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EVALUATION OF ENERGY LOSSES IN DC RAILWAY TRACTION POWER SUPPLY SYSTEM

ANALIZA STRAT ENERGII W UKŁADZIE ZASILANIA DC ELEKTRYCZNEGO POJAZDU TRAKCYJNEGO

A b s t r a c t

The article presents the global distribution of energy losses in a DC electric traction in specific cases and the impact of changing parameters on the efficiency of electricity transmission on the railway.

Keywords: electric traction, energy loss, DC supply system, electricity meters on the railway

S t r e s z c z e n i e

W artykule przedstawiono bilans strat energii w układzie zasilania trakcji elektrycznej DC, gdzie obciążenie stanowi lokomotywa elektryczna prowadząca pociąg towarowy. Analiza została przeprowadzona dla wybranego rzeczywistego fragmentu układu zasilania odcinka linii kolejowej. Ponadto zbadano również wpływ zmiany niektórych parametrów elementów układu zasilania oraz obciążenia trakcyjnego na sprawność przesyłu energii elektrycznej.

Słowa kluczowe: trakcja elektryczna prądu stałego, straty energii, zasilanie

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1. Introduction

The contemporary economic reality as well as changes in the structure of the PKP group and the growing importance of private carriers on the railway transport market justify the purposefulness of conducting an analysis of settlements regarding the electrical energy consumed by traction vehicles. Energy is supplied by PKP Energetyka S.A. to traction substations and then through the infrastructure (power supply system), most often managed by PKP Polskie Linie Kolejowe S.A., and in the case of some railway routes – by such companies as Infra Silesia, PKP Szybka Kolej Miejska w Trójmieście sp. z o.o. and Warszawska Kolej Dojazdowa, to traction vehicles. In light of the changes that have taken place, it would be worthwhile to consider the issue of electrical energy consumption by traction vehicles, taking account of the energy losses in the power supply system, in order to determine their values in relation to the total energy consumed by a vehicle for traction purposes and the energy lost in the power supply system.

1.1. Status of settlements regarding the electrical energy consumed by traction vehicles at the time of writing this article

PKP Energetyka S.A., with its registered seat in Warsaw, is the supplier of energy for traction purposes to the Polish railway network. It is the only distribution system operator in Poland that has its own distribution grid. The grid is 20.200 km long, and ranks fifth in the country with respect to the electrical energy sales volume. The "Electrical Energy Tariff" of PKP Energetyka S.A. is approved on an annual basis by the Energy Regulatory Office and is the document used to establish the costs of electrical energy consumed by electrical traction vehicles in Poland. The basis for settlements regarding the consumed electrical energy is the "contractual power", i.e. active power, consumed from or supplied to the grid as defined in the agreement on the provision of electrical energy distribution services. The value shall not be lower than the maximum value determined based on the average power over a period of 15 minutes, taking account of the factors reflecting the specifics of the end-user's power supply system and the amount of electrical energy drawn and consumed by the end user [1].

The power supply system for traction vehicles is divided into four parts, each owned by a separate entity: (1) The part from the grid supply point (GSP) to the substation. The demarcation point being an energy meter owned by this first entity. This part is owned by either PKP Energetyka S.A. or the Energy Distributor (e.g. Tauron), and supplies energy to PKP Energetyka S.A.; (2) PKP Energetyka S.A., which owns the subsequent parts of the system, i.e. traction substations (including all equipment, apart from a meter on the connection), track sectioning cabins, MV and HV switching stations at the substation, and feeder cables, the end of which forms the demarcation point between PKP Energetyka S.A. and PKP Polskie Linie Kolejowe S.A.; (3) PKP PLK S.A. owns the traction power supply and return systems together with traction poles, and is the manager of the infrastructure; (4) A current collector and any potential energy meters mounted on the vehicle belong to the carrier.

Based on the above-mentioned document, "Electrical Energy Tariff", PKP Energetyka S.A. makes settlements regarding the costs of electrical energy with the carrier, using one of the two methods, including fees for the sale and distribution of energy. The first one is a simplified index method (also called the payload-based method), whereas the other one is an accurate, meter-based method. The first method is older and it is based mainly on indexes attributed to a given train type, established by means of statistical data (a Railway Rolling Stock Performance bulletin together with a specification of operated trains) and theoretical calculations regarding payload, i.e. specific power consumption (SPC) and a correction factor, the so-called loss factor "k". The product of payload, indexes, and SPC is the value of electrical energy consumed in [kWh].

The meter-based method relies on the determination of the product of the value shown by the electrical energy meter mounted on the vehicle and a correction factor, the so-called loss factor "k". The methods employed for calculating the consumed electrical energy are presented in Fig. 1. The last loss factor "k" should be pointed up, as this factor is to ensure, for PKP Energetyka S.A., the compensation of electrical energy transmission losses incurred on elements of the power supply system along the section owned by the Manager of the infrastructure. The loss factor "k" constant was adopted, equal to one and one-tenth, which means that the company makes an assumption that energy losses in the power supply system (traction power supply system, traction power return system) total 10% in relation to the energy consumed by a vehicle [2].

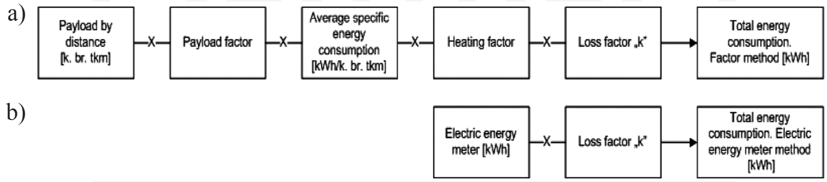

Fig. 1. Methods for calculating electrical energy consumption in PKP Energetyka S.A.: a) index method, b) meter-based method

1.2. Calculation of energy losses

The analysis of the DC power supply system for railway traction was limited to the elements managed by railway companies, i.e. from the AC electrical energy meter at the traction substation, to the pantograph/electrical energy meter mounted on the vehicle. In consequence, the area subjected to research comprised the following elements: traction substation, feeder cables and return cables, traction power supply system and traction power return system, and pantograph. Energy losses occur in each of the listed elements of the power supply system, with the assumption of zero losses made for the pantograph. The purpose of the analyses presented in the paper was to determine the efficiency of electrical energy transmission between the energy meter at the substation and any potential energy meter mounted on the locomotive as well as to establish the total energy losses in the power supply system, expressed as a specific value in [kWh] and as a percentage (the value of losses in relation to the total energy consumption – measured by the meter at the substation). Furthermore, energy losses in the power supply system of the vehicle were attributed to its respective component elements. Elements of the power supply system, in which electrical energy losses occur, are shown in Fig. 2.

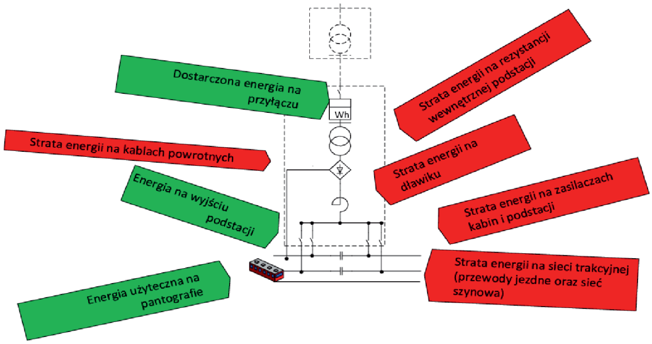

Fig. 2. Energy losses in the power supply system of an electrical traction vehicle

Based on the analysis of respective component parts of the power supply system, in which energy losses occur, the following conclusions were drawn.

Energy losses occurring on the feeder cables of the substation and track sectioning cabins and on the return cables depend on:

– length of feeder/return cables,
– cross-section of conductors/cables,
– material of which conductors or cables are made.

Energy losses on the internal resistance of the substation depend on the external characteristics of the substation and the ratings of the set:

– short-circuit power on the AC busbars of the substation,
– off-load voltage of the rectifier,
– number of active rectifier sets,
– rated power of the transformer,
– short-circuit voltage of the transformer, expressed as a percentage,
– rated voltage of the set,
– rated current of the set,
– voltage drop on a single diode of the set,
– number of diodes in a branch in the case of a series connection.

Energy losses in a cathode choke depend on:

– choke resistance.

Energy losses in the traction power supply system depend on the type of the system, i.e. the parameters that influence its specific resistance, namely the material, number of conductors and:

– cross-section of contact wires,
– cross-section of catenaries,
– cross-section of support wires,
– length of supply sections,
– wear and tear of contact wires,
– conductor temperature,
– presence of a track sectioning cabin,
– distance between the substations.

Energy losses in the traction power return system depend on:
- type of rails (their specific resistance),
- condition of the railway subgrade and inter-rail and inter-track connectors,
- length of a supply section.

2. Methodology of conducted research

For the proposed power supply system diagram (Fig. 4), theoretical calculations were carried out, making use of real-life data obtained with the assistance of the following companies: PKP Cargo S.A., PKP Polskie Linie Kolejowe S.A. and PKP Energetyka S.A. The analysis focused on a fragment of trunk line E30, namely line 133 (Dąbrowa Górnicza Ząbkowice–Kraków Główny), at the Trzebinia–Kraków Mydlniki section, 31.55 km long. Along this section, there are two traction substations equipped with two six pulse rectifiers, PK-17/3.3, and two track sectioning cabins. It is a double-track route, electrified at a voltage of 3 kV DC, and with contact wires designated YskB95-2C. A heavy freight train hauled by an ET22 series six-axel locomotive was adopted as a traction system load. Theoretical passages of the train along the considered route were carried out for a changing number of freight wagons. Based on the calculations for the theoretical passages, the following curves were obtained: current drawn by the locomotive as a function of distance as well as the changes of energy measured at the substation and at the vehicle as a function of distance. The model of the power supply system for a fragment of a railway line takes account of all its component elements. Each element of the diagram was replaced with the equivalent resistance, traction substations were modelled as voltage sources with the calculated substation resistance R_p, and a traction vehicle was replaced with an ideal current source, whereas the concentrated resistance of the contact wires was changing depending on the position (passage) of the train. Fig. 3, presented below, shows a simplified diagram of the power supply system for a fragment of the railway line selected for the analysis, and Fig. 4 contains an electrical diagram of the modelled circuit. The calculations (using the loop method) were performed by means of the PTC MathCad program and a Microsoft Excel calculation sheet. As a result, the energy drawn on the AC MV switching station side of the substation was calculated, the energy losses in respective elements of the modelled power supply system were determined

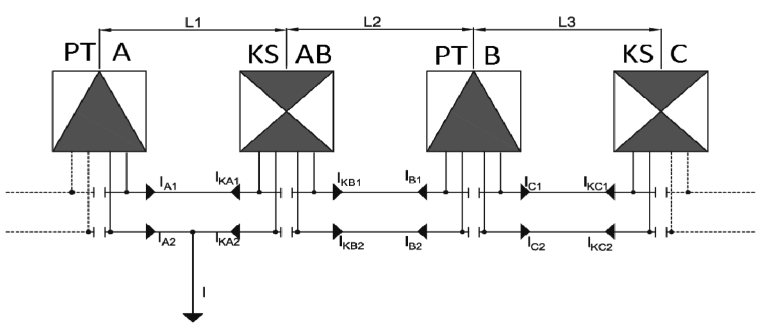

Fig. 3. Simplified model of the power supply system of a railway line section

and the energy drawn by the train was calculated. In addition, calculations regarding the efficiency of energy transmission to the vehicle were carried out, taking account of the following parameters: ambient temperature, the extent of wear and tear of contact wires and off-load voltage on the busbars of the traction substation [4–6].

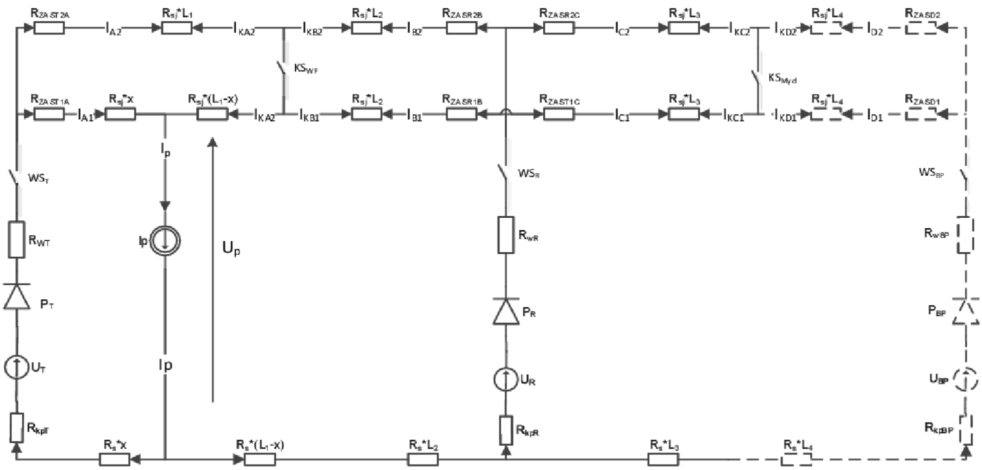

Fig. 4. Electrical diagram of the power supply system for a section of a railway line using the loop method

3. Distribution of energy losses in the analyzed power supply system

The analysis was conducted based on a theoretical passage of the freight train, with the following parameters: locomotive hauling the train – ET22, gross weight of the train – 1.879 t, adopted off-load voltage at the substation 3.450 V, ambient temperature – 20°C, and in accordance with the time table, the train passes without any stops from the Kraków Mydlniki station to the Trzebinia station. The efficiency of the electrical energy transmission was calculated as a relation between the readings of the energy meter mounted on the vehicle and the total of the readings of the electrical energy meters (placed directly before the rectifier sets) at the traction substations. For the examined section of the power supply system, this efficiency amounts to 88.05%, and for the train going in the opposite direction, it totals 87.20%. The plot showing the velocity as a function of distance and the current as a function of vehicle distance is presented in Fig. 5. The plot presenting the total energy drawn by the train and the total energy measured at the substations is shown in Fig. 6. The difference between the two curves represents energy losses in the power supply system analyzed in this article.

The average value of efficiency was determined to be 87.21% after averaging the results for several variants of theoretical passages, including variants with stops. Therefore, it can be assumed that energy losses in the analyzed power supply system total up to 12.79% of the energy supplied to the traction substation. The highest energy losses in the analyzed power wires ranked second and were followed by losses on the internal resistance of the substation; however, in the case where the value of internal resistance of the substation was adopted on the basis of the relevant literature 5, losses on account of R_p ranked second with respect to their level (Fig. 7 and 8).

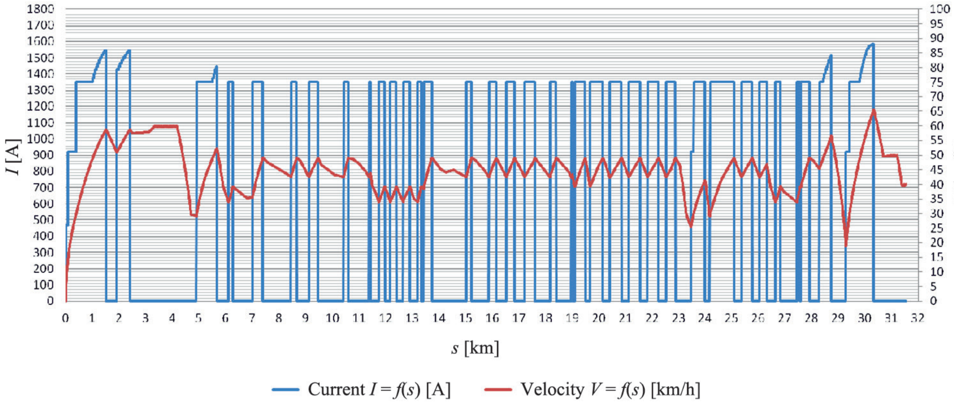

Fig. 5. Results of a theoretical passage for a selected case

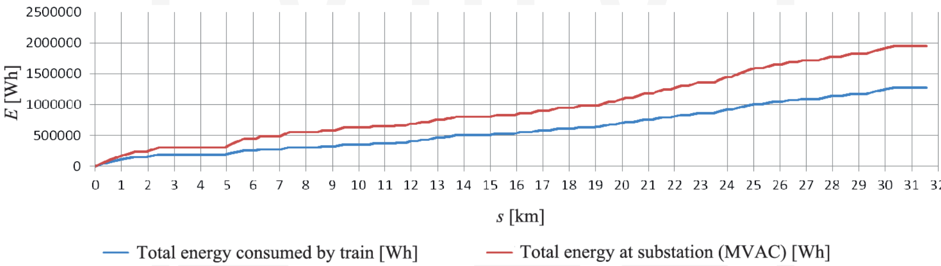

Fig. 6. Curves illustrating energy consumption recorded by the meters during the passage of the train

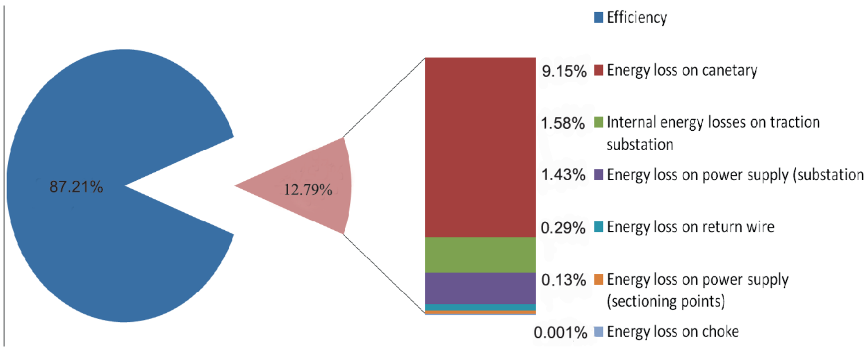

Fig. 7. Percentage breakdown of consumption of drawn energy in the analyzed case

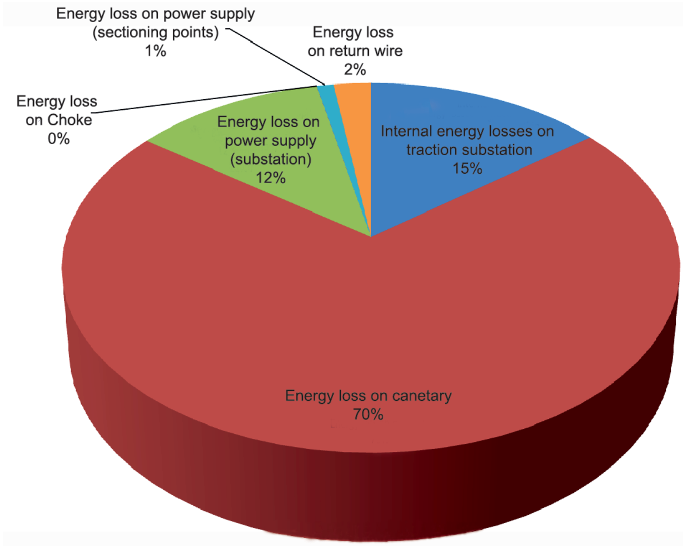

Fig. 8. Average balance of energy losses in the power supply system

4. Analysis of energy losses for a changing load and selected parameters of the power supply system

Additional calculations were performed for a changing traction load and changing parameters of its component elements after the initial assessment of the percentage distribution of energy losses in the power supply system.

The following parameters were subject to change (the reference value was marked on the charts):

- wear and tear of contact wires within a range from 1 to 0.55,
- (the reference value is equal to 1 – a wire showing no wear and tear; average value = 0.87, the so-called average wear and tear of a contact wire) (Fig. 9);
- ambient temperature, within a range from –10 to +55°C (the reference value is +20°C) (Fig. 10);
- off-load voltage at the traction substation within a range from 3.300 to 3.600 V (the reference value is 3.450 V) (Fig. 11);
- moreover, an analysis was conducted where the curve $I_{POC} = f(s)$ was replaced with a constant load (simulating an average load) I = const A; the analysis was carried out by changing the value of current every 100 A up to 1.500 A (Fig. 12).

The following conclusions were drawn based on the analysis of the obtained results:

a) the efficiency of energy transmission drops along with an increase in the extent of wear and tear of conductors. Changes vary from 80.25% at m = 0.55 to 87.07% in the case of a new conductor. Below the value of m = 0.8 (Fig. 9) of the analyzed factor, voltage drops at the points distant from the substation exceed the range specified in the standard;

b) at an increase in temperature, resulting from the increased specific resistance of contact wires, energy losses in the traction system are higher, falling within a range from 85.93% at 55°C to 88.05% at –10°C;
c) the efficiency of the power supply system increases along with an increase in off-load voltage at the substation. Within the analyzed range of values the highest recorded efficiency totaled 87.61% at 3.600 V and its lowest value was 86.49% at 3.300 V;
d) the dependence of the efficiency of the power supply system on changes in the value of constant load current is linear, i.e. the efficiency clearly decreases along with an increase in current. At a low value of average current, of the order of 100 A, the efficiency is close to a unit value, whereas for a limit system current, 1500 A, it totals 85%.

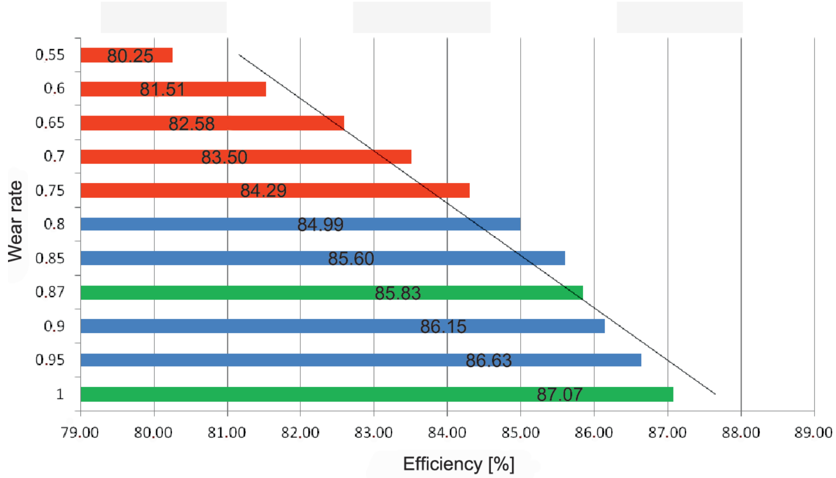

Fig. 9. Efficiency of the power supply system depending on the extent of wear and tear of contact wires

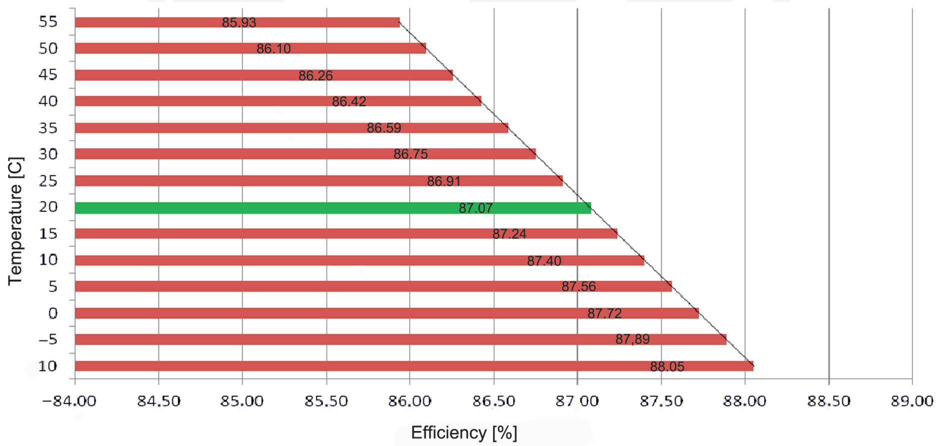

Fig. 10. Efficiency of the power supply system as a function of conductor temperature

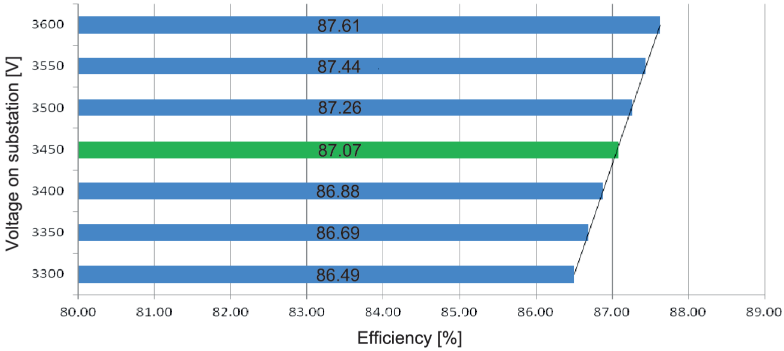

Fig. 11. Efficiency of the power supply system as a function of off-load voltage at the substation

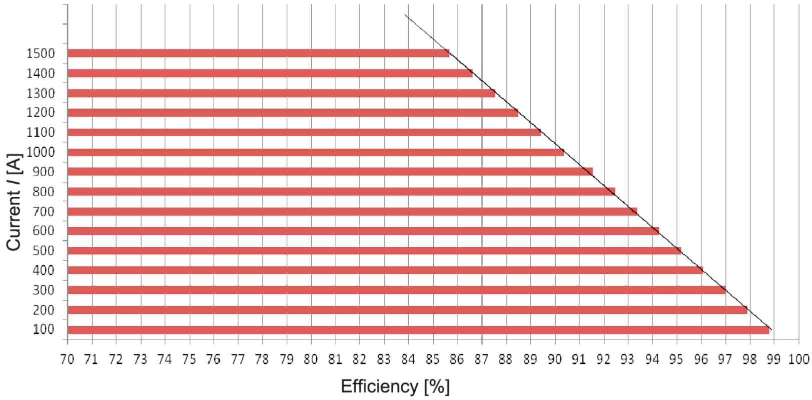

Fig. 12. Efficiency of the power supply system depending on the value of constant load current

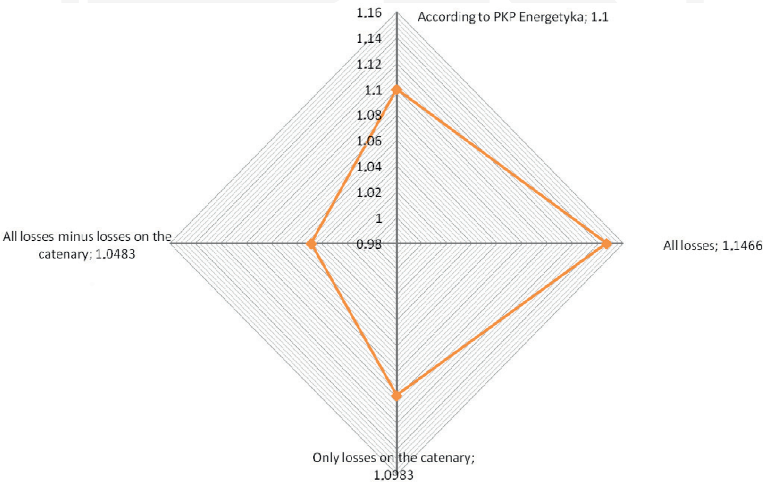

Fig. 13. Comparison of loss factors “k”

5. Conclusion

The efficiency of the electrical traction system (for the case analyzed in the article) calculated as the relation between the total readings of the energy meters at the MV AC input at the traction substations and the energy measured on the pantograph totals on average η = 87.21%. When several variants of the passage of the train were taken into account, the change in the efficiency was small – up to 0.32%. As the readings of the meter showing the energy consumption on the vehicle were known, it was possible, based on the calculation results presented in the article, to determine, with a reasonable accuracy, the corresponding readings of the potential energy meter installed at the medium voltage switching station (MVAC) of the DC traction substation.

Depending on the adopted definition of the loss factor "k", its average value is higher (when energy losses in all elements of the power supply system are taken into account) or lower (when energy losses on the traction system only are taken into account). In the loss factor "k", PKP Energetyka S.A includes only the losses incurred in the traction system and the currently used loss factor "k" totals 1.1. This value is close to the average value calculated in this article for the analyzed fragment of the power supply system (1.0983). Taking account of all the losses in the power supply system for the case analyzed in this paper, the factor totals 1.1466. The comparison of loss factors "k", the one used by PKP Energetyka S.A. and the one obtained from calculations for the case analyzed in the article, is presented in Figure no. 13. In the authors' opinion, in order to accurately determine the value of the discussed loss factor "k", it is necessary to conduct separate analyses for each case, taking account of the parameters of the real power supply system.

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