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ENERGY SAVINGS BY APPLICATION OF SUPERCAPACITOR STORAGE IN TROLLEYBUS SUPPLYING STATION – ANALYSIS OF EXPERIMENTAL RESULTS

OGRANICZENIE ZUŻYCIA ENERGII W TRAKCJI TROLEJBUSOWEJ PRZY POMOCY INSTALACJI STACJONARNYCH ZASOBNIKÓW SUPERKONDENSATOROWYCH – WYNIKI BADAŃ EKSPERYMENTALNYCH

Abstract

In 2011–2013, stationary supercapacitor storage developed by the Electrotechnical Institute in Warsaw was put into trial operation in the trolleybus substation "Północna" (North) located in Gdynia. The article presents the results recorded during supercapacitor storage operation and discusses the impact of the storage on energy consumption savings. Guidelines for selecting a location for stationary supercapacitor storage were carried out based on exploitation experience.

Keywords: supercapacitor storage, trolleybus, vehicle supply system, regenerative braking, energy consumption savings

Streszczenie

W latach 2011–2013 na podstacji trolejbusowej Północna w Gdyni testowany był stacjonarny zasobnik superkondensatorowy Instytutu Elektrotechniki w Warszawie. W artykule przedstawiono wyniki jego badań. Główny nacisk położono na analizę wpływu warunków ruchowych na efektywność oszczędności zużycia energii za pomocą zasobnika. Wyniki przedstawione w artykule są oparte o dane pomiarowe i mogą stanowić pomoc do określenia miejsc dla instalacji stacjonarnych zasobników superkondensatorowych.

Słowa kluczowe: superkondensatory, trolejbusy, układ zasilania pojazdu, hamowanie odzyskane, oszczędzanie energii

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1. Introduction

One of the main advantages of electric vehicles is the possibility of energy recovery during braking, which is called recuperation. Recuperation allows for a reduction of the energy demand by re-using the breaking energy. In recent years, research in the field of storing and re-using regenerative braking energy has become very intensive. This is caused by an increasing number of vehicles equipped with recuperation systems and global demands for reducing the consumption of electrical energy.

In typical DC supply systems of the public transport (tramways, trolleybuses), recovered energy can be re-used by auxiliary receivers in a breaking vehicle or by the other vehicles. If there is no vehicle, which is accelerating at the same time, this energy is turned into heat in breaking resistors. In order to avoid such a situation, energy storage systems can be used, e.g. supercapacitors or flywheels. Nowadays, many energy storages are in operation in tram, trolleybus and metro systems. Optimisation of the parameters and location of storage devices for regenerative breaking energy has become very significant [1–6].

Storage devices can be divided into two groups: on-board energy storage devices, which are placed in the vehicles and off-board energy storage devices, situated in traction substations or between them. Current research is focused mainly on two objectives. The first is to reduce the energy demand by introducing on-board energy storages in light electric vehicles like trams, trolleybuses or electrobuses [7–9]. The latter is to provide a supplying system for heavy electric vehicles (trains, metro) with an off-board energy storage [10–13]. In contrast to this, a lack of research in the field of off-board storage energy systems for light electric vehicles can be noticed. Tram and trolleybus transportation is highly developed in plenty of European cities. Many tram and trolleybuses operators consider putting into service off-board energy storage systems. This motivated the authors of this article to analyse the efficiency of regenerative breaking in the trolleybus supplying system using off-board energy storage.

2. Energy flow in a trolleybus traction network

Catenary and supplying stations (substations) of the trolleybus supplying system are means for electric energy transmission, both derived by substation rectifier units and by vehicles regenerative braking. As a result, the parameters and operating conditions of the power supply system are crucial for the course of the recuperation process in the trolleybus network.

To enable vehicles to use recuperation energy, it is necessary to fulfil two main conditions:
•   the voltage generated by the vehicle during braking must be higher than the voltage of the traction network,
•   there must be a recipient of the energy generated during braking.

The second condition involves the energy conservation principle, which implies the need to balance the energy given to and collected from the traction network. In case of typical trolleybus substations, which are equipped with uncontrolled rectifiers, the only energy recipient may be another vehicle. Another aspect related to the fulfilment of the second

condition is the existence of possible flow of energy between the breaking and accelerating vehicle. Therefore, there must be a galvanic connection between the vehicles. Consequently, the vehicles must be on the same power supply section, or two different power supply sections yet powered from one traction substation. Only in case of bilateral power supply of the traction network vehicles can be found in the area of two different substations. However, bilateral power is rarely used for the trolleybus traction.

Figure 1 shows the flow of energy from regenerative braking for vehicles situated within one section of the power supply. In this case, energy is carried by the traction network directly, without the involvement of the traction substation. This is an optimal variant of recuperation, characterised by the smallest transmission losses. In real conditions, such recuperation may take place only in case of high traffic density power sections, where, on average, there are at least a few vehicles.
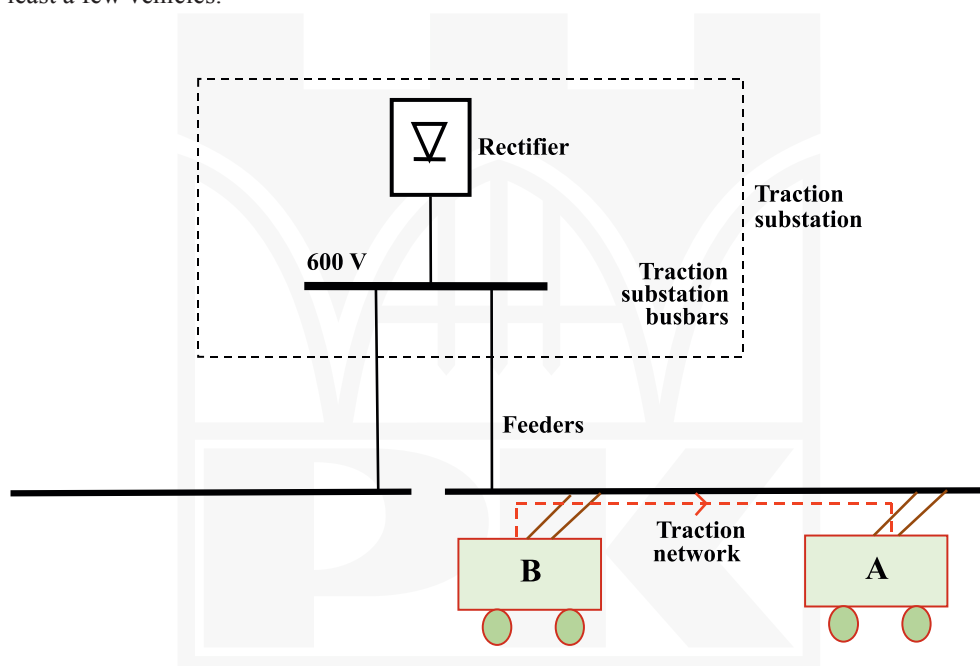
Fig. 1. Regenerative braking energy flow between vehicles situated at the same power supply section
(A – accelerating vehicle, B – breaking vehicle)

A more frequent case of regenerative braking energy flow is presented in Fig. 2, in which braking vehicle and receiving vehicle are on different power supply sections of the same traction substation. Electric energy flows through the feeders and traction substation busbars. This involves the occurrence of energy losses in the transmission of energy over a considerable distance.
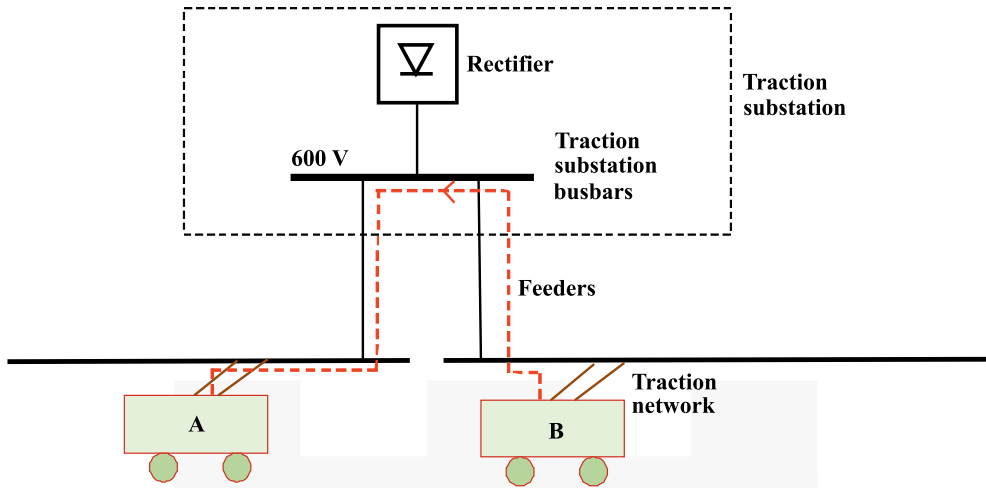
Fig. 2. Regenerative braking energy flow in case of vehicles located on different power supply sections of the same traction substation (A – accelerating vehicle, B – breaking vehicle)

3. Consideration of energy storage location

The aim of introducing energy storage is to collect recuperation energy when it is not possible to use it at the time of breaking. The stored energy can be utilised later, when the demand for power will appear. At the current advancement of technology, supercapacitor storages are the most promising option.

Supercapacitors may be placed in:
- vehicles,
- traction substations,
- locations close to the supplying system, but out of traction substations.

Placing supercapacitors in the vehicles involves increased trolleybus weight. As a result, the passenger volume declines. The weight of the vehicle storage system or a trolleybus is at a level of 500 kg, which means that the capacity will be reduced by 8 persons. In other words, for a typical trolleybus length of 12 meters, the capacity would decrease by 10%. Furthermore, an increase in weight results in a rise of electric energy consumption, which reduces the efficiency of energy recovery. Stationary electricity storages are not affected by those drawbacks.

From a technical point of view, the easiest solution is to place the supercapacitor storage inside a traction substation, as schematically shown in Fig. 3. The storage is then connected to the substation busbar. Such a solution does not require costly investments in construction and it is not associated with the problem of limited access to the urban area.

The load flow of the recovered energy, in the case of a supply system with the stationary supercapacitor energy bank, is presented in Fig. 4. Part of energy $E_{recuperation}$ generated in the traction drive during regenerative breaking is consumed by auxiliary receivers in the vehicle (lighting, heating, compressor, hydraulic pump etc.) – this energy was marked as $E_{auxiliary}$. The remaining energy is turned back into the supplying system and absorbed by other vehicles running within the supply section ($E_{network}$). The excess of the energy $E_{storage}$ is stored in the supercapacitor storage.
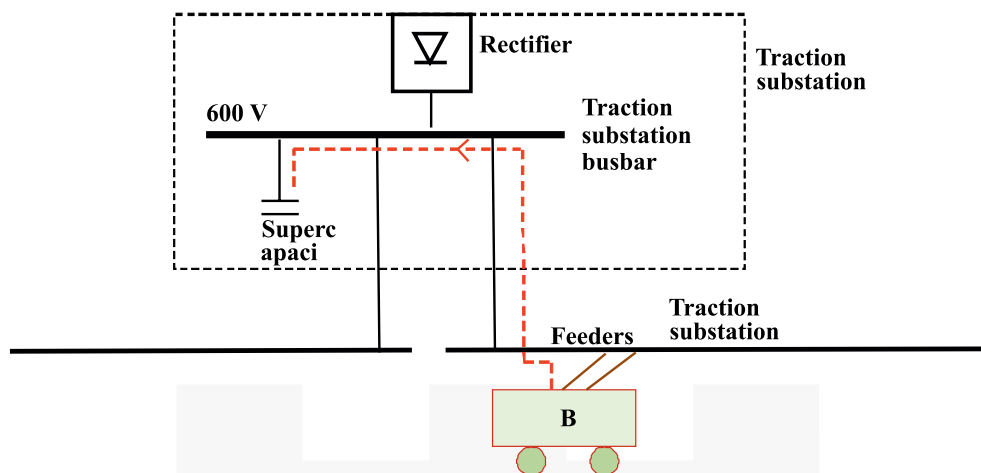
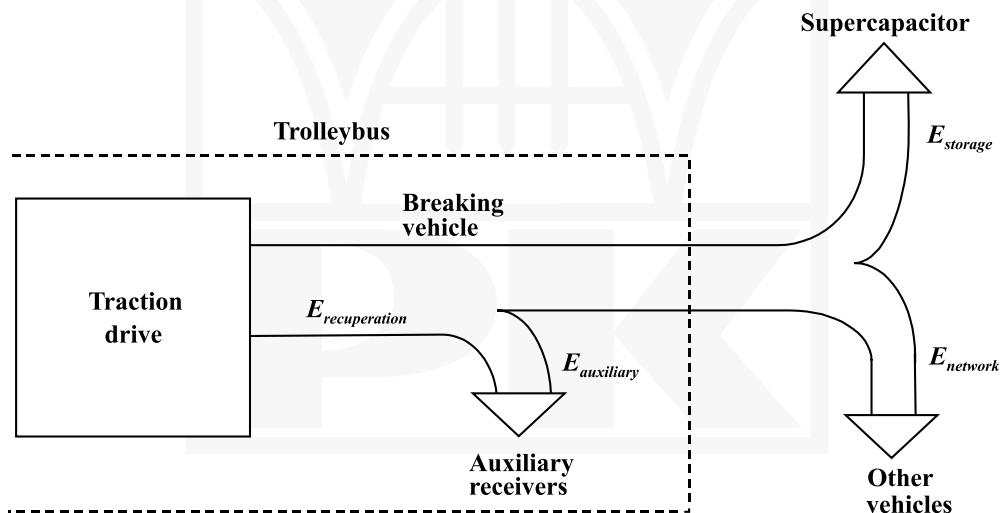Fig. 3. Placing a stationary supercapacitor in the traction substation

Fig. 4. The load flow of the recovered energy

4. Experimental setup

Experimental analysis of energy savings resulting from the introduction of supercapacitor storage placed in a traction substation was conducted in the city of Gdynia. Gdynia, with more than 250 000 inhabitants, is placed on the north side of Poland, by the Baltic Sea. Currently, there are 85 vehicles exploited in the trolleybus network, out of which 50% are equipped with recuperation systems. Energy savings in these vehicles, resulting from recuperation, are at a level of 20%.

A trolleybus is an electric rail-less vehicle of public transport, supplied from two-wire overhead catenary by two current collectors. The supply voltage is 600–800 V. The catenary is divided into sections, which are supplied from traction substations by feeders. The length of each supply section is ca. 1–4 km, the distance between substation is 2–10 km. The installed power of substation is 500–4 000 kW.

In 2009, the trolleybus transport company of Gdynia – 'PKT Gdynia', started cooperation with the Traction Department of Electrical Institute in Warsaw (IEL) in order to put into test the operation supercapacitor energy storage. The storage was designated for an installation in a trolleybus substation. The supercapacitor storage system was installed in April 2011. Research presented in this paper aim to provide an empirical model of determining the potential savings of energy consumption by introducing an energy storage unit. The influence of the road traffic density on the amount of energy accumulated in the supercapacitor storage was analysed.

The prototype of the supercapacitor storage was installed in the trolleybus traction substation "Północna". This substation was built in 1992. In 2010, it was completely renovated. Now, substation "Północna" is equipped with 2 rectifier units with 1200 kVA transformers and supplies 6 feeders. Nowadays, it is the biggest traction substation in Gdynia. The supercapacitor storage was placed in the space reserved for a possible installation of the third rectifier group (Fig. 5). The scheme of area supplied by substation "Północna" is presented in Fig. 6.

Fig. 5. Supercapacitor energy bank installed in the traction substation Północna in Gdynia;
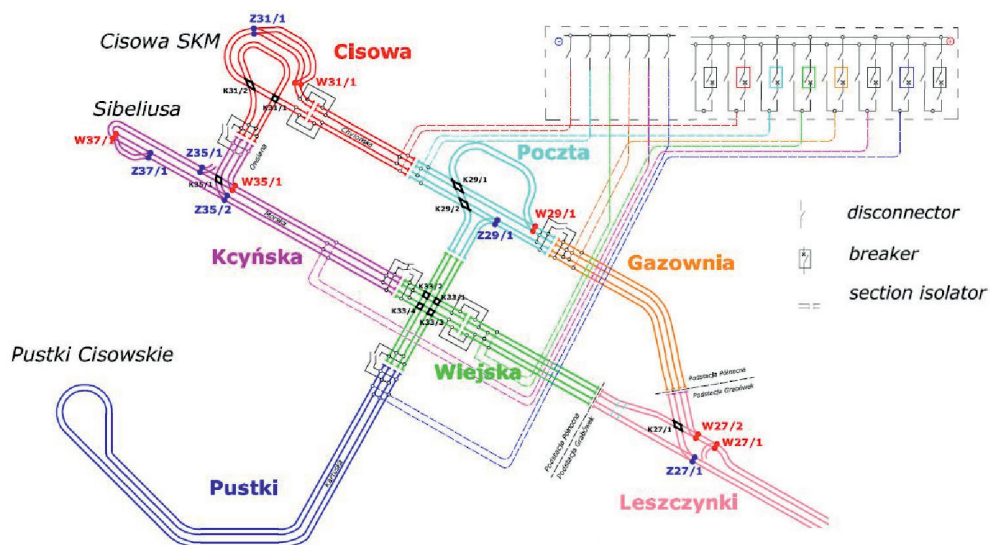1 – supercapacitor modules, 2 – DC/DC converter with the controller, 3 – protection modules and filter

Fig. 6. The scheme of supply area of the "Północna" substation

The supercapacitor energy storage consists of the following components (Fig. 7):
- Input module with the protection fuse and the input filter (F1, XO, CF1),
- 150 kW DC/DC converter (T0, T1, T2, D0, CF2, X1) ,
- 4 supercapacitor modules LS Mtron 201.6 V 41 F (SC1),
- supercapacitors discharge resistor R2,
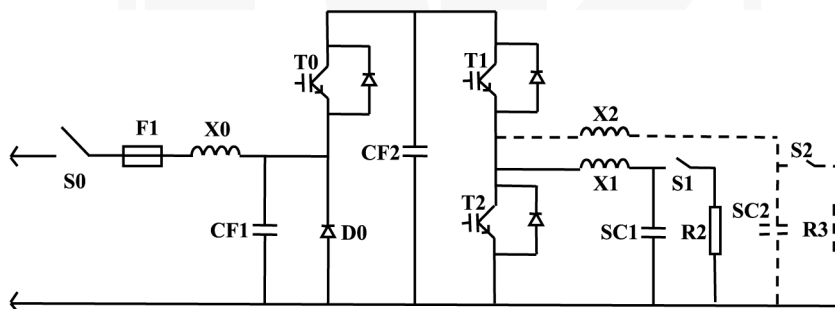- control system.

Fig. 7. Principal scheme of the supercapacitor energy storage

The energy capacity of currently installed supercapacitors modules is 0.7 kWh. Figure 5b shows the inside the supercapacitor system. The control algorithm of the supercapacitor system is based on measuring the busbar voltage U_F and the current of rectifier units I_r (Fig. 8).

The location of the supercapacitor system at the "Północna" substation was dictated by the organisational and operational aspects, but from an energy point of view, this substation is not an optimal choice for the installation of the storage system. The "Północna" substation
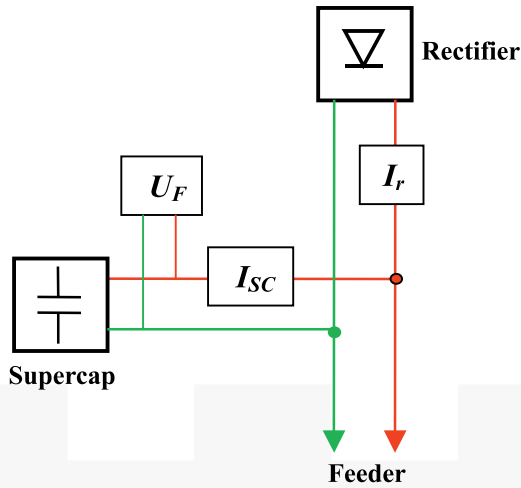
Fig. 8. Principal scheme of measurement points of the supercapacitor control system

has a vast supply area where, typically, many vehicles are on the run. This increases the probability of the energy flow between braking and accelerating vehicle. Therefore, the amount of unused recuperation energy is small and the installation of the supercapacitor energy storage becomes ineffective. In order to carry out the aimed research, connections setup of traction substation was modified, by blocking the flow of regenerative braking energy between the feeders. With this solution, it become possible to analyse the amount of energy accumulated from regenerative braking performed within a single supply section. It creates the conditions, which are present in the traction substation equipped with one feeder and it allows to test the supercapacitor system in different conditions of road traffic. The modification was conducted by placing the diode D in the standby switch circuit breaker WSR. A simplified diagram of the DC switchgear with the modifications is shown in Fig. 9.
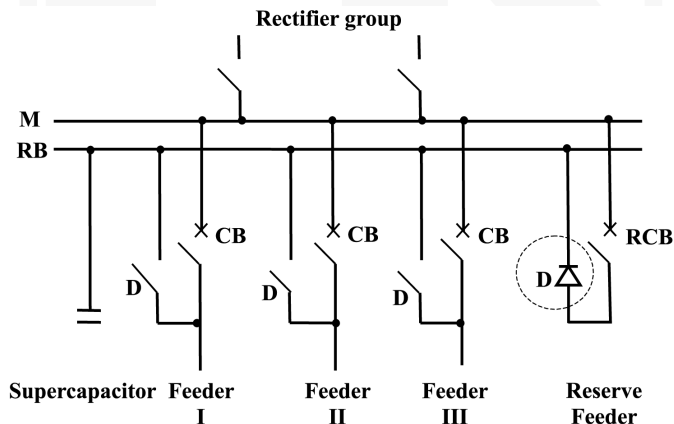

Fig. 9. Simplified diagram of the DC switchgear of traction substations with the modifications to the tests of supercapacitor energy storage

In the normal state of DC switchgear operation, currents flow from the rectifier groups by the main bulbar MB of the substation and the circuit breaker SB to the feeders. In case of regenerative braking, recuperated energy flows from the feeder, by the circuit breaker CB to the main busbar MB, and then is absorbed by other feeders. To block the flow of energy between feeders, a selected feeder must be switched to the supply through the reserve circuit breaker (RCB). It can be conducted by turning on the circuit breaker CB of the selected feeder, switching on the disconnector D of the selected feeder and switching the reserve circuit breaker RCB. Then, the supplying current flows through: rectifiers – main busbar MB – circuit breaker CB – diode D – reserve busbar RB-reserve circuit breaker RCB – the selected supply feeder. An additional diode D prevents the flow of recuperated energy to other feeders. When a vehicle recuperates energy, it is returned by the reserve busbar RB to the storage system. This way, it becomes possible to simulate conditions that occur in a small traction substation, with varying intensity of road traffic.

Figure 10 shows a selected part of the waveforms recorded during supercapacitor storage operation. Wavforms 1, 2, 3 are respectively: the feeder voltage U_F, storage system current I_{SC} and current absorbed from the rectifier groups I_R. A positive value of the storage system current means charging, negative – discharging. One of the instants of supercapacitor charging was marked by colour purple. The increase in the supply voltage during recuperative braking is visible. When the load of the feeder occurs, the supercapacitor is discharged – the load current is distributed between the storage system and rectifiers (circle of colour brown).
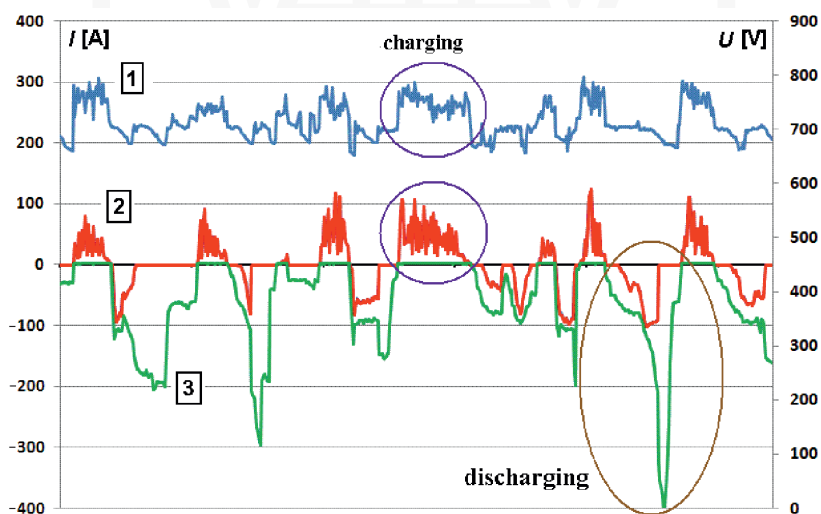

Fig. 10. A fragment of the recording of supercapacitor system operation, blue line – voltage of feeder, red line – supercapacitor current, green line – load current of substation rectifier

5. Measurement results

The main target of the measurements was to examine the work of supercapacitor storage with individual supply sections. As those sections are characterised by a variety of supplying area lengths, such an approach allows to evaluate the utility of the storage system in different traffic

conditions. The measurements of the storage system operation with individual supply sections were carried out within 10 days. Five feeders of the "Północna" substation were selected for the tests. The measurements were carried out during the day, between 9:00 and 19:00. At this time-range, the scheduled intervals of trolleybus traffic are constant. The measurements of the section "Gazownia" were made 4 times in different road conditions. Measurements "Kcyńska Wiejska" and "Gazownia Wiejska" refer to two supply sections slit together.

The measurements were recorded in two places: in traction substation and in the vehicles. This allowed to follow the amount of energy taken from the substation and stored in supercapacitor storage. This value was compared with the recording of the energy consumption of vehicles. As a result, the energetic balance was obtained.

The following parameters were registered:
- in the "Północna" substation:
  – voltage and current of the supercapacitor storage system,
  – voltage and current of the supply feeder,
- in vehicles:
  – voltage and current of the traction drive,
  – voltage and current of the auxiliary receivers.

Trolleybuses in Gdynia are equipped with the system of energy consumption management, which records the energy absorbed in the vehicle as well as the GPS position. It allows to determine precisely the energy consumed by trolleybus in individual supply sections. The registrations on the substation "Północna" were carried out by recorder HIOKI 8880, which was connected to reserve switch breaker field in DC switchboard.

The results of the measurements were post-processed in order to obtain:
- total amount of energy taken by feeder during a day,
- total amount of energy E_{stored} saved by supercapacitor system during a day,
- total amount of recuperation energy $E_{recuperation}$ recovered by traction drive in each of the trolleybuses on the chosen supply section,
- total amount of auxiliary energy $E_{auxiliary}$ consumed from the recovered energy $E_{recuperation}$ in each of the trolleybuses on the chosen supply section.

The part of recovered energy consumed by other vehicles $E_{network}$ was estimated as a difference between energy $E_{recuperation}$ and E_{stored} (Fig. 4).

The results of measurement analysis for vehicles are presented in the Fig. 11 and Fig 12. Fig. 11 presents the relative amount of energy recovered $E_{recovered}$ in trolleybuses equipped with the system of recuperation breaking. Fig. 12 presents the relative amount of recovered energy for a supply section. Those values are smaller than the previous because not every vehicle is equipped with regenerative breaking.

Figure 13 shows the values of $E_{auxiliary}$, $E_{network}$ and $E_{auxiliary}$ related to the total energy consumed by the trolleybus during running in individual supply sections. Fig 14 and 15 present the relation between the average number of the vehicles on the individual supply sections and the values $E_{network}$ and $E_{storage}$ referred to $E_{recovery}$.

It can be noticed that the load flow of the recovered energy strictly depends on the density of traffic on the supply sections. In case of the supply sections with high traffic intensity ("Wiejska", "Gazownia I" and "IV", "Kcyńska", "Kcyńska Wiejska", "Gazownia Wiejska"), the main part of the recuperated energy was absorbed by other vehicles which were running on the supply sections (Fig. 14). A large number of vehicles increases the probability of energy reception by other vehicles. On the other hand, when the intensity of traffic is small

("Gazownia II", "III" and "V"), supercapacitors store a significant part of the recuperated energy. The auxiliary receivers take 3.5–11% of the recovered energy, the amount of consumption mainly depends not on the traffic condition, but on the weather (heating and air-conditioning in vehicles).
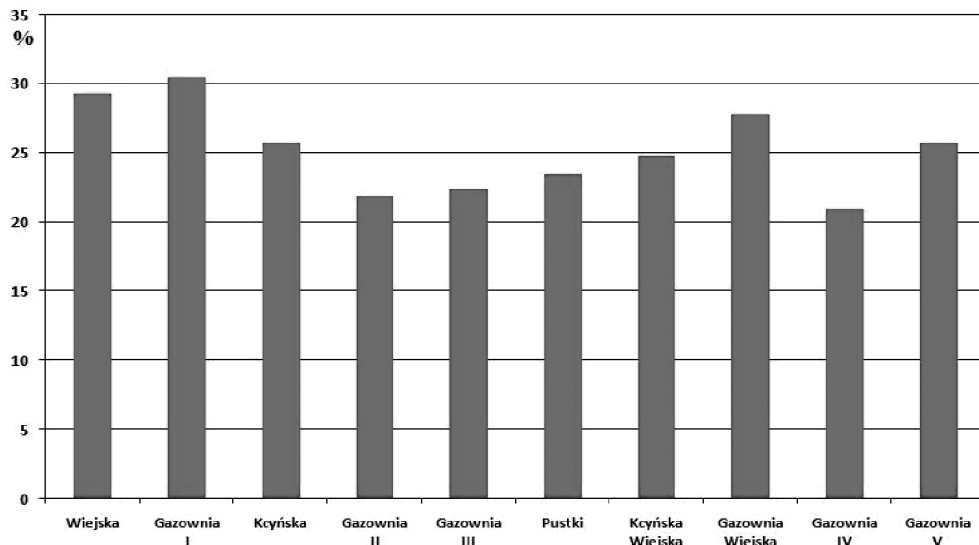
Fig. 11. The relative amount of energy recovered $E_{recovered}$ in trolleybuses equipped with the system of recuperation breaking
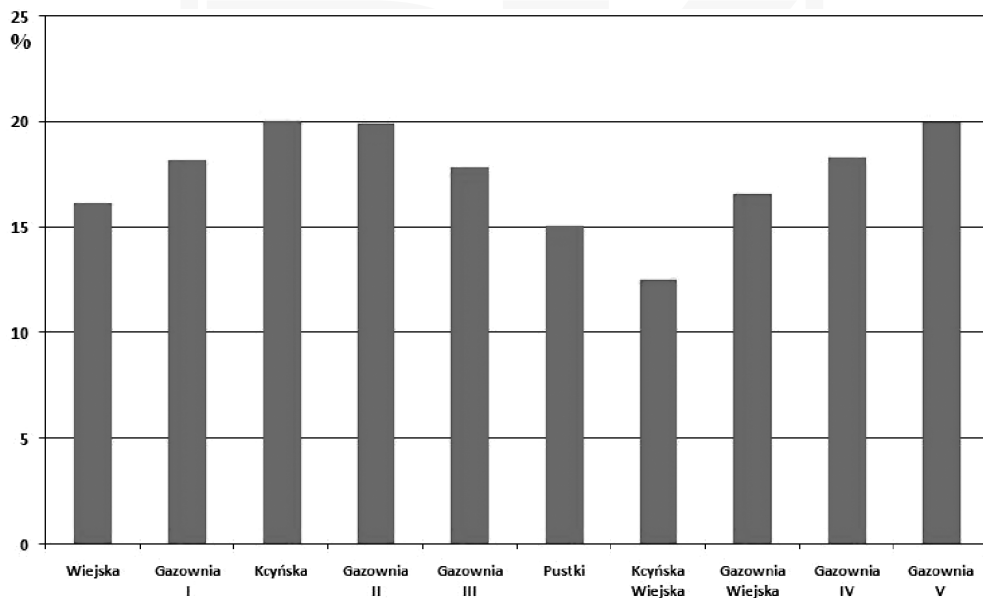
Fig. 12. The relative amount of recovered energy in all scale of supply section

The relation between density of traffic and the relative amount of recovered energy absorbed by other vehicles $E_{network}$ and saved by supercapacitor storage $E_{strorage}$ is presented in Fig. 14 and 15. It is easily seen that high traffic intensity conduct flow of regenerated energy on the way vehicle – vehicle, low traffic intensity conduct flow of regenerated energy on the way vehicle – supercapacitor.
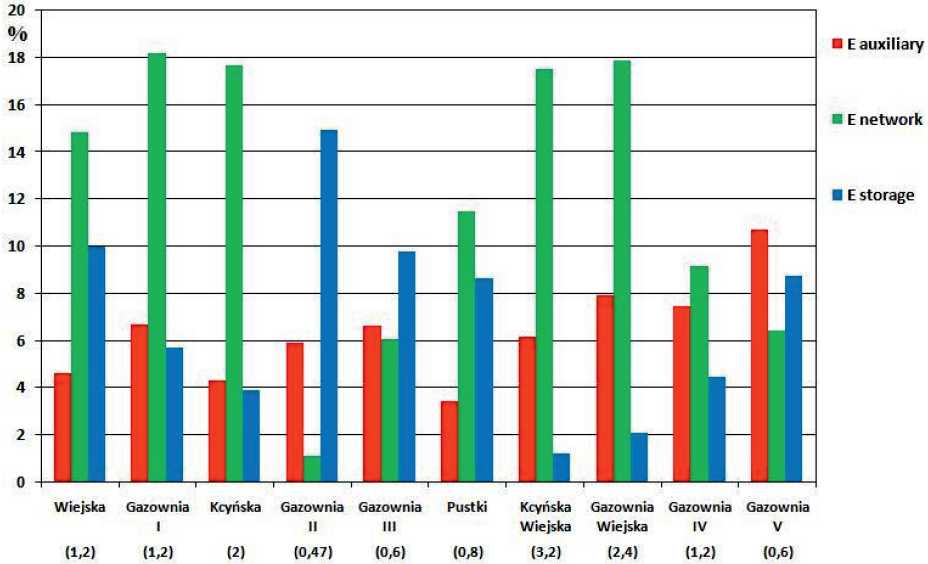

Fig. 13. The relatively amount of recovered in all scale of supply section – the average number of the vehicles on the supply sections is presented in the brackets
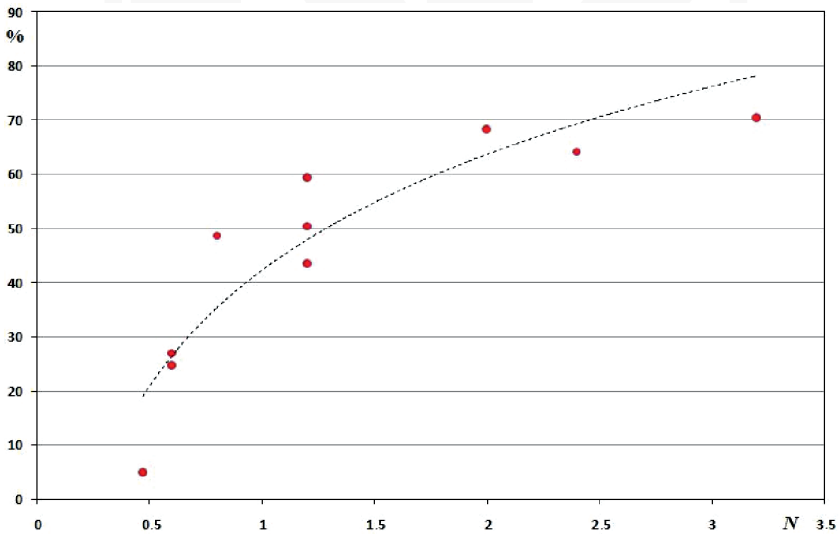

Fig. 14. Relation between the average number N of the vehicles on the individual supply sections and the value $E_{network}$ referred to $E_{recovery}$
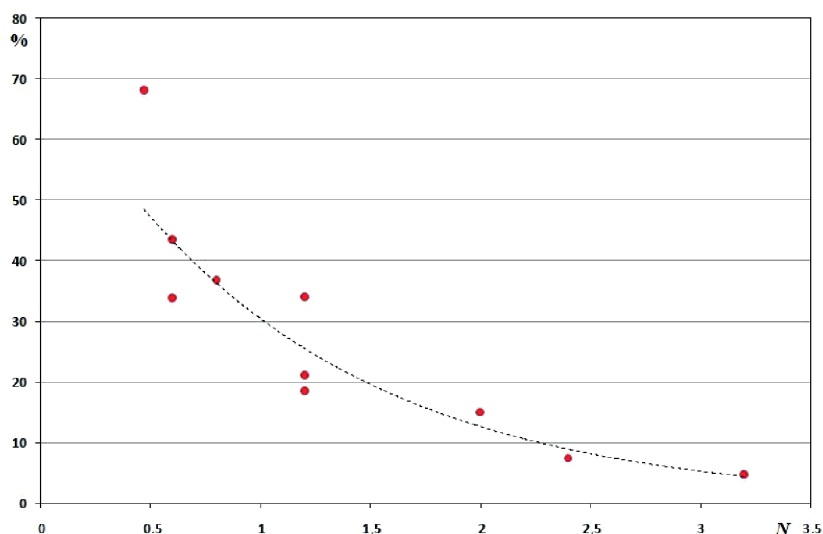
Fig. 15. Relation between the average number N of the vehicles on the individual supply sections and the value $E_{storage}$ referred to $E_{recovery}$

6. Conclusions

Recuperation allows for significant savings of electricity consumption – up to 35%. The use of energy storage in the analysed case resulted in a further decrease of the energy consumption by 15%. It should be noted that the energy savings resulting from the use of supercapacitor storage depend strongly on the operating conditions. In Gdynia, only 50% of all trolleybuses are equipped with a regenerative breaking system. In the future, the number of vehicles with recuperation will rise, and as a result, the savings related to the introduction of the storage system will be significantly bigger. Moreover, installing a supercapacitor system in a hilly area will bring significantly larger energy savings.

The fact that regenerative breaking energy can be consumed by other vehicles is often underestimated. Therefore, the expected effect of a installing supercapacitor system to store the breaking energy is overrated. Many countries, especially in Eastern and Central Europe, have a centralised power supply system with extensive areas of power supply and a large number of vehicles in motion. It can be concluded that, under these conditions, the benefits of installing the storages will be negligible. In many cases, the possibility of energy flow between vehicles can be increased by reconfiguration of the supply system, e.g. introducing a bilateral supply system, which increases the area of galvanic connected supply sectors, and as a result, increases the number of vehicles in traffic, which can exchange recuperated energy.

The potential energy savings may be achieved in the area of auxiliary systems in \ vehicle. Although, as shown by the measurements, the usage of recuperated energy is slight, it can be increased by improving the management system of the auxiliary receiver, for example, by using the recovered energy for heating the vehicle's interior.

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