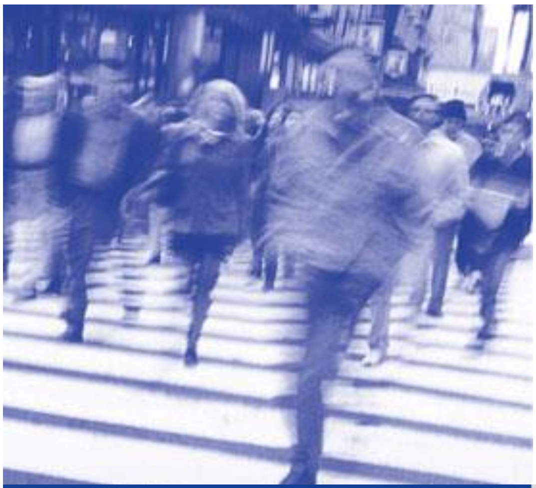

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Implementation Status Report G 2.2

Report on the efficiency of the installed supercap bank

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Report on the status of G 2.2 measure implementation

Report on the efficiency of the installed supercaps bank

29.01.2015, PKT Gdynia

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1. Supercaps bank storing braking recuperative energy of trolleybuses. Basic information.

1.1. Introduction to energy supercapacitor operation.

Contemporary electric vehicles may achieve high and at times even impressive energetic efficiency. The optimal usage of electric energy by vehicles is possible under the condition of adopting proper construction solutions both for the infrastructure and the vehicles themselves. For the choice of optimal in terms of energy but also economy and organization of construction solutions for electric vehicles what plays a vital, and frequently a decisive role is the place (e.g. topography of the traction network) and the way of exploitation.

Contemporary technology allows for taking advantage of a great potential of electric vehicles which is braking energy recovery. It obviously requires appropriate configuration of electric circuits, traction drives especially, which out of the nowadays manufactured ones are prepared for that any way, i.e. they do not need special complex extra systems (sometime only some additional output transistors allowing a natural outflow of energy into the supply system). Production of most today's power electronic traction drives does not generate a substantial increase in costs to recover braking energy when compared to their equivalents with electrodynamic braking lacking braking energy usage capability. It should be mentioned that in Poland legal regulations strictly demand electrodynamic braking in trolleybuses and trams. Although in rail vehicles electrodynamic braking is not required it gives considerable benefits, even though braking energy recuperation is not realized outside the drive system.

1.2. Physics and technique of a braking process.

The main purpose of vehicle braking is a controlled decrease in its speed or not allowing for its excessive rise in case of a down a hill ride, thus while braking kinetic energy resulting from the object's movement is taken from the vehicle and its form is changed. The law of conservation of energy states that taken energy must be given somewhere, i.e. altered into heat, electric energy, another kind of mechanic energy and/or another kind of energy in general. While electrodynamic braking, recuperative or non-recuperative, kinetic energy of a vehicle is changed into mechanical energy of rotational motion, which is received by electric traction motor (one or more) working as a generator, and the generated electric energy is subsequently sent further. According to the law of conservation of energy the energy generated by the traction motor must be received and sent further, as otherwise regenerative braking would not take place. So as to make braking a regenerative one, the energy generated by the traction motor during electrodynamic braking is sent outside of the drive to other electrical appliances in the same vehicle or by means of the traction network this energy could be sent out of the vehicle too. It often occurs that due to numerous reasons it is not possible to transfer the whole of braking energy to other appliances, but to keep the required force of braking its excess or this whole energy is lost in braking resistors, i.e. it is altered into heat which is given off to the environment. Electric vehicles equipped with electrodynamic braking, however without the energy recuperation system, sent all energy generated by the traction motor (motors) to braking resistors. In the examples discussed above the loss of energy in wires, motors and semiconductors was not taken into account.

An important condition for the efficiency of electrodynamic braking is ensuring the opportunity to make use of the highest power possible while braking. PKT Gdynia has at its disposal the traction network of a rated voltage of 600V, nevertheless the operational voltage may shift between 420 V to 800 V. What is perceived as a situation without the possibility to give braking energy back to the traction network is a situation when voltage exceeds 780 V and when it is lower than 420 V due to safety reasons as well as ensuring proper working conditions for the drive system. At times there occurs also a situation when the return of braking energy causes an increase of voltage in the traction network up to 780 V and thus a necessity to disperse the excess of braking energy in braking resistors so as to strictly prevent a further rise in voltage beyond 800 V. In PKT Gdynia traction network at most time and in most places there is a possibility to give over 100% of power, so also the braking energy not used by a trolleybus itself, by means of the network to other operating trolleybuses, however there are also spots where voltage reaches 770 V – 800 V, i.e. there is no full possibility to give braking energy back to the network. The analysis of the possibilities to give braking energy back to the traction network in case of PKT Gdynia trolleybus system was a subject of an extensive analytical study published in January 2013 within CIVITAS DYN@MO in the form of the Working Document no. G2.2/WD1 „Analysis of options for installing the supercap bank installations", on the basis of which PKT decided to install a separate supercapacitor at Wielkopolska traction substation.

Installing braking energy supercapacitors is also quite commonly applied in very vehicles, trolleybuses included. Such systems also have their energetic advantages and in addition they serve as an alternative source of power supply. However, due to typical characteristics of Gdynia trolleybus network and using traction batteries as the source of power supply for trolleybuses when out of the traction network, such a solution would not be advisable. If placed on Gdynia vehicles energy supercapacitors would remain practically unused. It should be also added that by the same size and weight traction batteries can amass much more energy than energy supercapacitors. Therefore, in Gdynia conditions, it was a much more optimal solution to install a separate supercapacitor collecting braking energy in places where there has been a frequent lack of full return of braking energy to the traction network.

The task of a braking energy supercapacitor is to catch and strore the excess of braking energy, which was not taken by trolleybuses and to give it back when the traction network is loaded by a trolleybus or more trolleybuses. In a system without the energy supercapacitor making full use of braking energy is possible only when in the moment of one trolleybus braking other trolleybuses take in the power not less than the given out one.

In order to better understand the operation of energy supercapacitor on Wielkopolska substation one can conduct a hypothetical experiment, i.e. to move in time braking, which would normally occur with incomplete energy recovery to the time when the traction network is loaded with trolleybuses being in the course of absorbing energy and the other way round. Though travel in time is impossible it is this very similar result we can imagine.

In real life the energy supercapacitor having exceeded some adjustable level of voltage on traction substation bus-bars starts to absorb such power so as to maintain this voltage. Adjusting the voltage to 735 V causes not exceeding the value of 740 V, and taking into consideration drops of voltage resulting from the flow of current given back to the traction network, between the collectors of a braking vehicle the voltage does not go beyond 770 V, i.e. braking energy dispersion in a braking resistor installed in a trolleybus is not activated. In this way braking energy is prevented from being dispersed. While voltage in the traction network falls below 690 V, and current is taken from rectifiers, which means loading with a trolleybus, the supercapacitor activates giving back the previously collected energy to traction network busbars.

2. Operation of the energy supercapacitor UCER-01 on Wielkopolska substation.

2.1. History of the energy supercapacitor UCER-01 exploitation.

In April 2014 installation of energy supercapacitor UCER-01 produced by the company MEDCOM was completed and a test start-up was conducted in cooperation with the company SESTO. In May 2014 on the basis of the data registered by trolleybuses a not completely optimal operation of the supercaps bank was discovered, as the device did not absorb the whole available excess of recuperation energy. These suspicions were proven and described in more detail by means of an oscilloscope with appropriate accessories. A correction made to the supercaps software program increased the level of energy charged to and discharged from the device by more than a dozen percent.

In July and August 2014 optimization of the appliance algorithm was being continued by a detailed analysis of the supercapacitor functioning on the basis of the registered data.

In September 2014 a possibility was introduced to remotely reconfigurate the supercaps bank, download the data from the recorder and observe its work in real time. From this time on mass collection of data has begun as well, the product of which analysis is this report.

In October and November optimization of supercaps adjustments was being carried out.

Basing on observations and a detailed analysis of registered data from several tens of days a few of adjustments of various parameters have been made.

As a result these activities produced even greater rise in the level of charged and discharged energy by other several percent, at the same time reaching nearly the highest possible level of usage of braking recovery energy in this system, i.e. total lack of excess energy dispersal by braking resistors in case of trolleybuses equipped with full recovery capability.

Further noticeable energy optimization of the system operation is only possible by a physical alteration of electricity connections of a substation and the traction network, as in energetic respect supercapacitor UCER-01 is now at its best possible setting.

Introduction of potential changes, and then the supervision of their consequences is solely viable due to simultaneous observation and analysis of the operation of the supercapacitor as well as trolleybuses with the ability to recover braking energy completely and to register their work.

2.2. The analysis of work and regulation of the braking energy supercapacitor UCER-01.

Braking energy supercapacitor UCER-01 gives a possibility of a remote change of settings and control of a device operation to a great detail. One of the project's assumptions was to gain broad experience in supercapacitor exploitation, which is only viable through close monitoring and analysis of its work.

The registrator built in UCER-01registers 43 physical values which are the result of measurements and calculations and 1 ordinal with a definition to every 1 second, which produces 3801600 numbers of data a day. Due to current needs 8 of these types of registered data undergoes a thorough daily analysis (processing), which means processing up to 691200 numbers on each 24 h daily operation. This provides an opportunity for a detailed energetic analysis of UCER-01 and a general one of Wielkopolska traction substation. As a result of experienced gathered so far it is being planned to expand this thorough analysis to other types of data in order to further analyze the operation of the appliance UCER-01itself, which will help to focus on potential current flaws of the equipment and change of parameters.

There is also a possibility to observe and set UCER-01 remotely. Remote observation and change of settings is viable thanks to internal company computer network. It is carried out by a special computer software program which enables also downloading the registered data. Thanks to solutions introduced remote change of the settings in UCER-01is possible and also immediate observation of its results, and if there is a need to do so one can quickly restore previous settings of modify them further. Drawing conclusions at once and introducing changes to the supercaps instantly led to a prompt optimization of UCER-01 work. This certainly would not be possible if we based our activities only on theoretical studies and reports underlying this project.

Data registered by trolleybuses turned out to be incredibly helpful, not to say absolutely necessary in the process of optimizing the supercapacitor's operation.
An influence of UCER-01 settings on electric parameters of trolleybuses during power supply from Wielkopolska substation was highly visible. The picture below highlights the importance of supercaps settings:

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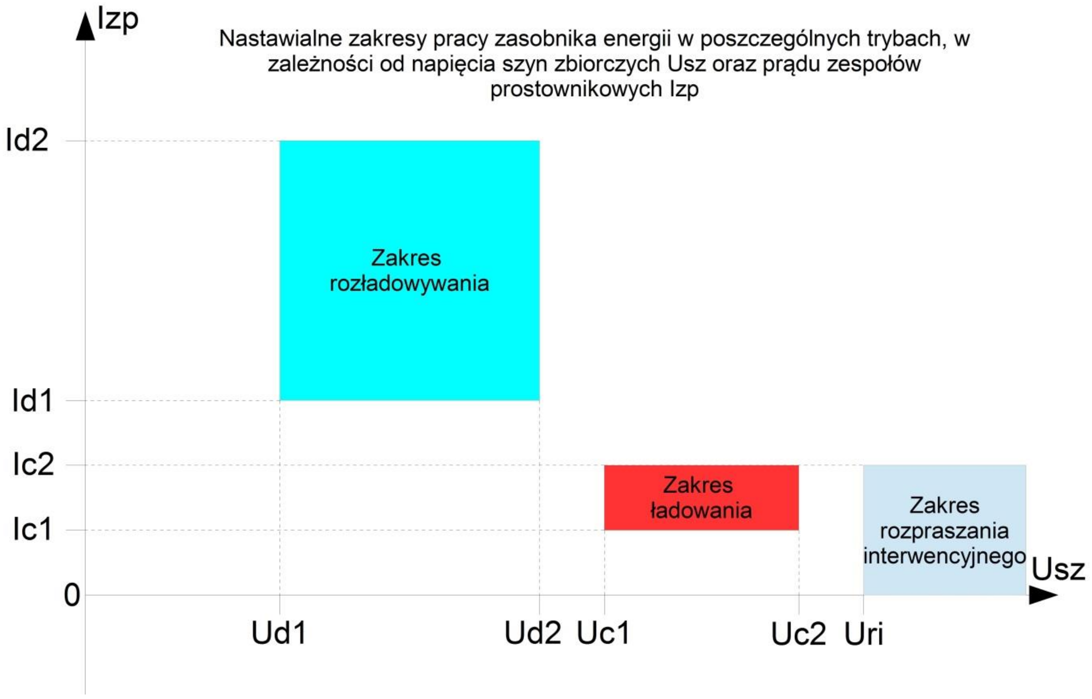
Pic. 1. Adjustable supercapacitor operating ranges in each mode



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The main task was adjusting the voltage on the busbars, i.e. the voltage by which there starts proper charging of supecondensers being a part of UCER-01, here Uc1. Inadequate settings might cause a total blockage of the supercaps operations or decreasing its efficiency. Change of settings required also taking into account the course of voltage in time. The voltage on main busbars of a traction substation does not contain only a permanent component, but also an alternating one resulting from the operation of 12-pulse rectifier system. What is more, the course of voltage changes due to the presence and activity of trolleybuses of different types. The effective, top and THD value of the voltage supplying power to the traction substation on the level of 15 kV has also an essential influence on the value of voltage on the main TS busbars, which should be taken into consideration too. One of the key parameters of a traction substation is voltage on main busbars in an idle mode, i.e. not loaded.

Considerable alterations in voltage were expected on the main busbars of a traction substation in an idle mode, however it turned out to be very stable, which points out high quality and stability of supplying substation with voltage of 15kV. Thanks to this voltage it was possible to come close with the setting of the supercaps Uc1 (minimal voltage by which the supercaps absorbs braking energy while keeping its value) to the voltage which occurs on the main busbars of a traction substation in an idle mode with a difference of ca. 13 V. In the period of running observations average daily voltage on TS main busbars in an idle mode was ca. 722 V with a divergence of ca. 1 V, whereas during the day the divergence is ca. 1 V. All in all, Uc1 was finally set to 735 V, which with regard to the necessity to stabilize the work of regulators means stabilization of voltage on TS main busbars during the energy absorption by the supercaps at the level of 740 V. Power dissipation in braking resistors of trolleybuses begins with the voltage of main traction converters filters as of 770 V to 780 V, i.e. with the setting Uc1 = 735 V, and by regulation of voltage on the main busbars at the level of 740 V we get a spare amount in case of a drop in voltage min. 30 V. In practice it means that if the fall in voltage caused by a braking current flow between a trolleybus and a supercapacitor through a resistance of wires will be lower than the aforementioned spare amount of 30 V, than we have a guarantee of a total nondissipation of the excess of energy in braking resistors at its complete consumption by a supercap.

According to the data registered by trolleybuses the voltage on the trolleybus collectors does not exceed 765 V during the absorption of the braking energy excess by UCER-01 on Wielkopolska substation even at very intense braking at the furthest point of the network in this power supply area. It shows that there is still some possibility to slightly adjust the work of the supercap by making minor settings. Although the optimal settings (taking into account the current conditions) for the supercap have already been made, one should still observe its operation due to the possibility of a permanent or temporary change of parameters of 15kV power supply. In case of any problems we could also correct the rectifier transformer gear on Wielkopolska substation.

The remaining settings connected with the absorption of the braking energy excess by UCER-01 bear any meaning predominantly as protection against not required operation states.

The setting Uc2 means the top limit of the absorption of energy by UCER-01. The value of the setting is Uc2 = 800 V. The voltage on the main busbars over 800 V during the braking energy absorption means and emergency mode, so it is safer to stop a regular operation of the supercap.

The settings of rectifier system currents Ic1 and Ic2 serve as a protection of the system against loading the supercondensers with energy coming from the rectifier system.

Ic1 = 0 A has only the verification role of the current measurements while Ic2 = 69 A is to refrain the supercap from working in case of a potential temporary jump in voltage 15 kV supplying the substation.

So that the supercap works at its optimum appropriate adjustments should also be made to the settings which are responsible for discharging the supercap, i.e. giving back the previously collected energy. Incorrect settings could cause full or close to the full charging of the supercap, which would make a partial or total take over of braking energy impossible. It would practically mean blocking of the equipment. Some values of the settings could also cause cyclic attempts to give back the braking energy to the unloaded traction network, i.e. artificial raising of the voltage in an idle state. Additionally, it could bring about some undesirable oscillations, and at the same time even some cyclic changes of the device operation mode.

The setting Ud1 has a character of a security against the supercap loading the traction network working in an emergency mode, i.e. during a short circuit or after turning off the rectifier system. What is more, this setting aims to stop the UCER-01operation in a situation when the voltage of the main busbars of the substation is lower than the highest possible voltage of supercondenser batteries, as it would require the change of DC/DC converter operation mode (it constitutes the UCER-01 block), which is not foreseen by the algorithm due to some essential reasons. At the moment the setting Ud1 is 400 V.

The setting Ud2 refers to the level of voltage of the traction substation main busbars below which it makes it possible to discharge the supercap, i.e. to give back the previously collected braking energy. At the moment the setting Ud2 is 690 V. In a normal situation the voltage of 690 V on the main busbars appears practically only after loading the traction substation by at least one accelerating trolleybus, that is when the opportunity exists to give energy from the supercap to the traction network. In case of supplying the traction substation from the network of 15 kV with a voltage reduced by several %, the voltage on the main busbars in an idle mode could be lowered below 690 V, i.e. below the Ud2 setting. In order to avoid such effects of the supercap incorrect operation there is also one more setting to be used Id1 = 100 A, which constitutes the minimal current of the rectifier system by which discharging of UCER-01 is possible.

The current of the rectifier system over 100 A and the voltage of the main busbars of the traction substation below 690 V make passing of energy from UCER-01 to trolleybuses viable. Although the current setting of Ud2 and Id1seem optimal, there have been attempts to correct them slightly, which caused higher average voltage of the supercondensers, including occasional full loading of the supercap by a simultaneous effect of a little reduction of rectifier system current peaks, which points to yet one more function of UCER-01.

The setting Id2 = 1500 plays also a protection role. If the current of the substation rectifier system is higher than Id2, it can mean an emergency mode, including a short circuit in a traction network or a trolleybus, i.e. the necessity to stop the supercaps work.

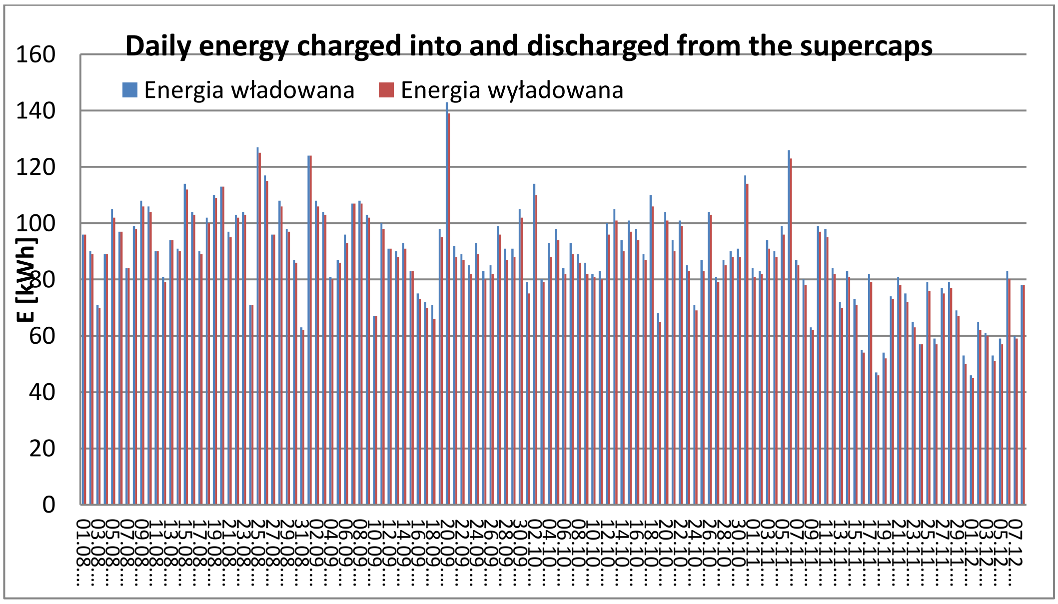
The setting Uri = 865 V has a protection function of the traction network against the excessive rise in voltage, which may arise due to incorrect operation of the supercap, the failure of the trolleybus drive during recovery braking, or other unexpected circumstances. If the voltage of the main busbars exceeds the value of Uri then UCER-01 will start the intervention dissipation of energy in the resistor until the excessive rise of voltage disappears or until the protection against the thermal damage of the resistor turns on. Including this function required some additional small amount of work while programming the supercap.

2.3. Results of the analysis of the data registered by the supercapacitor UCER-01. Electric and energy parameters.

Below are the results of analysis of some of the data for the period from 01.08.2014 to 12.08.2014 as a sample that best characterizes the device.

The period from 09.12.2014 to 30.12.2014 contains the days when the supercap was off for technical reasons, as a result of operational experience that proved it is possible to optimize the device UCER-01 by the manufacturer (the company MEDCOM from Warsaw). The optimization has exerted no significant effect on the energy parameters, but improves the working conditions of powerelectronic components. Due to the nature of the prototype, the supercap optimization was being performed in stages, which took several days. Taking into account the whole period would alter the results of the analysis and it would not provide the typical parameters of UCER-01.

The following graphic shows the daily energy values charged and discharged from the supercaps bank. As it can be seen the storage device in general takes more energy than it gives back, as about 2% of the energy is lost in the storage due to regular losses associated with the flow of current and, additionally, due to self-discharge of the supercapacitors. Self-discharging of the supercapacitors is especially noticeable at night, or when the supercap is charged and there is no trolleybuses traffic.



Pic.2. Chart of daily energy charged into and discharged from the supercaps

The graph also shows significant variation in the amount of energy captured each day, which is mainly due to the following reasons:

(1) A various amount of transport tasks in weekdays, Saturdays, Sundays and holidays.

The observation so far indicates that the largest energy capture by the UCER-01 can be expected on Saturdays, less on weekdays, and even less on Sundays. This is due to the fact that on weekdays a significant part of the energy output by the trolley is constantly consumed by other trolleybuses, that is without the participation of the traction substation and UCER-01. On Saturdays, Sundays and public holidays trolleybus traffic is less intense and the likelihood of the flow of energy between the trolleys is smaller as well, which is why most of the braking energy is recovered through UCER-01. You can see that on Sundays the probability of the flow of energy between the trolleys is even smaller than on Saturday, so UCER-01 plays a larger role in the recovery of braking energy then.

Tab.1. Average daily operation results of UCER-01 in various days of the week

Average daily operation results of UCER-01 in various days of the week						
Days of the week	Number of days	Average daily results in the period from 01.08.2014 to 07.12.2014				
		Charged energy [kWh]	Discharged energy [kWh]	Energy efficiency UCER-01 [%]	The energy discharged on the busbars of TS [kWh]	Relative savings from the work of UCER-01 [%]
Weekdays	92	89	87	97,8	1002	8,0
Saturdays	19	93	90	97,2	730	11,0
Sundays	19	81	79	97,7	557	12,4

(2) Different contribution of individual types of the rolling stock serving the area covered by the work of UCER-01.

The analyzed section is served by both types of trolleybuses – the ones with the recovery of braking energy to the traction network (the drives by the producers: 5 pcs. of IEL (DC), 10 pcs. of Enika, 32 pcs. of MEDCOM, 2 pcs. of CEGELEC but with incomplete recovery) and the ones completely without energy recovery to the traction network (22 pcs. of resistance DC; 1 pc. of IEL (DC simplified), 14 pcs. of CEGELEC). The share of individual types of trolleybuses in specific sections results mainly due to the organization and planning of traffic without taking into account their energy performance. Planning the traffic of trolleybuses with the recovery of braking energy to the traction network on specific routes in Gdynia conditions does not make sense, because in most areas of power there is almost full recovery of energy to other vehicles anyway. An exceptional area was the one supplied from the Wielkopolska TS until the launch of UCER-01 and also still less braking energy is recovered in areas supplied by the traction substations Sopot 1 and Sopot 2, where the traffic is really small.

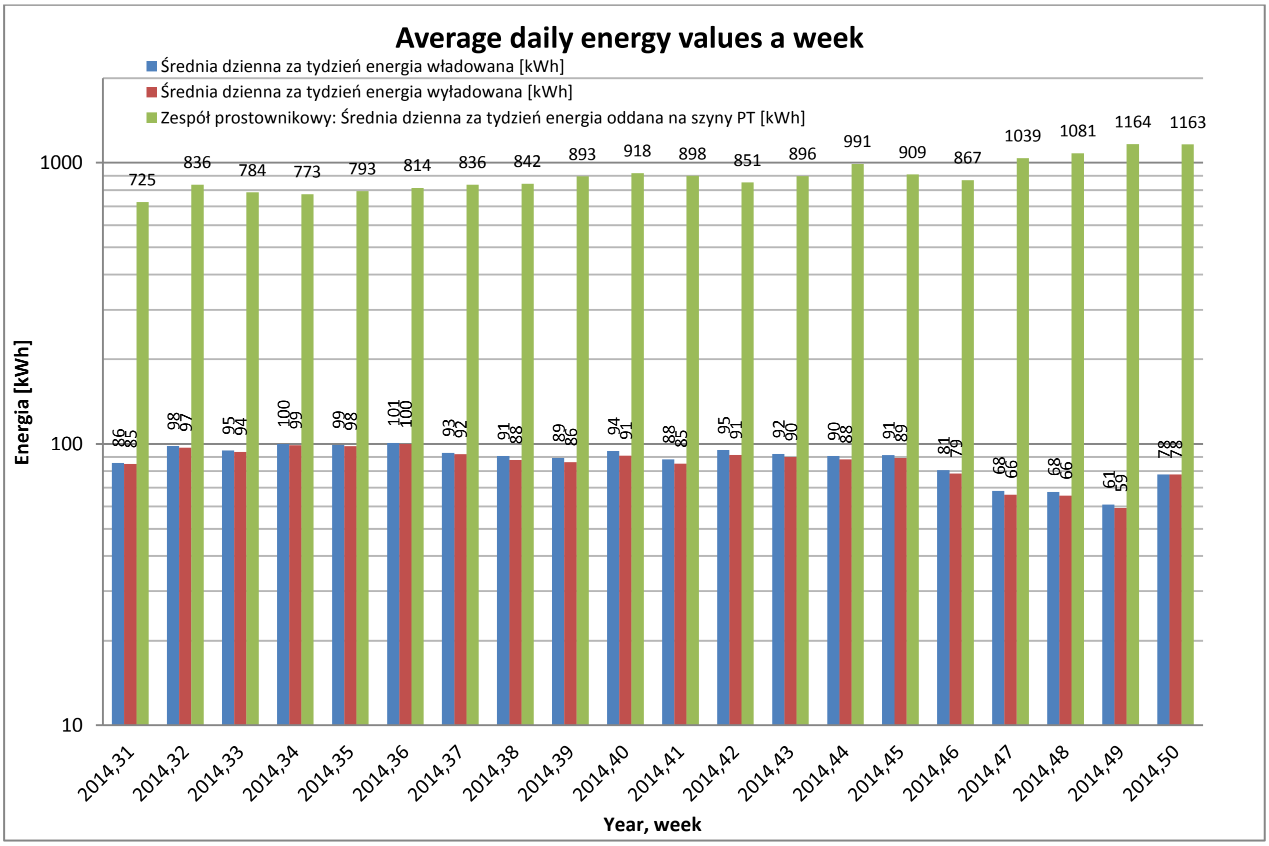
(3) Different weather conditions each day.

Turning on heating or air conditioning in trolleybuses increases the power consumption both while driving and during a stop, which significantly increases the likelihood of a partial or complete consumption of available braking energy by all trolleybuses located in the supply area. In this situation, a substantial part of the braking energy is recovered naturally without UCER-01.

Snow coverage on the road also exerts an impact on energy parameters of the trolleybus system, because it increases the resistance of motion resulting in longer start-ups and shorter braking.

The chart below presents the energy consumption on Wielkopolska substation and the energy charged and discharged by UCER-01 as daily average values for each week in 2014.

Pic. 3. Average weekly energy values of a supercapacitor operation



This form of presentation of the data helps to reduce the impact of random factors, which highlights the actual trends. You can see the influence of the seasons on energy consumption and the recovery of braking energy into the storage UCER-01.

The graph shows:

- A clear overall increase in energy consumption in 36 week of 2014, when a new school year began, which means there was been a slight increase in the modal split and in general in the number of passengers.
- From 37 to 45 week of 2014 there was noted a decrease in the recovery of braking energy by UCER-01, despite maintaining a slight increase in overall energy consumption. Autumn 2014 was characterized by relatively high temperatures, but still in the morning and evening the heating in trolleybuses was working in some limited extend.

- From 46 to 49 week of 2014 there was a significant decrease in recovery of braking energy by UCER-01 and an increase in overall energy consumption. These weeks were very cold cooling, so the heating in trolleybuses was working at its full.

Below there are general results of the energy storage device operation. It should be noted that the supercap caught nearly all the available excess braking energy, which trolleybuses were not able to take over at 1.45 km section, in both directions with the difference in levels of 33 m. Since 01.08.2014 only a few cases were registered when the charge the state of braking energy storage loading achieved the maximum 1.5 kWh of operation energy.

Tab.2. Energy results of supercaps operation

Energy results of UCER-01 supercapacitor's operation. Data as of 20.01.2015		
Energy supercapacitor	General from the beginning of exploitation	From 01/08/2014
Charged energy [kWh]	18838	13447
Discharged energy [kWh]	18472	13193
Average charged energy for 173 days from 01.08.2014 r. [kWh]	76,3	
Efficiency [-]	98,1	98,1

3. Possible further actions to improve the energy efficiency of the trolleybus traction system connected with Wielkopolska TS and UCER-01.

3.1. Extension of the energy supply area of Wielkopolska traction substation.

After launching UCER-01 the probability of recovering the braking energy from the supply area of Wielkopolska TS is very high. The level of recovery will not decrease even after extension of the area, and it will be the same also on the additional part of the extended network.

Other observations suggest that it is worth considering to extend the supply area of Wielkopolska TS to the adjacent section of Źródło Marii, which is now powered by TS Chwaszczyńska. The section of Źródło Marii with its length of 1.8 km ends at 0.3 km from Wielkopolska TS. This undertaking should reduce the voltage drops and the energy loss at the same time. Potential implementation of these changes can be followed by the deterioration of the energy efficiency on the area powered by TS Chwaszczyńska.

Any action should be preceded by a thorough and comprehensive energy analysis and include the consideration of possibilities to introduce changes in the infrastructure.

3.2. Coupling of the energy supply areas of Wielkopolska, Redłowo and Chwaszczyńska traction substations.

Energy coupling would allow the power flow between areas supported by different traction substations, surely limited by resistance of network and coupling devices. Such action would significantly increase the probability of recovering the braking energy and it would reduce the losses of energy caused by the flow of current through the resistance of the wires. The device UCER-01 after some relatively small changes in the program could act also as a load-leveling device in order to further reduce the losses associated with the flow of current through the resistance wires.

The energy coupling of areas powered by different TS is possible with the use of isolated coupling or an introduction of a two-way supply. These activities can greatly complicate the coordination of overcurrent protection on different TS.
Any action should be preceded by a thorough and comprehensive energy analysis and it should include analysing the possibility of changes in the infrastructure.

4. Conclusions concerning the efficiency of the installed energy supercaps bank

The experience gained by exploitation of UCER-01 at the Wielkopolska TS can hardly be directly transferred to any other new investments. The same device will operate differently in each location. A possible similar investment should be analyzed individually, because many factors affect the way of work and the energy efficiency of the energy storage. The point of using the braking energy storage device in another network should be analyzed by professionals with a vast knowledge of the stock operated by them, its infrastructure, and traffic. It is also necessary to run a comprehensive observation of the electrical characteristics present the traction network.

The UCER-01 device installed within the CIVITAS DYN@MO project at Wielkopolska TS in Gdynia is working as expected and it is at full readiness for managing the excess of braking energy, and has an optimal electrical parameters such as energy capacity, power and efficiency. The UCER-01 device from company MEDCOM (Warsaw) could probably be successfully applied in any other trolley traction network, if such need was be discovered by experts. The device UCER-01 has the ability to achieve significantly better technical results than on Wielkopolska TS if the local conditions allowed for that.

In conclusion, the braking energy storage devices installed on traction substations can bring significant energy savings if it is installed in a place where:
- trolleys with full recovery of braking energy are in use;

- traffic of the trolleybuses is relatively small, but big enough so that the investment could be profitable. In the analyzed section of the network all the time there should work at least one but no more than two trolleys at the same time;

- the trolleybus stops are quite frequent, yet between them trolleys usually achieve a significant speed, so they hardly run in an idle mode.

A detailed and comprehensive technical and economic analysis will be carried out in the final phase of the project (the second half of 2016.), and it will verify the profitability of the investment.