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Energy efficiency of a railway line supplied by 3 kV supply system – a case study of the application of an inverter in a traction substation

Efektywność energertyczna linii kolejowej zasilanej napięciem 3 kV DC – studium przypadku zastosowania falownika w podstacji trakcyjnej

Abstract

Due to energy saving policy in the European Union and development of power electronics technology, one might expect an increase in the use of solutions, such as inverters in the substations of the 3 kV DC power supply system. The paper includes a study case of the analysis of traffic conditions on the use of inverters in 3 kV DC system traction substations so as to send back trains' braking energy from a DC traction power supply to an AC power supply network. The authors presented possible estimated energy savings for a selected railway line. Furthermore, the character of a power waveform and energy available for transferring from a DC to an AC power supply network was discussed as well. The effectiveness of this solution largely depends on the nature of train traffic, so prior to applying the inverters, a detailed analysis is required.

Keywords: energy efficiency, railway line, traction substation

Streszczenie

Polityka oszczędności energii prowadzona w krajach UE oraz rozwój technologii w energoelektronice zwiększa możliwości stosowania rozwiązań, takich jak falowniki w podstacjach systemu 3 kV DC. W artykule przedstawiono studium przypadku analizy wpływu warunków ruchu na zastosowania falownika w podstacji trakcyjnej 3 kV DC w celu zwrotu energii hamowania odzyskowego pociągów do zasilającej sieci elektroenergetycznej. Pokazano szacunkowo możliwe do uzyskania oszczędności energii dla wybranej linii kolejowej. Omówiono charakter przebiegu mocy oraz wartość energii możliwą do przesłania przez falownik do sieci zasilającej. Efektywność stosowanych rozwiązań i celowość stosowania falownika silnie zależy od charakteru prowadzonego ruchu, dlatego istotne jest przed jego zastosowaniem przeprowadzenie szczegółowych analiz.

Słowa kluczowe: efektywność energetyczna, linia kolejowa, podstacja trakcyjna

1. Introduction

In a DC railway traction supply system under conditions of frequent stops (suburban traffic), there is usually energy surplus (in comparison to energy consumed by vehicles) from regenerative braking. In order to use this energy, it has to be collected in an energy storage device on the DC side or sent to the power system. However, the basic condition is the presence of consumers on the AC side and a power supply system with appropriate technical parameters.

With development of technology of power electronics switching devices, one has started testing inverter solutions, especially those added to the existing rectifier traction substations. Solutions for urban traction developed by companies such as ABB or Alstom [1, 7] are already well-known and widely used, but in a 3 kV DC railway traction, apart from test solution, there is no information on the use of inverters or storage devices in substations [9, 20, 21].

A converter planned for application in the substation might be used, both as an inverter and as an active power filter. When used as an inverter, it converts and returns energy to AC network during a vehicle braking phase, and when it operates as an active power filter, it compensates harmonic distortion caused by a traction substation rectifier.

In case of a technical analysis related to the application of inverters, one should take into account a range of factors influencing the operation of an inverter traction substation, including, among others:

- optimization of traction substation equipment, including, its dimensions and location, so as to obtain the best possible conditions for regeneration with a considerably small number of converters;
- control and characteristics of converters that influence heavily on the parameters such as: system receptivity, power factor and higher harmonics content in AC voltage and equalizing currents in a rectifier-inverter circuit;
- power demand on the AC side.

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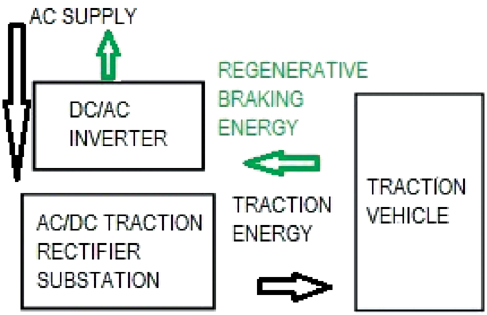

Fig. 1. Diagram of energy flow in a DC traction system with the use of an inverter in a traction substation

2. The results of inverter application

Application of inverters in a power supply system provides the following results [2–6, 8, 10, 11, 15–19]:

- the use of energy that otherwise would be dissipated in braking resistors or dissipated into heat at brakes;
- an additional energy source for a power grid under conditions of considerable load of a grid (Fig. 1);
- the possibility of energy transfer through a MV network to the point of increased power consumption.

It was also considered whether elimination of resistors from the vehicles (providing that to all recuperation energy could be sent to DC network) with provision of braking energy transfer into a substation is a good solution. However, safety requirements do not allow for a vehicle's operation without braking resistors on-board due to fact that contact between current collector of the vehicle and catenary could be lost and current transfer to catenary during recuperation is not always possible).

When using inverters in a traction substation, the following should be taken into account:

- higher investments (devices, area, building);
- larger energy losses in a substation, increase of rectifiers' load;
- an inverter should have higher rated parameters than the respective rectifier;
- increase of distortion from higher harmonics and voltage fluctuations in a MV network, problems with electromagnetic compatibility in a traction system [14] and radio-eletrical interference;
- increase of reactive power consumption and lower power factor and voltage fluctuations in an AC network, which might require the use of filters of higher harmonics or reactive power compensators;
- requirements to use intelligent systems for control, monitoriong and protection;
- the requirement for a traction substation to have, at the inverter operation mode, higher voltage than an idle state of rectifier operation (e.g. so current flows only from braking vehicles and not from rectifier units to an inverter);
- the necessity for arrengements with local DNO (Distribution network operator) regarding the possibility of energy return to a grid.

With respect to a regenerative substation with grid energy return to AC supply, the Rail Infrastructure Manager with cooperation with the DNO has established the conditions for an AC traction substation – so as to fulfil the needs of the electricity market, and to enable feeding energy back into a public grid.

In Poland, Izba Gospodarcza Komunikacji Miejskiej [Urban Traffic Central Office] makes efforts [10] for regenerative braking energy return from the urban transport systems to the AC network to be included in Energy Law. However, certain legal problems regarding the following issues have not been resolved yet:

- lack of definition of "energy recuperation" in Energy Law and lack of determination of its source of origin, in particular, the need for special treatment of recuperation energy as energy from the power system circulating in an electric traction system. Recuperation energy has to be used during a short period of a vehicle's regenerative braking, otherwise it is dissipated in a form of heat;

- lack of requirement of acceptance of the connected devices enabling recuperation energy return to an AC network imposed on the DNO;
- lack of appropriately defined manners for energy settlement;
- lack of legal intepretations regarding excise tax settlement;
- lack of support for the entities increasing energy efficiency of transport via increased recuperation efficiency.

In urban transport systems for many years inverters have been used in a thyristor technique, mainly the undergound systems (Brasil, ASingapur – powered by 750 V DC) and in Japan (1.5 kV DC). Current solutions of inverters with transistors allow for high efficiency, low harmonics content and a high power factor. In new substations, inverters are installed as rectifier and inverter units, and some additional inverter units [1, 7] are proposed for the existing substations.

3. Improving regenerative braking efficiency by means of additional equipment for a power supply system

During analyses of several solutions for recuperation efficiency improvement via application of an energy storage device or an inverter in a power supply system, the following should be taken into account [17]:

- traffic frequency;
- number of the required inverters or energy storage devices, their parameters and cost;
- scheme of sectioning and line power supply on the DC side;
- resistances in the DC circuits;
- an admissible voltage level in a catenary;
- amount of energy that can be taken over by other trains and the amount of energy that has to be received by an energy storage device / traction substation inverter;
- the additional costs of the equipment for rolling stock/a substation and savings that can be achieved – modern controlled rectifiers and inverters are equipped with the IGBT transistors [1, 7] that, due to PWM control, almost entirely eliminate the problem of harmonics and reactive power consumption, and the inverters connected to separate modules in parallel to classic rectifies may operate as filters of the current higher harmonics of rectifiers.

Introduction of regenerative braking is a new challenge and might cause the increase of disturbances from current and voltage higher harmonics under transient and steady states. The source of these disturbances includes both, a traction substation and a vehicle. When using rolling stock with DC and AC motors without recuperation, a substation constitutes an energy source with a variable component, and a vehicle is an energy consumer absorbing current distorted as a result of the operation of converters (choppers, inverters). In the case of recuperation, a vehicles becomes an energy source as well by generating, both, distorted current and voltage. In order to analyse this type of issue in a complex manner, one should take into account the mutual interaction of a substation, vehicles drawing energy and regenerative braking vehicles together with a catenary. Due to the complex nature of the phenomenon, it is required to use modelling and simulation techniques, and the models of objects should take into account their parameters (variables in a frequency function) and different operating states as well as position changeability. In such a multi-source supplied circuit with changeable parameters might, under certain, unfavourable conditions, occur resonances increasing even the slightest disturbances to considerable values. From the point of view of the compatibility of a power supply system, vehicles and low-current systems of control and signalling, the following are of high importance [14]:

- traction substation's parameters;
- presence or absence of a filter on the DC side, and the type of a filter;
- sectioning schemes;
- parameters of a catenary;
- parameters of a vehicle's input filter (a vehicle's input impedance);
- symmetry of voltage supplying a substation.

4. Case study of efficiency – simulation analysis of energy balance regarding installation of an inverter in a 3 kV DC substation for suburban traffic

During research for the case study, a series of simulation calculations were conducted in order to prepare a case study of energy efficiency with the use of a program developed at the Electric Traction Division of the Warsaw University of Technology [14, 16, 17]. The analyses were based on a 2-track section of a railway line of 30 km long supplied with 3 kV DC voltage with substations equipped with rectifiers, and additionally, with the use of an inverter in one of the middle substations. No power limitation was assumed, that is, the whole power provided at the input of an inverter P_{fal} (at DC rails of a substation) might be transferred to the 3-phase AC side. One conducted a parametric analysis for a section with regular suburban railway traffic with 4 MW trains running on 2 tracks of a line (with 10 stops) and at a constant sequence dt = 3 min to 30 min.

As a result simulation, one determined instantaneous waveforms (analysis step – 1 s) for the following values:

P_{pt} – power drawn from all substations feeding the analysed section,
P_{poj} – power drawn from a catenary by all vehicles running on a section according to the set timetable,
P_{rek} – recuperation capacity of all traction vehicles,
P_{fal} – power available at the 3 kV DC rails of a substation equipped with an inverter.

The value of power P_{sr} for simulation time (equivalent to energy during simulation) and the maximum values of instantaneous power P_{max} were determined.

Fig. 2 shows waveforms from simulation of instantaneous power drawn from a substation for train operation for dt = 3.5 and 10 min, and Fig. 3 for dt =10 min. Average power drawn from a substation during simulation was respectively, 23 MW (for dt = 3 min), 17.6 MW (for dt = 5 min) and 9.3 MW (for dt = 10 min). Fig. 3 and 4 show, respectively, power waveforms P_{pt}, P_{poj}, P_{fal} and P_{rek} for dt = 5 and 10 min.

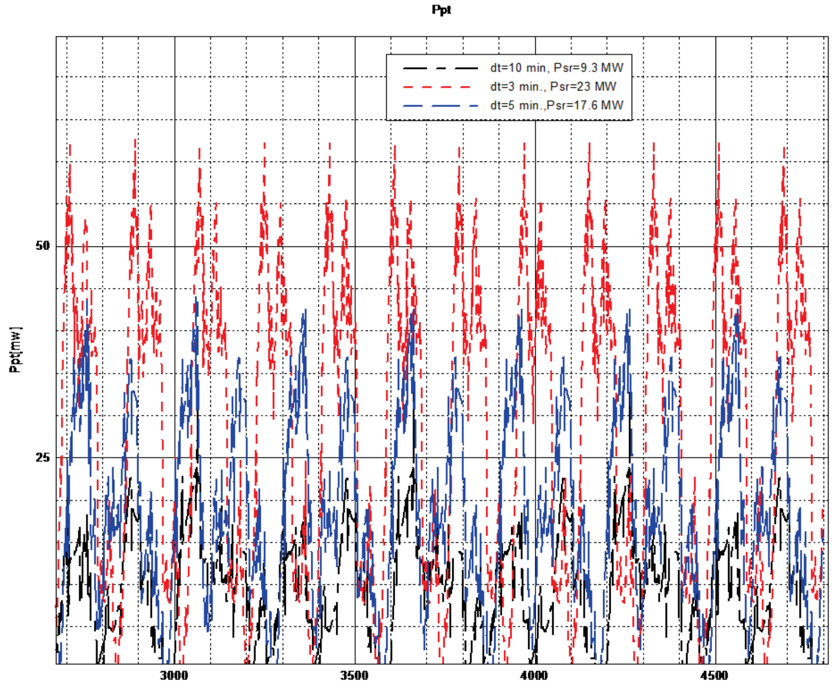

Fig. 2. Waveforms as a function of time of a substation's power P_{pt} for various times of a train sequence *dt*

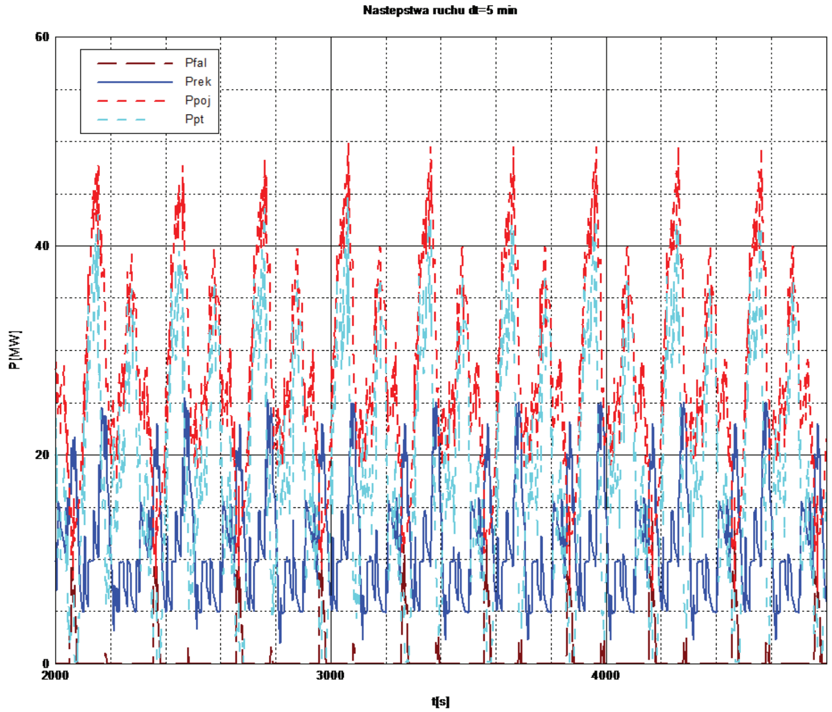

Fig. 3. Dependence of the waveform of power P_{pt}, P_{poj}, P_{fal}, P_{rek}, time intervals between trains dt = 5 min

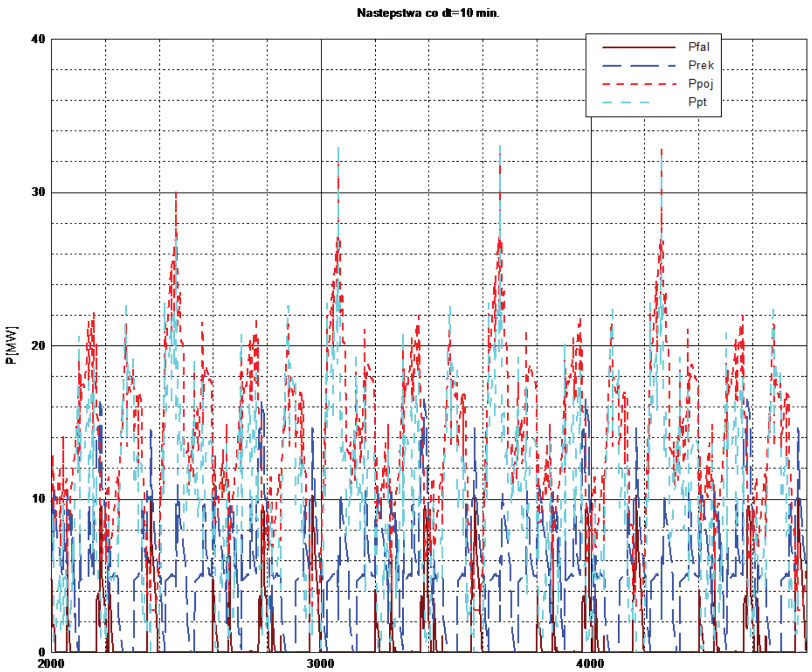

Fig. 4. Dependence of the waveform of power P_{pt}, P_{poj}, P_{fak}, P_{rek}, time intervals between trains dt = 10 min.

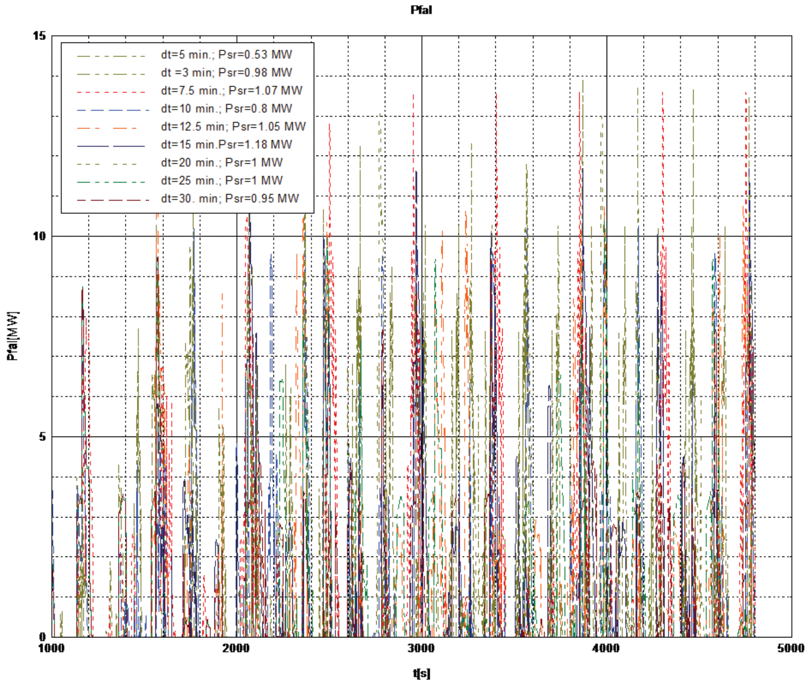

Fig. 5. Dependence of the waveform of power supplied to the inverter P_{fal} as a function of time for various time intervals between trains dt = 3÷30 min

Average value of power supplied to an inverter P_{srfal} during simulation is not too high (Fig. 6 – from 0.53 MW at operation with a sequence every dt = 5 min up to 1.18 MW with sequence dt =15 min). Assuming even a minimum value of average power P_{srfal} = 0.5 MW for 16 hours of traffic, one receives daily savings of 8 MWh and monthly of 180 MWh, taking into account only working days.

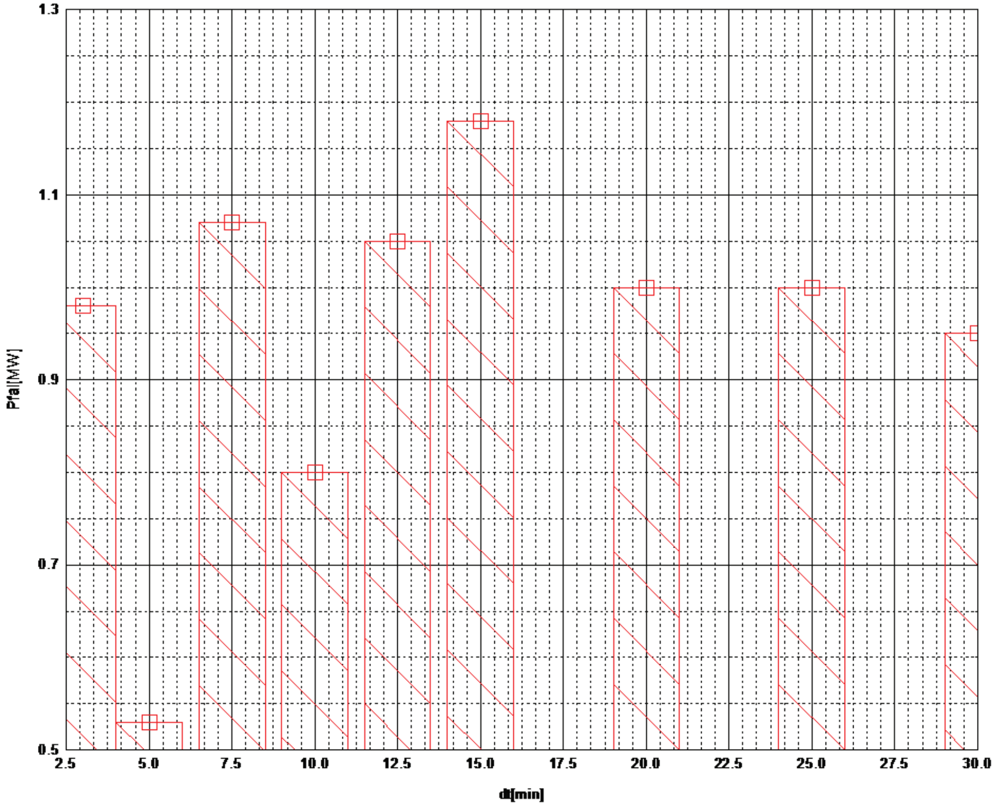

Fig. 6. Dependence of an inverter's average power P_{srfal} from time of train sequences dt

Energy efficiency of the application of an inverter will depend on the possibility of the AC power system to absorb pulse power P_{fal} reaching the inverter – power above 10 MW and duration time of several to a few dozens seconds (Fig. 7).

It relates to the change of receptivity of a 3 kV DC catenary (the possibility of exchanging energy between braking trains and trains taking energy) at the supply section and the overlap of braking processes of several trains. It is maximum power in particular P_{maxfal} that will determine the required rated power and overload capacity of an inverter, as well as influence its cost and financial profitability of the system. In order to receive power of up to 12 MW (except for the case for dt =5 min power P_{maxfal} does not exceed this value – Fig. 8) at overload of 300% one should install an inverter with 4 MW rated power at average used power of up to 1 MW.

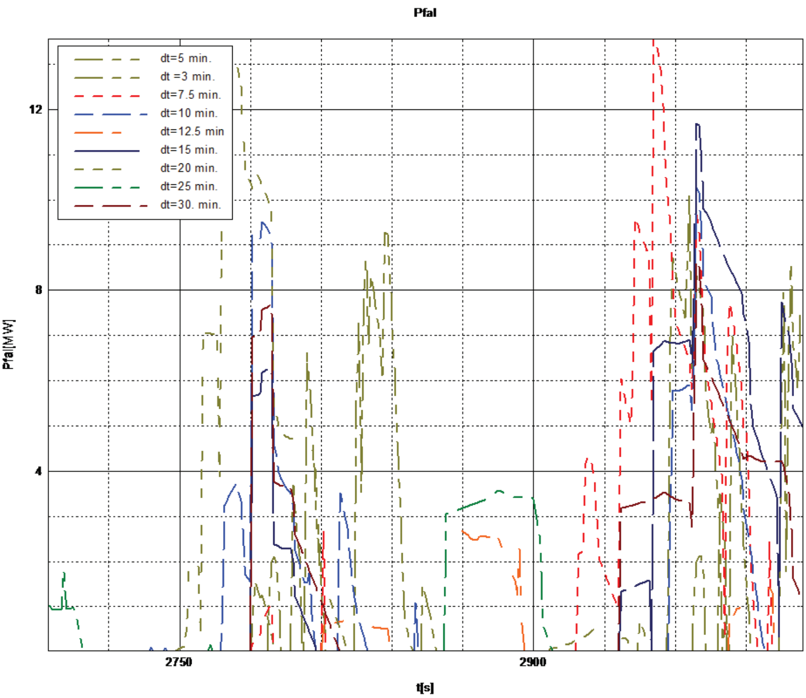

Fig. 7. Enlarged power waveforms P_{fal} from Fig. 5

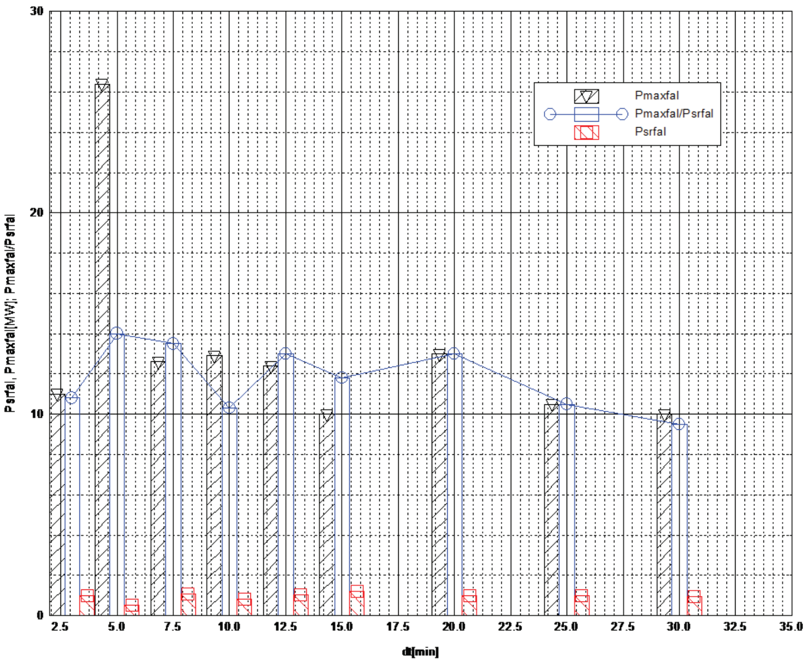

Fig. 8. Dependence of the maximum power P_{maxfal} and average power P_{srfal} of an inverter and the ratio of $P_{maxfal}/P_{srfalod}$ to train sequence times dt

5. Summary

Assuming a specific timetable on a given line enables estimating certain energy performance, and consequently, economic effects from the application of an inverter for regenerative braking energy return to the power supply network in 3 kV DC railway substations. However, even the slightest changes in the timetable, especially traffic density and shift of traffic in both directions, will result in significant changes of energy performance. Relative share of additional energy saved due to the application of inverters is particularly sensitive to these changes. Even at the same traffic density and with trains running with a time shift, significant changes regarding the efficiency of inverter application will occur in traffic directions (a DC traction system changes its receptivity when changes in traffic flow occurs) [18]. When the receptivity of a system is increased (increased transfer of regenerative braking energy between the vehicles), the efficiency of inverter use decreases. Inverter dimensioning should take place on the basis of the expected waveforms of power supplied to the point of inverter connection, taking into account the following aspects:

- current (power) in an inverter is of pulse nature, and it is maximum peak current that influences power of an inverter and a transformer (operating simultaneously) due to low constants of semiconductor thermal elements and limitation of commutating circuit reactance (transformer),
- the values of equivalent power during peak hours of inverter load.

If each traction substation is equipped with an inverter system, the power supply system will be receptive at any time; however, it would not be economically feasible, since:

- usually, the value of braking current is lower than the train start-up current, and in the case a braking vehicle is at large distance from the substation and transfers a part of its energy to the vehicle starting at a given time, it is not justified to transfer a small amount of energy to the inverter,
- if all substations are equipped with inverters, energy used so far between the trains will be transferred to the substation, which will result in increased size of converters and larger losses.

The ratio of instantaneous power to rated power for an inverter may considerably exceed the value of this ratio for rectifiers (braking time is shorter than the time of energy consumption by a vehicle). This may mean that in order to reduce the costs, it is required to limit the value of admissible inverter current and failure to use maximum available regenerative braking power that is pulse in its nature. It is due to the fact that from the point of view of the amount of energy used in the AC side, sending a short-term high power pulse is not efficient, and it is very costly (inverter power, ensuring operation stability of the AC network receiving power). A solution limiting recuperation power pulses might consist in using, together with an inverter, a storage device receiving short power pulses (e.g. of supercapacitor) on the 3 kV DC side.

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