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Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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TRAM POWER SUPPLY INFRASTRUCTURE MODERNIZATION FOR IMPROVING ITS ENERGY EFFICIENCY – POLISH CASE

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Abstract

Trams as electric means of transport were brought into worldwide operation in the 19th century, and after significant reduction of the systems being used at the end of the 20th century, the 21st century witnesses their return into towns in Europe. Introduction of modern rolling stock with regenerative braking, especially into old infrastructure systems, requires significant modernization of power supply infrastructure in order to deliver energy to more powerful wagons and to use recuperated energy effectively. The process of improvement of the re-use of energy returned by braking trams is to be analysed globally, both taking into account rolling stock and power supply infrastructure. Sending regeneration energy from a braking tram to the power supply network, requires a tram taking energy (the network is receptive); otherwise braking energy will be dissipated at a braking resistor. There are certain methods for modernization of the existing power supply schemes, which could increase receptiveness of the power supply network. In case there is not enough energy storage devices (ultracapacitors or battery) on-board of vehicles or in a power supply system (in traction substations or just connected to a catenary) could be installed. It is also possible to equip traction substations with inverters to transfer energy from a DC to AC network. The paper presents a review of parameters of power supply infrastructure of trams systems in Poland and a study case of their modernization in order to fit with new requirements and improve energy efficiency. Some results of application of such solutions with presentation of their effectiveness based on simulation analysis as well as data from measurements in real systems are enclosed.

Keywords: tram, power supply infrastructure, energy efficiency, recuperation

1 Introduction

Currently, trams are operated in 15 cities and areas in Poland (Warsaw, Lodz with suburban lines, Silesian conurbation, Cracow, Wroclaw, Poznan, Szczecin, Gdansk, Bydgoszcz, Torun, Elblag, Gorzów Wlkp., Grudziadz, Częstochowa and Olsztyn). After a long time of stagnation and liquidation of systems, one may observe a period of development of new lines and delivery of modern rolling stock, mainly due to availability of financial support from the EU.
Typically, a transport network of cities with population over 100,000 inhabitants is a parallel and horizontal network covering the area of the town. There are joints and close contours of tram lines. Due to configuration of tram routes, a central supply scheme is a typical one, when a traction substation is located in the centre of a contour created by tram lines and feeders radially supplying sections of catenary (Fig. 1a). The second power supply scheme is linear, with a traction substation located close to a tram line and feeders led parallel to tracks (Fig. 1b). Traction substations are mainly equipped with 6-pulse (older ones) and 12-pulse rectifiers (new ones or modernized) with oil transformers (older ones) or dry (new or modernized,

especially when substations are located underground). A DC switchgear is equipped with a dozen or so feeders, while return cables are less in number. Typically, a catenary is connected to a plus node of a traction substation while the minus one to rails. However, in a few tram systems, polarity is reversed [1].

2 Effectiveness of energy recuperation

Introduction of rolling stock with recuperation braking into tram systems, which is currently a standard, constitutes an opportunity to reduce energy consumption; however the process of further use of braking energy is to be analysed globally taking into account both rolling stock and power supply infrastructure. Manufactures of rolling stock define its traction and braking characteristics, but the feature to recuperate energy during braking makes just an opportunity for its use. A possible consumer of braking energy should have enough power demand during short time (10–20 seconds) of braking, and what is needed is a proper electrical connection between this consumer and the braking tram [1-3]. Therefore, operation of modern rolling stock poses a challenge for the existing tram power supply infrastructure to assure maximum possible energy savings. In order to adjust infrastructure to the demands of new trams, it is required to undertake an assessment of operation of power supply systems with new rolling stock, including pantograph-catenary interaction [4]. In most cases, such studies determined the existence of 'bottlenecks' and the need for modernization, which would allow for operation of typically more powerful new trams with a higher power demand from one side and the use of regenerative braking for energy consumption reduction from the other.
Studies undertaken by the authors for different tram systems and lines have shown that even low-cost investments in the existing power supply could give quick return due to energy savings, peak-power demand reduction and could assure proper quality and higher reliability (and other RAMS issues) of energy delivery to modern rolling stock.
In [5] there are conclusions from measurements in traction substations of Warsaw Trams. Registration of currents of feeders shown transit recuperation currents from one section of a catenary to the other – unilaterally supplied (Fig. 1a) via feeders and DC bus-bars in a traction substation, which accounts to 13 – 17 % of energy taken by a traction substation (with the theoretical potential of catenary recuperation reaching 24 %). Therefore, simulation undertaken by the authors in a study [6] (Fig. 2 – Ih transit current via feeder during recuperation) was confirmed by the measurements in real systems.

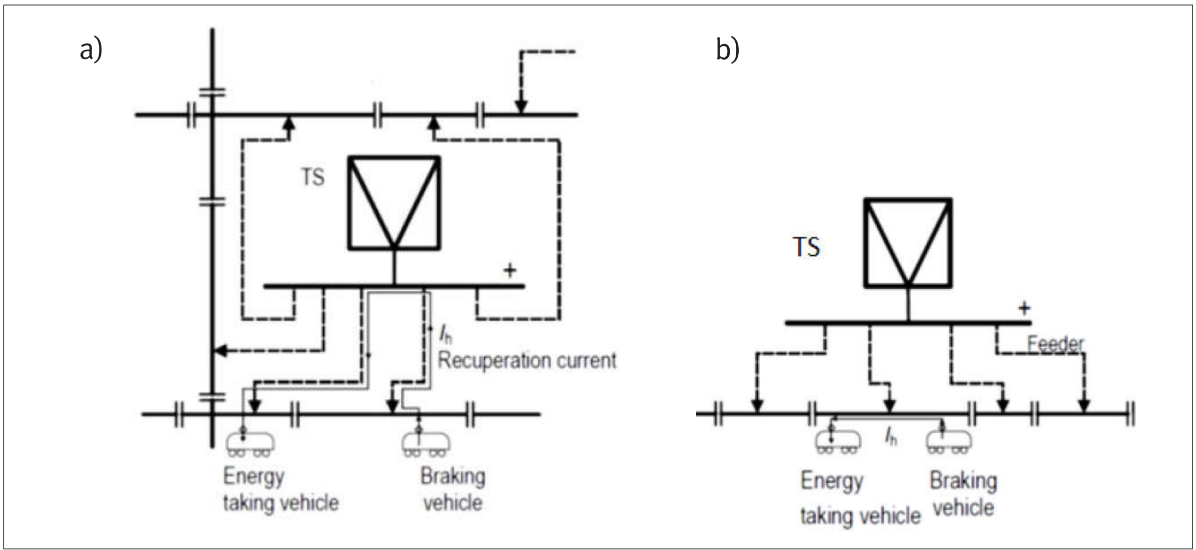

Figure 1 Exchange of energy between trams operating: a) at different sections in a central scheme of supply by a traction substation – TS, b) or at the same section (linear scheme of supply)

The typical power supply scheme for trams lines (outside junctions) in Warsaw Trams indicates: short sections of a catenary only in supplying trams running in one direction. So, a traffic cycle on a section (simultaneous starting and braking) makes it difficult to exchange energy between trams on the same section (Fig 1. b).

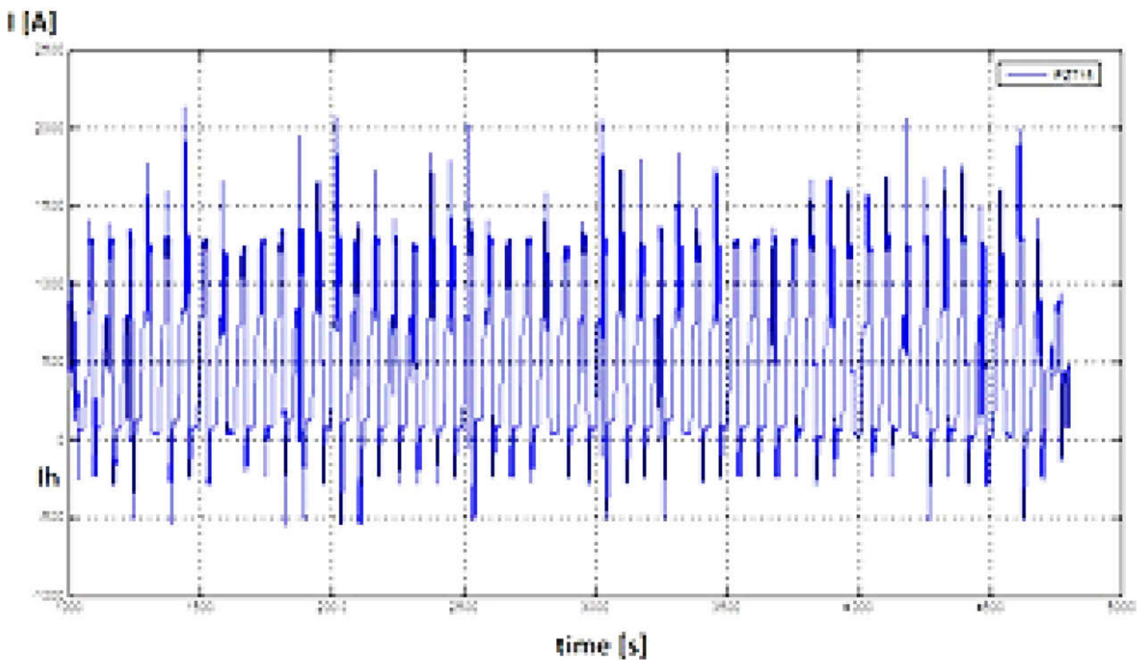

Figure 2 Feeders' current I with observed recuperation current Ih transfer (values below 0)

Measurements on board of trams have confirmed effectivenes of power supply system receptivity (up to 23–25 % of energy taken by trams has been returned to the catenary), and application of an energy storage device (ESD) on board of trams added another 7–9 %, which together constitutes over 30 % of energy saved due to regenerative braking [1,2].
Assuming annual mileage of 70,000 km per tram, the ESD on a tram saves between 16 to 20 MWh (depending on the type of a tram) per year. If this electrical energy is generated by coal power plants (dominating in Poland), it will give reduction in 20 t of CO_2 emission. Additionally, recuperation braking energy sent back by a tram to a catenary is approx. 90 MWh per year and assuming only 80 % of its re-use, it results in additional reduction of CO_2 emission amounting to 70 t. During comparison of the tram types, it was observed that AC trams showed much higher effectiveness of recuperation energy re-use than DC trams with choppers.
In some tram systems, when no ESD on board of trams is applied, application of ESD connected to a catenary in a traction substation may increase recuperation energy use. Studies undertaken by the authors have shown significant influence of traffic density on effectiveness of application of the ESD [6]. Fig. 3 shows years of return of investments (for two ESD – one with 1.0 kWh energy capacity, the other with 1.5 kWh) as a function of an average annual density of traffic given in trams per hour (it was assumed that only 50 % of trams is equipped with regenerative braking). It was observed that for low density of traffic application of 1.0 kWh investment in ESD is returned in shorter time, while for more dense traffic (above 18 trams/hour) bigger ESD becomes more effective.

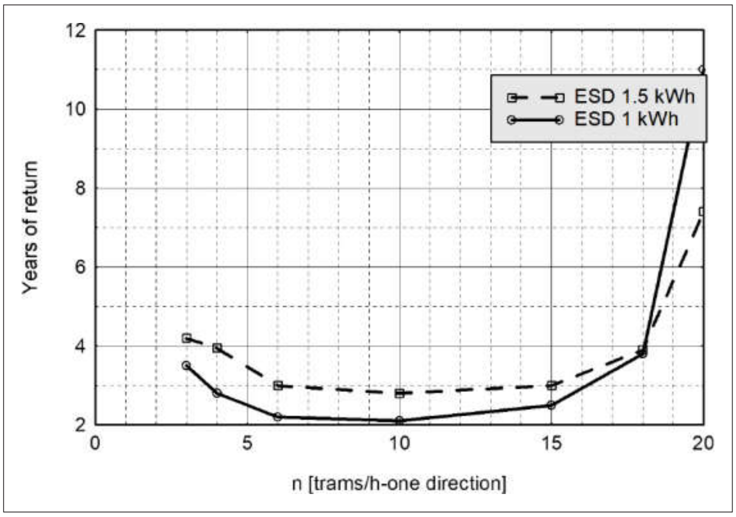

Figure 3 Years of return of investments in ESD connected to a catenary for two types of ESD: 1.0 kWh and 1.5 kWh as a function of an average annual density of trams in trams per hour per 1 direction of traffic.

3 Influence of modern trams on the functioning of power supply infrastructure

When modern rolling stock is bought, each time one may ask how putting it into service may influence the power supply infrastructure, especially when a power supply system has not been modernized. Mainly, it is important to decide if the consumers of recuperation energy will be only other trams or other devices such as: ESD on board of vehicles or in traction substations (for short term energy storage). Inverters in traction substations to transfer energy from the DC to AC side [1, 3, 7, 8] could be applied as well. Main advantages of regenerative braking for the power supply infrastructure are as follows: reduction of traction substation load (Fig. 4b power P_{ts} less by 20 % comparing with Fig. 4a) and voltage increase (especially during peak power demand – Fig. 5a).

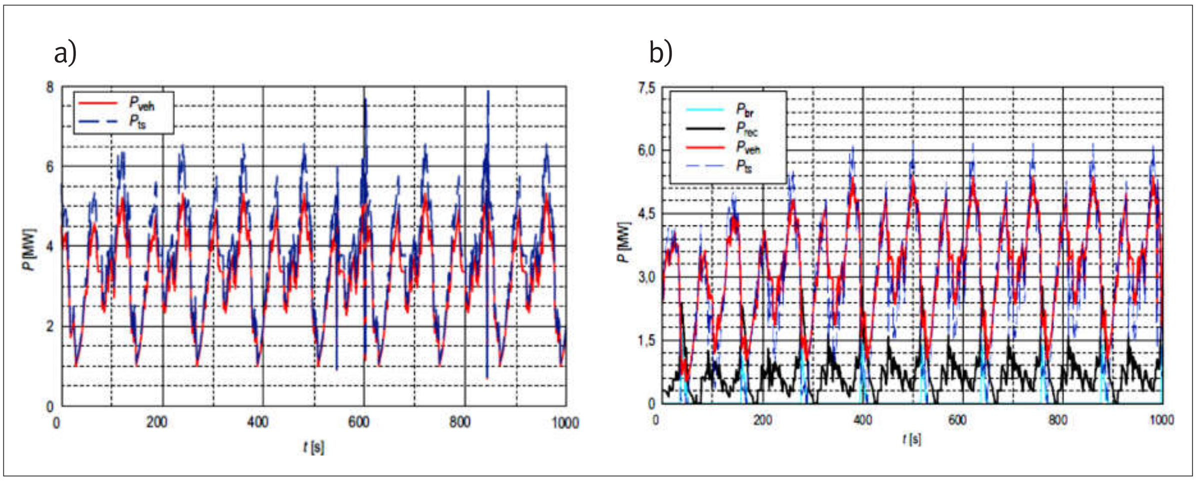

Figure 4 Powers in a power supply system a) without trams equipped with regenerative braking, b) 50 % of trams equipped with regenerative braking, symbols: P_{veh} – power taken by trams, P_{ts} – power delivered by a traction substation [average: 3.61 MW in case a) while 2.89 MW in case b)], P_{rec} – power of recuperation, P_{br} – power of braking resistors.

However, some disadvantages are observed as well, such as: increase of investment costs of rolling stock and power supply (bigger cross-sections of cables and catenary required, ESD, controlled rectifiers or inverters in traction substations), increase of instantaneous voltage in a catenary (Fig. 5 a – Ur) and rails (Fig. 5 b), EMC issues due to rolling stock power electronic drives control [9], problems with quick identification and elimination of short circuits in a catenary.

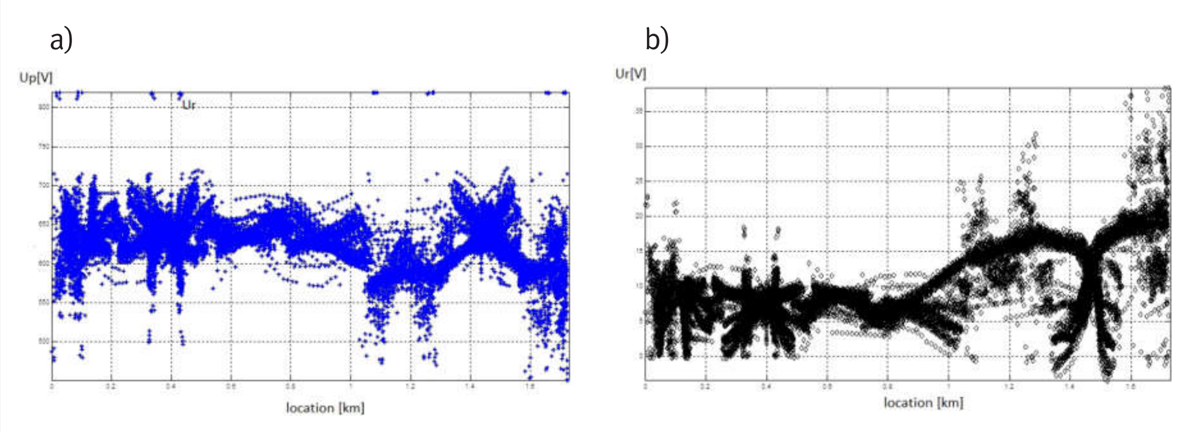

Figure 5 Voltage in: a) a catenary, b) rails

The last case could appear when a high-speed breaker of a feeder supplying a section of a catenary is activated due to short-circuit, and a recuperating tram is running along this section that is isolated from a substation supply section will be energized by a braking tram.

4 Modernization of the existing power supply infrastructure aimed at increasing energy efficiency

Increased demand for tram transport that has been observed in Poland – construction of new lines and modernization of old ones creates a need for searching for new solutions, which could allow modern rolling stock to operate and use their energy efficiency capacity, but also to assure minimization of investments in the power supply infrastructure. Due to the fact that a typical scheme of power supply in tram systems is a unilateral supply, one of the most obvious proposal could be application of bilateral supply from 2 different traction substations. However, it requires, among other things, coupling of control systems of both substations, and typically power supply systems of trams in Poland are not ready for the use of bilateral supply. Therefore, as a possible solution a quasi-bilateral two-point supply from the same substation by two feeders of this substation may be taken into account. Of course, that kind of solution is not an optimal one (since feeders have different lengths and are connected in different points of catenary), but in many cases it may appear to be the only one which could be implemented quickly at low cost. Switching from unilateral supply to bilateral (quasi-bilateral) is making load of feeders more uniform and voltage drops lower, but a difference of feeder resistances could be a significant factor in reducing these effects. However, due to the fact that modernization of a power supply infrastructure is costly, there is no general solution and every power supply system should be treated individually. As an example, during study [8] the following options of tram power supply modernization were analysed:

- cross-connection of a catenary of tracks by a non-polarized high-speed breaker (quasi bilateral supply within a zone of the same traction substation);
- longitudinal connection of sections (permanent) supplied by the same (quasi-bilateral supply) or 2 different substations (bilateral supply);
- changing position of: catenary isolator, point of feeder connection to catenary or return cables to rails;
- instalation of ESD on-board of trams, in a traction substation or application of ESD connected just to a catenary at the end of the line;
- increasing resistance of return cables by additional resistance (in order to make return currents flow in return cables more uniform).

5 Study case of modernization of a tram power supply system

In a set of study works of tram power supply infrastructure worked out by the authors, one of the important issues being in question is the effectiveness of the proposed solutions of modernization. Different criteria of assessment could be assumed, partially such as: expected energy savings, expected peak power demand reduction, reduction of costs of energy, reduction of exploitation costs [7, 9]. From an analysis of over 40 tram traction substation modernization studies, it appeared that in many cases simple, low cost solutions are possible (described in Chapter 4), which could make significant improvement in energy efficiency of the existing power supply systems. Globally, it was estimated that the suggested modernization, mainly due to increasing energy recuperation effectiveness, could reduce energy consumption in 2,800 MWh/year, reduction of peak power demand in 10–15 % and reduction of CO_2 emission amounting to over 3,000 t/year. Estimated time of return of the proposed investments according to the substation was from 27 to 41 months. Additionally, not quantified advantages include: stabilization of voltage in a catenary, reduction of voltage drops in rails (reduction of stray current flow), increased RAMS parameters of power supply.

6 Conclusion

Improvement of energy efficiency of the power supply infrastructure for modern trams requires its modernization. The paper underlines issues concerning a power supply system in order to assure effective energy delivery to trams with regenerative braking. Using experience from a set of study works undertaken for Polish tram power supply systems, some technical solutions and their financial effectiveness were discussed and results were compared with measurements in real systems. It was underlined that even low-cost modernizations in the existing infrastructure could give, according to the case, significant improvement and results in quick return of the investments. Sustainable development of towns requires efficient and ecological means of transport, i.e. electric traction. In Polish case, it is worth underlying that almost 100 % of road transport depends on imported petroleum [10]. Therefore, a strategic role of electric transport cannot be ignored in light of domination of rail transport in Polish towns.

References

[1] Szeląg A., Drążek Z., Maciołek T.: Elektroenergetyka miejskiej trakcji elektrycznej (in Polish) [Power supply systems of urban electric traction], pp. 1-338, INW Spatium,Radom, (2017)

[2] Ouattara, M., Gordon, Y.J.: FTA Report No. 0086, WMATA Energy Storage Demonstration Project, Final Report (June 2015)

[3] ABB Review, ENVILINE™ ESS voltage support case study How can Rail Transit Authorities mitigate voltage issues due to increased power demand?, ABB edition10.2014: https://library.e.abb.com/public/3f89a1a3b77dc59ac1257d73002dcde0/ ENVILIN%20ESS%20voltage%20support%20case%20study%20ver2.pdf (22.01.2017).

[4] Haladin, I., Lakušić, S., Duvnjak, I.: Evaluation of tramway overhead line system in city of Osijek, Proceedings MET'2017 Conference, Warsaw, (2017)

[5] Bajno, G.: Wpływ rekuperacji energii na układ zasilający podstacji trakcyjnej "Filtrowa" i "Annopol" w Tramwajach Warszawskich [Influence of energy regeneration on the power supply of the Filtrowa and Annopol traction substations in Warsaw Trams (in Polish)], Proceeding of 11th International Conference "Modern Electric Traction" MET'2013, Warsaw, Poland, (2013)

[6] Szeląg, A., Drążek, Z., Maciołek, T., Patoka, M., Steczek, M.: Studium układu zasilania trakcji tramwajowej Tramwajów Warszawskich sp. z o.o., [Study of power supply of tram traction in Warsaw Trams PLC], Electric Traction Division of Warsaw University of Technology on the order of Warsaw Trams Ltd., Warsaw (2011)

[7] Szeląg, A., Maciołek, T.: Power Supply of Trams in Poland – Current State and Perspectives of Development, Proceedings MET'2017 Conference, Warsaw, (2017)

[8] Steczek, M., Chudzik, P., Szeląg, A.: Combination of SHE and SHM – PWM techniques for VSI DC-link current harmonics control in railway applications, IEEE Transactions on Industrial Electronics", Vol. 64, Issue 10, Oct. 2017, pp. 7666-7678; http://ieeexplore.ieee.org/stamp/ stamp.jsp?arnumber=7900369.

[9] Maciołek, T., Szeląg, A., Drążek, Z., Patoka, M.: Aspekty efektywności i energooszczędności w procesie modernizacji układów zasilania trakcji tramwajowej (in Polish) [Effectiveness and Energy Saving Aspects in Modernization Process of Tram Power Supply Systems]. Pojazdy Szynowe, 3, (2011)

[10] Bartosik, M., Kamrat, W., Kaźmierkowski, M., Lewandowski, W., Pawlik, M., Peryt, T., Skoczkowski, T., Strupczewski, A., Szeląg A.: Bezpieczeństwo elektroenergetyczne dla pokoleń (in Polish) [Power sources and safety of electrical energy distribution in Poland], Przegląd Elektrotechniczny, 8(92), pp. 268-282 (2016)