ARCHIVES OF TRANSPORT
Volume 42, Issue 2, 2017
www.czasopisma.pan.pl www.journals.pan.pl
ISSN (print): 0866-9546
e-ISSN (online): 2300-8830
DOI: 10.5604/01.3001.0010.0529

ELECTRICAL POWER INFRASTRUCTURE FOR MODERN ROLLING STOCK WITH REGARD TO THE RAILWAY IN POLAND

Adam Szeląg
Warsaw University of Technology, Electric Traction Division, Institute of Power Engineering, Warsaw, Poland
e-mail: adam.szelag@ee.pw.edu.pl

Abstract: *Implementing high-speed trains on Polish railway lines requires a new approach to the issue of power and energy supply via a 3 kV DC power system. Due to the control systems used, modern rolling stock equipped with asynchronous drive allows maintaining a set speed, as far as a locomotive's power and voltage in a catenary allow it. Characteristics of traction vehicles with asynchronous drives enables run at voltage lower than the rated voltage, however, it entails decrease of consumed power (required for locomotives with power above 2 MW) and loss of motion dynamics. Modernisation of a railway power supply system conducted in Poland since the mid-1990s of the 20th century has intensified in the past couple of years (so-called MUZ-I program) due to the purchase of Pendolino trains, and it primarily include the main lines. A number of modernisation investments (lines E65, E20, E30) are implemented with co-financing from the EU funds. Due to the predicted trains' speed (200 km/h and above), in order to fulfil the requirements specified in TSI, a power supply system on these lines should ensure achieving high parameters, that is supply of trains with current up to 3.2 kA, while the so-called mean useful voltage should not be lower than 2.8 kV. The article presents solutions introduced on Polish railway and aiming at adjusting the power supply used to the TSI requirements. The range of conducted modernisation works allows for conclusion that the process is in fact a re-electrification of railway power supply systems.*

Key words: *electric trains, power supply system, TSI criteria.*

1. Introduction

A 3 kV DC system used in Poland since 1936 is capable of supply of energy for operation of vehicles with speeds up to 220÷250 km/h and power in the range of 6÷8 MW, provided that it is enhanced, since higher power consumption leads to considerable voltage drops and high loads. Modernisation of a power supply system (PSS) consists in increasing a cross-section of a catenary, decreasing distance between substations, and increasing power installed in substations (to above 10 MW) (Jabr & Dzafic, 2017; Jefimowski, 2016; Kuznetsov et al., 2015; Lewandowski, 2012; Ministry of Infrastructure, 2008; PN EN 50122 – 1, 2, 3; PN EN 50388; EU, 2014; Technical standards, 2010; Sychenko et al., 2015; Szeląg & Mierzejewski, 2005). It required a significant growth in the investment expenditures.
From the second half of the 1990s onwards, Poland witnessed undertaking of a program for modernisation of the main lines. It has mainly aimed at increasing speeds up to 160÷200 km/h and adjusting railway line infrastructure (including traction power engineering of power supply systems, catenary and non-traction load lines) to the requirements of European standards and regulations. The conducted works concern the operating railway lines, which causes some difficulties, both in terms of implementation and operation, as exemplified by modernisation of a Warszawa-Gdańsk line that has been performed for over 10 years now.
With respect to traction supply, the applied technical solutions encompass higher demands in the scope of technical and operational requirements. A new type of a substation with a single-step transformation with better parameters (power, energy transmission capacity, external characteristics, and decreased impact on the power supply system) has been implemented as early as in 1998. In the first decade of the 21st century, one has developed and implemented a new type of an overhead catenary made of a copper-silver alloy, characterised by an increased load-capacity for speeds up to 200 km/h.
Supply of Polish electrified railway line belonging to PKP PLK S.A., an infrastructure manager, with a length of approx. 12,000 km, is executed via over 460 rectifier traction substations (in recent years

they have been modernised to considerable extent), which convert alternating current energy of 50 Hz supplied by means of 3-phase lines with voltage of 110 kV or 15/20/30 kV. Until 2007, traction substations were divided in terms of ownership, currently, they are mainly the assets of PKP ENERGETYKA S.A. (a privatised company).

2. Requirements for modern electric rolling stock

Locomotives (drive units) of trains (ETV) are dimensioned for operation with rated voltage at the collector. The goal of a power supply system is to provide a locomotive with a required power, while ensuring an appropriate voltage level, which allows for the required traction parameters (force, acceleration and speed). In case a voltage level is lower than the required one, traction and operating parameters of a locomotive and train cannot reach rated values (Fig. 1). Issues of cooperation between a power supply system and traction vehicles on the interoperable lines, that is governed by TSI rules and regulations (Technical Specification for Interoperability), and all railway lines should be subject to plans of adjustment to TSI requirements (EU, 2014) – standard (PN-EN 50388). It refers to coordination of installed power and operating parameters of a power supply system and power demanded by trains. This standard defines quality criteria with respect to a power supply system of vehicles, however, this standard does not apply to vehicles that are in operation prior to introduction of thereof.

Due to increase of train powers, it is required to impose limitations on current consumed by trains regarding a maximum permissible value for a given line depending on a declaration (in a line register) of an infrastructure manager. ETV should also have the possibility of automatic control of consumption of current I_c (and power P_e) depending on voltage conditions in a catenary (voltage at a collector U_p). This particularly applies to a too weak power supply system, that is a one not suited for consumption of high power or for operation under emergency conditions (e.g. switching off of the substation), which has been presented in Fig. 2 (Standard PN-EN 50388, section 7.2.). This limitation does not apply to high-speed lines of the highest category.

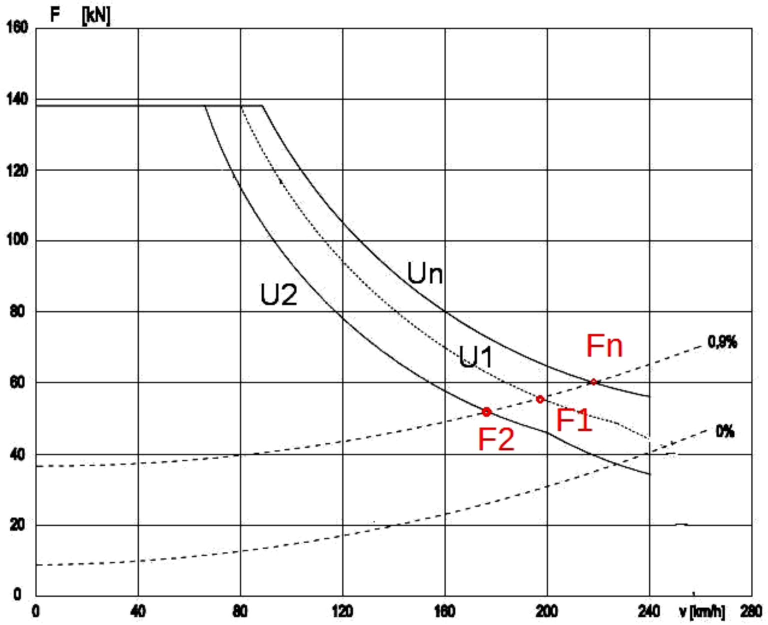

Fig. 1. Exemplary traction characteristics of a train F(v) depending on voltage ($U_n > U_2 > U_1$)

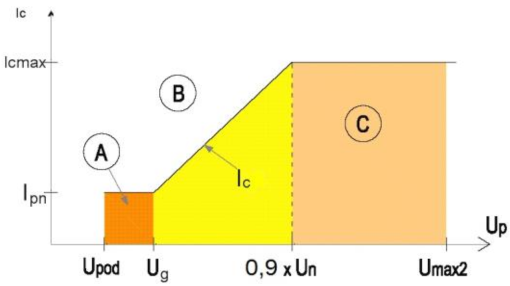

Fig. 2. Train current I_c limitations depending on voltage U_p at a collector (PN EN 50122 – 1)

A – area without consumption of current for traction needs,
B – area with reduction of current,
C – area without limit of current,
U_p – voltage in a catenary according to PN-EN 50163 [7,11],
U_g – voltage, below which ETV takes current only for non-traction needs,
I_{cmax} – maximum current I_c consumed by ETV at rated voltage (some trains, e.g. a trainset of Pendolino type, with 3 kV DC supply from a catenary, can consume full power at voltage above 3 kV DC),
I_{pn} – current I_c consumed only for non-traction needs (without traction),
U_{pod} – tripping voltage of under-voltage protection in ETV,
a_o – coefficient (0.9 for voltage U_p=3 kV DC).

In order to ensure compatibility of a power supply system with ETV already at a design stage, it is required to conduct study works aiming at evaluation of transmission capacity of a power supply system so as to guarantee supply of a sufficient amount and appropriate quality of electric energy to the ETV. The set design criteria should be met for the worst predicted conditions, that is peak load traffic (highest traffic density) of ETV, constituting the highest load for a power supply system.
With respect to electric energy supply, basic parameters include (PN-EN 50388):
- voltage (for 3 kV DC – Table 1)
- efficiency (capacity of energy transmission to all trains consuming a predetermined amount of power on a line), defined by mean useful voltage and maximum current consumed by a train (for a 3 kV DC system – Table 2) , and a train power coefficient with AC voltage supply; whereas trains with power below 2 MW should not be limited as far as current / power consumption is concerned,
- short-circuit breaking capacity (Table 3) and coordination of protection systems providing selective switching (Table 4),
- providing stability of cooperation between a substation and a traction vehicle, especially in AC power supply systems – limitation of overvoltages resulting from transient states and harmonics.

Voltage criteria used with respect to the electric traction power supply system allows for technical evaluation of an energy supply system and can be presented in a synthetic manner, mainly by means of mean useful voltage on a collector $U_{śruz}$, which constitutes an indicator for quality of energy supplied to rolling stock (it might be verified using measurements for the trains that are considered to operate under critical conditions – the most difficult voltage conditions).
The Standard PN-EN 50388 includes criteria for power supply quality evaluation in accordance with the following formula:

$$U_{śruż} = \frac{\sum_{I=1}^{n} \frac{1}{T_i} \int_0^{Ti} U(t)_{pi} \cdot I_{ci}(t)\, dt}{\sum_{I=1}^{n} \frac{1}{T_i} \int_0^{Ti} I_{ci}(t)\, dt} \tag{1}$$

where:
$I_{ci}(t)$ – current of ith *ETV*,
$U_{pi}(t)$ – voltage at a collector of i^{th} *ETV*,
T_i – ride time of i^{th} train,
n – number of trains during simulation (while establishing useful voltage for a zone); n=1 while determining useful voltage for a given ETV.

In comparison to the previously used, classic methods for average value determination, this criterion differs in a manner of voltage calculations in use of an integral value of instantaneous power divided by average current; it is possible to obtain these values only with the use of simulation techniques. This type of approach increases the importance of a voltage level during current consumption, which is justified by the influence of a voltage level in a catenary on operational and traction parameters of traction vehicles, high power in particular. In accordance with standard PN-EN

50388, voltage in a catenary should be in the range stated in Table 1.

According to the requirements of standard PN EN 50122 – 1, a value of mean useful voltage U_{sruz} should be above 2.8 kV – Annex C, Table C1 – on the lines with speeds in the range from 200 km/h and above), while on the lines with maximum speeds up to 200 km/ h – above 2.7 kV. Furthermore, a value of voltage on a collector should not be lower than U_{min1}, that is 2.0 kV for a 3 kV DC power supply system (PN EN 50122 – 1). Fulfilment of voltage criteria indicates acceptance for putting into service of, e.g. new rolling stock on the existing lines or new solutions (e.g. modernised power supply system) for a given type of traffic.

Establishing useful voltage value $U_{śruż}$ at the level of 2.8 kV means an increase of requirements regarding voltage values on a vehicle's collector, which was imposed by introduction of rolling stock for high speeds, in comparison to the lines with classic rolling stock operated (for conventional lines below 200 km/h – 2.7 kV).

At the same time, limitations of a maximum value of current consumed (current returned during braking) by ETV (together for traction and non-traction needs) have been introduced. For Polish railway lines these values are summarised in Table 2 and "Standards..." (Technical Standards, 2010). In case of a voltage drop, the value must be limited to the value below rated value, that is below a_0U_n (Fig. 2).

In order to enable operation of high power locomotives on the lines with limited transmission capacity, it is necessary to install a power consumption limiter (automatic or operated by a driver). Such a solution can also be applied on the connecting lines in high-speed trans-European corridors and on conventional lines undergoing modernisation and on connecting lines.

Table 1. Rated voltage and permissible traction voltage limits (PN-EN 50163)

Electrification system	U_{min2} [V]	U_{min1} [V]	U_n [V]	U_{max1} [V]	U_{max2} [V]
3 kV DC (average value)	2000	2000	3000	3600	3900

Permissible voltage levels in a catenary (at current collector ETV) are summarised in Table 1, assuming the following designations:

U_n – rated voltage
U_{min1} – the lowest continuous voltage,
U_{min2} – the lowest temporary voltage with duration of up to 2 minutes,
U_{max1} – the highest continuous voltage,
U_{min2} – the highest voltage with duration of up to 5 minutes,

Voltage level at the bus-bars of a traction substation with open all line switches cannot be higher than U_{max1}. During normal operation, voltage should be in the range between $U_{min1} \div U_{max2}$.

Under non-standard operating conditions of a power supply system, permissible voltage is in the range between $U_{min1} \div U_{min2}$.

When voltage U_{max2} appears, what should occur is voltage lower or equal to U_{max1} after any period.

During worsened operating conditions of a system, voltage U_{min2} constitutes a voltage lower limit for a contact wire at which trains can run.

Set-points of protection relays for under-voltage devices in a substation of a train should be in the range of (0.85 ÷ 0.95) voltage level U_{min2}.

One should take into consideration the possibility of overvoltages. Tests and measurements conducted under real conditions in a 3 kV DC system have shown occurrence of switching overvoltages above 10 kV, which necessitates the use of surge limiters both in vehicles and in substations.

Calculations of operating currents of vehicles, substations and catenary should be made using appropriate methods and simulation programs for the assumed traffic of load peak hours, with simultaneous determination of useful voltages on the analysed section of a line.

Table 2. Maximum train current [A] (PN-EN 50388)

Power supply system	High-speed railway line – category I	High-speed railway line – category II	High-speed railway line – category III
3 kV DC	4000	4000 (3200*)	4000 (2500*)

* on a Polish railway line

Table 3. Maximum short-circuit current of catenary–rails PN-(EN 50388)

Power supply system	Two-sided supply from a substation	Maximum short-circuit current [kA]
3 kV DC	YES	50

Table 4. Operation of a power switch (high-speed circuit-breaker) during short-circuit in a vehicle (PN-EN 50388)

Power supply system	Tripping sequence of breakers under the condition of internal short-circuit	
	Breaker in a substation – operation mode	Breaker in a vehicle – operation mode
3 kV DC	Immediate tripping (duration: 20÷60 ms)	Immediate tripping (duration: 20÷60 ms)

It is required to use systems for tripping of a vehicle's breaker that start within 3 seconds from power failure in a network, and for re-connecting not sooner than within 3 seconds after re-establishing power supply of a catenary. It is required to use automation systems for re-closing of power supply switches of catenary sections with control (or without) of a line test (catenary insulation test). In catenaries supplied with DC voltage, one should use systems limiting a current derivative di/dt to the value below 20 A/ms in 20 ms, until the value di/dt reaches 60 A/ms (in order to limit the possibility of tripping a high-speed breaker of a substation while closing a vehicle's breaker equipped with an input filter) with a proper minimum value of catenary inductance and substation's choke (PN-EN 50388).
By providing an appropriate level of voltage in a catenary, it is possible to optimize use of power installed in rolling stock, achieve required traction and operational parameters (acceleration, maximum speed) and efficiency. High transmission capacity of a traction power supply system allows also for energy supply to the vehicles under disturbance operating conditions and increase of a degree of reserve in case of failure in a power supply system. However seasonal weather phenomena could cause disruption of catenary supply reliability (Maciołek & Szeląg, 2016).

3. Influence of current and voltage limitation in a catenary on a vehicle's motion

In order to present an influence of limitations in current taken by a train (e.g. due to low transmission capacity of a power supply system and low voltage at a collector), Fig. 3 shows obtained simulation results of current taken by a high-speed trainset on a given route (at 100, 75 and 50% of available drive power, respectively), these curves have been limited in terms of a vehicle's current on individual route sections – marked as W1 (limitation range): 1000÷1800 A) and W1A (limitation range: 1000÷2200 A). As one might notice, almost on a whole route it will be impossible for a train to use maximum current required for development of 100% of power, on a majority of sections it will be possible to consume current for 75% of power, and on some of the sections even use of current providing 50% of power will not be possible. Such a case influences train motion acceleration and maximum achievable speeds (Fig. 4). Introduction of limitations in current consumption (resulting from power supply system efficiency and low voltage at a vehicle's pantograph) causes that on short sections with maximum permissible speeds between speed limitations, a train (with imposed limitations) is not capable of reaching the maximum speed (Fig. 4).

4. Categories of railway lines in Poland – influence on the standards

With respect to categorisation of high-speed railway lines according to PN-EN 50388, a division is as follows:

High-speed railway lines:

Category 1: dedicated and purpose-developed high-speed lines for speeds of 250 km/h and above (currently, no such lines in Poland),

Category II: specifically modernised high-speed lines for trains running at speed of 200 km/h (after modernisation the category will include the following Polish lines: CMK on a section between Grodzisk Maz.-Zawiercie, and Warszawa-Gdańsk, possibly),

Category III: specifically modernised high-speed lines at which maximum speed (due to a route specification and various speed limitations) is adjusted accordingly.

Conventional lines:

Category IV: a core of the TEN line for passenger or mixed traffic, with maximum speeds of v_{max}=200 km/h and v_{max}=140 km/h for freight traffic,

Category V: modernised Trans-European Network for passenger and mixed traffic for v_{max}= 160 km/h and freight v_{max}=100 km/h, these lines might include modernised / currently undergoing modernisation sections of line E20: Warszawa-Poznań-Wrocław,

Warszawa-Terespol, Opole-Wrocław, Kraków-Rzeszów,
Category VI: other new Trans-European Network lines for passenger and mixed traffic, with maximum speed of v_{max}=140 km/h and v_{max}=100 km/h for freight traffic,
Category VII: modernised Trans-European Network lines for passenger or mixed traffic, with maximum speed of v_{max}=120 km/h and v_{max}=100 km/h for a freight traffic.

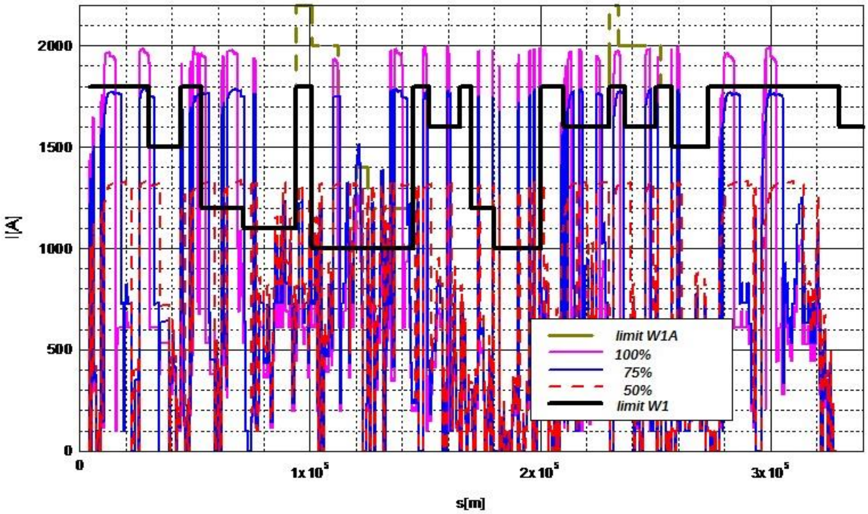

Fig. 3. Waveform of current consumed by a trainset as a function of a route depending on available power (100, 75 and 50%) of a train with current limitations W1 and W1A

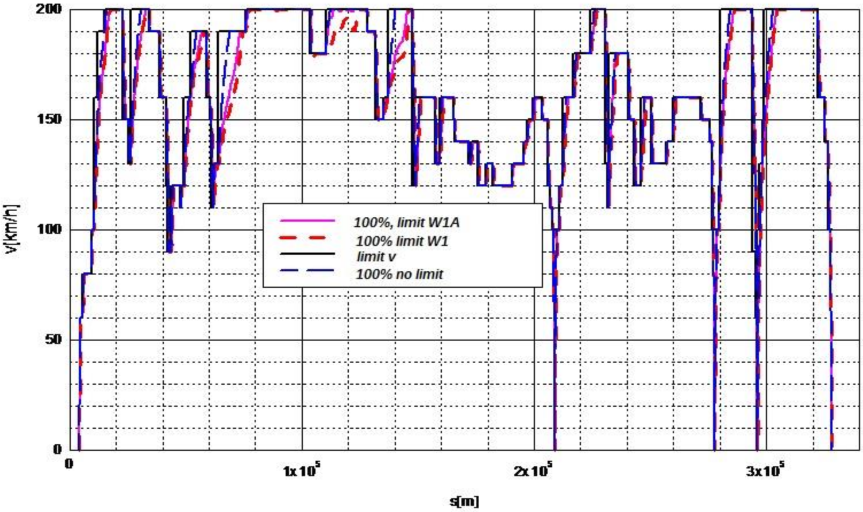

Fig. 4. Waveform showing train speed *v* as a function of a train position on a route with availability of 100% power without limits and with a forced current limits due to W1 and W1A limitations respectively; maximum permissible limited speed *v* is marked

Power demand for a line depends on a type of traffic and traffic density. Introduction of trains with increased mechanical power, 5.5÷6.4 MW, will influence the increase of peak power of a substation and increase of voltage drops in a catenary. A 3 kV traction power supply system, which was developed and implemented during the period of electrification after the World War II, was initially intended for traffic with speeds up to 120 km/h and lower locomotive powers, therefore, now it has a limited energy transmission capacity. Modernisation of a power supply system of a CMK line in terms of operation of a trainset of Pendolino type (forecast maximum speed in Poland is 200÷220 km/h), and for locomotive trains – 200 km/h, included modernisation of the existing and construction of several new substations on the most important sections (the longest distance between substations and the highest predicted loads), while maintaining the used catenary cross-section of 440 mm^2 Cu. One obtained a large installed power in traction substations per km – above 1.1 MW/km. Similar modernisation works have been completed on a line E-65 North (Warszawa – Gdańsk).

Due to such speeds, the power supply system of a CMK line must fulfil the requirements imposed on a 3 kV DC system, that is to be adapted for power supply of trains with 3.2 kA (Table 2), and mean useful voltage U_{sruz} should be less than 2.8 kV. It should be emphasised that the rated voltage of these types of trainsets is above 3.2 kV, while for locomotive trains is 2.8 kV. Under certain conditions, this may indicate the necessity to reduce power consumed by trainsets, and decrease of reached mechanical power below rated value of 5.5 MW. Maintaining a value of useful voltage at the level of 2.8 kV (which guarantees possibility of consuming slightly above 75% of power installed in these trains) should not, however, have a major influence on maintaining maximum speed due to low resistances to motion, and only slight influence on dynamics of a trainset. Further reduction of voltage and power below 75% of a rated power will cause noticeable decrease in dynamics and speed (Fig. 4). Theoretical analysis and experience from service of high-power locomotives have shown that in some cases compatibility issues will as well impose reduction of power developed by trains (Steczek et al., 2017).

The conducted analyses (Szeląg & Patoka, 2014; Szeląg & Mierzejewski, 2005) point to the fact that traffic of trains with mechanical powers of approx. 6 MW (and electrical at 7.5 MW – e.g. a Husarz locomotive) generates more load at speed in the range of 160 - 200 km/h. For a power supply system to fulfil the quantitative and quality criteria, it will require a distance between a traction substation not to be larger than 10-15 km, a catenary cross-section of at least 440 mm^2 Cu and internal resistances of substations below 0.1 Ω. When distances between substations are above 15 km, there might be a need to place a section cabin in a middle of a section.

Pendolino trains are characterised by a slightly lower mechanical power (5.5. MW), but due to very good operational and traction parameters (low resistances to motion) even for a train run at speed of 200 km/h, power demand will be largely below the rated value, and at 160 km/h, on a flat section, electrical power of 1.5 MW will be sufficient for maintaining this speed (with power for auxiliary needs – approx. 2 MW, that is current consumption at the level below 700 A) (Fig. 5), which is below the value required by a classic train with a locomotive EP09 or with a Husarz locomotive. Only while accelerating with dynamic changes of a driving manner, a Pendolino train might consume current above 2 kA (Fig. 5 – train near a substation consumes current of approx. 1800 A from a given substation, this train is also supplied with current of small values from an adjacent substation). Putting into service of a Pendolino train on lines with a power supply system of low efficiency, will require introducing limitations on consumption of maximum current (it is possible from a driver's desk), so as not to cause considerable voltage drops and tripping of high-speed breakers of substations' feeders.

Traffic of qualified trains that require higher powers on a route with a power supply system that has not been adjusted, should be limited and be based on importance of assumed network of connections (e.g. run through a connecting section or only temporarily, until modernisation of these lines for higher speed is finished).

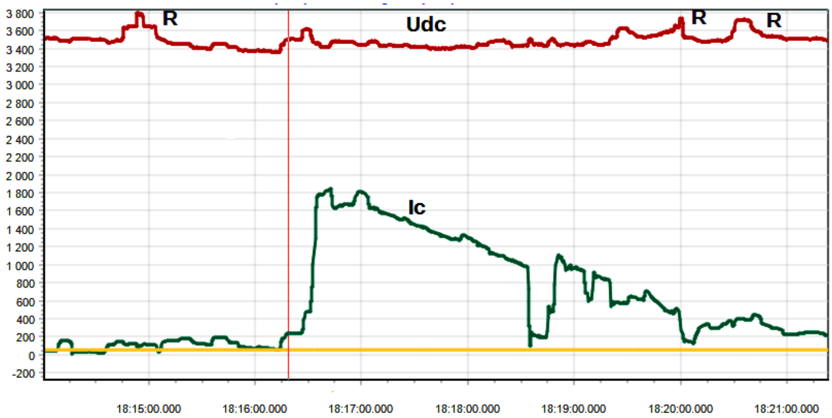

Fig. 5. Waveform of feeder current *Ic* and substation rails voltage *Udc* registered in one of the substations on a CMK line, noticeable recuperation – voltage above 3600 V – marked with letter R.

5. Summary

Modern trains require higher transmission capacity of a power supply system (higher powers) and energy of better quality parameters (voltage in a network). In order to achieve speeds of 120÷160 km/h on the lines planned for operation of Pendolino trains, it is sufficient to modernise a power supply system, as it has already started, has been partially finished and continued on lines E20, E30, E75 and E59 (Wrocław-Poznań), which are also expected for traffic of trains with power of 6 MW and speeds up to 160 km/h.

Railway lines with speeds above 160 km/h include mainly the E65 line (Warszawa-Gdańsk-Gdynia i Warszawa- Zawiercie). The other lines, which are to be modernised for operation of locomotives with mechanical power of 6 MW and maximum speed of 160 km/h, will enable energy supply for operation of Pendolino trains with speeds above 160 km/h; it is due to their considerably lower powers, very low resistances to motion and low current consumption at a steady speed, with possibility of its limitation to the value set for dynamic states.

Limit speed at 3 kV DC voltage supply in regular traffic is the speed of 250 km/h. After modernising power supply system on a CMK line on some sections and gaining valuable experience from operation at speed of 200 km/h, it will be possible to conduct trial speed increase up to 220-230 km/h. Modernised power supply system is efficient enough to supply energy to the Pendolino train at speeds 200-220 km/h, hence the system will not be an obstacle.

Catenary installed in a CMK line has a maximum speed of 200 km/h. Tests of a Pendolino train conducted in 2013 have shown its high operational parameters at higher speeds as well (speed record: 293 km/h).

Extensive modernisation of the main railway lines in Poland, including the existing 3 kV DC power supply system on a section Grodzisk Maz.-Zawiercie, after postponing implementation of KDP project (with expected electrification under 25 kV 50 Hz (Szeląg & Patoka, 2014)) for a period beyond 2030 allows obtaining a regular speed of above 200 km/h on a line constructed back in the 1970s (first for freight traffic, then passenger traffic with speeds up to 160 km/h – reached in the 1980s of the 20th century).

Distances between Warsaw and main agglomerations, which are not larger than 300 - 400 km, indicate that a railway lines network with maximum speeds of 200÷250 should be capable of providing operation of trains for the next 25-30 years (lifetime of the modernised devices of traction power supply), which would be competitive with road and air transport. The 3 kV DC power supply system existing in Poland is sufficient for energy supply for the purpose of train operation at the above mentioned speeds, however it is not the most efficient solution in terms of energy delivery.

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