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POWER QUALITY IN THE CIRCUITS OF TRACTION SUBSTATION

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Abstract – Rail transport in Poland uses direct current electric traction to power vehicles (locomotives and multiple units). It is therefore necessary to convert the AC voltage of the power system into the DC voltage of the traction system. The conversion of alternating voltage into direct voltage takes place in traction substations. Rectifier units installed at traction substations are used for this purpose. As a result, electric traction should be classified as non-linear consumers. In addition, the traction substation load changes dynamically. All this makes the electric traction a recipient generating a number of disturbances to the network. These disturbances affect the quality of electricity in the power system from which the traction substations are supplied, and the quality of energy in auxiliary and non-traction lines. The article presents the results of the analysis of measurements of electricity quality indicators recorded at selected points of the traction substation line. Parameters characterizing the quality of electricity were recorded, among others, in in the main line supplying the traction substation, non-traction needs line and auxiliary circuits. The presented article is another in a series of publications related to the assessment of the impact of DC electric traction on the power system.

Key words – power quality, electric traction, disturbances, voltage changes, higher harmonics, THD

JEL Classification – C80, D30, P18, Q40, Q49

INTRODUCTION

Rail transport used in Poland uses DC traction. This requires converting the alternating voltage of the power system into the direct voltage of the traction network. Transformation of alternating voltage into direct voltage takes place with the use of converters installed at traction substations. The use of converters causes that electric traction is classified as non-linear consumers. This has a significant impact on the quality of electricity in the power system, from which the electric traction is supplied. The use of a direct voltage of 3.3 kV significantly reduces the power of the traction units supplied from the substation. As a result, the speed of the trains is limited. Analysis and assessment of the impact of DC electric traction on the quality parameters of the supplied electricity is also the subject of many articles and studies [1-4]. One of the possibilities to eliminate the unfavorable impacts is the use of station and compensation-energy filters [5]. A very important issue is also to determine the range of propagation of harmonics of current and voltage along traction lines and to supply systems with higher voltage [6]. A very important issue is the introduction of high-speed trains in Poland. It is related to the design, construction and implementation of a new 25kV alternating voltage traction power supply system. This is to reduce energy consumption and reduce CO_2 emissions [7, 8]. Increasing the efficiency of the electric traction system and improving the quality of electric energy is significantly influenced by the increasing use of electric energy storage [9, 10] and braking of vehicles using energy recuperation [11-14]. However, the use of energy recuperation requires the use of special inverter sets [15-17] The research presented in the article is a continuation of the consideration of the impact of traction substations on the power system. The publication [18] presents an analysis of the impact of a traction station with six-pulse converters on the power system. The main aim of the authors was to estimate the disturbances generated by the traction substation both to the power system and other lines supplied from the traction substation. This paper presents an analysis of disturbances caused by a traction station with twelve-pulse converters. According to the authors, few publications discuss the generation of disturbances by direct current electric traction to other circuits of the traction substation in such a wide scope. Simultaneous registration at several measurement points allows for the identification of sources and the degree of disturbances caused by individual groups of consumers, with the greatest impact of DC traction. Most publications on the impact of electric traction mainly analyze the impact of disturbances generated by the substation on the power system. For example, in [19-22] an analysis of energy quality parameters recorded in networks supplying electric traction is presented. Often the analysis is based mainly on model tests [9, 11, 23-27]. The article presents in a comprehensive way (of course in the presented case of a given traction substation) the propagation of disturbances and their analysis on individual circuits (electric lines) of the traction substation, including the main supply line.

1. Places and method of measurement of energy quality parameters

The results presented in the article were recorded in the DC traction substation circuits with twelve-pulse converters installed. Three PQM 711 analyzers and the Memobox 800 analyzer were used to register electricity quality indicators. Measurements were carried out simultaneously in four points. The places of connecting the analyzers are shown in Figure 1.

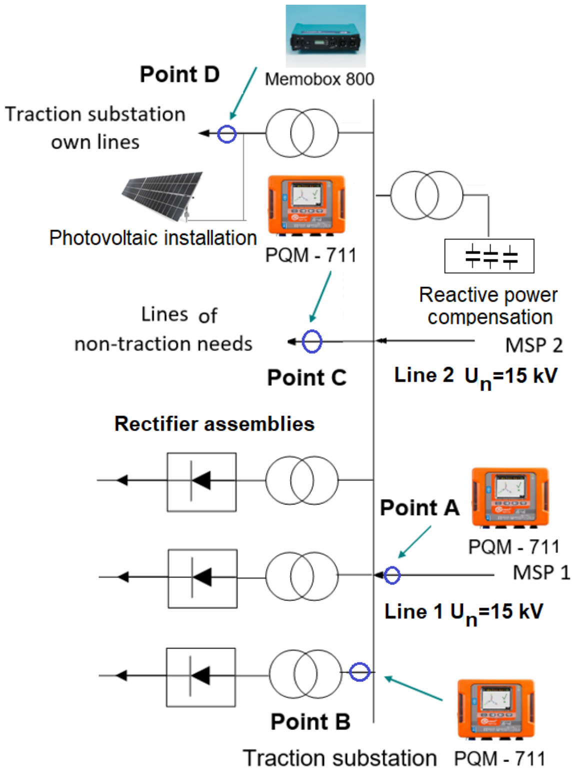


Fig. 1. Registration points for indicators characterizing the power quality

The measurements were carried out in accordance with the guidelines contained in the regulation [28, 29].

The permissible values of indicators characterizing the quality of electricity in public networks in Poland are specified in Regulation ... [29]. The Polish normative act was based on the European standard [28]. The permissible values of power quality indicators depend on the network voltage level. PKP Energetyka, as a company dealing mainly with supplying power to DC traction, also has a license to sell electricity on the energy market in Poland. Therefore, it is important to determine the magnitude of disturbances generated by the traction substation to the network from which other consumers are supplied. According to [29, 28], the quality of energy is assessed after a weekly measurement time. In addition, the parameters characterizing, for example, the voltage value are the average for a 10-minute period. In the case of a rapidly changing load on the traction substation resulting, for example, from the start-up of trains, fast-changing disturbances (e.g. voltage fluctuations and dips) are generated. The use of short measurement intervals (for example, 5 seconds) allows for a better assessment of the disturbances arising at that time. The measurement cycle covered a period of one week. Electricity quality parameters were also recorded in short measurement intervals. The measurement intervals adopted in this way made it possible to assess the impact of dynamic load changes on the parameters characterizing the voltage quality, e.g. in the line supplying the traction substation, non-traction needs lines and substation auxiliary circuits. The traction substation is powered from the main supply point by two lines with a voltage of U_n=15kV.

At the traction substation, the measurements were made at the following points: Point A - line supplying the traction substation with rated voltage U_n=15kV, Point B - Point C - non-traction needs line with supply voltage U_n=15kV, Point D - traction substation auxiliary circuits with voltage U_n= 0.4kV. In the case of receivers with significant power, dynamically changing load or non-linear nature, the parameters of the supply line are very important. The most important parameter is the value of the short-circuit power in relation to the power of the installed receivers. The short-circuit power at the Main Supply Point (MSP) of the traction substation is S_{CC}=497 MVA (at the level of U_n=15kV). The substation is powered by a 500m long Al cable line. The resistance of the primary supply line is R_L=0.037 Ω, and the reactance X_L=0.221 Ω. The rectifier units are powered by three-winding transformers with the power of S=4.5MVA. The rated rectified current (direct current) is I_{DCN}=1700A and voltage U_{DCN}=3300V.

Voltage and current transformers installed at the traction substation were used to record the electric power quality parameters (using PQM analyzers). Figure 2 shows how PQM analyzers are connected to the measurement circuits.

In the regulation on power quality parameters [29], the permissible ranges of voltage changes are given as a percentage of the rated voltage. Therefore, changes in voltages and currents were expressed as percentages, referring them to nominal values at the measurement points where the registration was made.

2. LINE SUPPLYING TRACTION SUBSTATION

Rail transport requires a reliable power supply. For this reason, traction substations are powered by independent power lines. In the case of the friction substation presented in the article, these are two lines with a rated voltage of U_n=15kV. DC electric traction, due to the converters used in traction substations, is one of the largest non-linear consumers supplied from the power system. The currents drawn by the substation are distorted currents. Figure 3 shows the course of currents recorded in the line supplying the traction substation (point A- Figure 1).

The size of the current distortion in the line supplying the traction substation is affected by: mainly the load of the rectifier units from which the DC traction is supplied and non-linear receivers supplied from the non-traction lines and substation auxiliaries circuits. Figure 4 shows the share of individual harmonics in the spectral distribution of the current recorded in one of the phases.

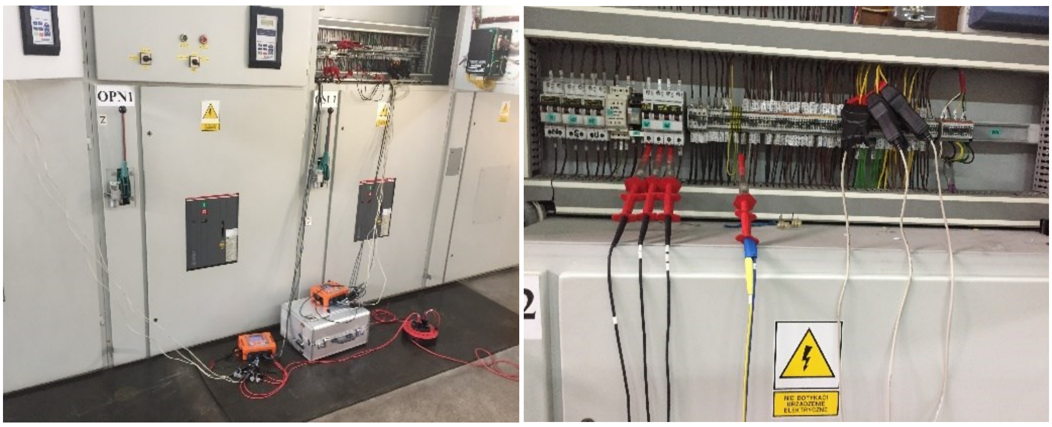


Fig. 2. Connecting PQM analyzers to measurement circuits

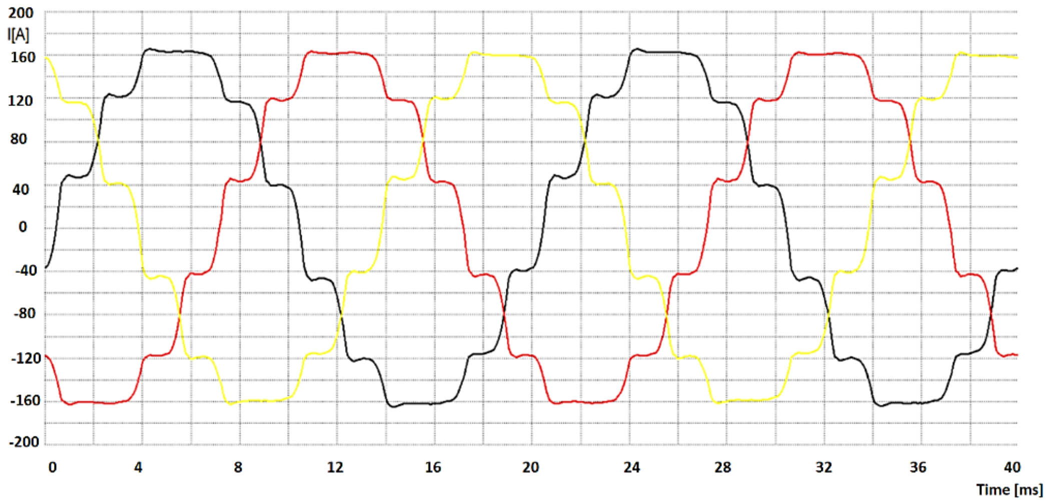


Fig. 3. Waveforms of currents recorded in the line supplying the traction substation

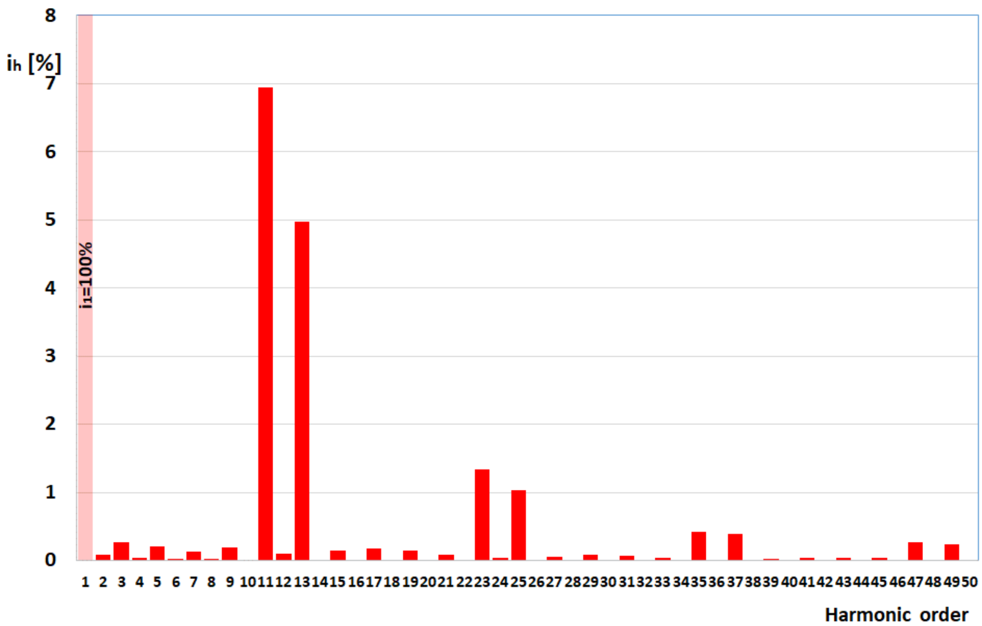


Fig. 4. Waveforms of currents recorded in the line supplying the traction substation

In the spectral distribution of higher current harmonics, there are mainly odd harmonics. The values presented in Figure 4 have been referred to the first harmonic (according to the formula 1), whose value is 100%.

$$i_h = \frac{I_h}{I_1} \times 100[\%] \qquad (1)$$

The assessment of the quality of electricity supplied by the supplier takes place at PCC. This is the connection point of the traction substation with the power system (Point A in Figure 1). The permissible values of the parameters characterizing the quality of the supply voltage are given in the Regulation ... [29]. Figure 5 shows the voltage Waveforms recorded in the PCC and the spectral distribution of the voltage in one of the phases.

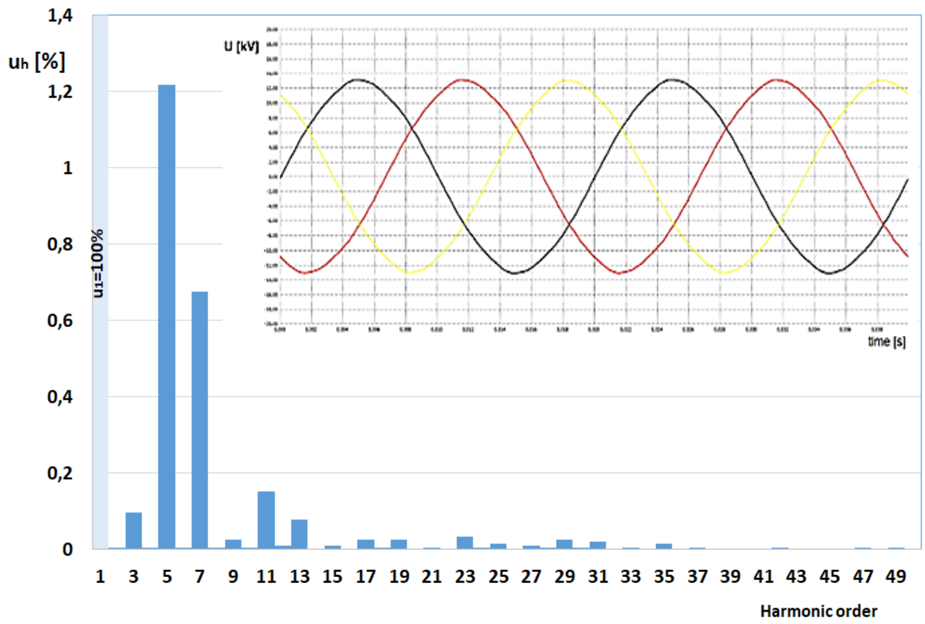


Fig. 5. Voltage waveforms and spectrum of voltage harmonics recorded at point A

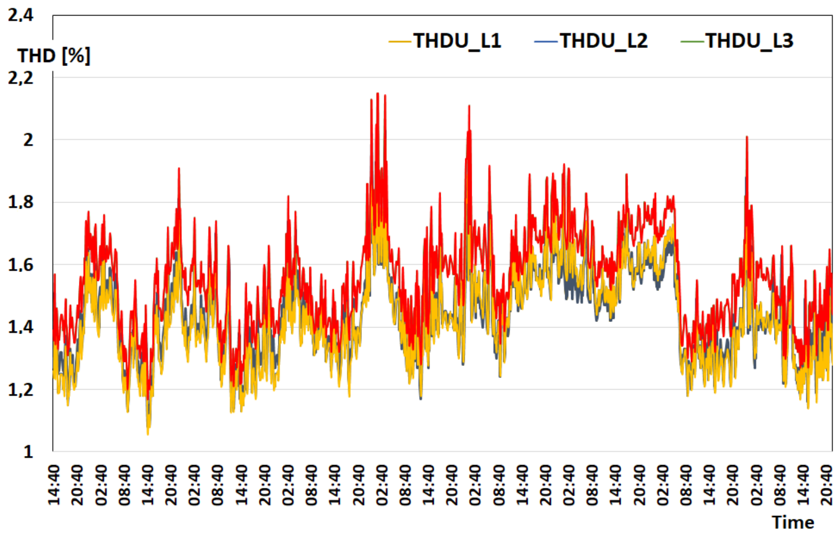


Fig. 6. Changes in the harmonic distortion factor THD_U recorded in phases L1, L2, L3

In the spectral distribution of higher voltage harmonics, there are mainly odd harmonics. The values presented in Figure 5 were related to the first harmonic (according to the formula 2), whose value is 100%.

$$u_h = \frac{U_h}{U_1} \times 100[\%] \qquad (2)$$

The voltage distortion in the PCC is affected by both traction substation loads and other non-linear receivers supplied from the power system. Changes in the harmonic distortion factor THD have a typical course for changes in the power system load - Figure 6. However, there are additional, rapid changes resulting from the variable (large) load of the traction station.

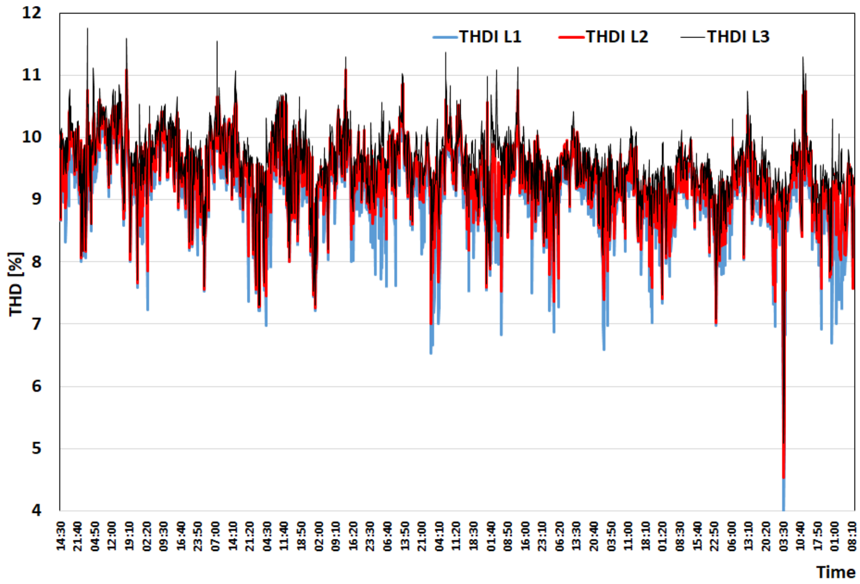


Fig. 7. Changes in the harmonic distortion factor THDI recorded in phases L1, L2, L3

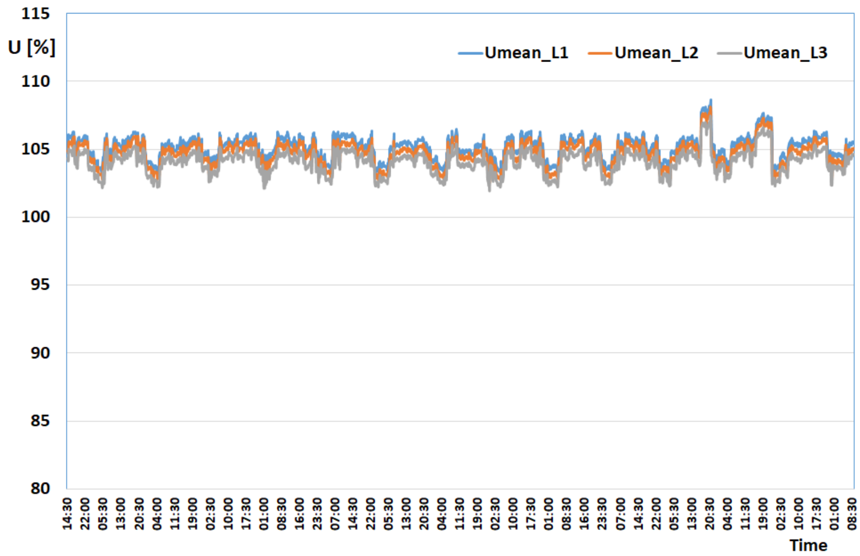


Fig. 8. RMS voltage changes recorded during the measurement week

Changes in THDU in individual phases have very similar values and course of changes during the measurements. The correlation coefficients between changes in THD in individual phases are: $r_{THDUL1L2}$ = 0.989, $r_{THDUL2L3}$ = 0.975, $r_{THDUL3L1}$ = 0.976, respectively. Figure 7 shows the changes in the harmonic distortion factor of the THDI current recorded in the PCC. Correlation coefficients between changes in THD current in individual phases are respectively: $r_{THDIL1L2}$ = 0.959, $r_{THDIL2L3}$ = 0.923, $r_{THDIL3L1}$ = 0.918.

Figure 8 shows changes in the average RMS voltage recorded during the week in the line supplying the traction substation. Correlation coefficients of voltage changes in individual line phases are respectively r_{UL1L2} = 0.996, r_{UL2L3} = 0.995, r_{UL3L1} = 0.997.

Based on the analysis of changes in voltages, currents and strain coefficients THDU and THDI, it was assumed in the further part of the article to consider disturbances in the phase with the highest values. In the case of measurements of electricity quality indicators in accordance with [], the values in the adopted measurement interval are averaged. For RMS voltage, the interval is 10 minutes. In the case of voltage disturbances lasting from milliseconds to tens of seconds, analyzing changes in a long measurement interval, significant cases affecting the correct operation of electrical devices can be omitted. Figure 9 shows the changes in the effective (a), maximum (b) and minimum values recorded during the week at the adopted 10-minute measurement intervals.

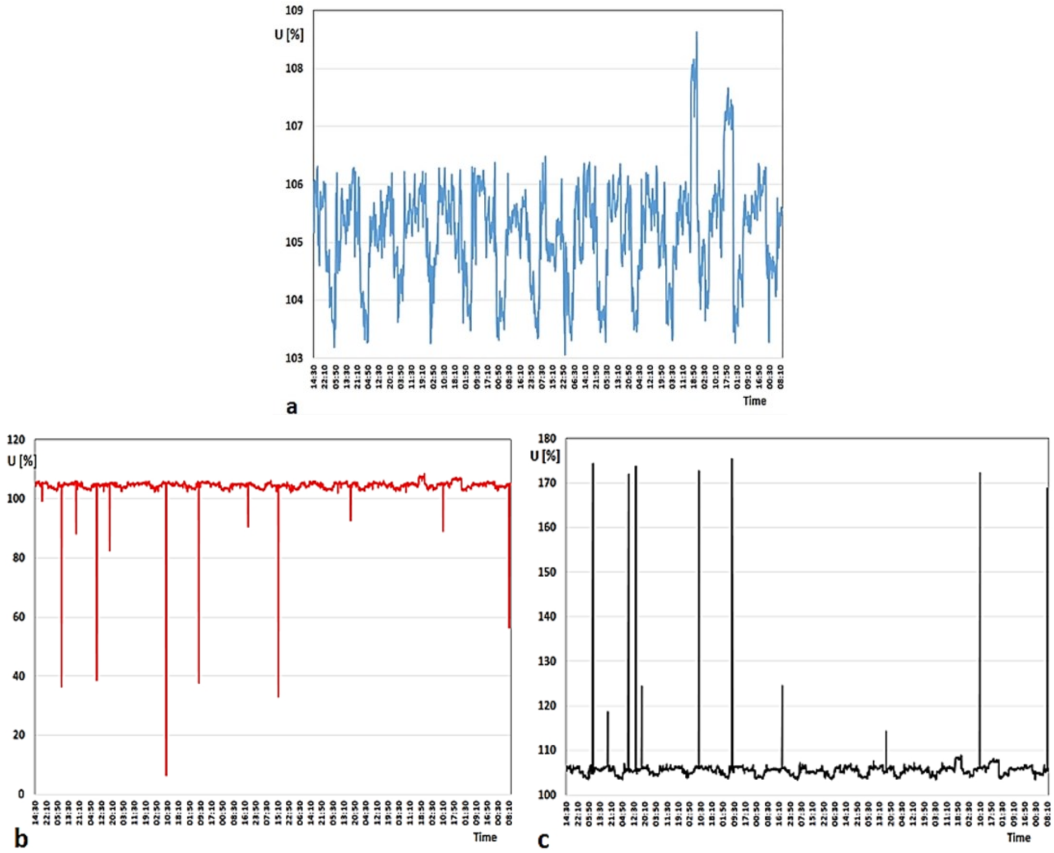


Fig. 9. Changes in RMS (a), maximum (b) and minimum (c) values recorded during the week at the adopted 10-minute measurement intervals

As a result of changes in the traction station load, a number of voltage dips and swells were recorded in the power supply network. These disorders have a very violent course. Figure 10 shows an example of a disturbance in the voltage supplying the traction substation. Figure 10 shows the supply voltage dip in the L2 phase and the voltage increase in the remaining phases. The disturbance time is approx. 1 second. After this time, the supply voltage values return to the state before the disturbance occurred.

Figure 11 shows the RMS voltage disturbance recorded in the L3 phase. After the initial voltage dip to approx. 45% Un, there is a rapid increase in the voltage value to 180% Un. Voltage changes are oscillatory and last about 2 seconds.

The light flickering phenomenon generated by lighting receivers is caused by rapid voltage changes. Figure 12 shows the changes in the short-term P_{st} and long-term P_{lt} of the flicker indicator recorded during the week of measurements in the line supplying the traction substation.

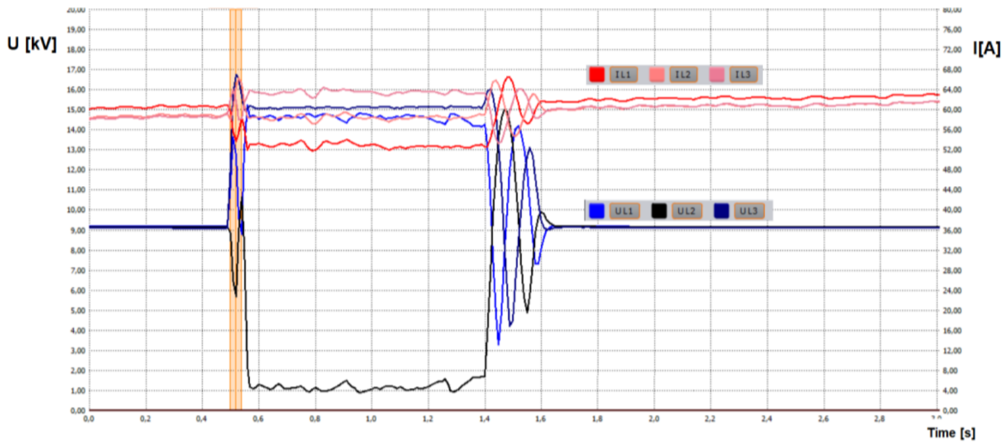


Fig. 10. Changes RMS values of voltages and currents recorded in the line supplying the traction substation

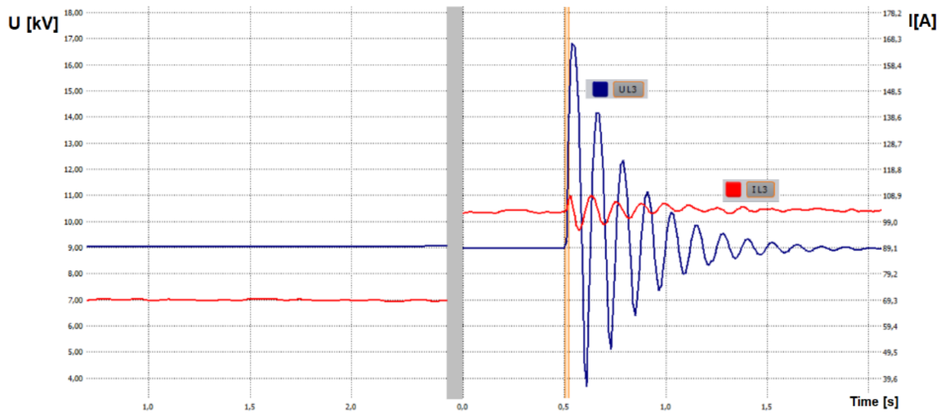


Fig. 11. Changes RMS values of voltages and currents recorded in the line L3 supplying the traction substation

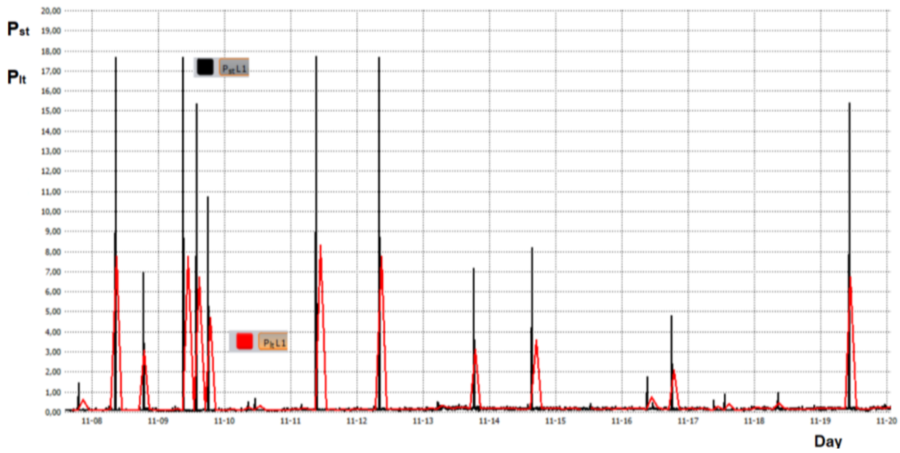


Fig. 12. Changes in the short-term P_{st} and long-term P_{lt} of the flicker indicator recorded during the week of measurements in the line supplying the traction substation

In the case of recorded such high values of the long-term light flicker index P_{lt}, one can expect annoying flickering of light. This flicker may occur for a short period of time. It depends on the number and time of occurrence of voltage fluctuations in the supply network.

3. Power supply for rectifier units

Twelve-pulse pre-converters are installed at the traction substation. They are powered by traction transformers. Traction vehicles are the main load of the substation. They are characterized by high unit powers and dynamically changing power consumption, especially at start-up. The need to convert AC voltage to DC causes the converters used for this purpose to distort the currents. On the impedance of the supply network, distorted currents cause distorted voltage drops, which in turn leads to distortion of the supply voltage in the PCC. Figure 13 shows the waveforms of voltages and currents recorded in the circuits supplying the rectifier units.

Figure 14 shows the current waveform and the spectrum of current harmonics for one phase. Values of higher harmonic currents are expressed as a percentage. The first harmonic current of i_{h1}=100% was taken as the reference value.

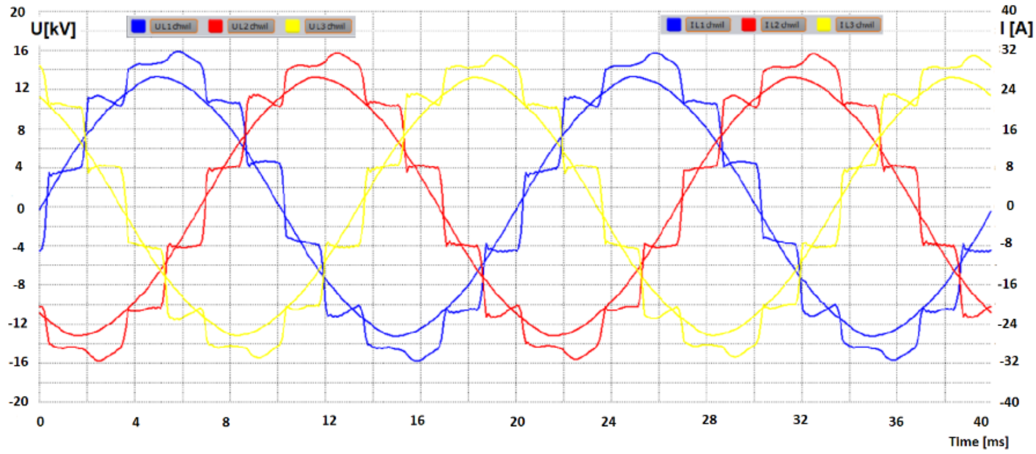


Fig. 13. Changes waveforms of voltages and currents recorded in the circuits supplying the rectifier units

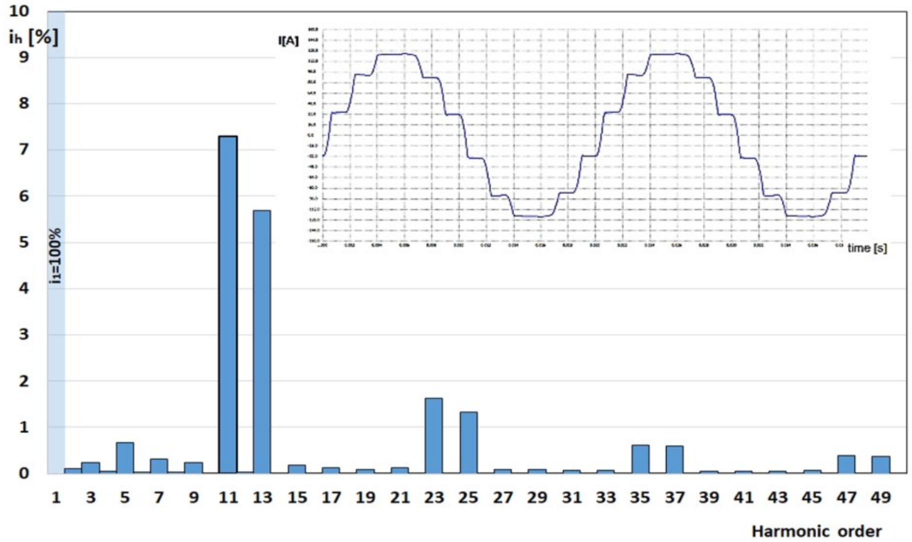


Fig. 14. Voltage waveforms and spectrum of voltage harmonics recorded at point A

Shown in Figure 14 show increased values of harmonics characteristic of twelve-pulse converters, i.e.: i_{h11}, i_{h13}, i_{h23}, i_{h25}, i_{h35}, i_{h37}, i_{h47}, i_{h49}.

Voltage disturbances are also caused by the dynamically changing load of the traction substation. Changes in the effective value of the current (I_{min}, I_{max}, I_{mean}) recorded during the week (a) and during one day of measurements (b) are presented in Figure 15.

In order to assess the impact of dynamic changes in traction substation load, measurements were made at measurement intervals of 5 seconds. Figure 16 shows the changes in the RMS current and voltage values recorded at 5-second measurement intervals in phase L1.

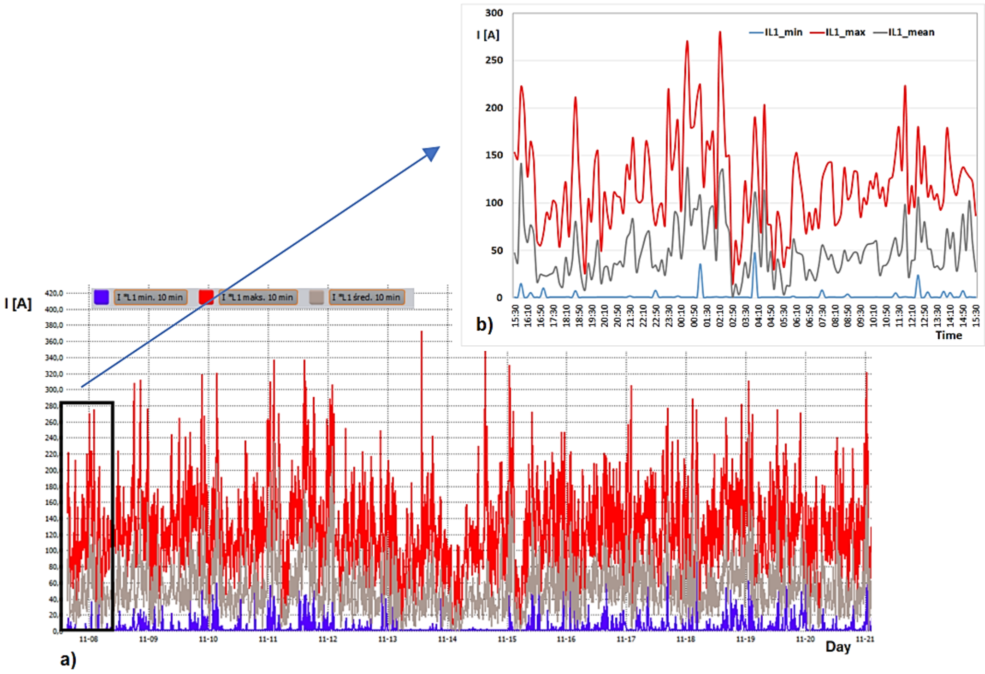


Fig. 15. Changes in RMS current value (I_{min}, I_{max}, I_{mean}) recorded during a week (a) and during one day of measurements (b)

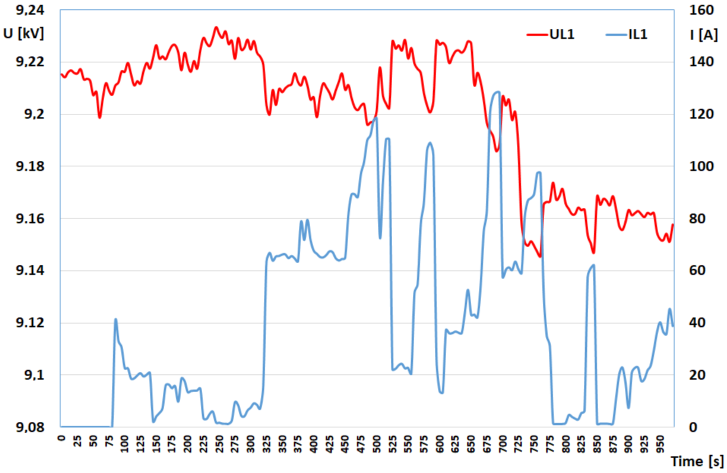


Fig. 16. Changes in RMS current and voltage value recorded at 5 seconds intervals

Dynamic changes in the currents drawn by traction locomotives are the main source of voltage fluctuations in the substation supply line. Especially during the start-up of trains, the destruction is greatest.

4. Line of non-traction needs

The proper functioning of rail transport requires electricity to be supplied to both the electric traction and facilities related to, among others, with the operation of trains. Non-traction needs lines are used for this. The power devices at railway stations and non-traction power devices located along the railway route.

PKP Energetyka, responsible for the supply of electricity to traction substations, holds concessions for the distribution, transmission and trading of electricity. Thanks to the concession issued by the Energy Regulatory Office, it is possible to sell electricity to individual consumers [30]. This allows to supply power to recipients located close to these lines, which are the only source of electricity.

Receivers of very different nature and power are supplied from the non-traction needs line. Some of them are receivers sensitive to power supply voltage disturbances, others, e.g. non-linear or with dynamically changing load, affect the quality of power in the power line. Figure 17 presents waveforms (oscillograms) of currents recorded in non-traction power lines. The distortion of the current curves from the sinusoidal waveform is visible.

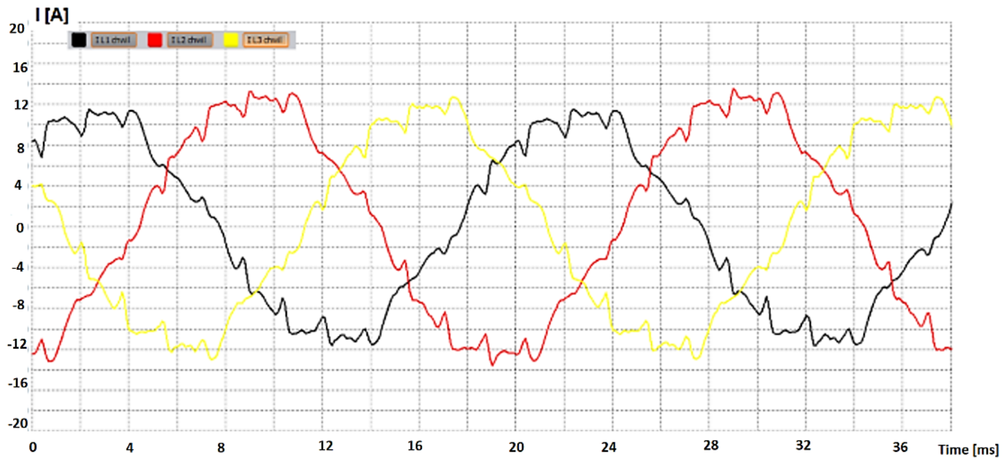


Fig. 17. Waveforms of currents recorded in line of non-traction needs

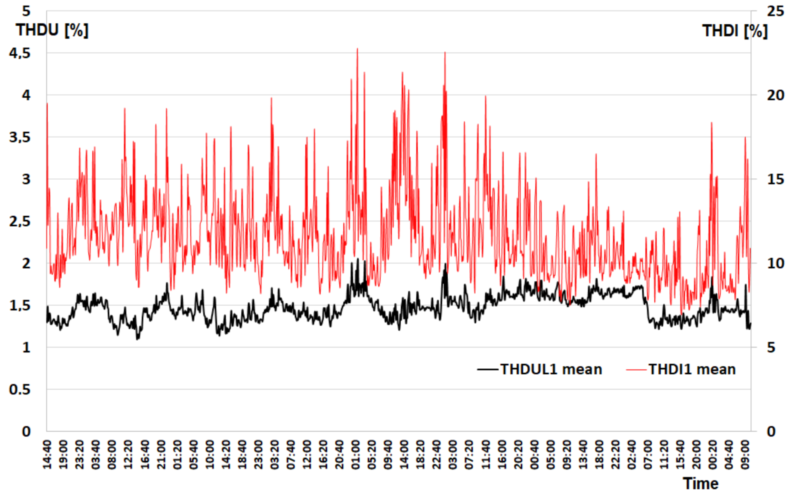


Fig. 18. Changes of the harmonic distortion coefficient THD_U and THD_I

Due to the fact that the energy is sold to commercial customers on the free energy market, the supplier should, to a greater extent than in the own needs circuits, ensure appropriate parameters of the supply voltage. In the analyzed case, the traction substation (Figure 1 - point A - U_n=15kV) is the power distribution point for: traction vehicles, receivers installed on the traction substation and receivers supplied from non-traction needs lines. Therefore, the quality of voltage at the power distribution point is affected by: traction vehicles (mainly), consumers supplied from non-traction power lines and changes in the power system from which the traction substation is supplied.

Figure 18 shows the changes of the harmonic distortion coefficient THD_U and THD_I measured during the week in the line of non-traction needs.

Changes in the harmonic distortion factor of the THDU voltage are similar to typical changes characteristic for the power system. Current distortion factor THDI depends on the degree of non-linearity of the load. The correlation between the waveforms is low and is: $r_{THDU\_THDI\_L1}$ = 0.363

Figure 19 shows the spectrum of voltage and current harmonics registered in the non-traction needs line (for the point where the current reached its maximum value). The first harmonic of the voltage u_1=100% and the current i_1=100% was taken as reference values.

The amplitudes of individual harmonics of voltages u_h and currents i_h are much more closely correlated. The correlation coefficient is r_{u_h,i_h} = 0.981. On the basis of the analysis of the measurement data, it was found that the distortion of currents in non-traction power lines was greatly affected by the distortion of the voltage supplying the traction substation. The distortion of the substation supply voltage depends on the traction load.

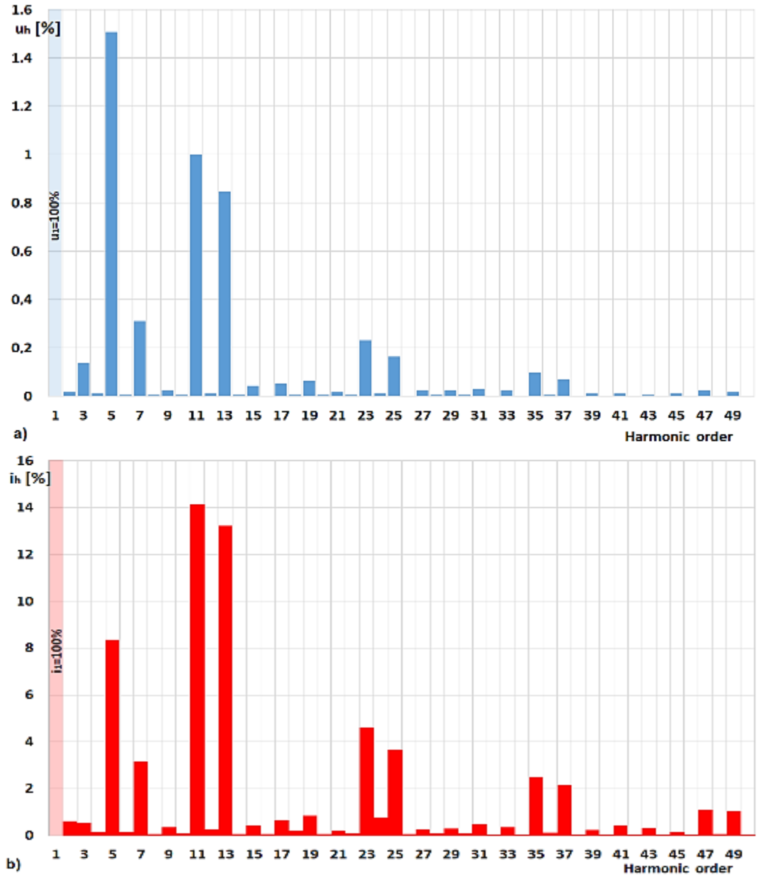


Fig. 19. Spectrum of voltage a) and current b) harmonics corresponding to the recorded waveforms in the non-traction needs line

Figure 20 presents the changes of the current and the harmonic distortion factor THDU registered in the traction supply line (a) and the non-traction line (a). Measurements were made at 5-second measurement intervals.

The use of short measurement intervals (5 seconds) allowed for a more accurate estimation of disturbances related to the dynamically changing substation load. Dynamic load changes result mainly from the start-up and acceleration of the traction units. The value of the current drawn at the moment of starting the train (Fig. 20.a) is about 18-20 times higher than the current value of the receivers supplied from the non-traction lines (Fig. 20.b). With such a large change in the current of the deformed traction train, a change in the deformation of the supply voltage waveform is visible (Fig. 20.b). In the analyzed case, the correlation coefficient for the waveforms in Figure 19a is: r_{ITHU}=0.915, and that of the waveforms in Figure 20.b is: r_{ITHU}=0.119. It can therefore be concluded that at the level of voltage U_n=15kV supplying the substation, the impact of non-traction consumers on the distortion of the voltage waveform (curve) can be neglected. Such a conclusion cannot be formulated in an obvious way in the case of the impact of non-traction receivers at the voltage level of U_n=0.4kV.

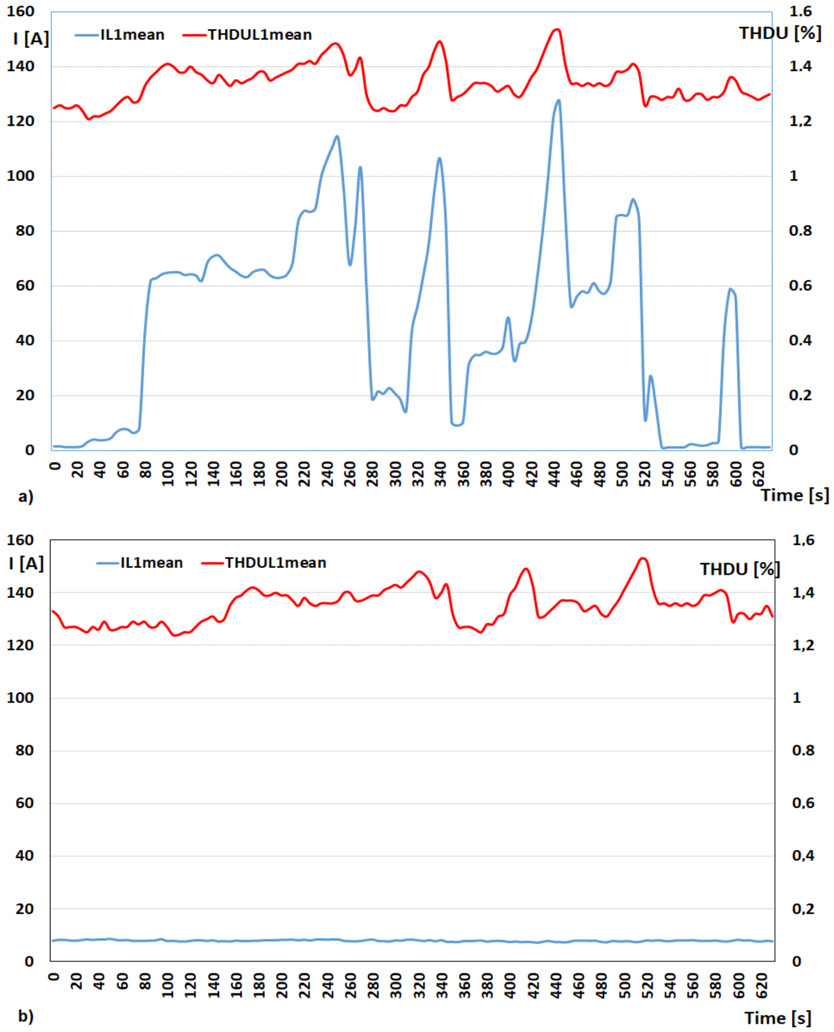


Fig. 20. Changes of the current and the harmonic distortion factor THDU registered in the traction supply line (b) and the non-traction line (b)

Disturbances arising in the substation supply line directly affect the quality of electricity in non-traction needs circuits. Voltage dips are one of the most common disturbances in the power system, and their elimination is very difficult, especially with high power of interfering receivers and irregular nature of load changes.

Figure 21 shows the course of the voltage and current during the disturbance registered in the L3 phase. The duration of the voltage dip is less than 0.5 seconds. As the voltage decreases, the current decreases as well. On this basis, it can be concluded that the cause of this disturbance is not the recipients of power supply from the non-traction needs line.

Another example of RMS voltage and current changes recorded during a disturbance in the L1 phase is shown in Figure 22.

The cause of the voltage dip in the non-traction demand line is a disturbance that occurred in the substation supply line or on the DC side of the electric traction.

Figure 21 and Figure 22 show disturbances only in the selected phase of the non-traction needs line. Such presented disturbances increase the readability of the drawings presented in the article. Of course, very often disturbances occur simultaneously in all phases of the line. Such a case is presented in Figure 23.

The analysis of current and voltage waveforms presented in Figures 21, 22, 23 shows that the cause of the disturbance is in the power system. This is evidenced by the fact that as the voltage decreases, the current decreases as well.

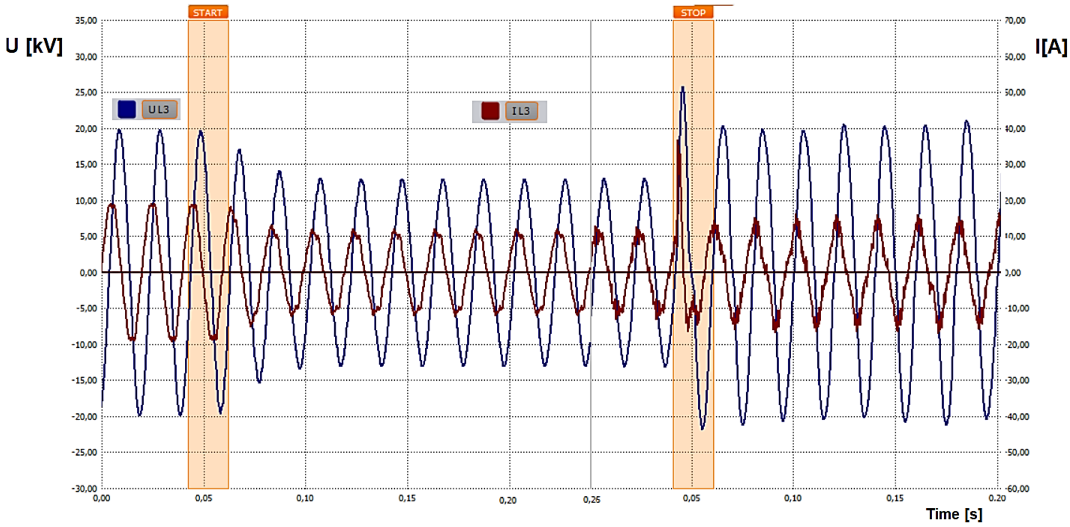


Fig. 21. Voltages and currents waveforms recorded in line of non-traction needs – phase L3

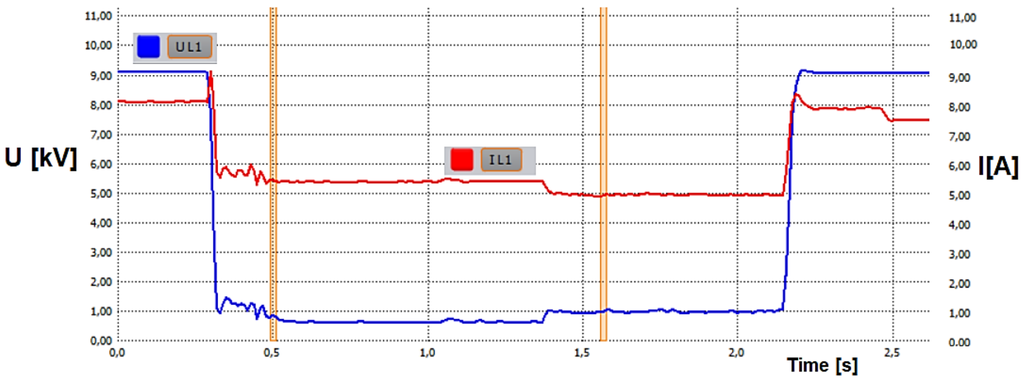


Fig. 22. Changes RMS values of voltages and currents recorded in line of non-traction needs – phase L1

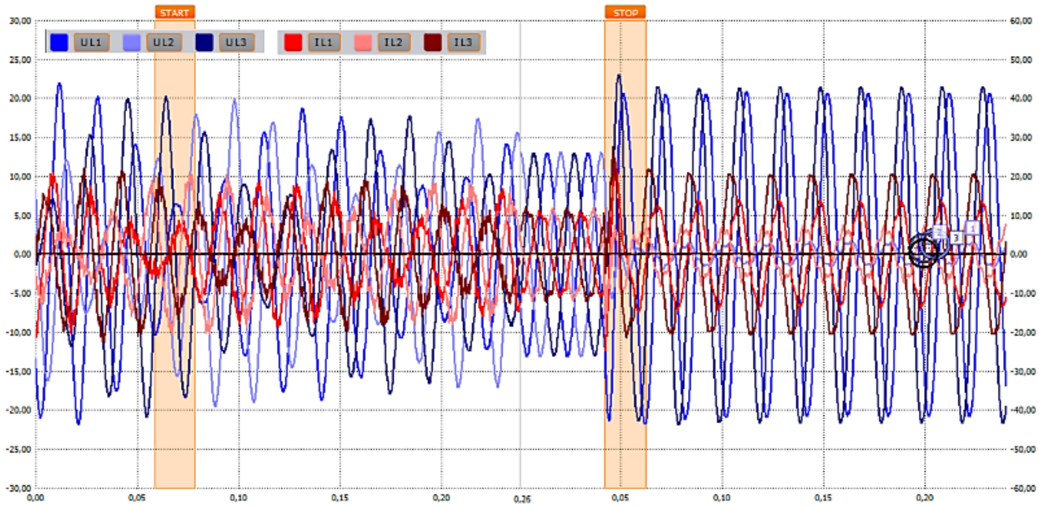


Fig. 23. Voltages and currents waveforms recorded in line of non-traction needs – phase L1, L2, L3

Fig. 24. Place and method of connecting the power quality analyzer Memobox 800

5. INTERNAL TRACTION SUBSTATION NETWORKS

The internal circuits of the traction substation are powered by a 15/0.4 kV auxiliary transformer. As a rule, two auxiliary transformers are used, one of which is redundant. These transformers supply the auxiliary circuits that have a very large impact on the operation of the traction substation. These include protection, control and signaling circuits. Especially the use of modern protections, control devices, data transmission devices requires the appropriate quality of the supply voltage.

In order to assess the quality of electric energy, indicators characterizing voltage quality were recorded. The measurements were carried out at the voltage level of U_n=0.4kV.

Figure 24 shows the place and method of connecting the power quality analyzer Memobox 800 (Figure 1 – Point D).

Changes in the voltage in the auxiliary circuits are closely related to the changes in the voltage in the substation supply line. Figure 25 shows the voltage waveforms measured at the same time in the substation's auxiliary circuits and the substation's supply line.

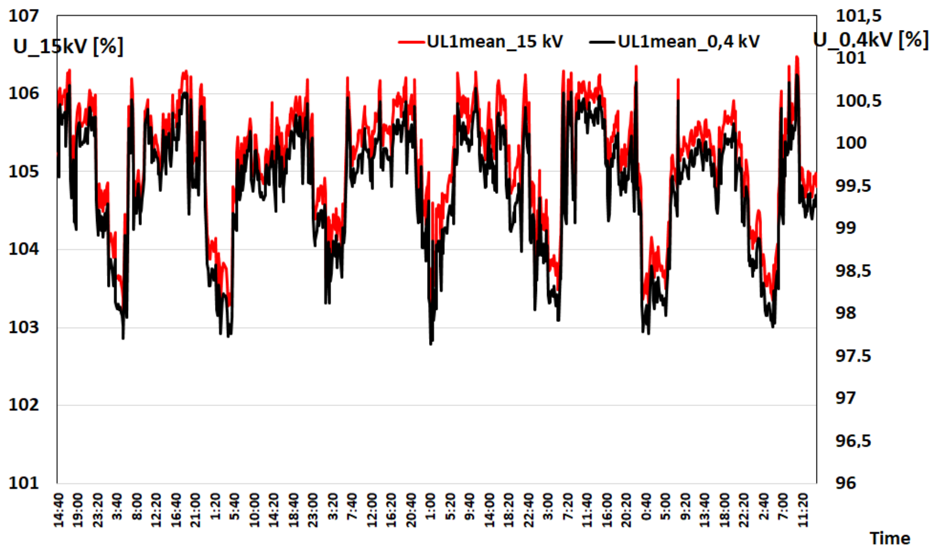


Fig. 25. Changes in RMS voltage recorded during the week in the substation circuits and the traction substation power supply line

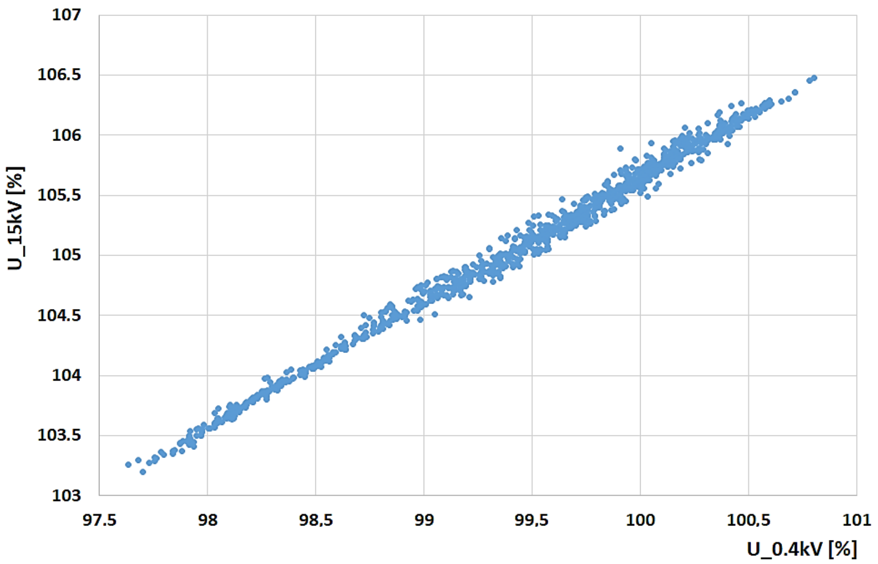


Fig. 26. Correlation between RMS voltage recorded during the week in the substation circuits and the traction substation power supply line

The correlation coefficient determining the dependence of changes between the voltages U_{15kV} and $U_{0.4kV}$ is r_{UAD}=0.996 – Figure 26.

The distortion of the voltage curve in the auxiliary circuits depends on the distortion of the voltage supplying the traction substation (voltage at the connection point of the auxiliary transformer). Figure 27 presents changes in the THDU coefficient registered during the week in the substation supply line and auxiliary circuits.

The correlation coefficient determining the dependence of changes between the THDU at the level of U_n=15kV and the THDU at the level of U_n=0.4kV is r_{THDU}=0.933 - Figure 28.

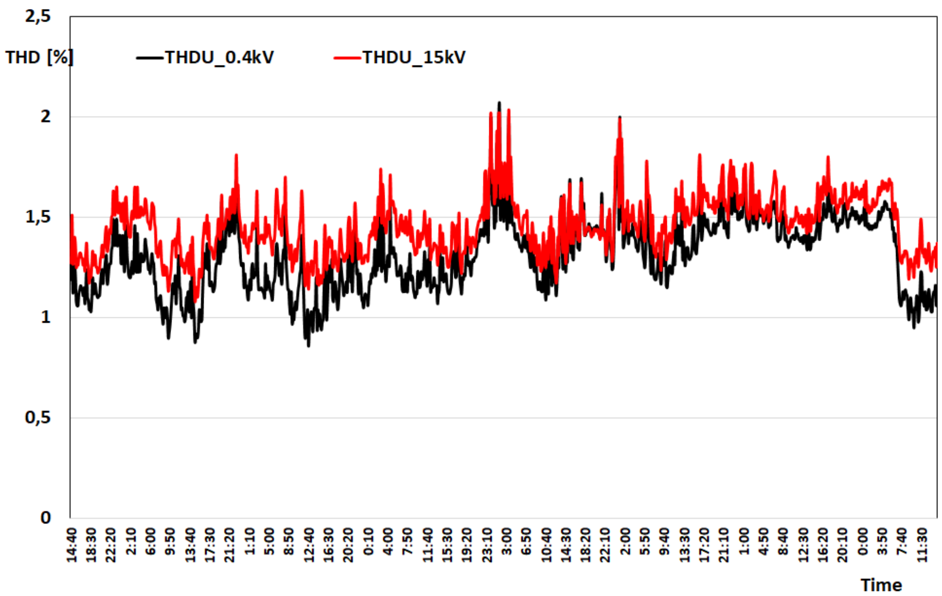


Fig. 27. Changes in THDU recorded during the week in the substation circuits and the traction substation power supply line

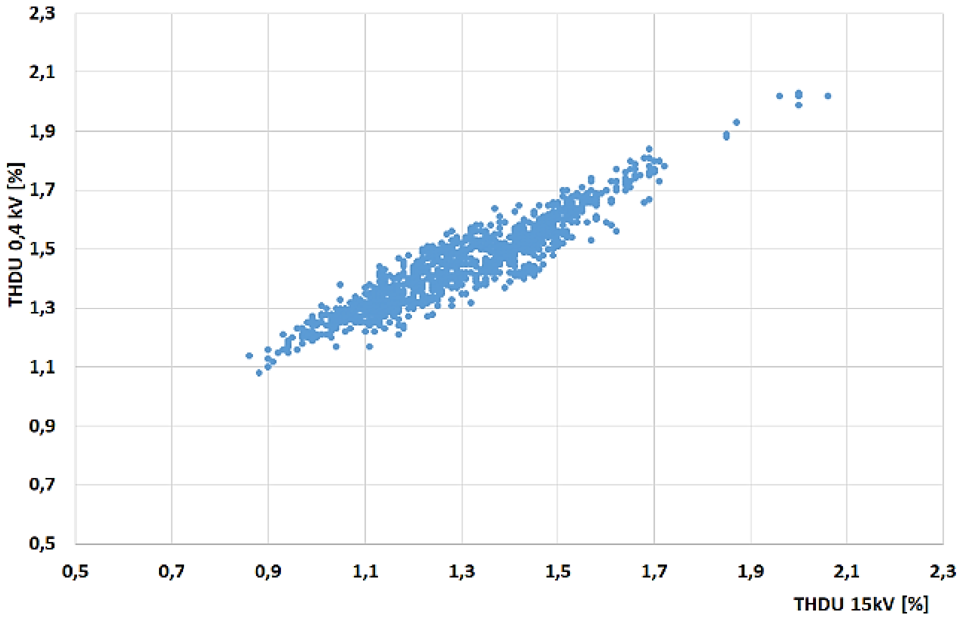


Fig. 28. Correlation between THDU recorded during the week in the substation circuits and the traction substation power supply line

On the basis of the analysis of changes in electricity quality parameters, it can be concluded that disturbances in lines supplying traction substations, non-traction lines and auxiliary circuits are caused by both the DC traction power supply system and the power system.

Based on the analysis of the measurements, it was found, based on the standard [19] and the Regulation on customer service standards in force in Poland [20], that the parameters characterizing the quality of electricity did not exceed the acceptable levels - Figure 29.

The substation in which the tests were carried out has a 6 kWp photovoltaic installation installed. 12 Risen 500Wp modules installed. The inclination angle of the modules is 15^0, and the azimuth of the installation is 127^0. The inverter used in the installation - Fronius Symo 6.0-3-M.

Figure 30 shows the arrangement of photovoltaic panels on the roof of the traction substation.

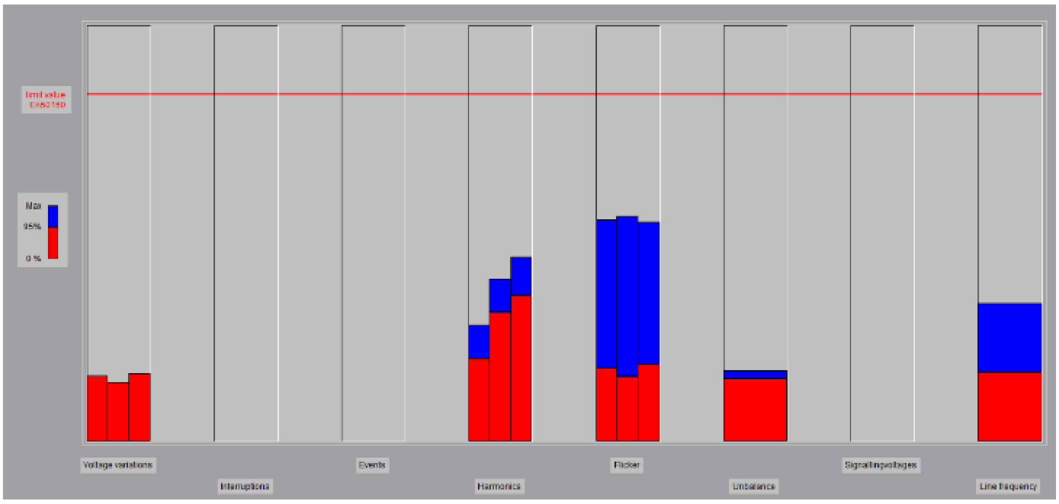


Fig. 29. Graphical summary of the measured energy quality indicators in the electrical network of the substation's own needs

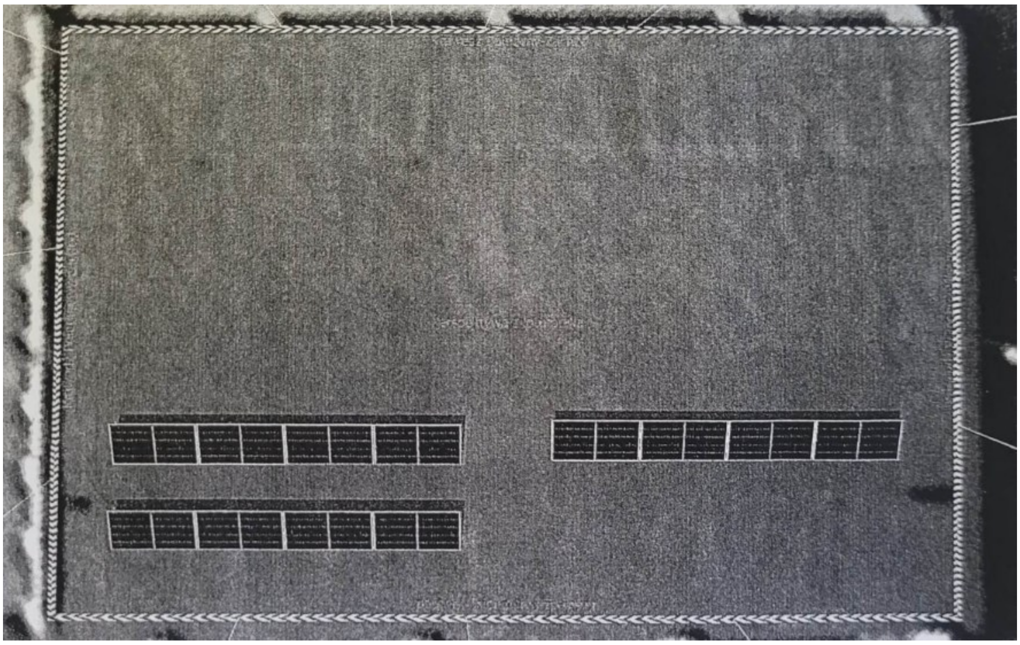


Fig. 30. Arrangement of photovoltaic panels on the roof of the traction substation

Powered from the photovoltaic installation are receivers connected to the traction substation's own needs network (400/230V). When the photovoltaic installation produces energy, there is a visible reduction in the current value in the line supplied from the auxiliaries transformer - Figure 31. Of course, the amount of energy produced by the photovoltaic installation depends on weather conditions.

Installing a photovoltaic installation reduces energy consumption by devices powered from non-traction power lines and affects the quality parameters of electricity.

In the case of connecting solar systems to low-voltage networks, there is often an increase in voltage. A similar phenomenon occurs in the analyzed case. During the operation of the photovoltaic installation, an increase in voltage was recorded - Figure 31, Figure 32. The increase in the voltage value is small, because all the energy produced is consumed by the receivers.

If several photovoltaic installations are connected to the low-voltage line, excessive voltage increase may lead to incorrect operation or damage to the receivers. This phenomenon is intensified in the case of low consumption of energy produced by photovoltaic installations (low auto-consumption).

6. Discussion

Electric traction is one of the largest consumers supplied from the power system. Due to the safety of train traffic, the traction substation supplying energy to vehicles requires power from two independent power lines.

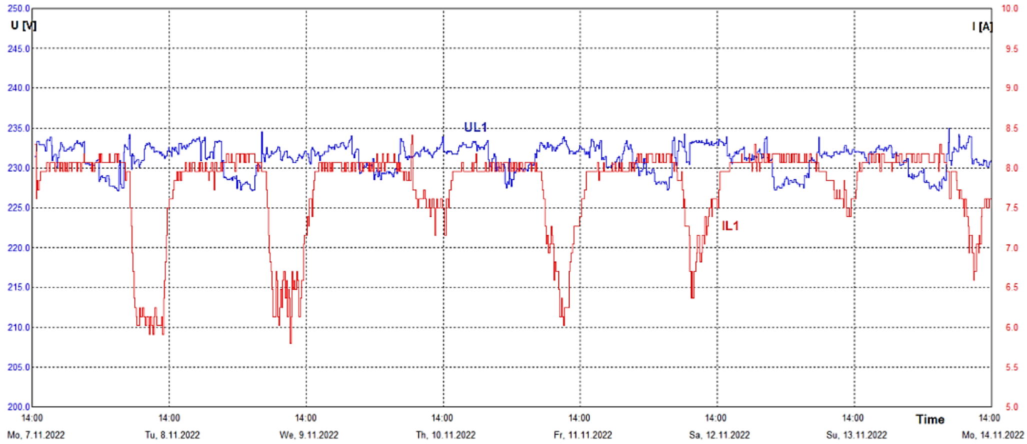


Fig. 31. Changes in RMS voltage and current recorded during the week in the substation circuits

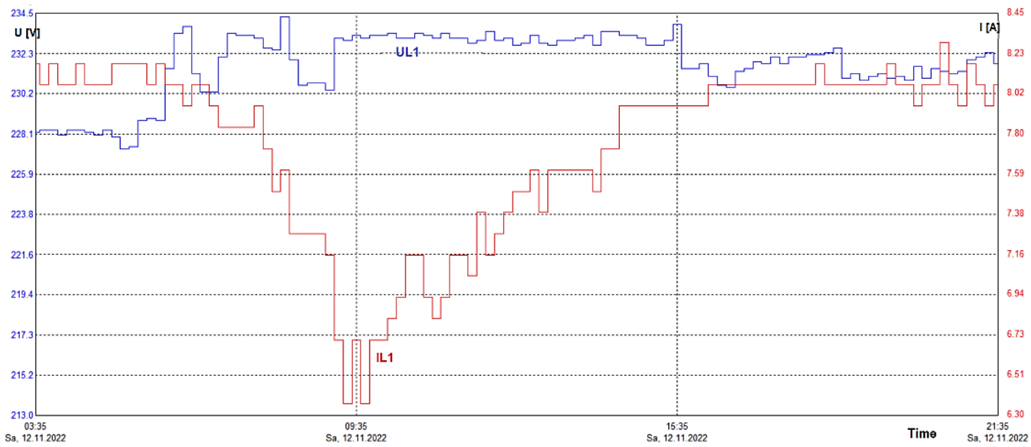


Fig. 32. Changes in RMS value of voltage and current recorded during one day in the traction substation circuits

Traction substations are a source of disturbances affecting the quality of energy in the power system from which they are supplied. One of the disturbances is the change in the voltage supplying the traction substation. These changes are characterized by very variable dynamics. Particularly during the start-up of large traction units, the RMS value of the voltage changes visibly. Figure 33 shows the changes in RMS voltage and RMS current recorded in the substation supply line during the start-up of the electric traction unit. Point L (I_{mean} Low) - Figure 33, applies to the case when the energy is taken only by receivers supplied from the auxiliaries and non-traction lines. The recorded current value is approx. 10A (Low). Point H (I_{mean} High) was determined for the highest current value of 132 A (high) , which is related to the energy consumption of the traction train. There is a visible decrease in the effective value of the voltage supplying the substation. Due to the rectifier devices used to convert alternating voltage into direct current, electric traction generates disturbances (collects distorted currents) affecting the voltage distortion in the power system. These disturbances are propagated to other lines, including lines supplying non-traction consumers.

Figure 34 shows the spectrum of harmonic current and voltage waveforms recorded at Point L and Point H (markings in Figure 33).

For the case, Point L, the spectrum of voltage and current harmonics are characteristic of typical waveforms recorded in the power system. The value of the deformation of the voltage curve supplying the traction substation is mainly determined by the nature of the receivers (degree of non-linearity) supplied from the power system, from which the electric traction is also supplied.

The increase in energy consumption by the traction substation related to the movement of trains causes an increase in the current value in the supply line- Point H (Figure 33). This current, in addition to a high RMS value, is characterized by a sinusoidal distortion. There are characteristic current harmonics, i.e. 11, 13; 23, 25; 35, 37, generated by rectifier units operating in a twelve-pulse system (Figure 34.b-red). The distortion of the current curve has a visible effect on the distortion of the supply voltage. increase). There are harmonic voltages of the orders: 11, 13; 23, 25; 35, 37. (Figure 34.a - ed.). Figure 35 shows the changes in RMS value of voltage and currents measured in the traction substation supply line (a), the rectifier unit supply line (b) and the non-traction needs line (c).

Analyzing the impact of the DC traction system on the quality of energy in the auxiliary and non-traction circuits, it was found that changes in the RMS voltage in the auxiliary and non-traction circuits depend mainly on the value of the power consumed by the traction vehicles - Figure 35.b.

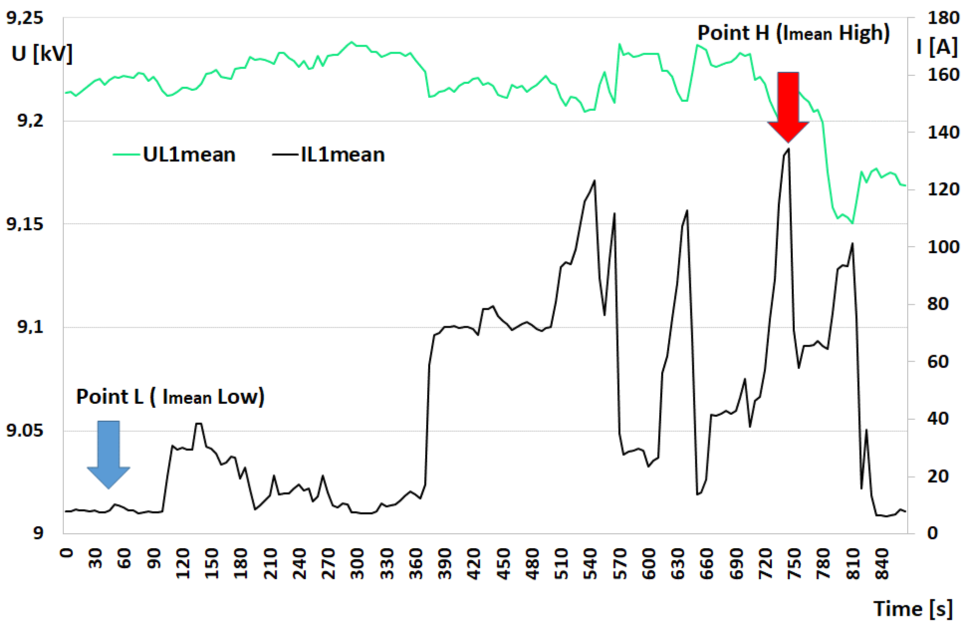
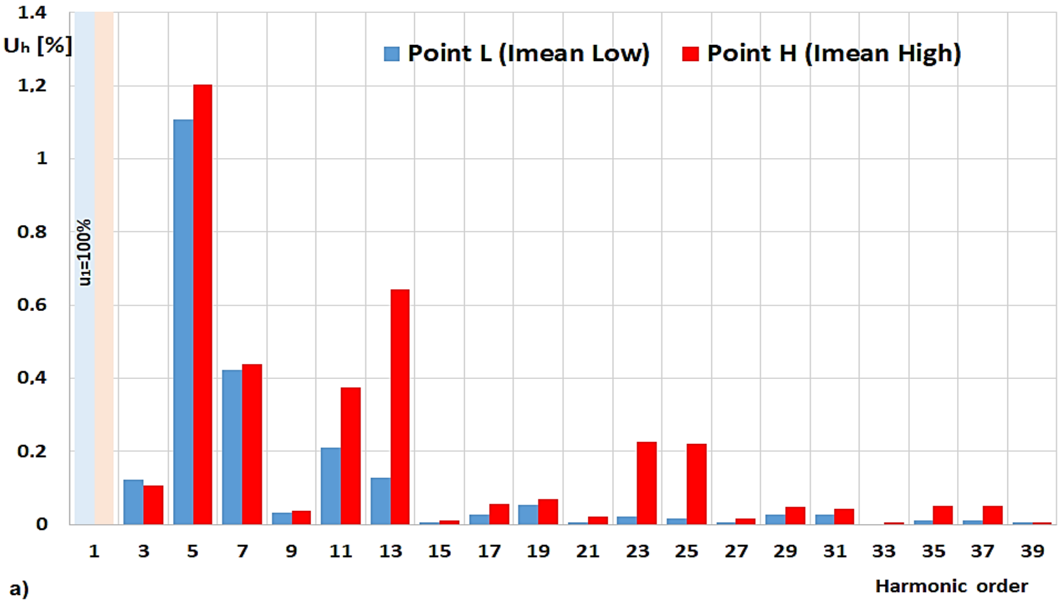


Fig. 33. Changes in RMS current and voltage value measured in the line supplying the traction substation



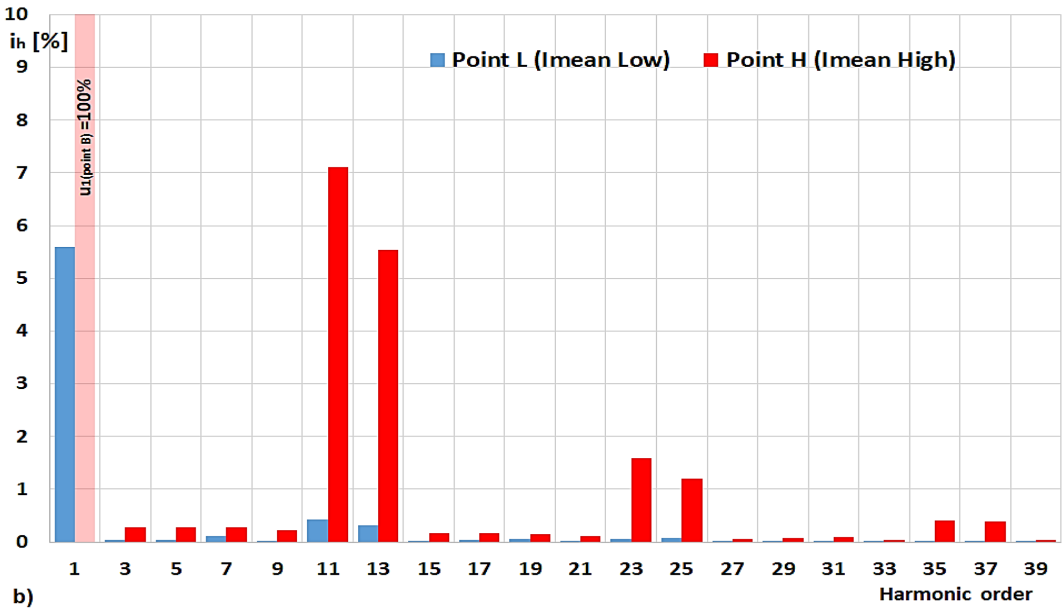


Fig. 34. Spectrum of voltage (a) and current (b) harmonics corresponding to the recorded waveforms in the line supplying the traction substation

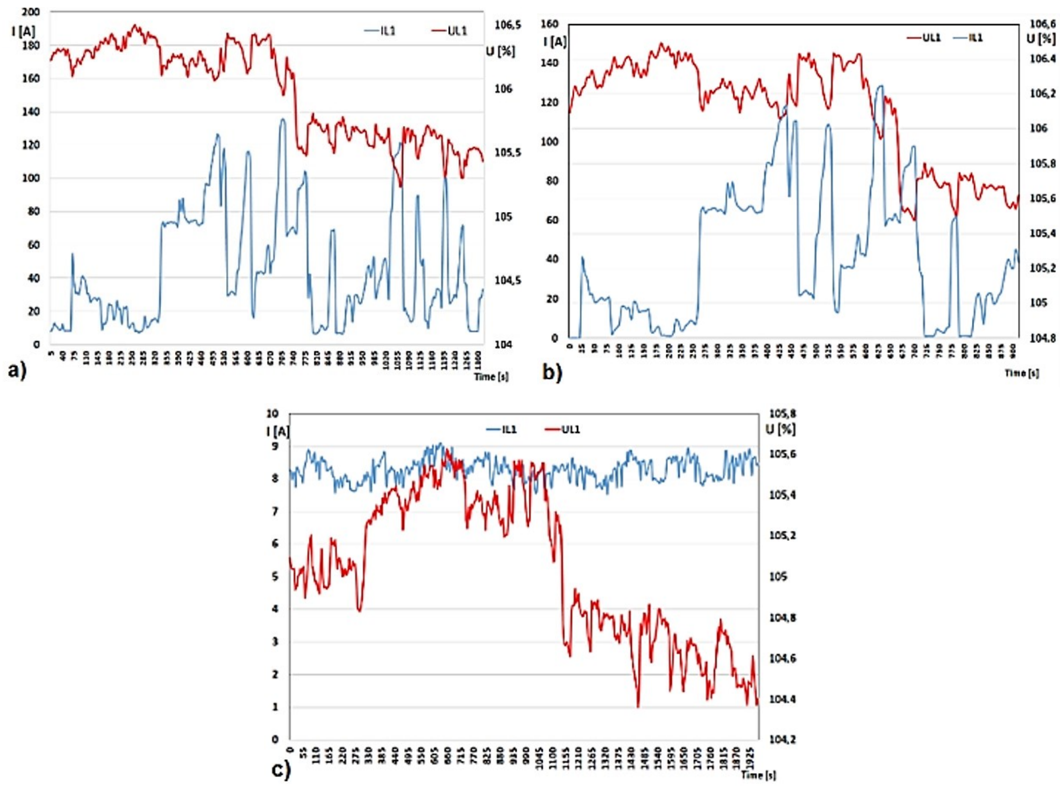


Fig. 35. Changes in RMS value of voltage and currents measured in the traction substation supply line (a), the rectifier unit supply line (b) and the non-traction needs line (c)

CONCLUSIONS

The collected measurement data, selected fragments of which have been presented in the article, will be helpful in model research involving the assessment of the impact of traction substation power supply conditions on the magnitude of disturbances generated by DC electric traction. As the analysis presented in the article shows, the quality of electric energy in the traction substation circuits is a superposition of disturbances: generated by the power system from which the substation is supplied, receivers powered from non-traction needs circuits and mainly by traction vehicles. Due to the safety of traction vehicles (trains), it is not possible to supply power to individual traction substation lines only. This means that only tests (measurements) in real conditions, with the use of recording power quality parameters in several points at the same time, allow for the identification and assessment of emerging disturbances. The value of the short-circuit power of the supply network in relation to the rated power of the traction substation has a decisive influence on the magnitude of disturbances. Knowing the actual parameters of the traction substation power supply network (supply voltage value, supply network impedance, transformer parameters at the Main Supply Point) and power parameters of the traction substation, a computer model can be developed. After performing the model (computer) tests, the correctness of the proposed model can be verified with the real substation power supply system.

JAKOŚĆ ENERGII ELEKTRYCZNEJ W OBWODACH PODSTACJI TRAKCYJNEJ PRĄDU STAŁEGO

Transport kolejowy w Polsce wykorzystuje do zasilania pojazdów (lokomotyw i zespołów trakcyjnych) trakcję elektryczną prądu stałego. Konieczne jest zatem przekształcenie napięcia przemiennego systemu elektroenergetycznego na napięcie stałe systemu trakcyjnego. Zamiana napięcia przemiennego na napięcie stałe odbywa się w podstacjach trakcyjnych. Wykorzystywane do tego celu są zespoły prostownikowe zainstalowane na podstacjach trakcyjnych. Sprawia to, że trakcję elektryczną zaliczyć należy do obiorców o charakterze nieliniowym. Dodatkowo

obciążenie podstacji trakcyjnej zmienia się w sposób dynamiczny. Wszystko to powoduje, że trakcja elektryczna jest odbiorcą generującym do sieci szereg zaburzeń. Zaburzenia te wpływają na jakości energii elektrycznej systemu elektroenergetycznego, z którego zasilane są podstacje trakcyjne oraz jakość energii w liniach potrzeb własnych i potrzeb nietrakcyjnych. Artykuł przestawia wyniki analizy pomiarów wskaźników jakości energii elektrycznej zarejestrowanych w wybranych punktach linii podstacji trakcyjnych. Parametry charakteryzujące jakość energii elektrycznej zarejestrowano m.in. w głównej linii zasilającej podstację trakcyjną, linii potrzeb nietrakcyjnych oraz obwodach potrzeb własnych. Prezentowany artykuł jest jednym z cyklu publikacji związanych z oceną oddziaływania trakcji elektrycznej prądu stałego na system elektroenergetyczny.

Słowa kluczowe: jakość energii elektrycznej, trakcja elektryczna, zakłócenia, zmiany napięcia, wyższe harmoniczne, THD

REFERENCES

[1] Szeląg A., Nikšić M. (2023) Advances in Electric Traction System, *Energies*, 16(3), 1346. https://doi.org/10.3390/en16031346.

[2] Żelazny R. (2018) Quality Of Electricity In Power Lines For Receivers PKP Polish Railway Lines S.A., *Zeszyty Naukowe Politechniki Rzeszowskiej* 297, Elektrotechnika 37, RUTJEE, z. 37 (1/2018), 37-48. https://doi.org/10.7862/re.2018.3

[3] Pawełek R. (2014) Impact of the traction substation on the power grid (in Polish: Oddziaływanie podstacji trakcyjnej na sieć elektroenergetyczną,) *Przegląd Elektrotechniczny*, 90(7), 234-238. https://doi.org/10.12915/pe.2014.07.52.

[4] Sikora A., Kulesz B. (2008) Dependence Of Traction Voltage Quality On Transformer-Rectifier System, *Zeszyty Problemowe - Maszyny Elektryczne*, 80, 63-67.

[5] Zheng W., Pei H. (2022) Detection of pantograph-catch arc in urban rail transit based on correlation filtering, *Proceedings of the International Conference on Cloud Computing*, *Internet of Things, and Computer Applications* (CICA 2022), Luoyang, China, 22–24 April 2022. https://doi.org/10.1117/12.2642625.

[6] Cipolletta G., et al. (2022) Detection of dips, swells and interruptions in DC power network. Proceedings of the *20th International Conference on Harmonics and Quality of Power*, Naples, Italy, 29 May - 1 June 2022.

[7] Pomykała A., Szeląg A. (2022) Reduction of Power Consumption and CO_2 Emissions as a Result of Putting into Service High-Speed Trains: Polish Case, *Energies*, 15(12), 4206. https://doi.org/10.3390/en15124206.

[8] Aguado J.A., Racero A.J.S. De La Torre S. (2018) Optimal operation of electric railways with renewable energy and electric storage systems. *IEEE Transactions on Smart Grid*, 9(2), 993–1001. https://doi.org/10.1109/TSG.2016.2574200.

[9] Petru Valentin Radu, Lewandowski M., Szelag A., Steczek M. (2022) Short-Circuit Fault Current Modeling of a DC Light Rail System with a Wayside Energy Storage Device, *Energies*, *15*(10), 3527. https://doi.org/10.3390/en15103527

[10] Jefimowski W., Szeląg A., Steczek M., Nikitienko A. (2020) Vanadium redox flow battery parameters optimization in a transportation microgrid: A case study, *Energy*, 195, 116943. https://doi.org/10.1016/j.energy.2020.116943.

[11] Steczek M., Chudzik P., Szeląg A. (2020) Application of a Non-carrier-Based Modulation for Current Harmonics Spectrum Control during Regenerative Braking of the Electric Vehicle, *Energies*, 13(24), 6686. https://doi.org/10.3390/en13246686.

[12] Alfieri L., Battistelli L., Pagano M. (2019) Impact on railway infrastructure of wayside energy storage systems for regenerative braking management: A case study on a real Italian railway infrastructure. *IET Electrical Systems in Transportation*, 9(3), 140-149. https://doi.org/10.1049/iet-est.2019.0005.

[13] Jiang Y., et al. (2014) Energy Harvesting for the Electrification of Railway Stations: Getting a charge from the regenerative braking of trains. *IEEE Electrification Magazine*, 2(3), 39-48. https://doi.org/10.1109/MELE.2014.2333561.

[14] Cui G., et al. (2019) Supercapacitor Integrated Railway Static Power Conditioner for Regenerative Braking Energy Recycling and Power Quality Improvement of High-Speed Railway System. *IEEE Transactions on Transportation Electrification*, 5(3), 702-714. https://doi.org/10.1109/TTE.2019.2936686.

[15] Jefimowski W., Szeląg A. (2018) The multi-criteria optimization method for implementation of a regenerative inverter in a 3 kV DC traction system. Electric Power Systems Research. 161, 61-73. https://doi.org/10.1016/j.epsr.2018.03.023.

[16] Jabr R. A., Džafić I. (2018) Solution of DC railway traction power flow systems including limited network receptivity. *IEEE Transactions on Power Systems*, 33(1), 962-969. https://doi.org/10.1109/TPWRS.2017.2688338.

[17] Zhang, G., et al. (2019) Inverter Operating Characteristics Optimization for DC Traction Power Supply Systems. *IEEE Transactions on Vehicular Technology*, 68(4), 3400-3410. https://doi.org/10.1109/TVT.2019.2899165.

[18] Olczykowski Z., Kozyra J. (2022) Propagation of Disturbances Generated by DC Electric Traction, *Energies*, 15(18), 6851, 1-22. https://doi.org/10.3390/en15186851.
[19] Kus V., Skala B., Drabek P. (2021) Complex Design Method of Filtration Station Considering Harmonic Components, *Energies*, 14(18), 5872, 1-17. https://doi.org/10.3390/en14185872.
[20] De Santis M., Silvestri L., Vallotto L., Bella G. (2022) Environmental and Power Quality Assessment of Railway Traction Power Substations, 2022 6th *International Conference on Green Energy and Applications* (ICGEA), Singapore, 4-6 March 2022. https://doi.org/10.1109/ICGEA54406.2022.9792029.
[21] Xu X., Chen B. (2009) Research on Power Quality Control for Railway Traction Power Supply System, Published in: 2009 *Pacific-Asia Conference on Circuits, Communications and Systems*, Chengdu, China, 16-17 May 2009. https://doi.org/10.1109/PACCS.2009.117.
[22] Seferi Y., Blair S.M., Mester C., Stewart B.G. (2020) Power Quality Measurement and Active Harmonic Power in 25 kV 50 Hz AC Railway Systems, *Energies*, 13(21), 5698, 1-17. https://doi.org/10.3390/en13215698.
[23] Wu S., Mingli Wu M., Wang Y. (2021) A Novel Co-Phase Power-Supply System Based on Modular Multilevel Converter for High-Speed Railway AT Traction Power-Supply System, *Energies*, 14(1), 253, 1-17. https://doi.org/10.3390/en14010253.
[24] Xie S., Zhang Y., Wang H. (2021) A Novel Co-Phase Power Supply System for Electrified Railway Based on V Type Connection Traction Transformer, *Energies*, 14(4), 1214, 1-21. https://doi.org/10.3390/en14041214.
[25] Panpean C. et al., (2021) Harmonic Mitigation in Electric Railway Systems Using Improved Model Predictive Control, *Energies*, 14(7), 2012, 1-16. https://doi.org/10.3390/en14072012.
[26] Ma L., Du Y, Zhu K., Yang F., Xiang S., Shu Z. (2021) Decentralized Control Strategy for an AC Co-Phase Traction Microgrid, *Energies*, 14(1), 7. https://doi.org/10.3390/en14010007.
[27] Kong, W.; Qin, L.; Yang, Q.; Ding, F. (2004) DC side short-circuit transient simulation of DC traction power supply system. Published in: 2004 International Conference on Power System Technology, PowerCon 2004, 182–186. https://doi.org/10.1109/ICPST.2004.1459989.
[28] PN-EN 50160; Parameters of the Supply Voltage in the Public Power Networks. Polish Committee of Standardization: Warsaw, Poland, 2014. Available online: https://sklep.pkn.pl/pn-en-50160-2010e.html (accessed on 18 February, 2023).
[29] Ordinance of the Minister of Economy of 4 May 2007 on the Detailed Conditions for the Functioning of the System. Available online: http://prawo.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20070930623 (accessed on 14 September 2022). (In Polish).
[30] Requirements towards Allowed Limits and Parameters of Disturbances for Devices of Track Occupancy. Control on Railway Lines Operated by PKP PLK S.A., Ie-115, Warsaw, Poland. 2015. Available online: https://www.plksa.pl/files/public/user_upload/pdf/Akty_prawne_i_przepisy/Instrukcje/Wydruk/Wymagania_Ie_-115_internet.pdf (accessed on 18 February, 2023).