receive generated energy, the vehicle is modelled as a voltage source of a voltage value adequate to permissible voltage for recuperation.

4.3. Vehicles location calculation across the traction section

Vehicles are being dislocated across the power section according to the probability distribution of vehicles placement in the given place.

Probability $P(s_{1}, s_{2})$ to find the vehicle between points with coordinates $s_{1}$ and $s_{2}$ is proportional to the time of travel between these two points, which can be written:

$$
P(s_{1}, s_{2}) = k \cdot \frac{s_{2} - s_{1}}{v_{\text{av}}}
$$

(5)

where $v_{\text{av}}$ – average speed on the road between points $s_{1}$ and $s_{2}$; $k$ – coefficient of proportionality.

This probability is equal to the integral of the probability density $p(s)$:

$$
P(s_{1}, s_{2}) = \int_{s_{1}}^{s_{2}} p(s) ds
$$

(6)

marking the difference $s_{2} - s_{1}$ as $\Delta s$ we can write:

$$
P(0, \Delta s) = k \cdot \frac{\Delta s}{v_{\text{av}}} = \int_{0}^{\Delta s} p(s) ds
$$

(7)

on $\Delta s \to 0$ this equation takes the form:

$$
p(s) = k \cdot \frac{1}{v(s)}
$$

(8)

where $v(s)$ is speed profile, which means that the density of the probability of finding a vehicle in a given point is inversely proportional to its speed $[30–33]$.

An exemplary speed profile is presented in Fig. 6. Fig. 7 presents the vehicles location probability $p(s)$ for the speed profile from Fig. 6.

4.4. Vehicle current calculation

The key objective of the module of determining the vehicle current is taking into account the quasi-constant nature of the vehicle speed (Fig. 3). Therefore, the vehicle current is determined randomly based on a histogram of the vehicle current. This histogram is generated in the block of initial calculations (Section 4.1). The main element is considering the random nature of driving, which stems from the repeated pressing and releasing of the trolleybus accelerator pedal. Consequently, the current consumption from the traction network is equally random. This is achieved by introducing the hysteresis driver’s behaviour model, which reflects the subjective nature of the driver’s decisions about pressing the accelerator pedal.

Vehicle’s current consumption may be written as the following:

$$
I_{p} = I_{t} + I_{\text{aux}}
$$

(9)

where $I_{t}$ is the current for the traction and $I_{\text{aux}}$ stands for the auxiliary devices current consumption.

Fig. 6. An exemplary speed profile; $s$ – the vehicle location, $v$ – speed (I – accelerating, II – driving at constant speed, III – braking).

Fig. 7. A layout of the vehicles ($s$) location probability ($p$) for the speed profile from Fig. 6 (I – accelerating, II – driving at constant speed, III – braking), $s$ – position, $p$ – probability.
Determining the current consumption $I_t$ starts with finding the actual propulsion system state. This is done basing on speed’s $v(s)$ derivative with the assumption of no negative distance increments (no reversing). We can differentiate the following situations then:

- if $dv/ds > 0$, then the trolleybus is accelerating;
- if $dv/ds = 0$ and $v > 0$, then the trolleybus is cruising with the quasi-constant speed;
- if $dv/ds < 0$, then the trolleybus is braking;
- if $v = 0$, then the trolleybus is in standstill, then the $I_t = 0$.

4.4.1. Starting and braking

When in the starting phase the vehicles’ current consumption $I_t$ is calculated as multiplication of current consumption $I_{ch}$, based on its characteristics, and random factor $c$ evenly distributed across the range $<c_{min}; c_{max}>$:

$$I_t = c \cdot I_{ch} \tag{10}$$

The factor $c$ models the differences in driving the particular vehicles (various acceleration values) that originate from fluctuating traffic conditions and various driving styles of the drivers. Similar method is used when calculating the regenerative braking current.

4.4.2. Cruising with quasi-constant speed

The module’s aim is to model the random way of starting and stopping the work of a trolleybus (Fig. 3) in order to maintain constant vehicle speed. This is done on the basis of a vehicle driver’s subjective decision. The probability histograms for the vehicle’s current consumption for a number of medium speeds are prepared.

Current consumption when travelling with the quasi-constant speed is modelled by random estimation biased with probability distribution. Mean of realizing such vehicle movement, and therefore that probability density distribution depends on the working-technical conditions, that are:

- velocity determined from the velocity profile depending on vehicle location,
- randomly selected type of the vehicle,
- route gradient, defined in the input data.
Vehicles’ location presence probability distribution – used for current consumption calculation, also including random factors – is evaluated basing on actual traffic conditions and sets of probability distributions, prepared during the initial calculations.

Current consumption probability distribution for quasi-constant speed movement is evaluated basing on theoretical values calculated for all the possible parameter combinations in the three dimensional matrix $P$:

$$P(v_j, i_k, n_l) : (n_{j*}) \times (n_{i*}) \times (2)$$

where:

- $v_j = v_{t1}, v_{t2}, \ldots, v_{tn}$ – cruising speed ($v_{t1}$ and $v_{tn}$ respectively are the minimal and maximal speed values);
- $i_j = i_{t1}, i_{t2}, \ldots, i_{tn}$ – route gradient ($i_{t1}$ and $i_{tn}$ respectively are the minimal and maximal gradient values);
- $n_{l1}, n_{l2}$ – propulsion type (resistor propulsion, chopper propulsion).

Probability distribution is calculated in the initial calculations module, in quasi-constant speed travel simulation sub-module (Fig. 8).

Trolleybus can be in one of three states of work: starting, running and stopping. The propelling motion is calculated based on starting and braking characteristics $F(v)$, vehicle current from analogical characteristics $I(v)$. Taking under consideration trolleybuses specifics we assume that running at the constant speed is achieved in the following way:

- when running on flat or uphill route, by switching to and from the starting and running phases, that is by throttling the speed controller,
- when running downhill, by switching to and from the running and braking phases, that is by throttling the brake controller.

Transition between the phases is modelled with hysteresis characteristics that reflect driver’s behaviour. They are presented in Fig. 9. The value $H$ is the decisive variable. Speed thresholds at with the mode switching occurs $v_{min}$ and $v_{max}$ are randomly generated in order to reflect differences in driving styles. Fig. 10 presents an example run, the $(v_{max-1}, v_{min-1})$ and $(v_{max-2}, v_{min-2})$ are two randomly generated pairs of speed values.

The modelling of a vehicle movement is done on the basis of solving the mechanical equation of vehicle movement. Trolleybus motion is described in Eq. (12). It uses the traction characteristics $F(v)$ and motion’s friction $W(v)$. In this model the trolleybus is represented as a point with mass, described by the following set of equations:

$$
\begin{align*}
\frac{m \cdot k}{dt} &= F(v(t)) - W(v(t)) \\
\frac{ds}{dt} &= v
\end{align*}
$$

where $k$ is the factor of rotating masses, which in trolleybus traction is estimated to be 1.2.

5. A verification of the Monte Carlo method

The research was conducted in the trolleybus network of Przedsiebiorstwo Komunikacji Trolejbusowej in Gdynia, where the measurements of load in the power supply system were carried out. Conducted records comprised a comparative material for a simulation model verification. The measurements of voltage in the traction network were made by means of RSN-01 recorder placed on the traction network pole. The measurements of the feeders currents were made by means of HIoki 8807 recorder placed on the traction substation.

The simulation research was carried out in Scicos/Scilab program. Figs. 11 and 12 show the layout histograms of currents value density probability resulting from a simulation run for scheduled and irregular traffic on the power supply section. In both cases these histograms were relating to identical measurements data recorded in realistic conditions, namely irregular traffic.

Figs. 11 and 12 depict an influence of the traffic punctuality on the feeder load current value visible in the increase of the maximum feeder current value while taking into account in irregularity of the trolleybus rides. The effect of irregular trolleybus running is periodic and simultaneous occurrence of a large amount of vehicles on the power supply section in relation to the regular traffic, as a result of which the probability of simultaneous start-ups of several trolleybuses is on the increase.

![Fig. 9. Schema of the hysteresis driver’s behaviour model.](image)

![Fig. 10. Example trolleybus runs with a quasi-constant speed, the states $H$ of the hysteresis model of driver behaviour are presented. The hysteresis model changes the actually used traction characteristic (Fig. 8) and as a result the velocity $v$ changes.](image)

![Fig. 11. The histograms of the feeder $I$, a simulation for the traffic consistent with the timetable.](image)
The bars visible on histograms corresponding to 30–150 A values mean the need currents of non-traction trolleybuses. In the city traffic the relative travelling time with the current intake is at the level of 0.3, due to which for 70% of the operation time a vehicle goes without pressing the gas pedal or it stops at the trolleybus stop or the crossroads so its current taken from the network is then of a non-traction needs current value.

Fig. 13 presents a histogram of a voltage layout in end the power supply section of the traction network. One can observe a rise in the traction network voltage over the voltage of substation busbars, which results from the increase of network voltage by vehicles doing regenerative braking.

What can be observed is a significant convergence of the histograms of load currents and voltage in the trolleybus power system, which were obtained through simulation and based on the achieved measurements. In addition, the applied method of modelling of the irregularities in vehicle movement can significantly improve the accuracy of the calculations (Figs. 11 and 12), which proves the validity of this method in the context of the complex nature of traffic congestion. Therefore, it is reasonable to conclude that the developed method allows obtaining the reliable values of the power supply system load parameters.

The above findings allow for a conclusion that the accepted model is correct and its use for further analysis is fully justified.

6. Simulation research findings

On the basis of a developed method of the trolleybus transport power supply system modelling there was conducted a comparison of the three earlier presented variants of increasing the extent of recuperation exploitation in the power supply area of Chwaszczyńska and Wielkopolska substations. The simulation was carried out basing on the current trolleybus timetables thus it was assumed that there are five lines: 23, 24, 27, 29 and 31 working in the analyzed area.

For the calculation an assumption was also accepted that all trolleybus lines will be operated by Solaris Trollino 12 trolleybuses, which are equipped with a drive system with an asynchronous motor of 175 kW power and having a technical capability of regenerative braking to the traction network. The speed profile was based on the current timetables and the traffic speed limits.

The calculations show that in case of the basic power supply system variant (variant 2 defined in Section 3), the total annual electric energy consumption will be about 2.4 GWh, which is adequate to the costs of electric energy of approximately 450,000 PLN (Fig. 14). The introduction of bilateral power supply will result in a yearly saving of circa 32,000 PLN. The supercapacitors installation on the other hand will lead to lowering the electric energy consumption to the level of 117,000 PLN. While assuming a 10-year lifespan of supercapacitors it can be claimed that this investment will be economically justified if the maximum price of one supercapacitor is about 585,000 PLN. The method applied does not allow though for determining the required supercapacitor’s capacity, therefore it is impossible to quote the exact price of supercapacitor systems. The capital expenditure connected with the start-up of a bilateral power supply to the traction network (variant no. 3) is considerably lower than expenditure on the other power supply variants. In the variant no. 3 it is necessary to introduce a coordination of the breakers of Wajdelaty and Żróde Marii fast feeders in Wielkopolska and Chwaszczyńska substations, which could be executed by means of the remote control system anticipated for the start-up in 2010. A time–current safety device \( I(t) \) of the feeders would complement it.

An impact of bilateral power supply introduction on the feeders current value is visible in Fig. 15, which shows the minimum voltage

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**Fig. 12.** The histograms of the feeder \( I \), a simulation for irregular traffic.

**Fig. 13.** Histograms of voltage \( U \) in the final point of the power supply section.

**Fig. 14.** A comparison of annual costs of energy consumption for the analyzed variants.

**Fig. 15.** The diagram of the minimum voltage level on the trolleybus receivers in the location function.
level in the traction network in the distance function, and in Fig. 16a and, which depicts the diagrams of voltage dispersion on the trolleybus receivers in the function of their location (Fig. 16a presents current state, Fig. 16b presents proposed change). The vertical congestions of data points in the form of four vertical shadowed stripes, which are visible on the dispersion diagrams, correspond to the trolleybus stops locations, where there is the biggest probability of the vehicle’s occurrence. It should be noticed that the introduction of bilateral power supply causes a considerable increase of the voltage level stiffness in the traction network. 

The calculations conducted above indicate a much higher saving of electric energy consumption in case of supercapacitors installation than at introduction of bilateral power supply of the traction network. On the other hand, capital expenditure connected with installation of these supercapacitors is much higher than that required at the bilateral power supply introduction and one may have doubts upon financial profitability of such an investment [34–36]. The introduction of bilateral power supply provides energy consumption savings at practically zero expenditure. This saving is particularly visible in case of a decentralized power supply system, i.e. supplying power to the traction network from small, single-unit substations giving power to one or two feeders. One should notice that this way of supplying power is becoming more and more popular in public transport. In relation to this a conclusion can be drawn that bilateral power supply of the traction network should become a standard solution applied in public transport, since it brings electric energy savings as well as improves voltage stability in the traction network. This is the cheapest way of enhancing the extent of regenerative braking. Unfortunately, this way of feeding power is practically not used in Polish public transport.

Another solution having its application in public transport is linking the busbars of two substations by means of stand-by feeders. Public transport power supply systems are characterized by very complex cable systems, which frequently allow for linking the traction substation direct current while busbars skipping traction networks. These connections make it possible for the energy recovered during regenerative braking to flow between the power supply areas of traction substations. An additional advantage of such a solution is lack of necessity to introduce fast current breakers dependencies between traction substations, which are necessary in case of classic bilateral power supply.

One of the other ways of enhancing regenerative braking effectiveness in the electric traction is the introduction of timetables coordination system, which increases the chance for simultaneous braking by one of the vehicles (a ride downhill) and a start-up of the second one (a ride uphill). However, this solution does not have a practical application in trolleybus transport owing to a considerable inequality of the vehicles movement caused by the traffic congestion.

As practice shows a crucial element having an influence on the extent of regenerative braking exploitation is a maximum voltage level in the traction network, up to which the realization of efficient regenerative braking is possible, and the higher this level the more efficient energy recovery. On the other hand though, too high a voltage may cause damage to other vehicles. As it has been already highlighted in the earlier part of the article in Gdynia a maximum level of this voltage is 750 V (at rated power supply voltage of 600 V). This factor is especially important in case of vast power supply systems, at which significant voltage drops occur.

The main findings can be summarized as follows:

1) The new method of trolleybus supply system simulation was introduced.
2) The irregular movement of vehicles has been included in the simulation model.
3) The analysis of breaking energy recovery from global perspective was realized.
4) The method of increasing of energy recovery where compared.
5) The impact and advantages of bilateral supply system was shown.

7. Conclusions

In the analyzed case (for the current Chwarszyńska substation power supply area) it is firstly recommended to introduce bilateral power supply. Whereas the decision about energy supercapacitors installation on traction substations must be preceded by a more detailed analysis. The model used does not provide an opportunity to conduct such an analysis. A principal disadvantage of the worked out simulation model is the lack of a possibility to determine the supercapacitors capacity. In the Monte Carlo method the state of the system is analyzed at randomly chosen time periods, which do not occur in succession. It is therefore not possible to take into account the state of the system in the preceding interval, and as a consequence it is not possible to determine the amount of energy in the supercapacitor. However, generally, acquired findings are enough to define potential possibilities of energy recovery.

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