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SŁAWOMIR DRAPIK, ADRIAN KACZMARCZYK, JANUSZ PRUSAK, BARTOSZ WOSZCZYNA*, PAWEŁ MARKOWSKI**

THE CHARACTER OF LOAD VARIABILITY OF TRAM TRACTION SUBSTATIONS THAT SUPPLIE LINES WITH DIFFERENT SPECIFICITY OF TRAFFIC

CHARAKTER ZMIENNOŚCI OBCIĄŻEŃ TRAMWAJOWYCH PODSTACJI TRAKCYJNYCH ZASILAJĄCYCH LINIE O RÓŻNEJ SPECYFICE RUCHU POJAZDÓW

Abstract

The paper presents the load currents of two tram traction substations. These substations power lines with different characteristics of tram traffic. Loads were analysed for one working day and one public holiday. Attention was paid to the differences and similarities in the current waveforms. The demand level was assessed, with respect to the rectifier units in the substations. The time series method was used, inter alia, and chiefly an analysis of the characteristics of autoregression and partial autoregression was carried out, to act as a diversity index with respect to the nature of variability in the analysed traction load currents.

Keywords: electrical traction, tram traction substations, variability of traction loads

Streszczenie

W artykule przedstawiono prądy obciążenia dwóch tramwajowych podstacji trakcyjnych. Podstacje te zasilają linie o różnej specyfice ruchu tramwajów. Analizie poddano obciążenia dla jednego dnia roboczego i jednego dnia świątecznego. Zwrócono uwagę na różnice i podobieństwa w przebiegu prądów. Oceniono zakres zapotrzebowania na zespoły prostownikowe w podstacjach. Zastosowano m.in. metodę szeregów czasowych, a głównie analizę charakterystyk autoregresji i autoregresji cząstkowej jako wskaźnika zróżnicowania charakteru zmienności analizowanych prądów obciążeń trakcyjnych.

Słowa kluczowe: trakcja elektryczna, podstacja tramwajowa, zmienne obciążenie trakcyjne

* M.Sc. Eng. Sławomir Drapik, independent specialist, M.Sc. Eng. Adrian Kaczmarczyk, specialist, FPU Elster s.c, Ph.D. Eng. Janusz Prusak, M.Sc. Bartosz Woszczyna, Department of Traction and Traffic Control, Faculty of Electrical and Computer Engineering, Cracow University of Technology.

** Paweł Markowski, student, Faculty of Mechanics, Cracow University of Technology.

1. Introduction

The authors of the following article have been dealing with the analyses of load variability of tram traction substations [5–7, 9] for some time. Another thing, which arouses interest in this area, is the load variability of the tram traction substation's rectifier sets. The familiarity with the character of this variability can be the basis for taking further action in the range of improving design methods for infrastructure objects of urban electrical railway transport. The results and analyses of the load measurements of two tram traction substations, located in different parts of city, are presented below.

2. Selected research areas

One of the analysed traction substations, "Czyżyny" [3] (PT-1), supplies a traction line on arterial roads. What is clearly noticeable is the reasonably central location of this substation, in the area of town with a complex hub of railway and road transport, characterised by significant traffic. The other substation, "Nowa Huta" [4] (PT-2), is located near one of the two tram depots in Cracow. This substation also supplies two tram terminals.

An interesting issue for the authors appeared to be the evaluation of the load rectifier sets occurring in each of the traction substations mentioned above. Each of the substations is equipped with four rectifier sets of summary rated power of 3,200 kW.

Those sets are marked in V load class [13], which means that long-term overloading lasts 2 hours and amounts to 150% of the rated current, whereas short- term overloading lasts 1 minute and amounts to 200% of the rated current. Fig. 1. shows the location of the substations "Czyżyny" (PT-1) and "Nowa Huta" (PT-2) in relation to the contours of Cracow city.

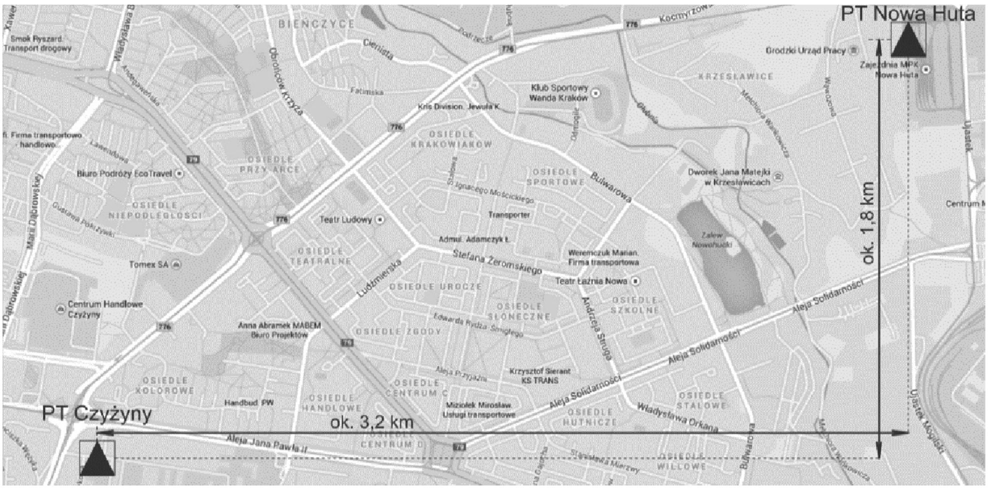

Fig. 1. Location of tram traction substations "Czyżyny" (PT-1) and "Nowa Huta" (PT-2)

3. Measurements results

The basis for calculating and analysing were measurement results of the traction load current obtained for research or didactic purposes, from the Board of Communication and Transportation Infrastructure in Cracow [14, 15]. The registered measurements concerning currents. in particular power supplies, have been made with a frequency of 1 Hz. Summing of the above currents were needed in order to evaluate the load of rectifier sets.

Figures 1 and 2 show the final effects of these summing, that is, the courses of momentary traction currents values, for chosen period of time taken into account substations. One working day (23/10/2013 – Wednesday) and one holiday (27/10/2013 – Sunday) have been taken into consideration.

A) B)

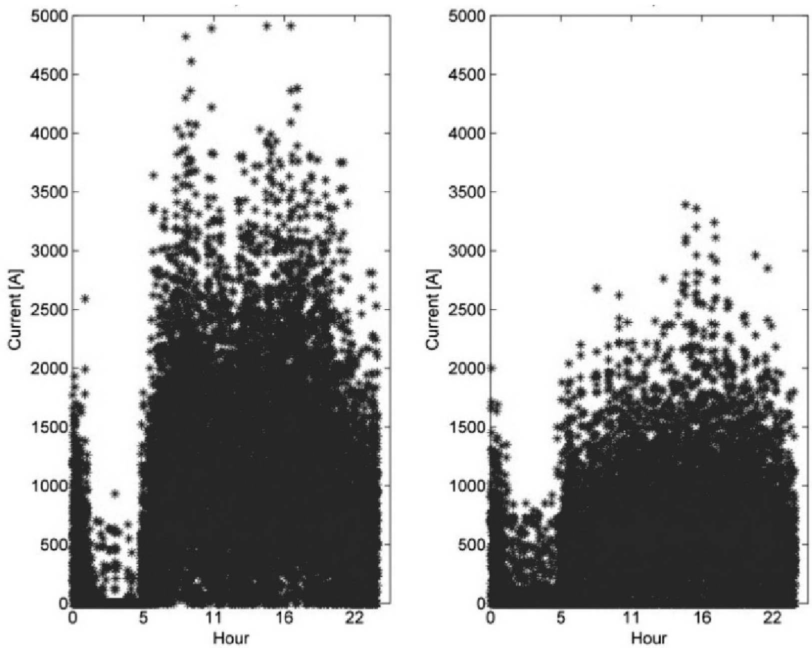

Fig. 2. The course of momentary electric current value of traction substation load "Czyżyny" (PT-1) on: A) 23/10/2013 (Wednesday); B) 27/10/2013 (Sunday)

Figures 2 and 3 indicate that the registered traction loads have a considerable range of variability. The period of reduced load, at the time of night break when the trams stop running, is demonstrated in each of the four cases. It can be noticed that on the holiday (loads), currents are lower than on the working day. The above estimations have a rather approximate (descriptive) character.

Conducting quantitative (detailed) analyses provides the results, which enable for a comparison of the value and character of the tram traction substations loads taken into account.

A) B)

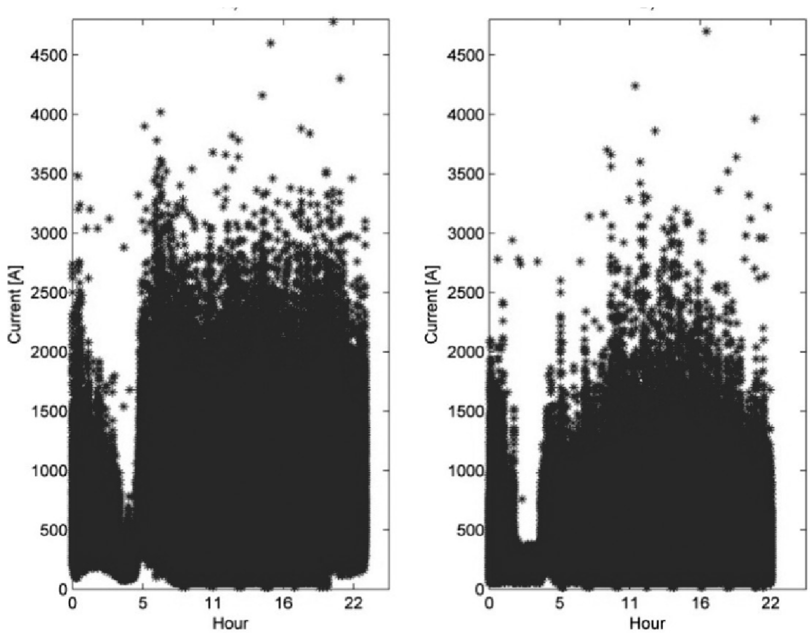

Fig. 3. The course of momentary electric current value of traction substation load: ”Nowa Huta” (PT-2), on: A) 23/10/2013 (Wednesday); B) 27/10/2013 (Sunday)

4. Selected results of measurements analysis

The results of analysis of courses traction load currents for the mentioned tram traction substations are presented below. The quantities and electrical indicators, as well as mathematical presenting and the specificity of variability of load currents deriving from supplied rolling stock, have been shown and compared.

Due to the thermal working conditions of traction substation devices, firstly, attention has been paid to work at peak load times. What also seems to be interesting are time periods, when substations work below their rated capabilities.

The results presented in table 1 above are related to one day in each case, that is, each analysis concerns 24 hours. Taking into account the average values of currents, it can be claimed that, on the working day, the PT-1 substation is slightly more overloaded than the PT-2 substation (about 5.6%); on holiday, both substations are overloaded equally. It follows that the PT-1 substation load on holiday decreases in greater extent than the PT-2 substation and amounts to about 58.45% of the load from the working day.

Taking into consideration the shape factor, i.e. the quotient of rms current to its average value, it can be noticed that this factor for the PT-1 substation for the working day as well as the holiday is higher compared with the factor for the PT-2 substation. It shows that the load current variability of the PT-1 substation, on both days, is higher than that of the PT-2 substation.

Table 1

Summary of currents and factors values characterising analysed loads

No. sys. PT	1	1	2	2
Date of measurement	23/10/2013	27/10/2013	23/10/2013	27/10/2013
Day of the week	Wednesday	Sunday	Wednesday	Sunday
Minimum	0	0	0	0
Maximum	4890	3390	4780	4700
Range	4890	3390	4780	4700
Average	796.66	465.72	751.85	465.9703
Rms	1097.50	677.27	939.78	606.61
Median	640	350	600	340
Standard deviation	754.87	491.73	563.83	388.40
Variance	569830.93	241801.59	317904.24	150850.37
Skewness	1.01	1.23	1.11	1.79
Kurtosis	3.80	4.65	4.20	7.92
Shape factor	1.38	1.45	1.25	1.30
Crest factor	4.46	5.001	5.09	7.75
Experimental factor	6.14	7.28	6.36	10.09

It can be pointed out later that, in the case of both substations, this factor is higher on the holiday rather than on the working day. On the holiday, there is increased load variability compared to the working day.

Taking into account the crest factor, i.e. quotient of maximal value of current to its rms value, it can be stated that this factor is greater for the PT-2 substation on the working day as well as on the holiday; for both substations, this factor is greater on the holiday. Experimental factor, is a quotient of maximal value of current to its average value, i.e. it is certain modification of a crest factor. Measured maximal values of load current are ranged from 3390 A to 4890 A. Long-term load current of both traction substations resulting from quantity of installed rectifier sets and established load class amounts to about 480 A.

In table 1, as can be noticed, the minimal values of current in each substation, on both analysed days, take the value of 0 A. In the case of an analysis of three railway traction substations supplying a railway hub of Cracow, not even once, during a period of 24 hours, the load has reached zero value. Statistic indicators constitute extended information on the character of variability of the analysed traction loads. In Fig.4. and Fig.5, the empirical and theoretical distributions of both analysed substations (PT-1 and PT-2) have been presented.

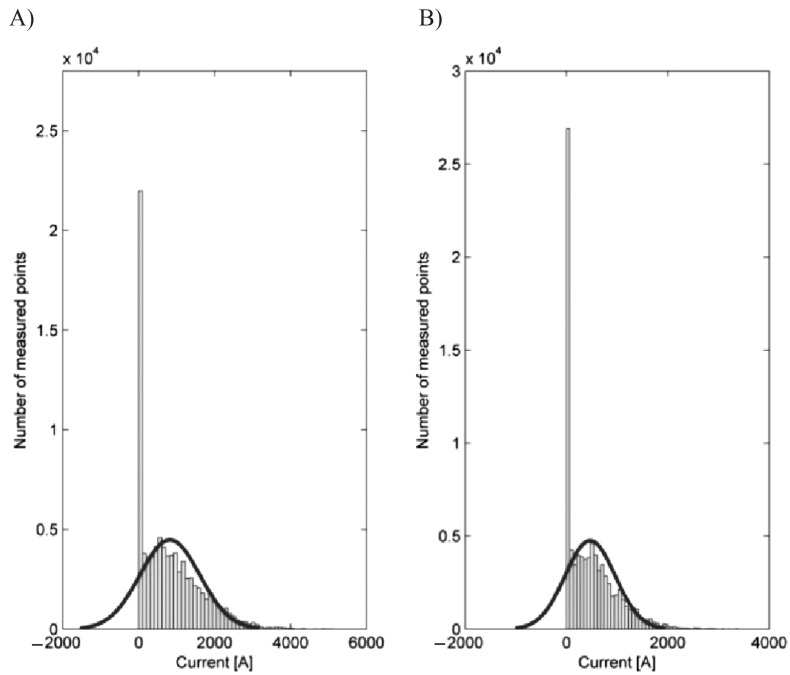

Fig. 4. Histogram of momentary electric current value of traction substation load “Czyżyny” (PT-1) on: A) 23/10/2013 (Wednesday); B) 27/10/2013 (Sunday)

Figure 4 shows histograms of the registered momentary electric current load value for traction substation “Czyżyny” on the 23rd (A) and on the 27th (B) of October 2013. The presented data indicate that for over 20% of substation’s working time on 23/10/2013, and almost 29% its working, on 27/10/2013 in its supplying area, there is no traction vehicles traffic. It is very crucial information, which shows how long rectifier sets work without being loaded.

As it results from the comparison of both distributions – empirical and theoretical, for measurements registered on Sunday, the course shape of the theoretical curve indicates lower current load values of the traction substation in relation to the working day (Wednesday, in this case). This observation can be confirmed by the use of a standard deviation parameter, which expressed in numerical form indicates that a lot measure values are scattered around its average. For class A the value of this parameter amounts to over 754 A, whereas in variant B it is about 491 A (according to Tab. 1). Both empirical distributions have a leptokurtic character. The value of kurtosis for the above data is positive, which are clearly indicated by data shown in Figure 1. A skewness parameter is positive, since both obtained distributions are designed for right-hand traffic.

Figure 5 shows the histograms of registered momentary electric current value of traction substation load “Nowa Huta” on the 23rd (A) and the 27th (B) of October 2013. The presented data indicate that about 3% of traction substation’s working time on 23/10/2013 and over 2% of its working time on 27/10/2013 in its supplying area there is no traction vehicles traffic.

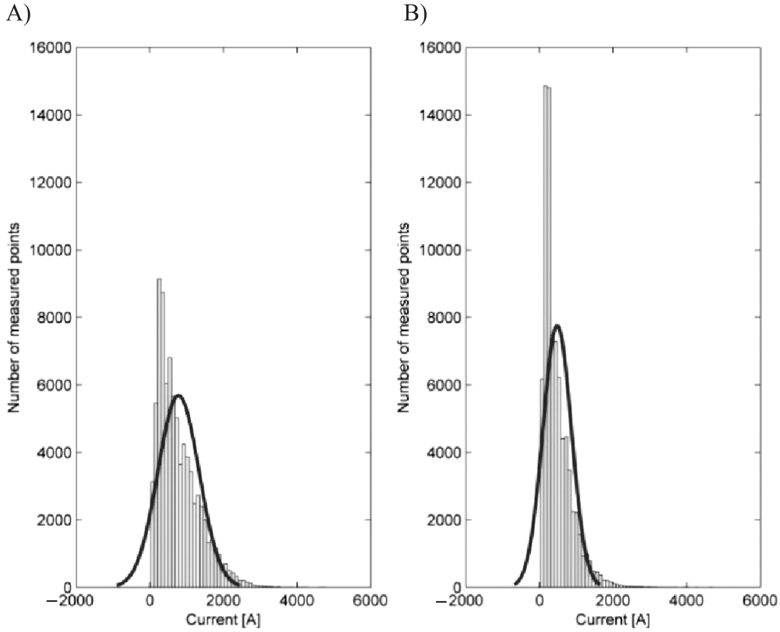

Fig. 5. Histogram of momentary electric current value of traction substation load "Nowa Huta" (PT-2) on: A) 23/10/2013 (Wednesday); B) 27/10/2013 (Sunday)

Comparison of both distributions – empirical and theoretical (presented in Fig. 4), leads to the conclusion that for measurements obtained on Sunday, the course shape of the theoretical curve indicates considerably lower current load values of traction substation "Nowa Huta" in relation to the working day. It is worth noticing that on 23/10/2013 (Wednesday), the traction substation "Nowa Huta" registered over 6 times less values indicating to the operation of rectifier sets at idling speed in relation to PT "Czyżyny" for the same day. However, in the case of comparing the measurements of both traction substations on 27/10/2013, PT "Nowa Huta" obtained over 12 times less of its values.

Such a big difference during the working time at idling speed of rectifier sets of both traction substations results from the fact that PT "Nowa Huta" supplies a tram depot. Repair and operational works, as well as manoeuvre works, cause that almost uninterruptedly, all day round, in the areas supplying by rectifier sets of this substation, there are moving traction vehicles that use its energy. This fact is particularly visible in graph box (Fig. 10) presented later on in the article.

For statistical analysis, in order to increase their qualities, it would be worth increasing the sampling rate. It results from the specificity of statistical methods and, in consequence, the computer programs for statistical analyses, which require a great quantity of data. In order to meet these expectations, it is advisable to increase the sampling rate at the time of taking measurements, for instance, up to 2 kHz – which is recommended by the norm [12].

Figures 6 and 7 show the bar charts reflecting graphic time balances of appearing traction loads for courses presented in Figures 2 and 3. In this case, the results of measurements have been ordered according to the parameters of rated rectifier sets that the analysed substations are equipped with.

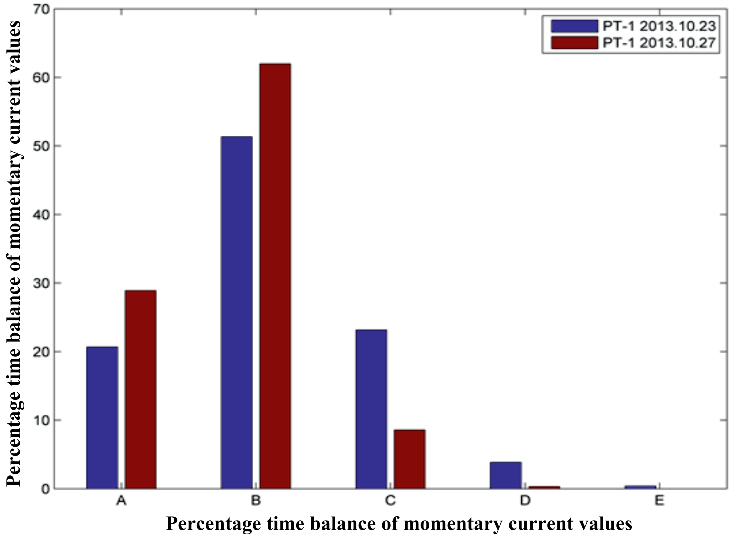

Fig. 6. Percentage time balance of momentary current values of tram traction substations load “Czyżyny”

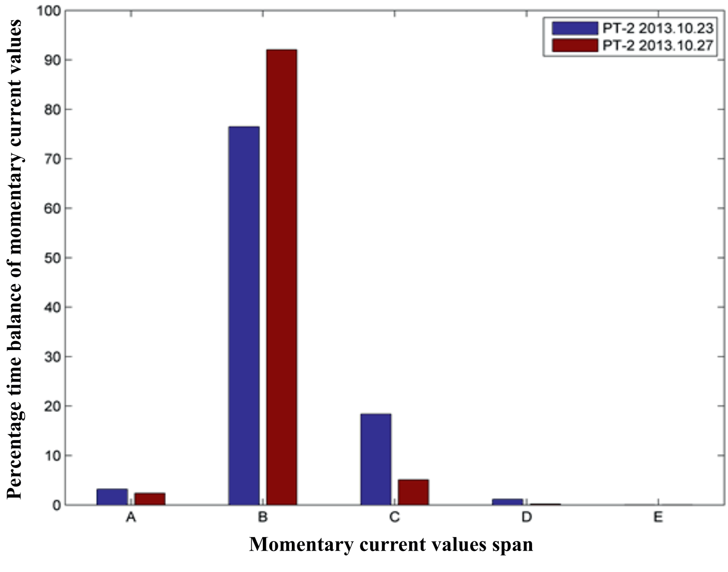

Fig. 7. Percentage time balance of momentary current values of tram traction substations load, “Nowa Huta”

Letter A: means the time balance of occurring loads 0 A (i.e. the lack of load). **Letter B**: means the time balance of occurring loads of values greater than 0A and not higher than a long-term load of one of the rectifier sets (here: 0 A < I load ≤ 1.2 kA). **Letter C:** means the time balance of occurring loads of values greater than a long-term load current of one of the rectifier sets and not higher than a long-term load of two rectifier sets (here: 1.2 kA A < I load

≤ 2.4 kA). **Letter D:** means the time balance of occurring loads of values greater than a long-term load current of two rectifier sets and not greater than a long-term load of three rectifier sets (here: 2.4 kA A < I load ≤ 3.6 kA). **Letter E:** means the time balance of occurring loads of values greater than a long-term load current of three rectifier sets and not higher than a long-term load of four rectifier sets (here: 3.6 kA A < I load ≤ 4.8 kA).

The charts above (Fig. 6 and Fig. 7) clearly describe the load character of both traction substations. As an example, the time balance A for the PT-1 substation shows that about 20% of time in relation to a day (approx. 4.8 hours) on the working day, the rectifier sets are not loaded; however, in case of the PT-2 substation, there are no loads for about 3% of the time (approx. 0.72 hours). Carrying on the interpretation of some results – the time balance B for the PT-1 traction substation shows that about 51% of time in relation to a day (approx.12.24 hours) on the working day, one rectifier set, in the range of currents not greater than a long-term load, would be needed to supply the loads, similarly one rectifier set would be enough to supply the loads in the case of the PT-2 substation, but for about 77% of time in relation to a day (approx. 18.48 hours).

On the basis of the analysed charts, what can be evaluated is the theoretical time of demands at traction substations (PT-1 and PT-2) for one rectifier set (balance B), for two rectifier sets (balance C), for three rectifier sets (balance D) and for four rectifier sets (balance E) on the working day as well as on the holiday. As it was emphasised in the introduction, the presented results are related to two days in relation to a year (approx. 0.55% time) apart from that, what has not been taken into account is the loads balance with possibility to overload the rectifier sets, which is why more decisive remarks or even conclusions have not been formulated.

The Figures below present the analysis results with the use of time series theory [1] of registered load of traction substation “Czyżyny” on 3/10/2013. Figures 8 and 9 have been obtained according to the authors’ earlier publications [5, 9], traces of autocorrelation and partial correlation. Those charts show that for analysed case there is a considerable variability of traction substation load. It turned out that the studies on whole day loading of traction substation, which in determined night hours is loaded in lower range is clearly demonstrated in specificity of obtained traces. From 1 a.m., the value of registered load PT “Czyżyny” is reducing, so that it could increase from 4 a.m. (it is clearly visible in Fig. 2).

It is due to the technical break in the traffic of traction vehicles in the area supplied by this substation. This fact causes that using the time series for analysis does not make it possible to interpret unambiguously the results obtained with such a method. This observation is apparently reflected in Fig. 9, showing the partial correlation trace of analysed daily load of a traction substation.

Figure 10 presents the comparison of the loads of tram traction substations with the use of box chart in each case. The so-called “box” shows 50% of the measurement points [10]. The symbol, which is marked inside the box, indicated the location of median, i.e. the value dividing the set of measurement points into two equal parts. Two extreme horizontal lines of the chart indicate minimal and maximal values. The charts A and B are, in particular, related to the PT-1 substation appropriately on the working day (A) and on the holiday (B), whereas the charts C and D are related to the PT-2 substation also on the working day (C) and on the holiday (D). Such a way of presenting the results enables one to estimate in a simple (optical) way the differences or similarities in the specificity of the range variability of current loads of both substations. For instance, on the holiday (charts B and D), both substations use a similar amount of energy (tab. 1) for traction purposes, average currents are almost equal and amount to about 466 A. However, a diversified view of both charts (Fig. 10) shows different ranges of current load variability of each substation.

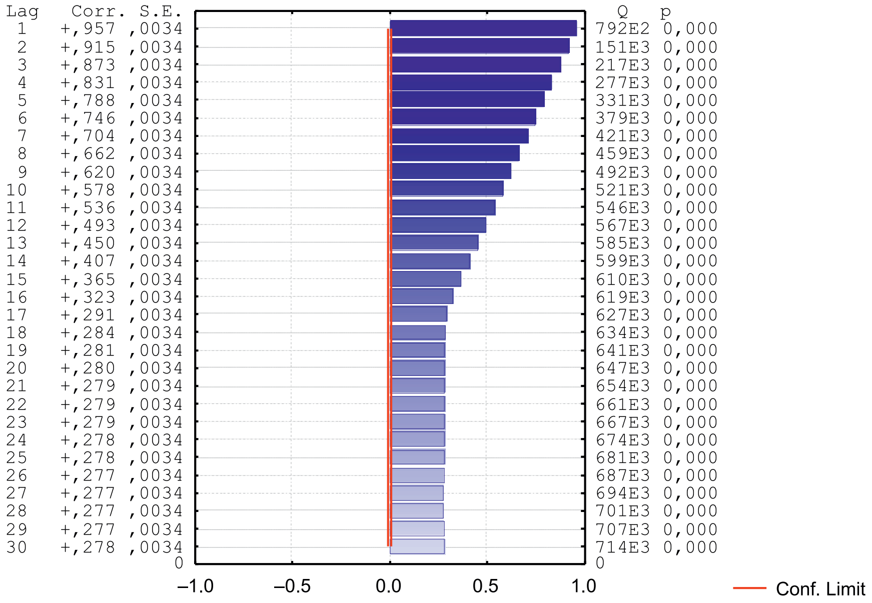

Fig. 8. Autocorrelation Function of tram traction substation load “Czyżyny” on 23/10/2013

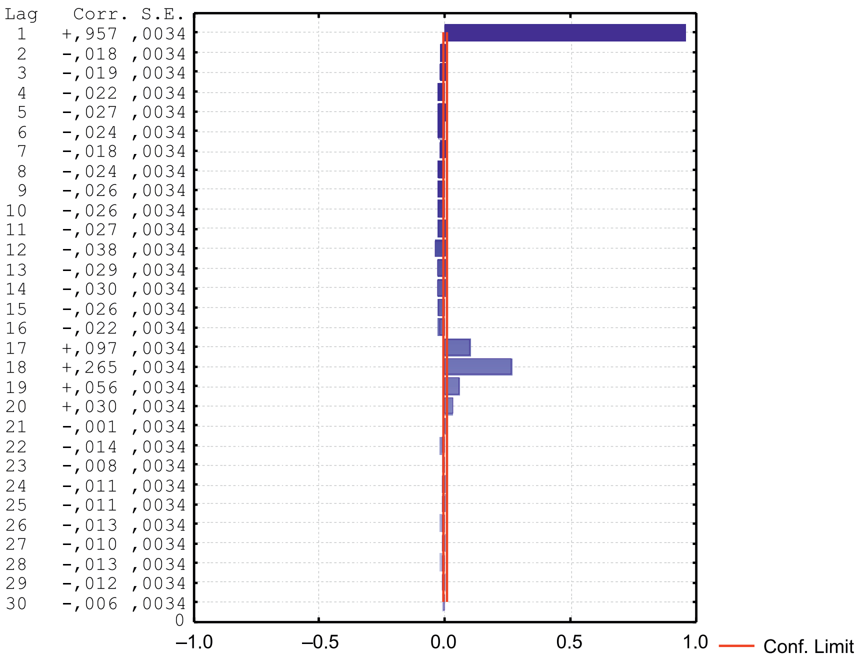

Fig. 9. Partial Correlation Function of the loads of tram traction substation “Czyżyny” on 23/10/2013

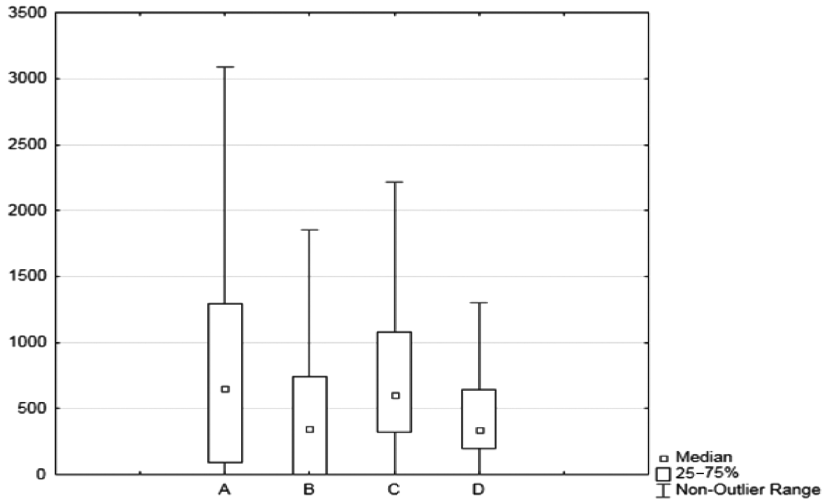

Fig. 10. Comparison of tram traction substations' loads: A) PT-1 23/10/2013, B) PT-1 27/10/2013, C) PT-2 23/10/2013, D) PT-2 27/10/2013

5. Conclusions

On the basis of the presented measurement results and analyses, some remarks can be made. As it was mentioned in the introduction, the results being analyses concerned the real exploitation situation. They did not have an academic character allowing, sometimes, certain simplifying assumption.

In the range of the conducted measurements and analyses, it can be stated that:

- Loads (currents) of analysed traction substations are characterised by considerable variability in relation to the day;
- Equipping both traction substations with rectifier sets is accomplished with considerable reserve;
- the differences in the range and character of loads of both analysed traction substations do not influence the final evaluation of the range of oversizing rated electrical power of rectifier sets;
- In loads time balance, especially in case of the PT-1 substation, the considerable lack of loads (idle running of rectifier transformers) is noticeable.

The ways of analysing tram traction substation loads presented in the article different give consistent results. Diversified ways of presenting the results allow to evaluate the range and character of this load variability. At present, the authors of this article are interested in particular in the range (scale) of using the power of installed rectifier sets at the traction substations. It is in accordance with the authors' approach, which is advocating the need of taking further action in order to improve the designing methods of traction substations.

Analyses for majority of substations, with additional consideration of data regarding for example; rolling stock, route profile, a distance between stations, timetables would enable, in greater range, to formulate remarks related to the correctness for choosing the equipment, in this case, tram traction substations. Such studies would require additional funds/measures, due to the time involvement of a research team or purchase of measurement apparatus enabling to make measurements with higher frequency than currently.

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