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SMART GRID TECHNOLOGIES IN ELECTRIC POWER SUPPLY SYSTEMS OF PUBLIC TRANSPORT

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Abstract

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. It can be achieved by reducing the transmission losses in a supply system or by the improving the usage of the regenerative breaking. The article presents an analysis of applying these two options for increasing recovery energy by application of Smart Grid solutions in public transport systems. Analysis will be based on the example of trolleybus transport system in Gdynia.

Keywords trolleybuses, Smart Grid Systems, energy recuperation, electric traction, traction substation, energy savings

1. Introduction

The development of zero-emission public transport is one of the elements of the horizontal EU policy. Municipal transport is currently responsible for 40% of CO_2 emissions of the entire road transport in Europe. The transport sector is responsible for 30% of total energy consumption and 27% of greenhouse gas emissions. Greenhouse gas emissions must be reduced by 60% by 2050 [1, 2]. What is more, the instability of prices of liquid fuels has an extremely negative impact on the economy. Therefore, it becomes necessary to use more alternative energy sources in public transport [3, 4].

An alternative to liquid fuels is electricity. Today, we may notice an increase in the popularity of electric cars and electric buses powered by automotive batteries; however, the most effective way of providing electricity to vehicles is still a unipolar overhead line, as is the case for rail vehicles, or a bipolar line in the case of trolleybus service. Unfortunately, a large part of Europe's electricity is obtained from thermal power stations, which are also a source of greenhouse gas emissions. For this reason, the development of electric means of transport is actively supported by the European authorities, as evidenced e.g. by funding initiatives popularizing ecological municipal transport systems from the Community budget. An example of such a project is *Trolley* [6], which was implemented in the years 2010–13 and was aimed at popularization of trolleybus service and development of energy-saving technologies applied therein. A similar project is the *Actuate* project, which aims to highlight the importance of driving techniques for the energy consumption of electric transport and the implementation of the so-called eco-driving concept. Currently, a group of selected European cities implements the *Dyn@mo* project whose aim is the development of modern, energy-efficient technologies in public transport. The program directed solely at the technical aspect of energy efficiency of tram service is *Osiris*, which involves transport companies and manufacturers of broadly understood electrical equipment for trams [5, 6]. The purpose of the article is to point out the importance of the spatial structure of municipal overhead line power supply system to energy consumption and to demonstrate the possibility of reducing the energy consumption of municipal transport with Smart Grid solutions.

2. The structure of the power supply systems of municipal electric traction

Any electrical machine is able to work in two directions of energy flow. In the case of traction motors, this means the possibility of generator operation during braking of the vehicle, involving the conversion of vehicle kinetic energy into electrical energy, thereby production of the braking torque. This energy was at first dissipated in braking resistors located in the vehicle. The development of electric drive systems, especially high-power semiconductor drives, resulted in the spread of recuperation in trams and trolleybuses. It involves recuperation of electric energy during braking of the vehicle, and its re-use [11-14].

Important issue is to ensure the conditions for the use of electricity generated during braking. In the classic supply system, where substations are not equipped with the energy-storing devices, the flow of recuperative braking current may take place in two ways [11, 16]:

1) in the path: vehicle – overhead line – vehicle, when the braking vehicle and accelerating vehicle are in the same power supply section,
2) in the path: vehicle – overhead line – feeder – busbars of the traction substation – feeder – overhead line – vehicle, when the vehicles are in two power supply sections.

In both cases, the recuperation energy is absorbed by the second vehicle in the power supply section able to receive the energy, i.e. the vehicle is in motion. However, in common situations in the power supply areas, there are no vehicles able to absorb the energy. Then the recuperation energy is dissipated in the braking resistors. The result is under-utilization of the potential for recuperation. It can be concluded that the greater the area of substation supply is, the greater will be the chance of finding a recipient of energy during regenerative braking, i.e. the greater will be the number of vehicles that may receive that energy. For this reason, it is advantageous to build vast power supply areas to accommodate many moving vehicles. An alternative is to collect braking energy in electricity banks or to convert it to alternating current and return it to the power supply network.

In addition to the effective use of recuperation, the spatial structure of the overhead line power supply system affects the energy transmission losses in the overhead line. Transmission losses are dependent on resistance of the conductor, or power cables and the overhead line. This in turn depends on their length. The increase in the distance between substations, increased length of the power cables increases the transmission losses. A significant source of energy dissipation in the supply systems are losses in long power cables, whose length can be up to several kilometers [14].

3. Smart Grid technologies in municipal overhead line power supply systems

Contemporary urban overhead line power supply systems consist of many elements: traction substations, vehicles, energy banks, vehicle charging stations, remotely-controlled overhead line disconnectors. Thus, it becomes necessary to provide an adequate structure of urban overhead line power supply systems that would enable optimal use of all elements of the power system and to ensure synergy between the individual elements. Accordingly, the municipal power supply systems become the dissipated energy networks with many sources of power supply, receptions of a different nature and the possibility of dynamic reconfiguration. Therefore, it becomes necessary to apply the Smart Grid technologies applicable in the commercial power industry [17 - 18].

The following Smart Grid technologies may be used in the municipal overhead lines:

1) charging stations for electrical buses and cars supplied from the overhead line, which may use the recuperation energy of vehicles [18, 19],
2) remote control of the disconnectors system in the overhead line, enabling immediate reconfiguration of the power supply of the overhead line in the case of damage,
3) smart protection devices allowing for detection of damages in the overhead line from remote network systems,
4) stationary and vehicle energy banks: supercapacitors, storage energy systems,
5) traction substation inverters to return recuperated energy to AC supply system.

The possibilities of reusing of regenerated energy are presented in Fig. 1.

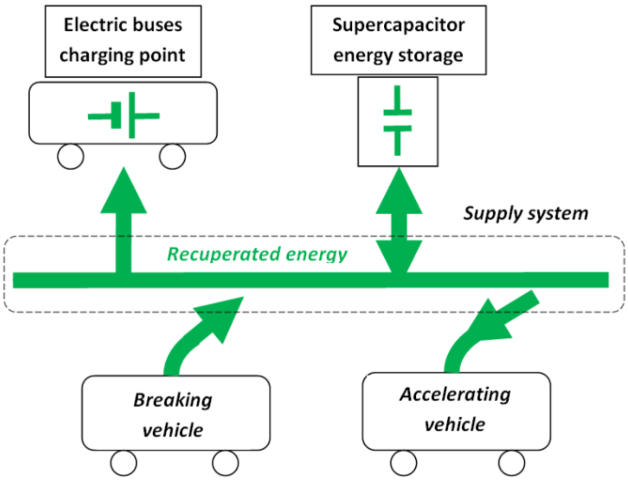

Fig. 1: The scheme of the recuperated energy load flow in a Smart Grid supply system

3.1. Modernization options for the power supply system

Gdynia is a harbour city at the Baltic sea with a population of 250,000. In 1943, its trolleybus network was put into operation and gradually developed, later to become the largest in Poland. Gdynia's trolleybus carrier, Przedsiębiorstwo Komunikacji Trolejbusowej (PKT), currently operates a fleet of 85 trolleybuses on 12 services in a network the length of which reaches almost 50 km. Gdynia's trolleybus network is powered from 10 traction substations in a unidirectional supply system. The traction substations differ with respect to the size of areas to which electricity is supplied and the number of rectifier sets, each substation powering 1 to 6 sections. Gdynia's trackless trolleys consume nearly 10 GWh of electrical energy per year and are considered one of the biggest energy consumers in the city. Therefore, one may reasonably expect that some steps towards reducing power consumption would be appropriate [6, 7]. In the article the study of improvement of Gdynia trolleybus supply system is presented.

The three parts of trolleybus system are the subject of analysis. They are supplied by the following substations (Fig. 2):

- Substation Grabówek – named as substation No. 2,
- Substation Redłowo – named as substation No. 6,

- Substation Sopot – named as substation No. 7,
- Substation Sopot Reja – named as substation No. 8,
- Substation Wielkopolska – named as substation No. 9,
- Substation Chwaszczyńska – named as substation No. 10.

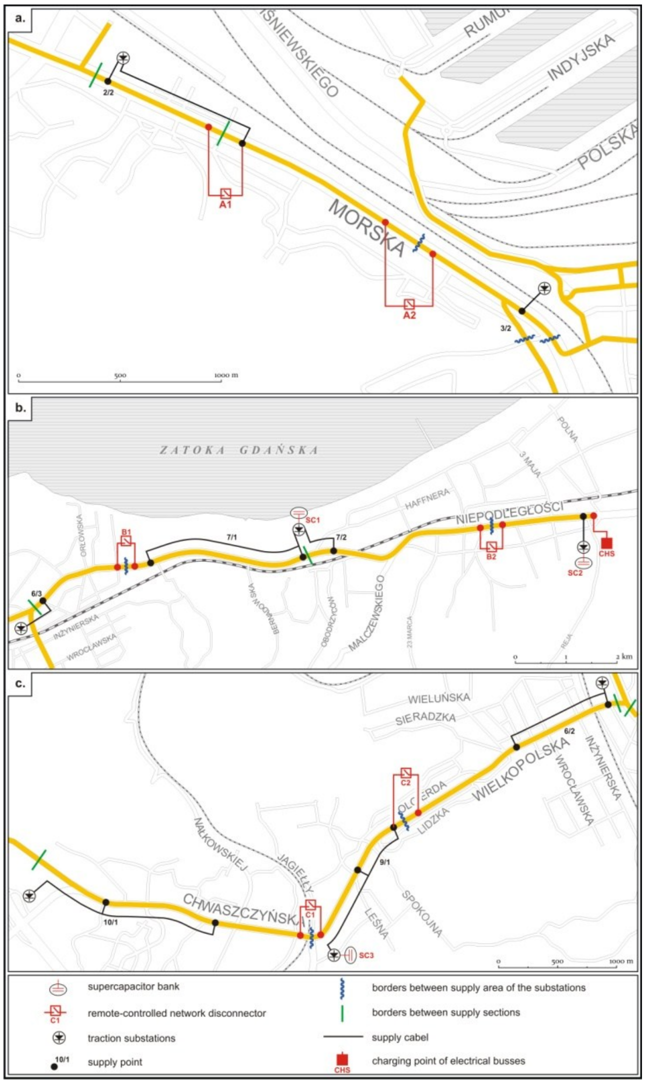

Fig. 2: Three parts of the Gdynia trolleybus system which are the subject of analysis: modernization options for the power supply system

The comparative analysis included three options for power supply of the described areas:

1) The present state
2) The supercapacitor banks' system SC1 and SC2 in substations 7 and 8 (Fig. 2b) and SC3 in substation 9 (Fig. 2c).
3) Modification of the power supply system by introduction of the Smart Grid technology. It involves the installation of remotely-controlled switches connecting power supply sections:

- A1 between sections 2/2 and 2/3 (Fig. 2a),
- A2 between sections 2/3 and 3/2 (Fig. 2a),
- B1 between sections 6/3 and 7/1 (Fig. 2c),
- B2 between sections 7/2 and 8/1 (Fig. 2b),
- C1 between sections 10/1 and 9/1 (Fig. 2c),
- C2 between sections 9/1 and 6/2 (Fig. 2c),

and electric buses CHS charging stations in the supply section 8/1 (Fig. 2c).

Calculations were performed using the Monte Carlo simulation method [11, 20]. The power of charging electric buses in the CHS charging station (Fig. 2c) at the level of 100 kW.

4. Monte Carlo simulation 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 accumulations of an algorithm, then

$$f = \lim_{n \to \infty} f_n \tag{1}$$

Process performs a limited number of iterations before it is stopped. This process is strictly determined: every algorithm results in an identical solution [14].

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. Utilising 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 $e > 0$:

$$\lim_{n \to \infty} P\left(\left| f - f_n \right| < \varepsilon\right) = 1 \tag{2}$$

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 computational process is not deterministic as it is defined by set of random samples' outcome.

Methods using algorithms that rely on repeated random sampling to obtain are called Monte Carlo methods. In this method, precise assessment of various relationships between the input data and searched values is not necessary to precisely. That states for a great advantage of such approach thus enabling multiple factors' impact analysis. Monte Carlo method is also used to analyse sophisticated stochastic controls that are too complicated to be modelled utilising the analytic approach (i.e. arrays of stochastic processes) [11].

Continuing, we are able to model system of electric traction power supply [11, 20]. In this case 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. 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.

The simulation model is based on the following input data:

1) trolleybus timetables,
2) deviations in the implementation of timetables that are designated using studies of punctuality of public transport conducted by ZKM Gdynia
3) trolleybus velocity profile – the relationship between the expected speed of vehicles and their location,
4) traction characteristics of trolleybuses.

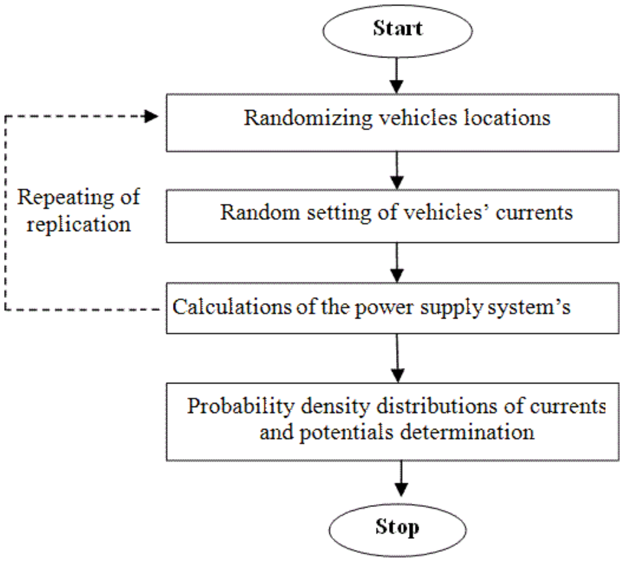

Fig. 3: General scheme of the traction power supply system simulation model using the Monte Carlo method

A histogram of the probability of the number of vehicles located within a power supply section at the same time was established using timetables and deviations from their implementation. The velocity profile, i.e. the relationship between the location of vehicle *s* and its expected velocity *v*(*s*) was the basis for determining the probability distribution of the location of individual vehicles along the power supply section (Fig. 4, 5).

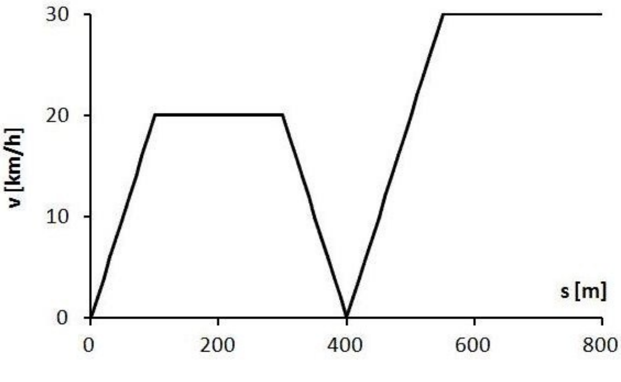

Fig. 4: A layout of the vehicles velocity profile *v*(*s*)

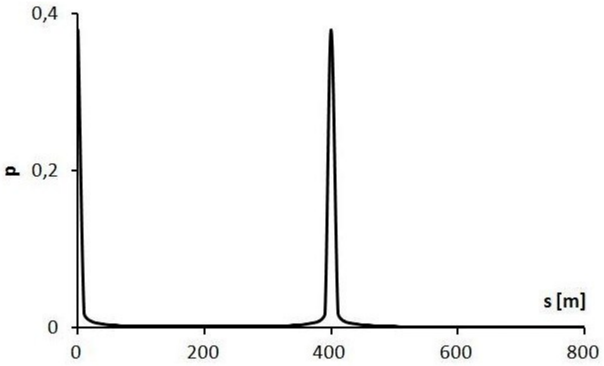

Fig. 5: A layout of the vehicles location probability *p*(*s*) for the velocity profile from Fig. 4

This probability *p*(*s*) was inversely proportional to the expected velocity at a given location. The operating status of the drive unit and then the trolleybus current were determined using the derivative of the velocity profile (accelerating, breaking). The currents and voltages in the power supply system were calculated iteratively using the node-voltage analysis until reaching the convergence of voltages *V* in the calculation model. Fig. 3 provides a simplified diagram of the simulation model.

Fig. 6: Remotely controlled disconnectors of the overhead line (the city of Gdynia).

An important issue related to the implementation of bilateral power supply in an overhead line is to ensure effective breaking capacity. In the case of long power sections supplied from two substations, there may be a situation where short-circuit current is too low for effective switching of a protection device. This is due to low popularity of bilateral power supply in municipal transport power systems. However, technology of the modern protection devices can solve this problem. It is now possible to equip traction substations with time-current protections and differential protections, which help to locate even the distant short-circuits in the overhead line. Those protections may be connected by means of a GSM network with a remotely-controlled overhead line disconnectors (Fig. 6) which, in the case of detecting a short-circuit and its interruption, automatically reconfigure the supply system. This allows for reduction of the area without power in the event of a damage to the overhead line.

Fig. 7: Electric bus charged from the trolleybus overhead line (the city of Pardubice).

It is proposed that the Sopot Reja turning loop was equipped with a charging point CHS for electric buses (Fig. 7). It is the integration point of trolleybus and bus transportation, intended as the starting point of many lines of electric buses serving the city of Sopot. The electric buses can be the receivers of recovered energy - this energy can be use for purposes of charging. Thus, it is reasonable to use trolleybus power system and an overhead line for charging electric buses, which will help increase the use of recuperation energy. The solutions of charging electric buses from the trolleybus network are tested in several European cities (Fig. 7).

5. Results of simulation analysis

Table 1 presents comparison of the results of calculations for the analysed options. It also presents financial overlays related to the implementation of each of those solutions. For simulation purposes, it was assumed that the entire rolling stock is fitted with regenerative braking. The trolleybus lines are served with Solaris Trollino 12 equipped with traction engines with a capacity of 175 kW and weight 15 000 kg.

Table 1 Results of the comparative simulation analysis

	Area I		Area II			Area III		
	Option I	Option III	Option I	Option II	Option III	Option I	Option II	Option III
Power input	454 kW	432 kW	58 kW	48 kW	48 kW *	293 kW	262 kW	268 kW
Transmission	11%	8%	7%	6%	5%	10%	10%	7%
Energy recuperation level	23%	24%	8.4%	23%	23%	30%	34%	33%
Use of energy recuperation	88%	91%	34%	92%	92%	80%	96%	94%
Financial outlays	-	20 000	-	200 000	20 000	-	100 000	20 000

* does not include charging power of electric buses

6. Conclusions

Introduction of two Smart Grid tools is presented in the article:

- bilateral supply of overhead catenary,
- charging station for electric buses.

The synergy of these solutions allows for increase of energy recovery, with the small financial investments.

As shown by simulation analysis, with the proper introduction of elements of the Smart Grids, it is possible to achieve performance close of regenerative braking close to efficiency using supercapacitor banks. However, the costs involved in the construction of the Smart Grids are many times smaller than those related to supercapacitor banks. What is more, the Smart Grids are capable of reducing transmission losses in the supply system.

A key element in determining the effective use of recuperation is the topology of the overhead line. In the case of supply areas with a significant number of vehicles, i.e. with high traffic volume or high intensity, the use of braking energy in the vehicle – vehicle path is very visible, which removes the need for additional devices absorbing recovery energy, such as supercapacitor banks or substation inverters. The failure to use recuperation energy occurs in areas with low traffic.

Accordingly, to increase the use of energy recovery, at first it is necessary to consider the possibility of reconfiguring the supply system, which will facilitate the flow of braking energy. In many situations, very good results can be achieved at a low cost. Small substation power supply areas galvanically isolated from the rest of the network should be avoided. Supply areas of such substations should be interconnected to create the largest area of recuperation energy flow.

Therefore, it is recommended to introduce bilateral supply of the overhead line to allow for an increase in the utilization rate of recuperation and reduced transmission losses. Bilateral power supply may be used both in central and in decentralized power supply systems. Examples of bilateral power supply solutions were presented in the previous section of the article. The power supply system designed taking into account the flow of recuperation energy is able to accept the vast majority of the recovered energy. The use of banks is appropriate in the areas of the overhead line of a specific nature, i.e. in mountainous areas or ones of unusual traffic distribution.

An important element that could improve the use of recuperation energy are charging stations for electric buses. Electric buses have become an increasingly popular means of transport in the cities; however, their charging poses a problem. It requires the construction of charging stations, which is related to the need of preparing appropriate infrastructure whose main element is the transformer stations for bus charging points. To this end, an overhead line for a tram or trolleybus transport can be used (Fig. 4), which has many advantages. In such a case, the existing infrastructure may be used, so there is no need to build additional transformer stations. In addition, the charging stations for electric buses are an alternative for the banks of recuperation energy, which requires only minor capital expenditures. Currently, hubs integrating many means of municipal transport, such as buses, trams, trolleybuses and trains are built. Such hubs may be also used for integration of power systems. Those places are characterized by common braking of vehicles, which results in a significant amount of generated recuperation energy. As indicated by the measurement tests, recuperation is most intense in locations of frequent starting and stopping. Therefore, in these places it is reasonable to build electricity charging points.

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