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THE RANGE OF LOAD VARIABILITY OF RECTIFIER UNITS WITH A CONCENTRATED DISPOSITION OF TRAM SUBSTATIONS AS EXEMPLIFIED BY A REAL TRAM LINE

PODSTACJE TRAMWAJOWE O ZAGĘSZCZONEJ LOKALIZACJI – ZAKRES ZMIENNOŚCI OBCIĄŻEŃ ZESPOŁÓW PROSTOWNIKOWYCH, NA PRZYKŁADZIE RZECZYWISTEJ LINII TRAMWAJOWEJ

Abstract

The first part of this paper presents a comparison of the measured and simulated results of the load variability of rectifier units of a tram traction substation. The subject of the tests was a power supply substation for the contact line of a tramway, the profile and traffic of which was known. After a positive appraisal of the applied simulation method, an assessment of the range of load variability for the rectifier units took place for a hypothetical situation involving the concentrated disposition (layout) of the traction substations (so-called micro-substations). The results acquired under the described circumstances are presented in the second part of this paper.

Keywords: tram traction substation, traction load variability, traction micro-substation

Streszczenie

W pierwszej części artykułu dokonano porównania wyników pomiarowych i symulacyjnych dotyczących zakresu zmienności obciążania zespołów prostownikowych tramwajowej podstacji trakcyjnej. Obiektem badań była rzeczywista podstacja zasilająca sieć trakcyjną na linii o znanym profilu i występującym na niej ruchem tramwajów. Po pozytywnej ocenie zastosowanej metody symulacyjnej – przeprowadzono ocenę zakresu zmienności obciążeń zespołów prostownikowych dla hipotetycznej sytuacji, polegającej na zagęszczeniu lokalizacji podstacji trakcyjnych (tzw. mikropodstacji). Uzyskane dla tych okoliczności wyniki znajdują się w drugiej części artykułu.

Słowa kluczowe: tramwajowa podstacja trakcyjna, zmienność obciążeń trakcyjnych, mikro-podstacja trakcyjna,

1. Introduction

Tram traction power supply systems used in our country consider changing to 'Poland' as this would be clearer and more conventional are all based on the same diagram [13, 24, 16] which has been in operation for a few dozen years. Also trams have been operating equally efficiently (more accurately, DC rail vehicles, equipped with resistor start-up systems and DC serial engines). Industry experts (but not only they) know that modern tram rolling stock has and asynchronous motors. Clearly, invested means into tests and design works as well as common acceptance of new solutions in opinion making and decision making environments bring positive results. Moreover, in the case of power supply systems, new solutions which are better adjusted to the specific loads they are subjected to must be based on extensive testing and analyses [3, 4, 8, 10, 12, 15, 17, 21, 22, 23].

Interesting results of tests [11] regarding use of, to a certain extent, doubled power supply in Warsaw trams concern mainly increase in efficiency of the railing stock under new circumstances.

During examinations and testing, researchers pay attention to the nature of traction loads, in particular, loads placed on rectifier units at substations [1, 9, 22, 23]. Research findings form the basis for solutions intended to improve the power supply to tram systems via overhead lines. In this paper, at the example of a real (active) tram line there was assessed an impact of application of other (selected) system solutions, concerning power supply for the tram contact line, on specificity of the traction.

2. Route profile and tram traffic

Traction loads depend on many factors [13, 14, 16]. Hereunder presented the most essential data reflecting the specifics of the considered tram line section. In the case of other sections of tram line, the acquired results may differ; this is because of their dissimilarity (just to mention the characteristics data hereunder)

The selected section of the tram line is supplied by a single traction substation; it is an ultimate double track extreme line with a loop at its end [7]. The length of the cruising section is 1800 m and the length of the loop is 300 m. In Fig. 1, there is presented course of the line at the background of the city plan, where the yellow color means the cruising section and the red one means the loop.

The tram line is located at 234 m a.s.l. 'at the loop' the track then rises to 262 m a.s.l. at a distance of approx. 1200 m from the loop. The track then drops to 252 m a.s.l. at the end of the power supply section. From the presented data, the difference between the highest and the lowest points at the track is 28 m.

Table 1 presents data regarding the profile of the vertical track that is inclination of the track-way to the level. In this case it is a product of change of the track height in meters and the length of the section where it exists, in km. Consequently, the result is in per promil.

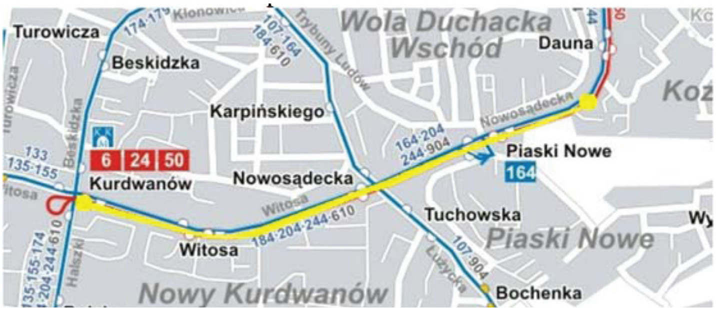

Fig. 1. Course and location of the studied tram line section [19]

Table 1. Vertical profile of the track [19, 20]

	Distance [m]	Length	[‰]
1	Pętla	300	0
2	0	43	10
3	43	46	13
4	89	84	15,5
5	173	49	9
6	222	171	5
7	393	49	13.5
8	442	125	22
9	567	52	33.5
10	619	234	45
11	853	29	37.7
12	882	38	30
13	920	38	28
14	958	101	26
15	1059	41	22.5
16	1100	38	19
17	1138	110	6.5
18	1248	32	–6
19	1280	41	–9
20	1321	41	–11
21	1362	107	–13
22	1469	81	–27
23	1550	11	–40
24	1561	55	–32.5
25	1616	113	–25
26	1729	41	–13.5
27	1770	35	3

It can be observed that the vertical profile of the track is rather varied. The steepest uphill section is located at the 619th meter of the track as measured from the loop and it is 45 per promils In the track there are a total of 14 sections with an inclination which exceeds 15 per promils.

Table 2 presents data relating to the horizontal profile of the track. This is information regarding for which points on the track it is necessary to include additional resistances when doing calculations since the tram is not travelling in a straight line.

Table 2. Horizontal profile of the track [19, 20]

	Distance [m]	**Length [m]**	**Radius [m]**
1	Pętla	300	40
2	0.0	370	∞
3	370	105	186.2
4	475	288.75	452
5	763.75	96.25	186.2
6	860	280	∞
7	1140	43.75	45.2
8	1183.75	17.5	∞
9	1201.25	17	79.8
10	1218.25	43.75	42.5
11	1262	105	∞
12	1367	165	1048
13	1532	268	∞

At the tram loop there is a sharp turn (radius 40 m) and the trams must turn back onto a relatively short section (300 m). On the track there are 7 bends and 5 straight sections. The sharpest bends are situated at 1140 m (radius 45 m) and 1218 (radius 42 m) from the loop.

Data in the above table is necessary for simulation calculations with the applied theoretical drive method [16]. Obviously, some other data is required, such as data relating to stops on the tram-line or technical parameters of the vehicles themselves. In this paper, exemplary results of simulations are presented for the type 105N tram (Fig. 2) and the type NGT-6 tram (Fig. 3) for a drive from the loop (Fig. 1) to the downtown area.

Applying, among others, the above diagrams there were acquired certain resultant loads on the power supply cables and rectifier units described in the further part of the paper. It should be remembered that other circumstances, such as other track profiles, other tram railing stock and other data, type of which is not a secret for experts, may result in different final results.

A factor which has an impact on a value and a nature of loads on rectifier units there are also time-tables acc. to which trams drive (they should drive), in the area of the power supply of every traction substation. In Table 3, in a collective manner there is presented quantity of tram vehicles within the power supply area of the examined traction substation, with the assumption that trams drive in accordance with their scheduled timetables [20].

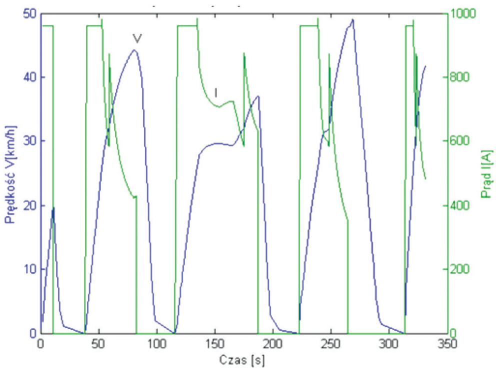

Fig. 2. Diagram of the current and speed for a theoretical drive of the type 105N tram (Blue – V(t); green – I(t)) (own materials)

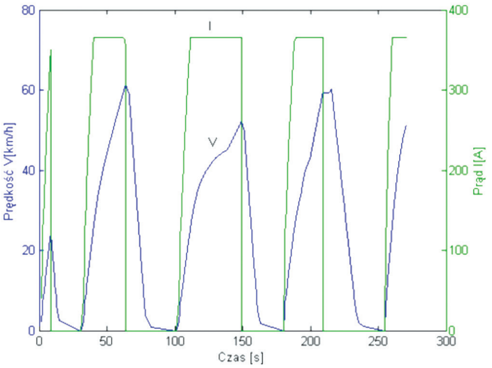

Fig. 3. Diagram of the current and speed for a theoretical drive of the type NGT-6 tram (Blue – V(t); green – I(t)) (own materials)

Table 3. Number of drives for particular lines (own materials)

Line no.	Number of drives from the loop	Number of drives to the loop	Total
Business days			
6	73	76	149
24	57	55	112
50	144	144	288
Total	274	275	**549**
Saturdays			
6	36	36	72
24	54	53	107
50	87	86	173
Total	177	175	**352**
Sundays and holidays			
6	-	-	-
24	51	49	100
50	84	83	167
Total	135	132	**267**

As can be concluded from the above table, at the time of tram driving (04:30 to 23:50, according to the timetables) during a business day, a total of 549 trams drive which works out as being 0.47 vehicles per minute. At the peak time, there was an average of 0.7 vehicles driving along the track per minute; this is a fairly high concentration of tram traffic.

The statement above is important in the context of the assessment of the specifics of existing rectifier unit loads, in particular in terms of applying their rated parameters which are described later in this paper.

3. Traction loads – results of measurements and calculations

This section presents the traction loads placed on the rectifier units of the operated traction substation calculated both on the basis of the measured results [7] and acquired by means of computer simulation based predominantly on the theoretical drive method [16].

The authors used a rather rare opportunity to compare the measured and computational results in order to have a reference to applied computational method.

Analysing the results herein it should be noted that there are various complex factors which temporarily affect the course of tractions loads [13, 14, 16]; this means that the recorded loads may seriously differ on different for the same timetable and the same remaining parameters (these have been partially described previously) [1, 3].

Figure 4 presents a diagram of traction current loads calculated on the basis of currents from 'feeders', with a frequency of 1 Hz for a business day.

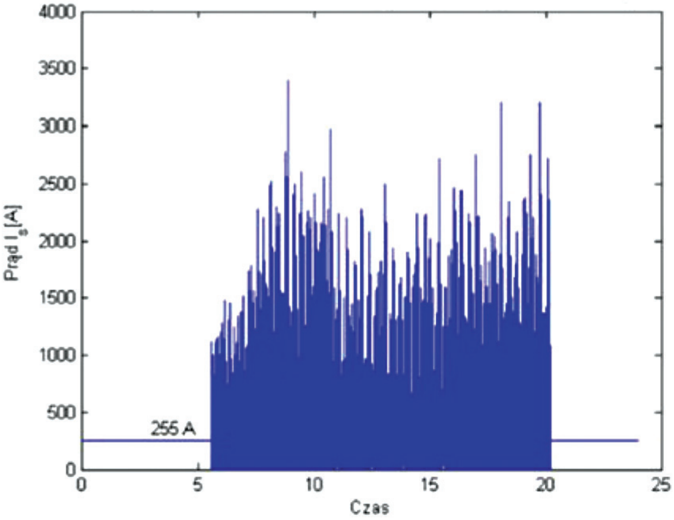

Fig. 4. Diagram of temporary currents on bus bars of the DC switchgear of the traction substation during a business day (own materials)

On the basis of the measurement data, it was determined that the average value of the current consumed by trams over 24 hrs was 255 A and the maximum value of the current was 3400 A – this occurred at around 9.00 am.

Figure 5 presents the course of the actual current capacity at the background of limits arising from the application of three rectifier units rated [9] at the substation [5].

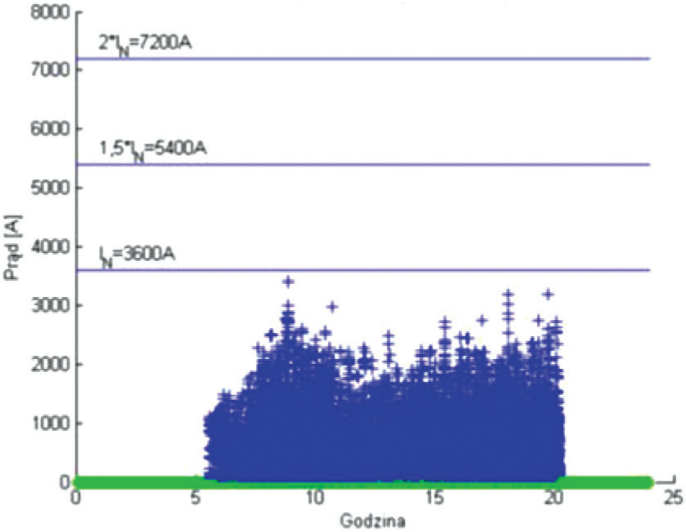

Fig. 5. Diagram presenting comparison of short-currents with rated data of the three rectifier units (own materials)

As shown in the above diagram, the total load placed on the rectifier units over a period of 24 hrs remains below the maximum long-term permissible load (I_N = 3600 A). Calculations revealed that for the presented case, the total time of no load (current of 0 A) was 50.4% of the 24 hr period. For 48.8% of the 24 hr period, the current did not exceed 1200 A. In order to secure such a load, it would be enough to have a single rectifier unit without the need to use its overload capabilities.

Figure 6 presents a diagram of simulated traction loads for rectifier units according to drive timetables valid on a business day.

In this case, the average value of the current over 24 hrs was 291 A, which is 14% higher than the measured value (255 A, Fig. 4). The highest temporary value of the current occurred before 5:00 p.m. and was 3,015 A. This is lower than the measured value (3,400 A, fig. 4) by approx. 11%.

Additionally, for the simulated course of the traction current (Fig. 6) there was checked total time (during 24h) of non-existence of the load (current equal 0 A). The obtained result of 45.7% was slightly lower than the measured data (50.4%). For 51.5% of the 24 hr time period, the current did not exceed 1,200 A. In this case, the value was slightly higher than the measured data (45.8%).

Previous experiences of the authors regarding the analysis of loads on tram traction substations [1, 3] prove that the loads in question may differ from each other on successive days. For the examined substations, it is possible to find days when measured results are close to simulated results, but opposite examples can also be found. The assessment of the nature of traction loads is still open

Continuing the comparison of the course of loads (Figs. 4 & 6), Table 4 shows values of shape and peak coefficients characterising the variability of electric runs [6].

Table 4. Comparison of the shape coefficient and peak coefficient for measured and simulated currents (own materials)

Type of a coefficient	Measurements	Simulation
Shape coefficient k_{kszt}	1.86	1.60
Peak coefficient k_{sz}	7.18	6.46

Both of the coefficients for the measured currents are slightly higher than the simulated currents; in particular, the shape coefficient is higher by approx. 14% and the peak coefficient by approx. 10%. This means that under actual conditions, the runs are more variable than those acquired theoretically.

Figures 7 & 8 present an assessment of the results acquired in a manner not described in the literature (this also apples to Fig. 5). The relationship between traction loads for successive hours and the rated parameters that is the long-term current load of the rectifier units of the examined traction substation is graphically presented.

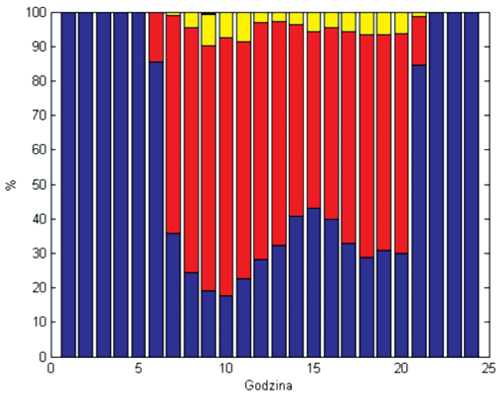

Fig. 7. Diagram of percentage content of currents in ranges for successive hours at bus bars of the examined substation on a business day – results of measurements (own materials)

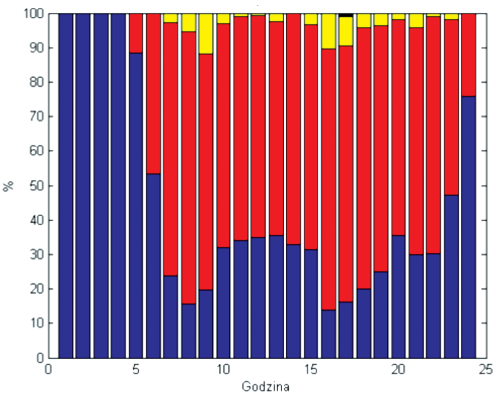

Fig. 8. Diagram of percentage content of currents in ranges for successive hours at bus bars of the examined substation on a business day – results of calculations (own materials)

Blue indicates the percentage time at every hour of the day when the short-term current is 0 A (no tractions load). Red indicates current from 0 A to 1,200 A (range of long-term load of a single rectifier unit). Yellow refers to current from 1,200 A to 2,400 A (it concerns two rectifier units), while black refers to currents exceeding 2,400 A (three rectifier units).

The results presented in the previous two figures can be interpreted in various ways, depending upon requirements. For example, similarities and differences between measured values and computed values can be identified in a measurable way. It is also possible to see the timescale, for example, when rectifier units are not loaded, or for how long a single unit would be sufficient for a substation if only its long-term load was considered (without taking overload risk into account).

The results presented herein can provide the basis for interpreting other results, which can be achieved only by means of simulations; this concerns cases demonstrated below.

4. Concentrated location traction substations

Figure 9 presents the configuration of a contact line power supply which exists in the area of supply of the selected tram traction substation [5, 11].

As can be observed in Fig. 9, this substation is connected with a contact line by means of power supply cables, so-called 'feeders', which are individually named. Particular sections of the contact line supply are electrically separated by sectional isolators. Disconnecting switches visible in the schematic design, shunting the section isolators, at the time of normal use are open. For example, section isolator no. 8502 separates sections of the contact line powered by various neighbouring traction substations.

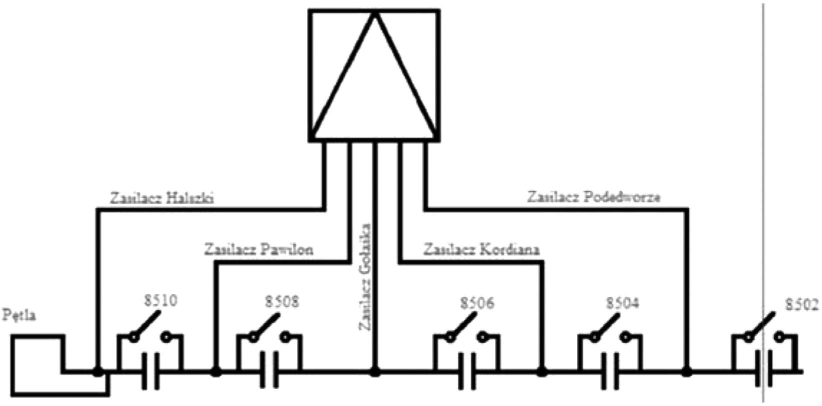

Fig. 9. Schematic design of the contact line power supply for the case under examination [5]

Certain aspects regarding the specifics of load variability of the traction substation's rectifier units supplying the contact line according to the diagram in Fig. 9 have already been demonstrated in this paper.

In Fig. 10, a proposal for the contact line power supply is presented for the same power supply area, but from separate miniaturised substations characterised by a concentrated disposition (layout).

It is noticeable that miniaturised sub-stations, marked as micro-substations in Fig. 10 (μP), are functionally assigned to existing feeders (Fig. 9) supplying energy to *five separate sections* of the contact line. As a result of such a power supply system, neighbouring micro-substations can carry out doubled (double side) energy supply for selected power supply sections by means of disconnecting switches which shunt the sectional isolators.

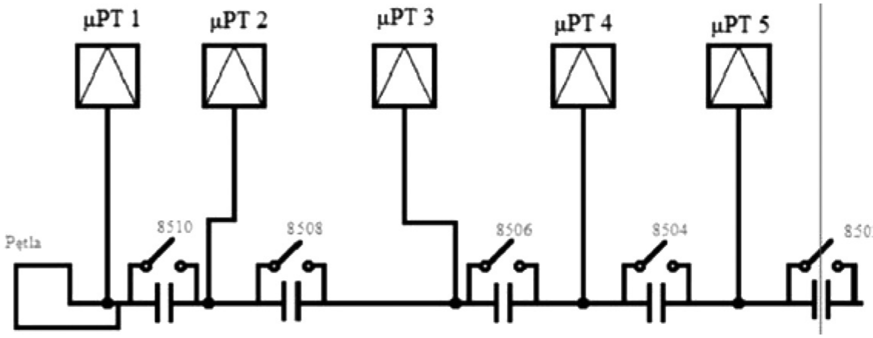

Fig. 10. A scheme design of the contact line power supply in the case of concentrated disposition of miniaturised substations (own materials)

Figure 11 presents a simulated course of the load of micro-substation no. 2, powering the section between sectional isolators nos. 8510 and 8508.

In Fig. 11, it is also marked that the average value of the load current over the 24-hour period was 83 A and the maximum value was 2,247 A. It was also calculated that the total time of no load was 76.8% of the day.

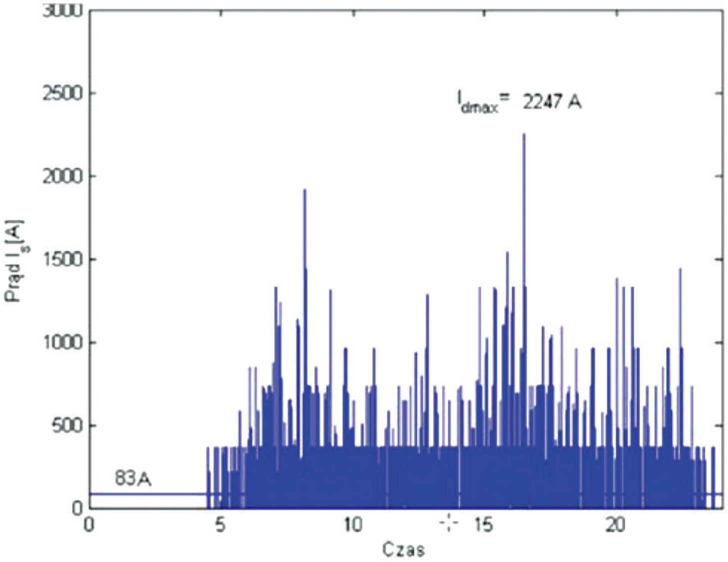

Fig. 11. Diagram of traction currents posing a load for the micro-substation no. 2 (own materials)

Assessment of the above simulated results can be extended on the basis of the previous point, which concerns data acquired by means of measurements and simulations.

Table 5 shows the coefficients of the shape and the peak [6] for the course of traction loads of micro-substations nos. 2 and 3, in the case of individual operation (single supply) and parallel operation (doubled supply), after switching off the sectional disconnecting switch no. 8508 (Fig. 10).

Table 5. Coefficients of the shape and peak of traction load currents for varied systems of contact line power supply from micro-substations nos. 2 and 3 (own materials)

Traction substation	**Shape coefficient k_{kszt}**	**Peak coefficient k_{sz}**
Micro-substation no. 2	2.51	10.48
Micro-substation no. 2 (parallel operation)	2.09	9.72
Micro-substation no. 3	2.44	9.46
Micro-substation no. 3 (parallel operation)	2.05	8.61

On the basis of the values of the coefficients in Table 5, it is clear that in the case of the doubled (two-side) power supply, the variability of traction loads is limited. Additionally, the total no load time concerning micro-substation no. 2 was shortened over the course of 24 hrs by up to 61.9%. One can expect reduced voltage limitation at tram current collectors [14, 16, 13, 18] and other benefits arising from a doubled power supply system.

Calculations were also performed regarding the selection of rectifier units for micro-substation no. 2 with the assumption of there being a doubled power supply that is for parallel operation with micro-substation no. 3.

The presented results concern a variant with a miniaturised rectifier unit. It was decided that the unit in question will be rated 5th overload class as the presently used rectifier unit [9]. However, the constant load current will be three times less that is it equals 400 A [5]. Figure 12 presents a course of simulated load at the background of limits arising from the application of two miniaturised rectifier units at a micro-substation.

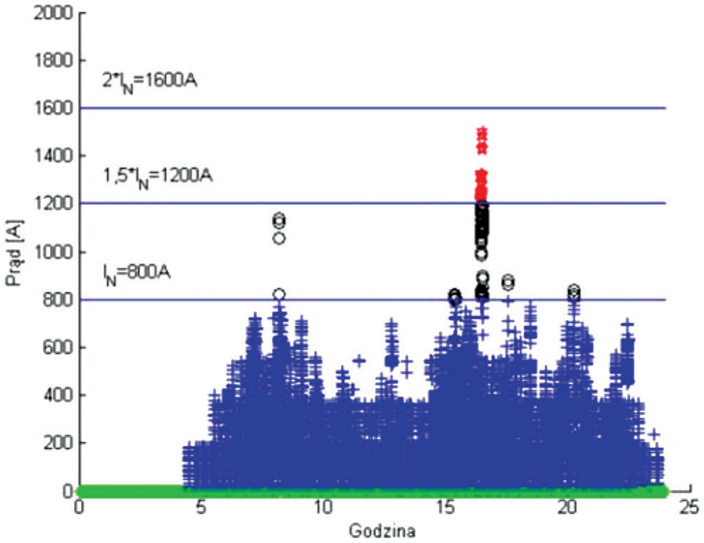

Fig. 12. Graph presenting a comparison of short-term currents and assumed rated data of two miniaturised rectifier units (own materials)

As observed in Fig. 12, the resultant rated parameters of two rectifier units will not be *again,* exceeded in the examined case. Most of the time, short-term currents have values below the rated value ($I_N = 2 \times 400$ A = 800 A).

In five cases, short-term currents stay within the range between the rated current value (800 A), and value of the long-term overload ($1.5 \times I_N = 1200$ A). However, in one case, short-term currents were within a range exceeding the long-term load (1200 A), but they did not exceed the value of the short-term load ($2 \times I_N = 1600$ A).

Comparing the diagrams presented in Figs. 12 & 5, it can be observed (optical value) that the range of use of parameters of micro-substation no. 2 rectifier units is better (more complete) than the currently used traction substation.

In the Faculty of Tractions and Traffic Control at the Technical University in Kraków a prototype model (mock-up) was erected representing a section of the tram control line power supply system. A unique attribute of this mock-up is that it has been designed and erected in order to test phenomena (currents, voltages) occurring in the elements of the power supply system. Existing in Europe (e.g. in Poland: experimental track of the Institute for Railway in Żmigród – Węglewo) testing grounds are designed to test railing stock this. The testing of new ideas for power supply systems is not possible in the field. Figure 13 presents a picture of the erected mock-up from the side of the front plate; the basic functional panels designed to expand the measurement capabilities that can be performed are indicated.

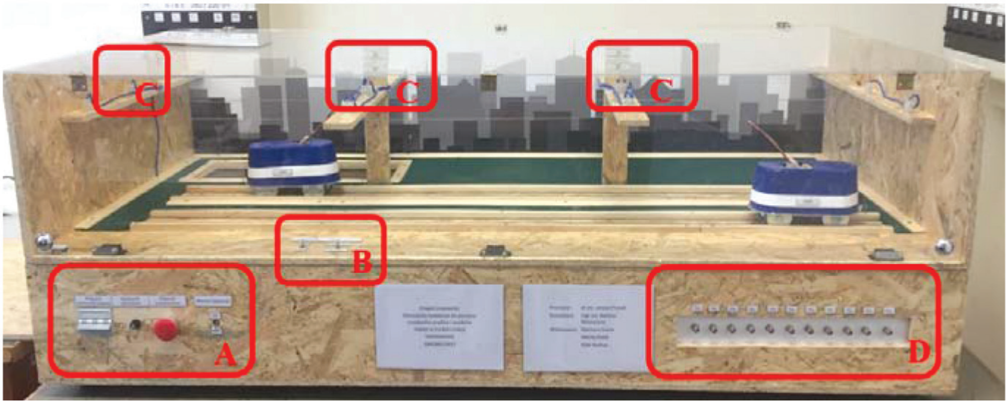

Fig. 13. General view of the mock-up, where: A – panel switching on the stand; B – substation additional resistance control panel; C – line and sectional disconnecting switch; D – measurement lines panel

Either state what or simply delete this with use of the mock-up, certain measurements were made for typical (for a present operation) connections in the DC power supply system. Satisfactory results had been acquired which means results were expected. It can be expected that results for atypical connections that are worthy of examination will also be reliable. The performed measurements enabled us to identify imperfections within the erected model; however, this is the typical situation in the case of prototypes.

The presented idea for the application of traction micro-substations to supply tram contact lines could be a stage of works focused on improvement of the municipal transport electrical power supply system.

5. Summary

The application of simulation methods for determining traction loads based on a theoretical drive brings results which, at the present stage of analyses, can be considered to be sufficiently accurate.

Application of the tram power supply system based on the concentrated disposition (layout) traction substations (so-called micro-stations) requires the erection of rectifier units with parameters suitably adjusted for the new solutions. This remark also concerns remaining technical equipment for these substations this is confusing as I can't work out exactly what point you are trying to make here.

Presented specificity (nature) again, this doesn't work – I'm not sure what you are referring to of short-term traction substations enables, among other things, the identification of time periods with zero load currents.

The presented solution of a supply system based on the traction micro-stations enables the non-complicated application of a doubled, railway type supply, with all the advantages associated with this solution.

Application of the mock-ups reflecting DC electric traction power supply systems (here, for trams), due to observances may promote didactic and training processes as well as R&D goals resulting in modernization of such systems in order to increase, e.g. their efficiency. Obviously, tests, particularly tests of new solutions on properly erected mock-ups do not pose a competition, but they are intended and desired supplementation of results acquired by means of simulation calculations. The most important and valuable results are those acquired from measurements of 1:1 scale objects. The application of mock-ups before tests in real conditions will, in the authors' opinion, reduce the costs of the tests due to the possibility of initial choice of the best parameters solutions

The presented system solutions and results picturing a nature of traction loads may be the inspiration for further solutions for improving the efficiency of tram power supply systems. In the electric power supply systems of municipal and suburban transport, direct voltages are applied, although other types of voltages have been applied in railway transport in many countries. Commencing the modernisation of operations would mean large scale investments; this is unquestionably good news for business environments I'm which want to support this type of transport.

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