MEASUREMENTS OF THE POWER QUALITY FACTORS AT THE COUPLING POINT OF DISTRIBUTION AND TRANSMISSION SYSTEMS

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INTRODUCTION

Electricity market and restructuring of the electric power sector caused that the power quality became an issue of particular importance on every voltage level, including transmission systems. Requirements and provisions related to the electric power quality are incorporated into contracts for electric power delivery from transmission systems. The grounds for contractual provisions are few IEC standards concerning this voltage level, CIGRE recommendations, and provisions of published foreign documents pertinent to the issue. Identification of the power quality in transmission system is urgently needed in order to formulate properly the contracts and asses the suitability of analogical foreign documents for Polish circumstances. For the purpose of this task, the power quality factors in distribution lines delivering electric power from transmission system have been measured at the Power Distribution Company – Cracow (PDC Cracow). The measurements have been carried during seven months, from December 2001 to July 2002, in three measurement points at the point of coupling of the transmission (220 kV) and distribution system (110 kV).

SUPPLY NETWORK CHARACTERISTIC

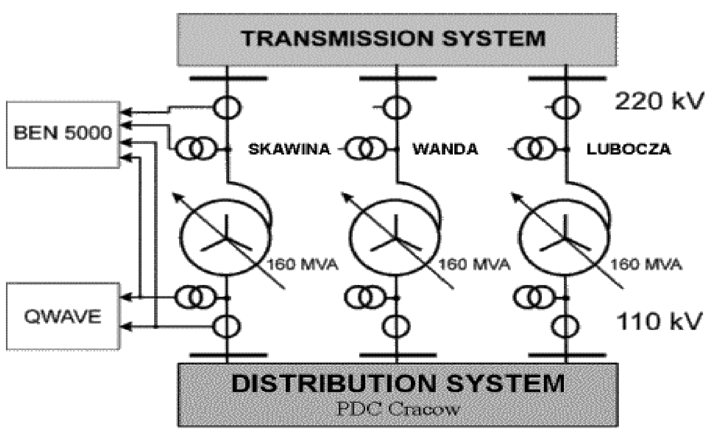


Fig. 1. Block diagram of the PDC Cracow distribution system connections to the transmission system

Main part of the 110 kV distribution system operated by the PDC is a ring-operated network. The power flow does not depend on a single operator, it mainly depends on the distribution of generation between generating units. The whole 110 kV distribution system is operated as a system with solidly grounded neutral. The number of end customers, connected to the distribution system exceeds eight hundred thousand. End customers' contracted power is (a) 389 MW in 110 kV network, (b) 648.8 MW in MV network, (c) 3511.2 MW in LV network.

THE MEASURING SYSTEM

The PDC operated 110 kV distribution system is connected with neighbouring operators' distribution systems and with the 220 kV transmission system by means of three autotransformers, 160 MVA each, installed at three substations (a) LUBOCZA – industrial and household customers (short-circuit capacity S_{SC} = 3571.9 - 3709.1 MVA), (b) WANDA - predominantly industrial customers (S_{SC} = 4349.4 MVA), (c) SKAWINA – near to heat and power generating plant - (S_{SC} = 4148.5 - 4666 MVA). At these points have been installed instruments for the power quality factors measurement. The following quantities have been recorded: frequency, long supply interruptions, voltage variations, voltage fluctuation, voltage distortion, voltage unbalance, voltage dips and short interruptions, and voltage swells. The measuring instruments were provided with modems, which enabled transmission of recorded data via public telecommunications network and their acquisition in the main computer, located at the University of Mining and Metallurgy. The analysis is based on values averaged in 10-minute intervals. For each measuring point and for each event has been determined the value of so-called measurement efficiency coefficient - λ, defined as the ratio of the measurement time, during which the results were obtained, to the total time of measuring instruments connection. Voltage dips, swells and short interruptions are described using their characteristic factors. In time of their duration, other disturbances have not been analysed.

RESULTS OF MEASUREMENTS

Long supply interruptions

The following long interruptions have been recorded at the substations: SKAWINA – one, duration 2 h 39 min; LUBOCZA – two, of duration 4 h and 7 h 27 min respectively and one single-phase interruption of 10 min 5s duration; WANDA – two, of duration 2 h 39 min and 10 h 21min.

Table 1. Frequency

Phase	*f* [Hz]						
	Min.	Avg.	Max.	CP05	CP50	CP95	CP99
WANDA							
L1	49.92	50.00	50.10	49.97	50.00	50.03	50.04
L2	49.93	50.00	50.10	49.97	50.00	50.03	50.04
L3	49.93	50.00	50.10	49.97	50.00	50.03	50.04
LUBOCZA							
L1	49.92	50.00	50.09	49.97	50.00	50.03	50.04
L2	49.93	50.00	50.09	49.97	50.00	50.03	50.04
L3	49.93	50.00	50.13	49.97	50.00	50.03	50.04
SKAWINA							
L1	49.92	50.00	50.25	49.97	50.00	50.03	50.04
L2	49.80	50.00	50.09	49.97	50.00	50.02	50.04
L3	49.92	50.00	50.09	49.97	50.00	50.02	50.04

Frequency

Over the whole measurement time the frequency has been contained within range 50 ±0.1 Hz (Table 1).Over the whole measurement time the frequency has been contained within range The exception was SKAWINA (heat and power generation plant bus-bars), where the frequency increase up to 50.25 Hz was recorded.

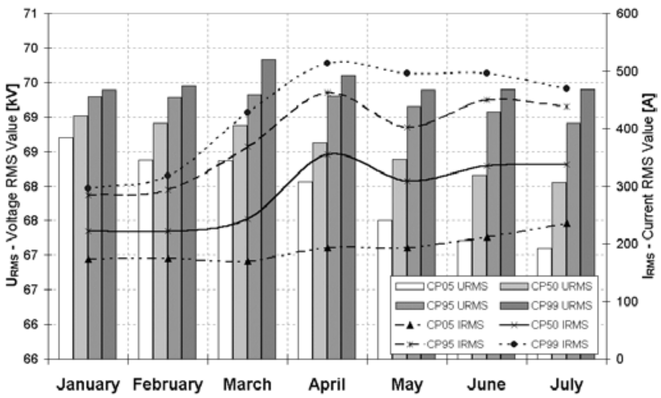
Table 2. The rms values of phase-to-neutral voltages

Phase	Voltage value [kV]							*T* [%] for *U*	
	Min.	Avg	Max.	CP05	CP50	CP95	CP99	<0,9	>1,1
WANDA									
L1	0.21	68.32	70.21	67.45	68.62	69.24	69.53	0.32	0.20
L2	0.19	68.46	70.41	67.58	68.76	69.39	69.69	0.32	0.48
L3	0.18	68.34	70.21	67.44	68.64	69.28	69.55	0.32	0.20
LUBOCZA									
L1	0.18	68.24	70.40	67.48	68.53	69.17	69.45	0.00	0.00
L2	0.19	68.43	70.58	67.66	68.69	69.42	69.72	0.00	0.00
L3	0.17	67.18	69.67	66.09	67.42	68.55	68.88	0.00	0.00
SKAWINA									
L1	0.18	68.66	69.98	67.80	68.78	69.36	69.56	0.07	0.02
L2	0.18	68.80	70.10	67.92	68.92	69.50	69.71	0.07	0.25
L3	0.19	68.41	69.73	67.56	68.54	69.11	69.31	0.07	0.00

Voltage magnitude

Measurement efficiency coefficient λ: WANDA - 0.98; LUBOCZA – 0.91; SKAWINA – 0.96. Table 2 shows the minimum, average and maximum values, and percentiles: CP05, CP50, CP95, CP99 for rms phase-to-neutral voltages. The last two columns give information on the percentage of time (with respect to the total measurement time), during which the voltage value was 10 % less or greater than the nominal voltage value (U_N). At all measurement points has been found a reduction of the rms voltage values in consecutive months of measurement (Fig. 2).

In LUBOCZA and WANDA a strong correlation occurred between the voltage value and current in the monitored line in terms of time: day, week, month (Fig. 4). Correlation level decreases during weekends and holidays. An increase of load during industrial plants operation and evening peak load, mainly from household customers can be noticed in the 24- (Fig. 3). Figure 5 presents an increase in the voltage rms value due to the line step unloading shown against an example, 24-hour voltage change characteristic.



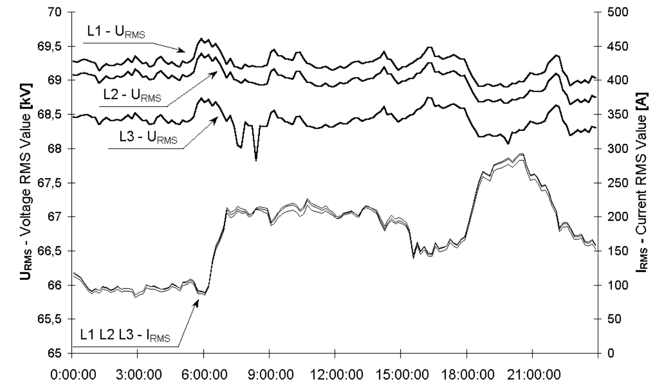
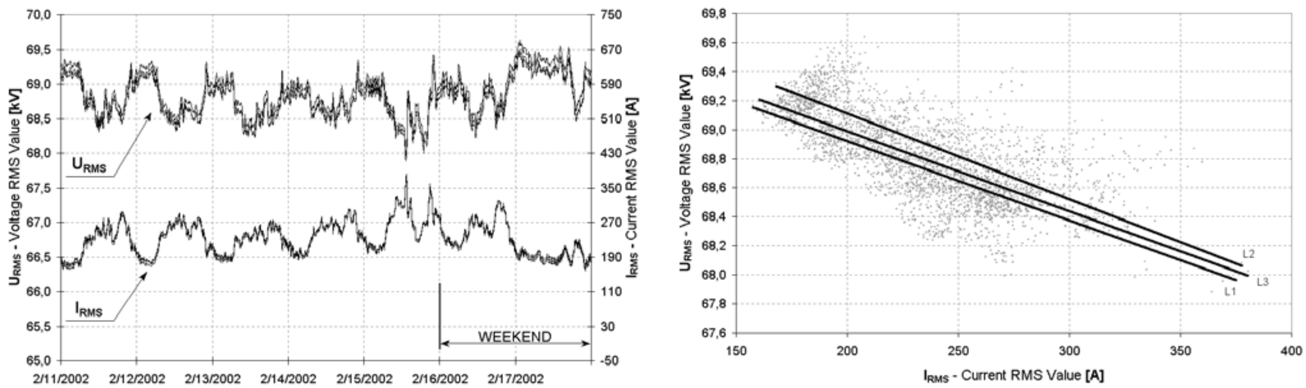


Fig. 2. Changes in the voltage factors in specific months against changes of current (WANDA)

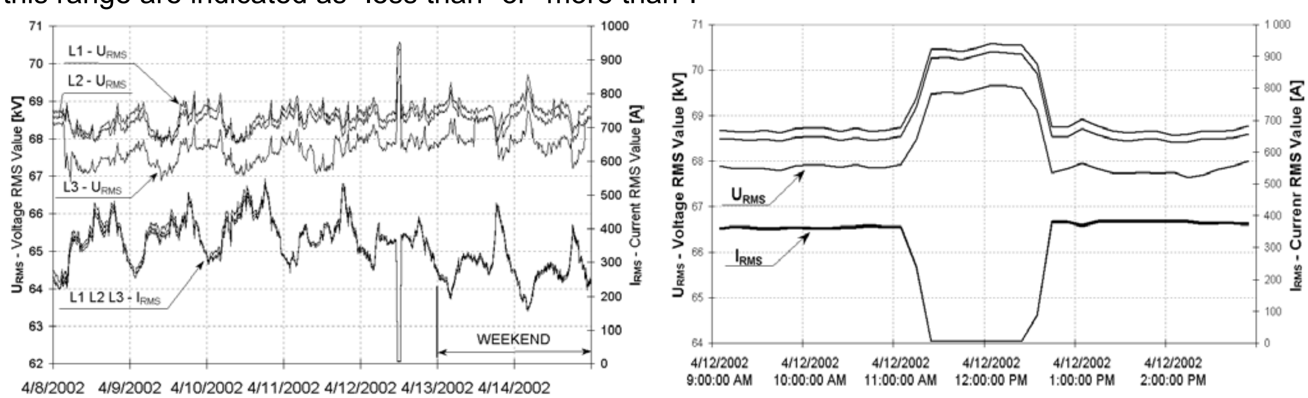
Fig. 3. Example of 24-hour change in phase-to-neutral voltages and currents (LUBOCZA)



(a) (b)

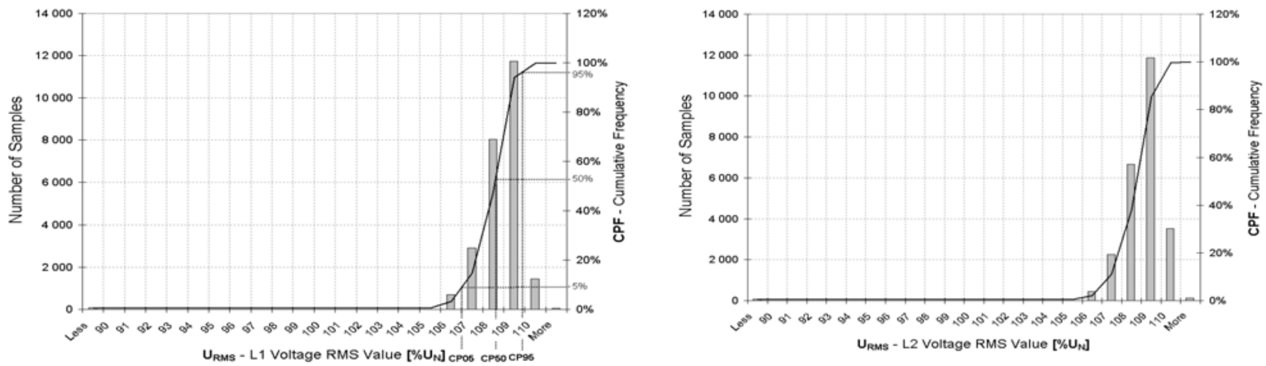
Fig. 4. Changes in the rms value of phase-to-neutral voltages during the example week, and mutual relation of phase-to-neutral voltages and currents (WANDA)

Figure 6 shows an example of CPF characteristics for the voltage rms value. The range of voltage variations is selected to comprise the range from 90 % U_N to 110 % U_N. The samples, which are beyond this range are indicated as "less than" or "more than".



(a) (b)

Fig. 5. Example of week's change in phase-to-neutral voltages and currents (LUBOCZA)



(a) (b)

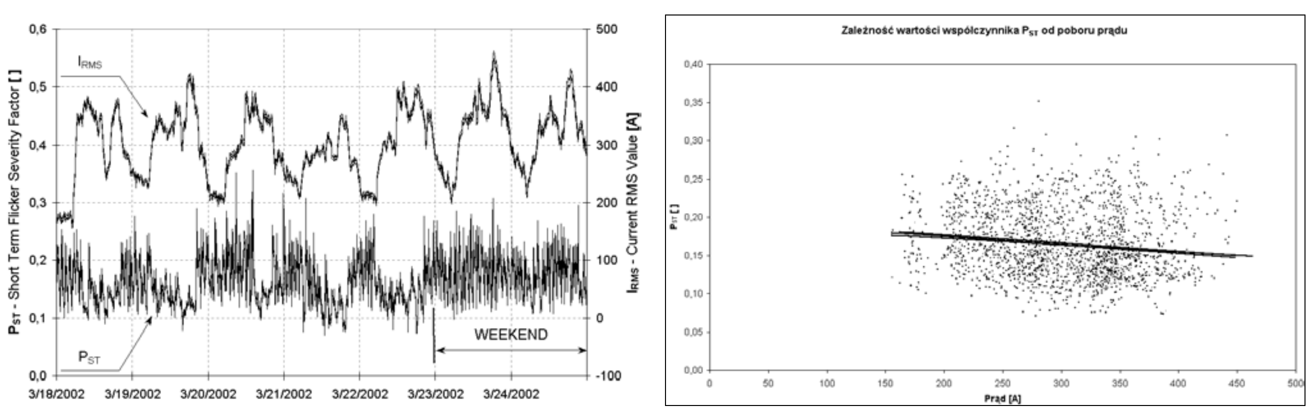
Fig. 6. Example CPF characteristic for phase-to-neutral voltages rms values (WANDA)

Voltage fluctuations

Table 3. Short term flicker severity P_{st}

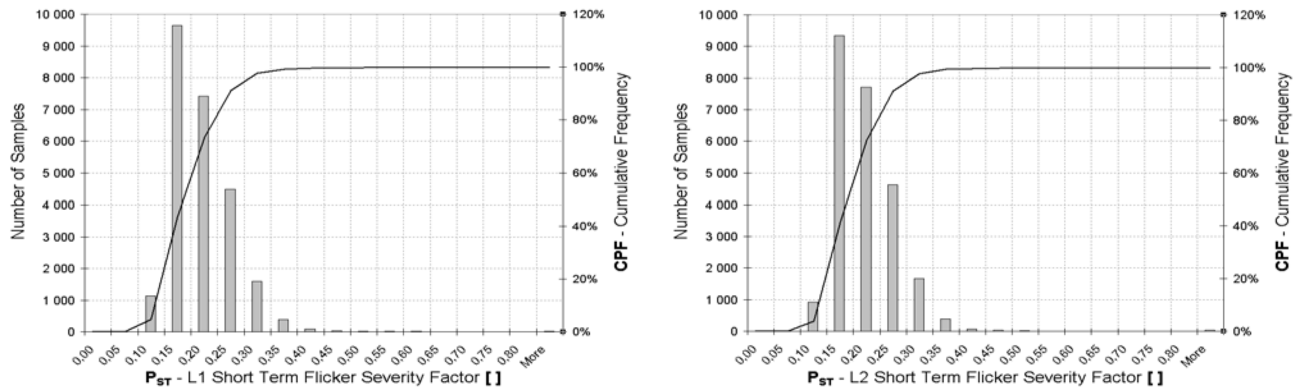
Phase	P_{st}							T [%]
	Min.	Avg.	Max.	CP05	CP50	CP95	CP99	> 0,8
WANDA								
L1	0.00	0.17	2.99	0.10	0.16	0.27	0.34	0.09
L2	0.00	0.17	3.18	0.10	0.16	0.27	0.34	0.15
L3	0.00	0.17	2.88	0.10	0.16	0.27	0.34	0.10
LUBOCZA								
L1	0.00	0.28	6.95	0.18	0.27	0.39	0.47	0.10
L2	0.00	0.27	51.64	0.17	0.26	0.36	0.45	0.15
L3	0.00	0.32	55.85	0.17	0.26	0.62	1.10	2.01
SKAWINA								
L1	0.00	0.18	3.22	0.10	0.18	0.28	0.34	0.12
L2	0.00	0.18	3.39	0.10	0.18	0.27	0.33	0.14
L3	0.00	0.18	2.68	0.10	0.18	0.27	0.34	0.26

Short term flicker severity P_{st} **-** Measurement efficiency coefficient λ: WANDA – 0.98; LUBOCZA – 0.91; SKAWINA – 0.96. Table 3 shows the minimum, average and maximum values, and percentiles: CP05, CP50, CP95, CP99 for the short term flicker severity P_{st}.The last column gives information on the percentage of time during which the P_{st} values exceed level 0.8. Figure 7 shows an example short term flicker severity P_{st} characteristic and its dependence on the current changes. At each substation the correlation of these two quantities is weak. Figure 8 presents example CPF characteristic over whole set of measured values for the short term flicker severity P_{st}. The samples, which value is greater than 0.8 are indicated as "more than". At all measurement points an increase of the voltage fluctuations has been found in consecutive months of measurement (Fig. 9).



(a) (b)

Fig. 7. Changes in the short term flicker severity P_{st} of phase voltages during the example week(WANDA)



(a) (b)

Fig. 8. Example CPF characteristic of the short term flicker severity P_{st} (WANDA)

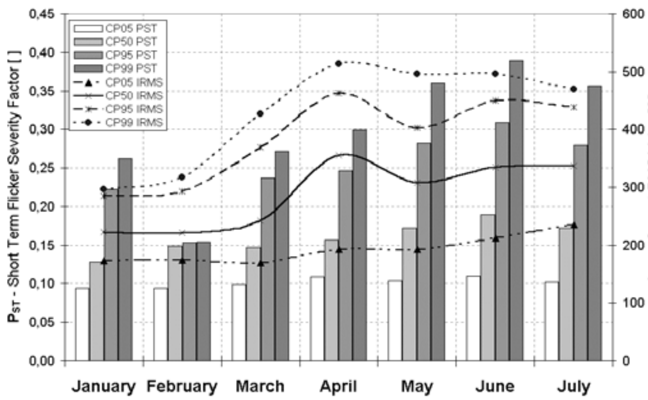


Fig. 9. Changes in the short term flicker severity P_{st} in specific months against changes of current (WANDA)

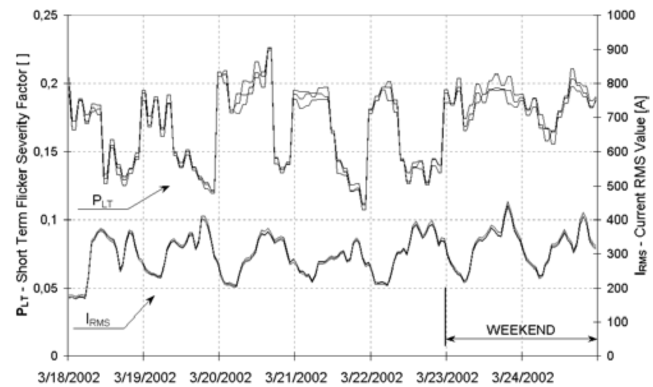
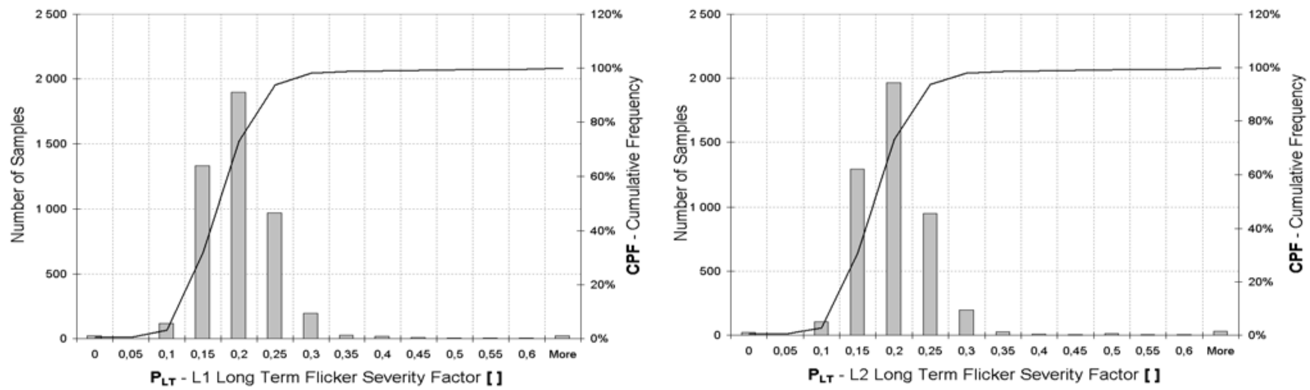


Fig. 10. An example characteristic of week's change in the long term flicker severity P_{lt} (WANDA)

Table 4. Long term flicker severity P_{lt}

Phase	P_{lt} Min.	Avg.	Max.	CP05	CP50	CP95	CP99	T [%] > 0,6
WANDA								
L1	0.00	0.18	1.37	0.11	0.17	0.26	0.37	0.43
L2	0.00	0.18	1.27	0.11	0.17	0.26	0.46	0.65
L3	0.00	0.18	1.26	0.11	0.17	0.26	0.40	0.52
LUBOCZA								
L1	0.00	0.29	2.19	0.20	0.28	0.39	0.55	0.50
L2	0.00	0.27	2.27	0.18	0.26	0.35	0.53	0.79
L3	0.00	0.34	5.46	0.18	0.28	0.70	1.24	7.82
SKAWINA								
L1	0.00	0.20	1.41	0.12	0.19	0.25	0.41	0.58
L2	0.00	0.20	2.07	0.12	0.19	0.25	0.50	0.82
L3	0.00	0.20	2.04	0.13	0.19	0.26	0.61	1.04

***Long term flicker severity P_{lt}* -** The measurement efficiency coefficient λ: WANDA – 0.96; LUBOCZA – 0.94; SKAWINA – 0.93. An example characteristic of week's change in the long term flicker severity P_{lt} is shown in Fig. 10. Table 4 presents the minimum, average and maximum values, and percentiles: CP05, CP50, CP95, CP99 for the long term flicker severity P_{lt}. The last column gives information on the percentage of time (with respect to the total measurement time), during which the long term flicker severity P_{lt} value exceeds level 0.6. Figure 11 shows example CPF characteristic over the whole set of measured values for the long term flicker severity P_{lt}. The samples, which value is greater than 0.6 are indicated as "more than". A tendency toward increase in the voltage fluctuations, in consecutive months of measurement, has been found at all measurement points.



(a) (b)

Fig. 11. Example CPF characteristic of P_{lt} (WANDA)

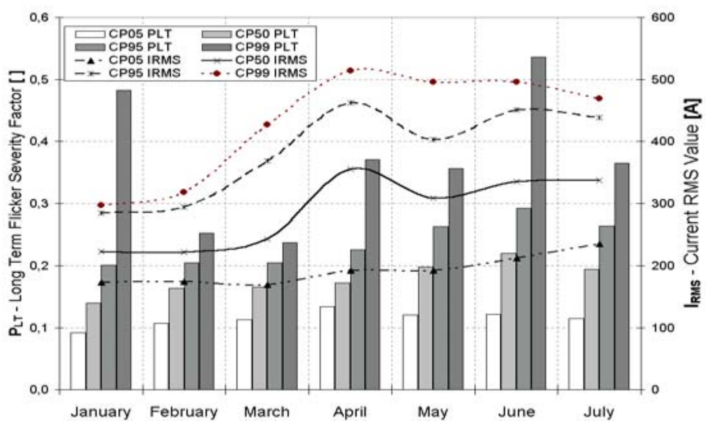


Fig. 12. Changes in the voltage factors in specific months against changes of current (WANDA)

A tendency toward increase in the voltage fluctuations (P_{lt}) has been found at the WANDA substation in consecutive months of measurement (Fig. 12). At the SKAWINA substation the voltage fluctuation level is constant.

VOLTAGE DISTORTION

Measurement efficiency coefficient λ: WANDA – 0.92; LUBOCZA – 0.86; GPZ SKAWINA – 0.91.

Total harmonic distortion THD - A typical change in the THD during workday and holiday 24 hours is shown in figure 13. During most of time, these values are correlated with the current changes. An increase in the voltage distortion factor due to the greater share of household loads (TV sets) during the first World Cup match of Polish team in Korea, and reduction of the total load at the same time, is visible in figure 14. Changes of the THD factor are regular in specific days of week. Over the week the THD factor achieves its maximum value at the final phase of weekend (Fig. 15).

Table 5 shows the minimum, average and maximum values, and percentiles of the voltage THD with respect to the voltage nominal value. The last column gives a percentage of time during which the THD value exceeded 2.5 %.

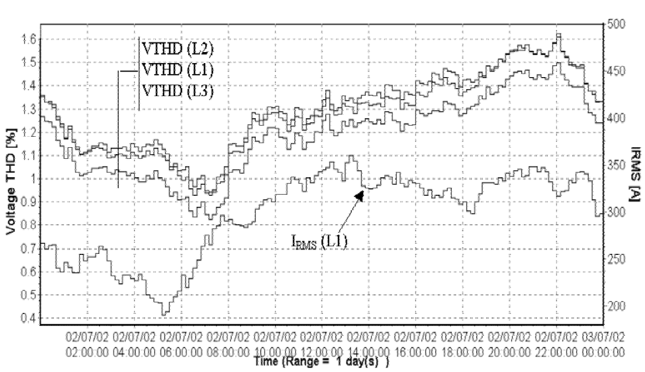


Fig. 13. Change in the phase-to-neutral voltages distortion factor during the example workday 24 hours (WANDA)

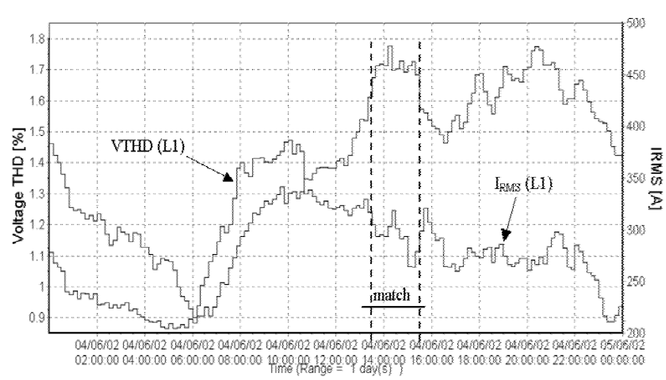


Fig. 14. Football match Poland vs. South Korea, the phase-to-neutral voltage and phase current THD (WANDA)

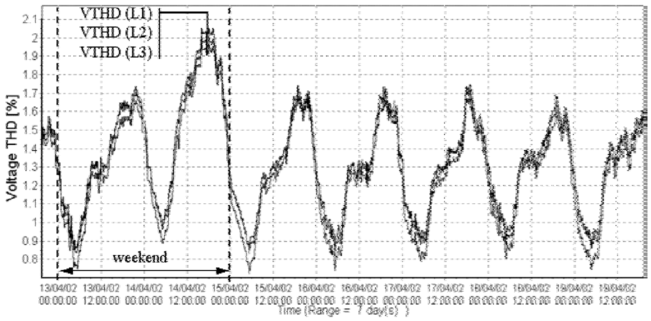
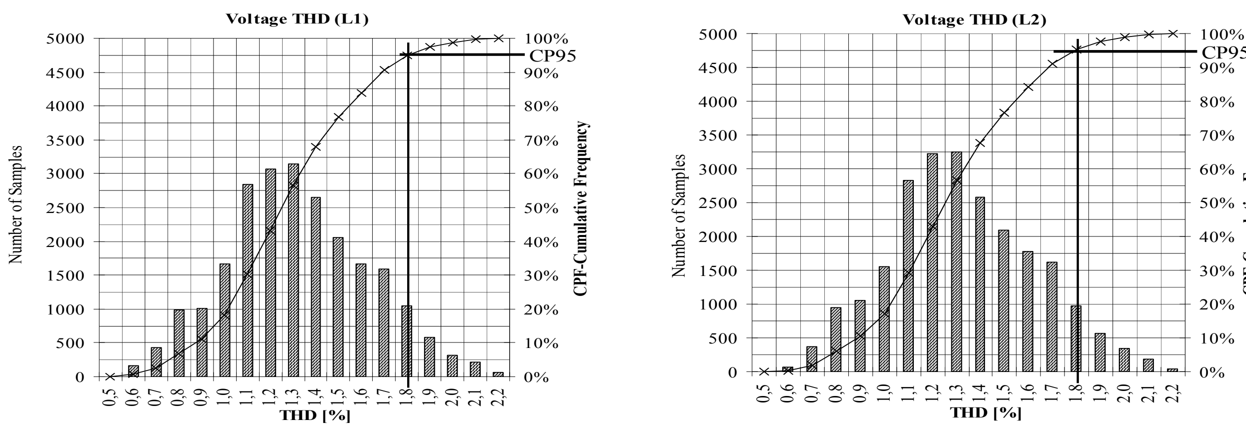


Fig. 15. Week's variation of the phase-to-neutral voltage THD (WANDA)

Table 5. Voltage distortion factor THD

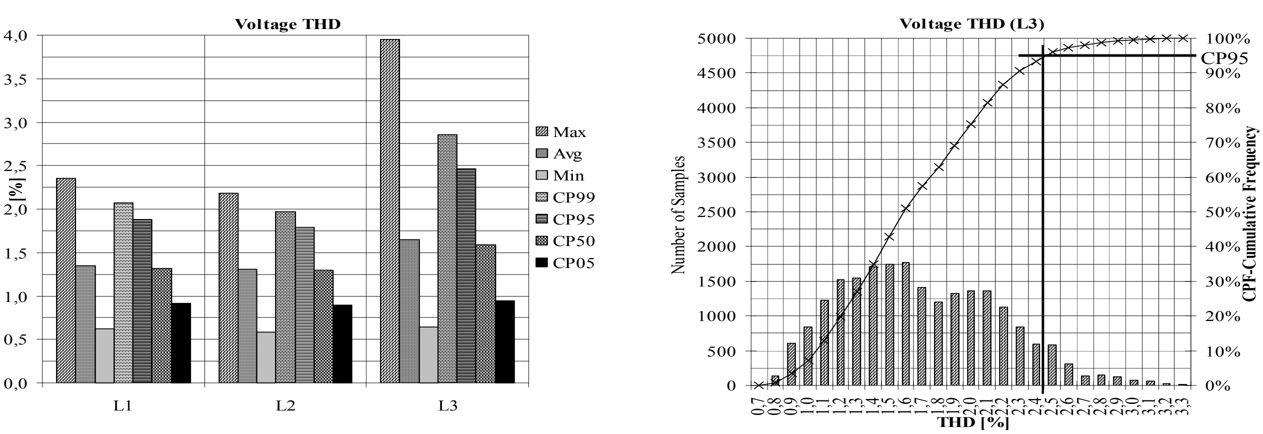
Phase	THD [%]							*T* [%]
	Min.	Avg.	Max.	CP05	CP50	CP95	CP99	>2,5 %
WANDA								
L1	0.20	1.27	2.19	0.76	1.25	1.80	2.02	0
L2	0.19	1.27	2.22	0.78	1.25	1.79	2.00	0
L3	0.19	1.20	2.11	0.70	1.18	1.72	1.92	0
LUBOCZA								
L1	0.63	1.34	2.35	0.91	1.31	1.87	2.07	0
L2	0.58	1.31	2.18	0.89	1.29	1.79	1.97	0
L3	0.64	1.64	3.95	0.94	1.59	2.46	2.85	3.46
SKAWINA								
L1	0.03	1.26	2.18	0.77	1.25	1.77	1.99	0
L2	0.03	1.22	2.19	0.74	1.21	1.72	1.95	0
L3	0.03	1.10	2.46	0.66	1.09	1.57	1.76	0

Example CPF characteristics of the voltage THD factor are shown in Fig. 17. Phase L3 at the LUBOCZA exhibits particularly strong distortion, clearly visible in Figures 18.



(a) (b)

Fig. 17. CPF characteristics of the phase-to-neutral voltages distortion factor (WANDA)



(a) (b)

Fig. 18. Histogram of the voltage THD values and CPF characteristic for phase L3 (LUBOCZA)

At WANDA and SKAWINA the THD factor value reached its maximum in July (Fig. 19), at LUBOCZA in April.

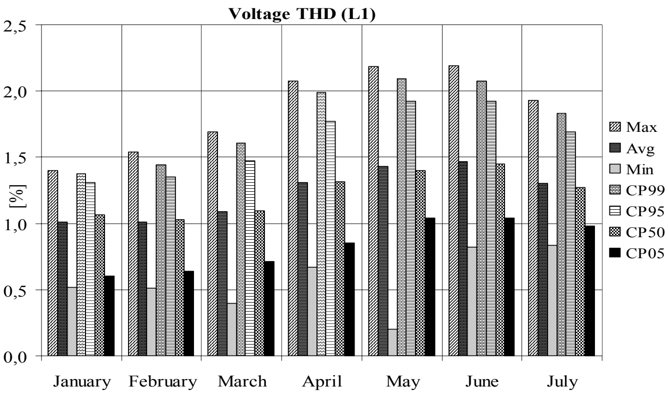
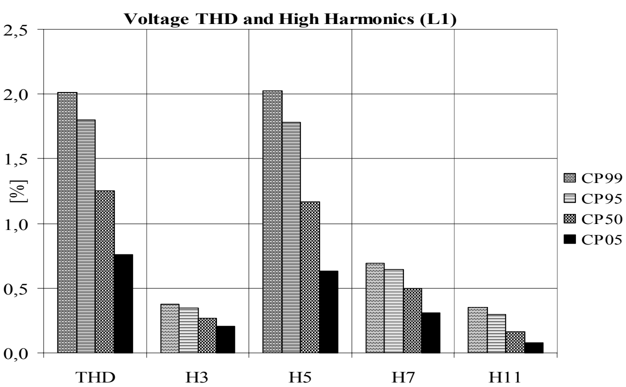
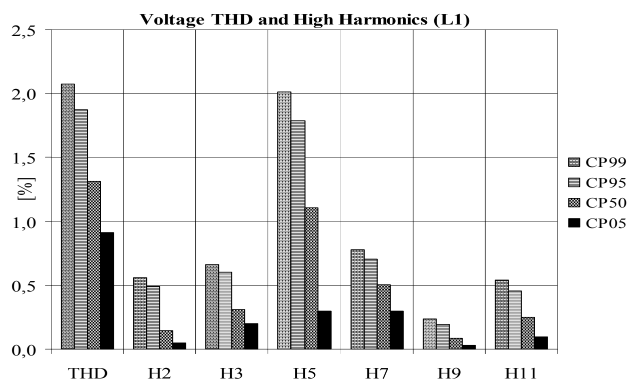


Fig. 19. Variation of the voltage distortion factors in consecutive months of measurement (WANDA), analogically for other phase voltages

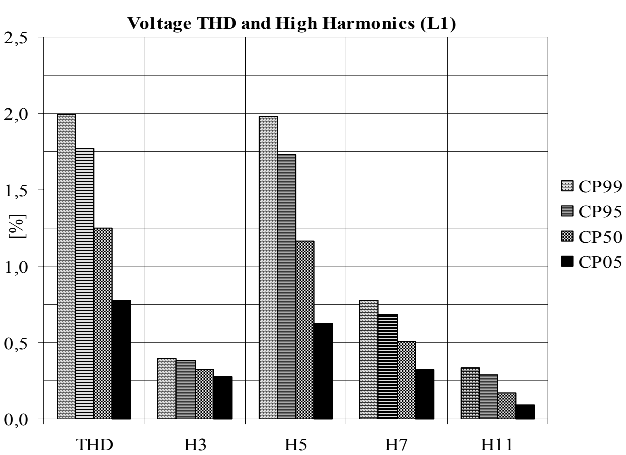
Voltage harmonics - Measurement efficiency coefficient λ: WANDA – 0.98; LUBOCZA – 0.91; SKAWINA – 0.96. At WANDA and SKAWINA harmonics of orders 3, 5, 7 and 11 were predominant, at LUBOCZA additionally the second harmonic (Figs. 20).



(a)



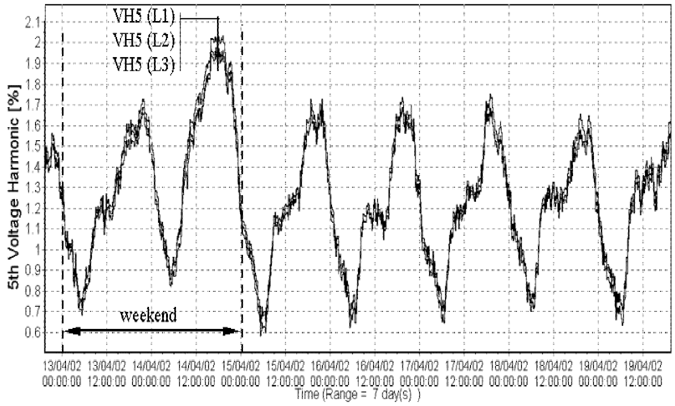
(b)



(c)

Fig. 20. Prevalent voltage harmonics at WANDA (a), LUBOCZ (b), SKAWINA (c), analogically for other phase-to-neutral voltages

The 5th harmonic is of the greatest value, like the 7th and 11th harmonics it is strongly correlated to changes in the load current of the monitored line. In 24-hour characteristic these harmonics reach their maximum during final part of weekend. An example week's characteristic of the 5th harmonic is shown in Fig. 21. Similarly to the THD factor, it reaches its maximum values during May and July for WANDA (Fig. 22) and SKAWINA and in April for LUBOCZA.



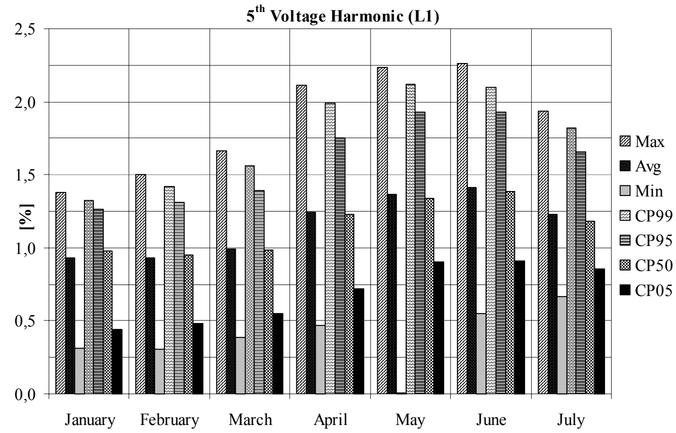


Fig. 21. Example of a week's change in relative value of the phase-to-neutral voltage 5th harmonic

Fig. 22. Example change in the 5th harmonic factors in specific months of measurement (WANDA); analogically for other phase-to-neutral voltages and other substations

Voltage unbalance - Measurement efficiency coefficient λ: WANDA – 0.97; LUBOCZA – 0.91; SKAWINA – 0.96. An example week's characteristic of the unbalance factor (the ratio of the voltage negative to the positive sequence symmetrical component) is shown in Fig. 23. Its value was noticeably greater during weekend. Particularly high level of the unbalance occurs during the evening load peak – 20:00-23:00.

Table 6. Voltage unbalance factor

Unbalance factor k_a [%]							*T* [%]
Min.	Avg.	Max.	CP05	CP50	CP95	CP99	>1,0 %
WANDA							
0.08	0.18	0.27	0.3	0.17	0.23	0.24	0.0
LUBOCZA							
0.07	1.57	4.86	0.38	1.54	2.86	3.17	64.2
0.08	1.57	4.06	0.42	1.55	2.84	3.16	71.9
SKAWINA							
0.12	0.38	2.35	0.18	0.39	0.60	0.71	0.10

Table 6 shows the minimum, average and maximum values, and percentiles of the voltage unbalance factor. The last column gives a percentage of measurement time, during which the unbalance factor value was greater than 1.0 %.

It can be assumed that due to the large number of events (voltage dips, swells, supply interruptions) on phase L3 LUBOCZA the value of unbalance factor is overestimated. The table 6 also gives the unbalance factor values for the substation LUBOCZA, for 1-hour averaging time.

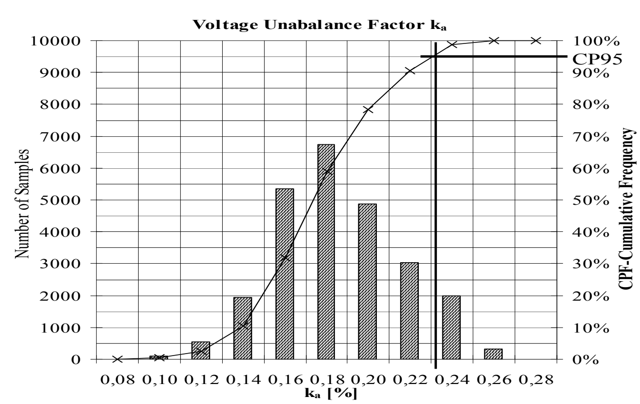


Fig. 23. Typical change of the k_a factor during the example week (WANDA)

Fig. 24. CPF characteristics of the unbalance factor (WANDA)

Figure 26 shows CPF characteristic of the voltage unbalance factor over the whole measurement period. It can be assumed that due to the large number of events (voltage dips, swells, supply interruptions) on phase L3 LUBOCZA the value of unbalance factor is overestimated.

Table 7. Change in the voltage unbalance factors in specific months of the measurement (WANDA)

Phase	Month	k_a [%]						
		min.	avg.	max.	CP05	CP50	CP95	CP99
L1.L2.L3	January	0.12	0.16	0.20	0.14	0.16	0.19	0.20
	February	0.11	0.16	0.24	0.13	0.16	0.20	0.21
	March	0.11	0.17	0.23	0.13	0.17	0.21	0.22
	April	0.08	0.15	0.22	0.11	0.15	0.20	0.21
	May	0.11	0.20	0.27	0.16	0.20	0.24	0.25
	June	0.10	0.19	0.26	0.14	0.19	0.24	0.25
	July	0.11	0.19	0.26	0.15	0.18	0.24	0.25

Table 7 shows change in the unbalance factor value in specific months of the measurement. Similar trend can be seen for GPZ LUBOCZA and SKAWINA.

Voltage swells - Tables 8 and 9 give a summary of recorded voltage swells.

Table 8. Voltage swells at WANDA

Swells	10ms<=t<100ms	100ms<=t<500ms	500ms<=t<1s	1s<=t<3s	3s<=t<20s	20s<=t<1min
110%<x<=120%	0/0/0	0/0/0	0/0/0	2/1/2	0/3/0	2/2/2
120%<x<=140%	0/0/0	0/0/0	0/0/0	0/0/0	2/0/2	0/0/0
140%<x<=160%	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
160%<x<=200%	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
x>200%	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
Number of recorded swells:18						

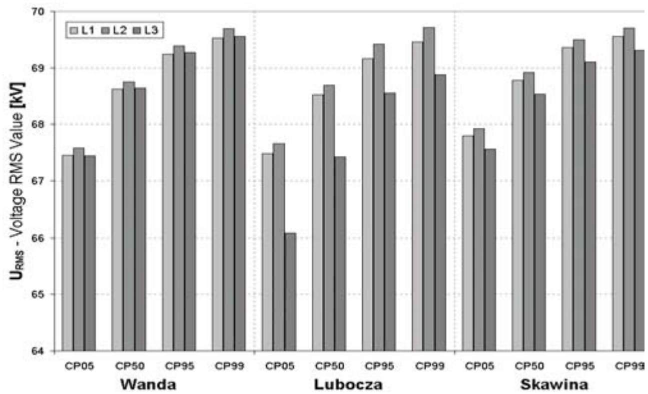
Table 9. Voltage swells at SKAWINA

Swells	10ms<=t<100ms	100ms<=t<500ms	500ms<=t<1s	1s<=t<3s	3s<=t<20s	20s<=t<1min
110%<x<=120%	0/0/0	0/0/0	0/0/0	0/1/0	0/1/0	3/3/2
120%<x<=140%	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
140%<x<=160%	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
160%<x<=200%	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
x>200%	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
Number of recorded swells: 10						

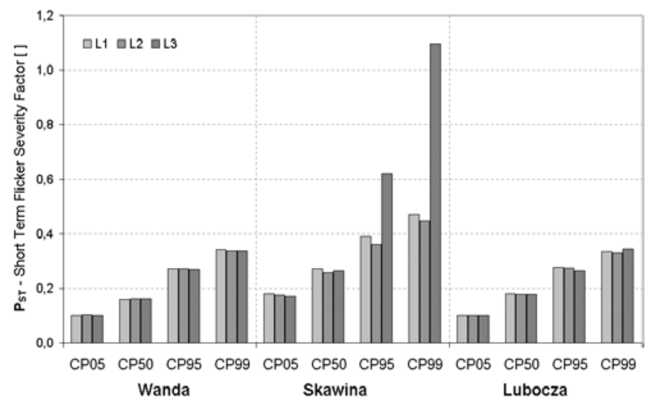
Only two voltage swells were recorded at LUBOCZA: 1 s 55 ms (113 % U_N) and 2 s 177 ms (113 % U_N).

Summary

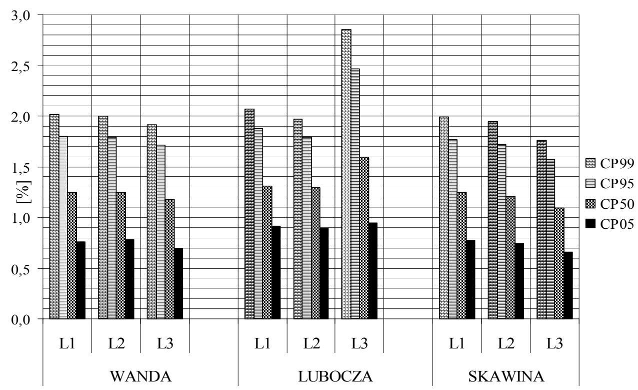
Figures 25 show comprehensive results of the measurement for all substations: U_{RMS}, P_{st}; P_{lt} THD; unbalance factor. For each disturbance, the substation LUBOCZA, supplying large, steelworks loads, seems to be the most unfavourable case.



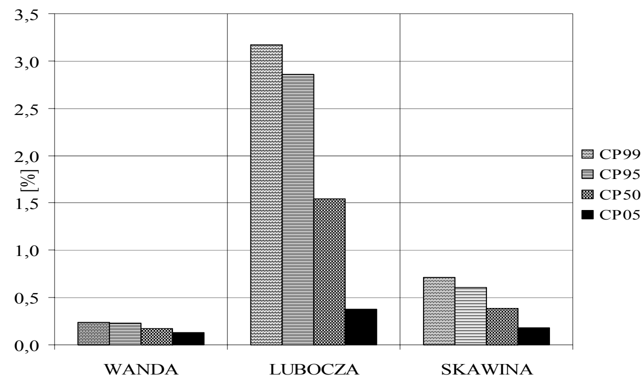
(a) voltage rms



(b) short term flicker severity P_{st}



(c) THD factor



(d) of unbalance factor

Fig. 25. The comparative charts

References

[1] QWave, User Manual
[2] BEN 5000, User Manual

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