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An influence of a complex modernization of the DC traction power supply on the parameters of an electric power system

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Abstract. Urban and suburban public transport constitute basics of functioning of modern, urbanized metropolises. It is a comfortable, economic and ecological means of transportation. Thus, a stable and fast growth of this solution. One of its components is the power supply system. It should allow functioning of the whole transportation system, maintaining the following criteria: energy efficiency and modernity. These criteria have contributed to creation and modernization of power supply systems. Where it comes to DC systems, such an investment includes: replacing 6-pulse rectifiers with 12-pulse rectifiers and raising rated supply voltage. In this article, the authors have presented research results, based on measurements of electrical energy parameters before and after a modernization of a suburban transportation traction system. These parameters have been divided into two groups. The first consists of parameters mentioned in the EN50160 norm. Another group consists of parameters not mentioned in the norm. What has been presented are waveforms and graphs showing these parameters. In the final part of the article a discussion on reasonability of introducing new, modernized traction power supply system for suburban transportation has been performed.

1 Introduction

The issue of energy efficiency in the traction power system constitutes one of the most basic and most important questions of modern means of transportation. The energy efficiency is both the energy consumption of transportation processes, and the influence of the traction power systems on electric power systems. In order to improve the energy efficiency of DC traction systems, among other things, one can modernize traction substations. This includes the following actions: replacing 6-pulse rectifiers with 12-pulse rectifiers (typical procedure in traction power supply systems) and raising rated voltage of the power supply (sporadic procedure). Research results of electrical energy parameters in the municipal traction power system before and after the modernization of the traction substations were shown. The modernization included both changing the rectifiers, and raising the traction power supply voltage from 0,6 kV DC to 3 kV DC. At the same time, traction vehicles used were replaced by newer models. The new vehicles are equipped with the energy recovery function. The measurements carried out concerned primarily the power quality parameters and the parameters related to the electrical energy consumption.

2 The power supply system

One of the most basic issues of electrical transport is its energy consumption and energy safety [1-5]. The issue of real value of the power supply voltage of traction units and electrical energy given back to the units are basic technical problems of DC traction power supply systems [6-14, 18-22]. Additionally, there is an issue of the influence of a DC traction substation on the power supply of an electric power systems. Changing power supply systems, which has already been mentioned at the beginning of the article, serves the purpose of minimizing all negative phenomena related to their functioning.

Replacing 6-pulse rectifiers with 12-pulse rectifiers along with raising rated voltage of the traction network power supply is aimed at achieving the following effects [11-12, 15-22]:

- improving voltage stability,
- reducing losses in the transmission and distribution of electricity,
- reducing electricity deformations retrieved from a commercial power system.

Replacement of rectifiers requires a significant reconstruction of traction substations. Raising rated voltage of the power supply results in the necessity to raise the insulation level of the traction power network. This may involve replacing the traction power network, traction insulators and protection systems.

The mentioned actions constitute modernization costs which should be compensated by achieving planned effect.

The case analyzed by the authors involved a traction substations system modernization, without any changes in the power supply system of the commercial power system. Both before, and after the modernization of the substations, they were supplied from Point of Common Coupling (PCC) - rated voltage of U_n=15kV, work with

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tap-changer 110/15,75 kV/kV. One, representative traction substation has undergone a measurement analysis. Before modernization, two 6-pulse rectifier units with DC U_n=0,6kV worked in the substation. After the modernization there were two 12-pulse rectifier units with DC U_n=3,3kV. Basic blocks of each of the rectifier units are:

• a rectifier transformer type TOTp-6300/15, with nominal power 6300kVA and transformer ratio 15kV/2x1,29kV,

• a diode rectifier type PD-17/3,3, with rated voltage 3,3kV DC and rated current 1700A and class III overload.

A block scheme of the traction power supply of one of the traction substations has been presented in the Figure1.

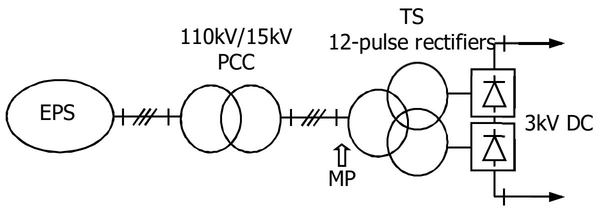


Fig. 1. A block scheme of the DC traction power supply after the modernization (EPS - Electric Power System, PCC - Point of Common Coupling, TS - Traction Substation, MP - Measuring Point).

DC power supply system load consisted of traction units: EN94 (LKc-310 DC motor, 8 pcs. per draft, power 56,5 kW) and EN97 (TME 42-26-4 AC motor, 8 pcs. per draft, power 180 kW).

3 An analysis of electrical energy parameters in the examined traction substation

Quality parameters in electrical energy in the power system are physical quantities describing discrepancies between real waveforms and ideal sinusoidal waveforms of a three-phase circuit. These parameters and their allowed values are defined in the PN 50160 (EN 50160) norm [23]. What was performed in the examined object were 24/7 measurements of electrical energy parameters on the 7th and 8th of April (before the modernization) and on the 7th and 8th of June (after the modernization). Daily measurements were chosen due to the fact of the repetitiveness of the traction load cycle, resulting from invariability of the traction units' time schedule. In the analyses presented in the article, both daily, and hourly periods (daily peak hours – 7:30 – 8:30 a.m.) were taken into account. A high similarity of measurement conditions, necessary for a comparative analysis, was kept. Measurements before and after the modernization were performed on week days, with outside temperature above 20°C (heating in the vehicles was switched off). The measurement equipment were PQM-711SONEL meters, allowing for measuring electrical energy parameters.

A registration was performed with 200ms averaging time, with actual value sampling of 10,24 kHz. Measurements were conducted in indirect systems from current and voltage transformers, on the primary side of the transformer (15kV). For both systems one of the secondary winding was devoted only for metering-billing or billing purposes.

3.1 Power quality parameters in the PN 50160

PN 50160 defines acceptable electrical energy quality parameters with reference to 10-minute periods. In the analysis, the 200ms period measurements were averaged to 10-minute periods. Below, the PN 50160 parameters before and after the modernization have been compared.

• RMS value (PN – 95% 10-minute average RMS values should fit into a ±10% U_n variation band), both "before" (15,406/15,446/15,402kV$_{min}$/15,951/15,981/15,938kV$_{max}$), and "after" (15,469/15,491/15,441kV$_{min}$/15,895/15,918/15,86997kV$_{max}$) PN requirements are fulfilled,

• a negative sequence symmetrical component – (PN – 95% from a 10-minute average RMS value set should fit into a range from 0% to 2% of a positive sequence value component), both "before" (0,08% min/0,22% max), and "after" (0,015% min/0,21% max) PN requirements are fulfilled,

• voltage harmonics – (PN – throughout each week 95% from a 10-minute average RMS set for every harmonics should be lower or equal to the values presented in Table 1 and Table 2), odd harmonics values that are not the multiple of 3, "before" and "after" have been presented in the Table 1, odd harmonics values that are the multiple of 3 "before" and "after", on the other hand, have been presented in the Table 2.

Table 1. Odd harmonics components other than a multiple of 3 according to: PN; "before" and "after" modernization.

Order	PN	Research "before"	Research "after"
5	6%	0,2%	0,9%
7	5%	1,0%	0,8%
11	3,5%	0,2%	0,7%
13	3%	0,2%	0,7%
17	2%	0,1%	0,1%
19	1,5%	0,1%	0,07%
23	1,5%	0,1%	0,2%
25	1,5%	0,03%	0,1%

Table 2. Odd harmonics that are the multiple of 3 according to: PN; "before" and "after" modernization.

Order	PN	Research "before"	Research "after"
3	2%	0,2%	0,3%
9	1%	0,05%	0,07%
15	0,5%	0,02%	0,03%

• THD – (PN – lower or equal to 8 % throughout each week), "before" (0,82/0,82/0,8%min /2/1,98/2,04%max), and "after" (0,99/1,06/0,9%min/1,82/1,92/1,82%max) PN requirements are fulfilled.

Power Quality parameters mentioned above both before, and after the modernization are compliant with the PN 50160 norm. A special emphasis should be put on the two of them, i.e. RMS values and a power supply voltage harmonics set. The consequence of increasing the traction voltage from 0.6 kV to 3 kVDC was the possibility of using rolling stock with the recovery of electricity. Additional reduction of the current consumed from the electric power system was achieved thanks to the work of the PCC transformer with tap-changer 110/15,75 kV/kV. As a result, what happened was a decrease in the value of current taken from the power system and, consequently, a decrease in voltage drops in the power supply system. This has been presented on a graph with the supply voltage "before" and "after" – Figure 2 (a measurement in a daily peak hour with 200ms averaging).

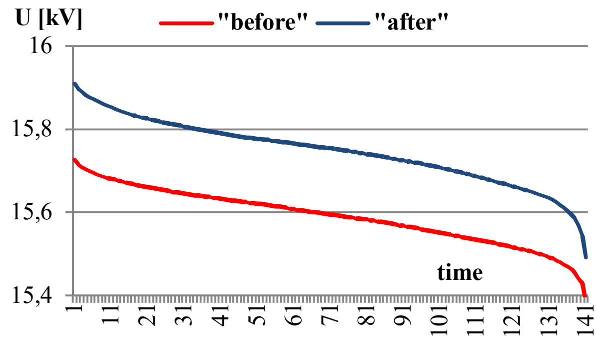
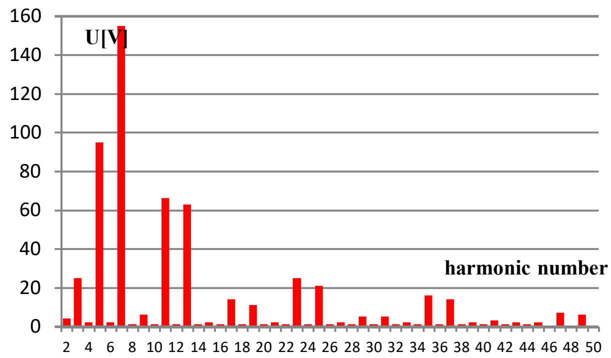


Fig. 2. RMS values of the supply voltage (side 15kV) before and after the modernization.

A comparison of share of harmonics in the supply voltage "before" and "after" is not explicit because there has been a replacement of a 6-pulse rectifier with a 12-pulse rectifier (Table 1 and Table 2). One would assume elimination of harmonics of the 5th, 7th, 17th, 19th order. However, in the measurement results such an effect is not completely visible. The cause of this, most probably, is not the influence of the analyzed rectifier on the power supply system, but a reverse process. In our opinion, in the analyzed power system the 6-pulse rectifier that generated the above-mentioned harmonic components was worked. As a result of the supply voltage including the 5th, 7th, 17th, 19th harmonics, the current flows through a winding of the primary side of the rectifier transformer. Despite of that, share values of these harmonics are low and far from the norm.

Voltage harmonics have low values, however their occurrence should be analysed. There is a possibility that their values will go up (it might be related to a predicted raise in the traction burden), in this case it will have a negative influence on keeping the value of the electrical energy quality parameters. The analysis has been conducted basing on the correlation of the harmonics of current and voltage. Apart from the harmonics characteristic for 6-pulse and 12-pulse rectifiers, harmonics of the 3th, 35th, 37th, 47th, 49th order were also taken into account. The last four are also characteristic harmonics, which are omitted in the PN norm. However, because of their significant values in the readings taken, the authors have decided to include them in their work. Figure 3 presents spectrum of voltage harmonics (1 hour during maximum burden, without the 1st harmonic) before and after the modernization.

"before"



"after"

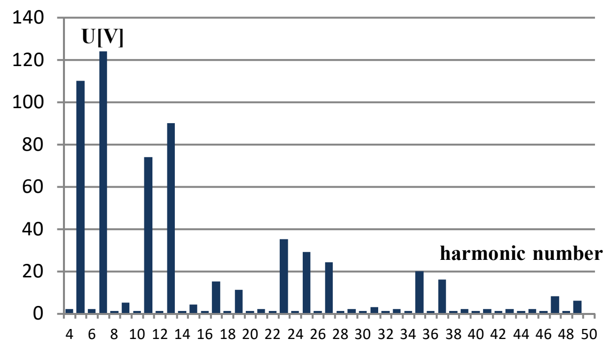


Fig. 3. Spectrum of voltage harmonics before and after the modernization (side 15kV) (picture PQM-711).

The analysis has been conducted for two variants. In the first one, correlation between voltage harmonics and current taken (RMS value) has been calculated. In the second one, correlation between voltage harmonics and corresponding with them current harmonics has been calculated. Graphic results for the chosen harmonics have been shown in the Figure 4, 5 and 6.

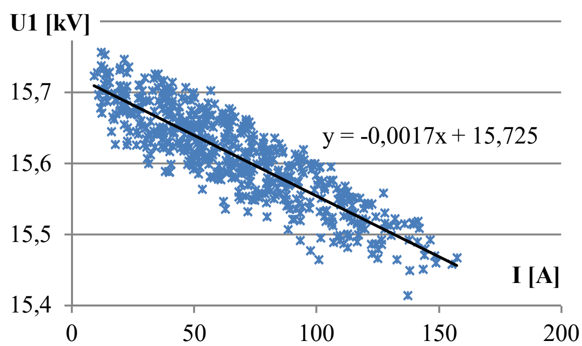


Fig. 4. Correlation between current I (RMS value) and the 1th voltage harmonic – the reading taken in the MP.

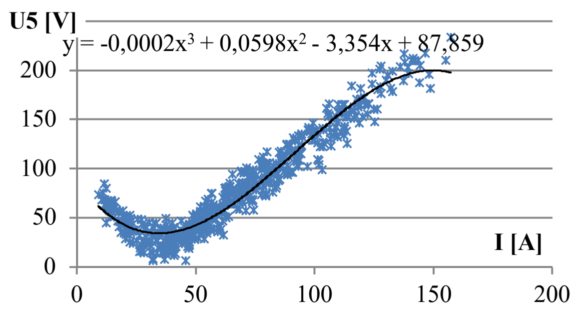


Fig. 5. Correlation between current I (RMS value) and the 5th voltage harmonic – the reading taken in the MP.

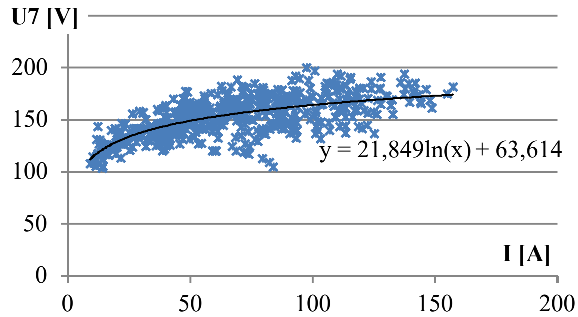


Fig. 6. Correlation between current I (RMS value) and the 7th voltage harmonic – the reading taken in the MP.

Values of the correlation ratio between various readings have been presented in the Table 3 and 4.

Table 3. Values of the correlation ratio between current (RMS) and voltage harmonics – an analysis in the MP.

	U5	U7	U11	U13	U17	U19	U23	U25
"before"	0,91	0,64	0,41	0,33	0,43	0,08	0,12	0,02
"after"	-0,05	-0,26	0,70	0,71	0,53	0,13	0,85	0,78

	U1	U3	U35	U37	U47	U49
"before"	-0,87	0,04	-0,06	-0,01	0,06	0,01
"after"	-0,70	-0,21	0,40	0,49	0,10	0,13

Table 4. Values of the correlation ratio between current harmonics and voltage harmonics – an analysis in the MP.

	U5	U7	U11	U13	U17	U19	U23	U25
"before"	0,90	0,73	0,45	-0,16	0,06	0,34	0,23	0,14
"after"	-0,13	0,36	0,68	0,71	0,49	0,04	0,79	0,71

	U1	U3	U35	U37	U47	U49
"before"	-0,87	-0,15	-0,12	0,01	0,03	0,07
"after"	-0,70	0,02	0,17	0,20	0,18	0,23

A correlation analysis has been conducted in reference to the total current (RMS value) and its harmonics. One can assume that a more detailed description of these phenomena is possible thanks to the correlation using individual current harmonics. The approximation error has been calculated for particular pairs of data. What results from them is that for lower order harmonics (up to 17th) using the RMS value and current harmonics do not vary significantly.

Values of the correlation ratio for the characteristic harmonics of the 6-pulse and 12-pulse rectifiers have high values (over 0,5). Voltage harmonics are strongly dependent on the current harmonics.

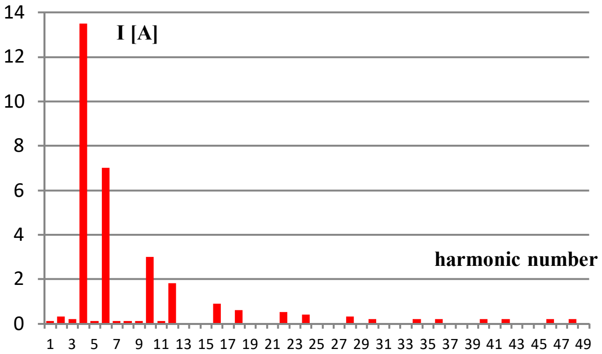
Low value correlations between current and voltage of high values are significant. Such connection suggests that a particular harmonics occur in the electrical system voltage power supply. This is a consequence of voltage deformation not resulting from the current taken by a 6-pulse or 12-pulse rectifier. Such cases take place for harmonics of the 35th, 37th, 47th ,49th order.

3.2 Power quality parameters not included in the PN 50160

The parameters mentioned in the 3.1 paragraph mostly result from the value and character of the current taken by the traction power supply system.

- RMS value of the driving current – as a result of the conducted modernization, a decrease in the value of the current taken from the power system has taken place (increased energy recovery level between the units). Figure 8 presents a graph of the current RMS value "before" and "after" in a chosen power supply phase.
- harmonics of the driving current – as a result of the conducted modernization there has been a decrease in the amount of harmonics in the driving current. Figure 7 presents a harmonic spectrum of a single-phase current for the "before" and "after" periods (without 1st harmonic).
- electrical energy value – as a result of the modernization and an increase in energy recovery level by the vehicles, there has been a decrease in value of the taken current and, consequently, power. As the consequence of reducing the power factor tgφ from 0,33 "before" to 0,18 "after" is the reduction of reactive power consumption. The reactive energy consumption was decreased after modernization by 35% in relation to its consumption before modernization. Similarly, active energy consumption decreased by 25% in relation to its consumption before modernization. Decreasing the consumption of active and reactive energy from the electric power system by a modernized rectifier set is the most important argument confirming the rightness of the actions taken.
- increases, dips, blackouts and transients of voltage – because of a high level of randomness of these phenomena, measurements one day "before" and one day "after" do not result in a sufficient amount of data. In the measurement period both "before" and "after" single occurrences of a dip and a transient took place.

"before"



"after"

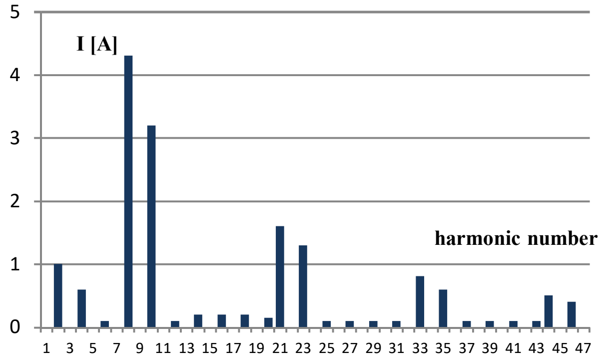


Fig. 7. A spectrum of harmonics of the driving current (side 15kV) before and after the modernization (picture PQM-711).

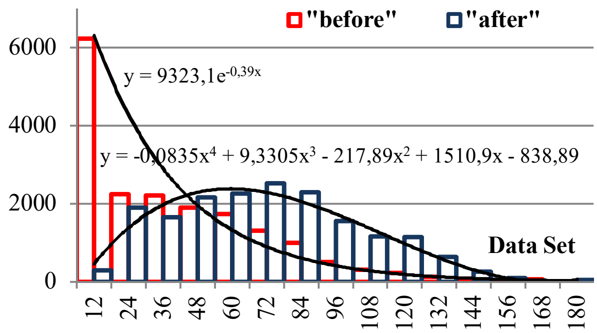


Fig. 8. RMS values of the driving current (side 15kV) before and after the modernization (a single-phase power supply).

4 Conclusions

This article has presented research results of the electrical energy parameters taken from the power system before and after the modernization of the traction substation of public transport. It has shown only the most important parameters that help answering a question about advantages of the conducted modernization. The aim of the modernization was: using in the traction traffic a railway rolling stock with a recovery energy function, minimization of the influence of the DC traction system on the electric power systems, minimization of the voltage drops in the power supply system and increasing the power given back to the traction units. Using energy recovery between the vehicles has given impressive results that has contributed to financial effects. In order to have a complete assessment of this effect one would have to compare expenditures incurred related to the investment and energy savings. Unfortunately, the authors have not been able to access a full financial documentation of the investment. Minimization of the influence of the DC system on the commercial power system is an issue difficult to assess. It is related to the fact that both before, and after the modernization electrical energy quality parameters had values significantly over the PN 50160 norm. One has to assume that the modernization has meaningfully raised the supply of these values. Thus, it is possible to increase a system load without any negative effects where it comes to the electrical energy quality. The situation is similar with regards to the drops of voltage and power given back to the traction units.

In the conclusion of the article, one should wish for further modernizations of the power supply systems in public transport.

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