VOLTAGE DIPS AND SHORT SUPPLY INTERRUPTIONS IN CONTRACTS FOR THE ELECTRIC POWER SUPPLY FROM HIGH VOLTAGE TRANSMISSION SYSTEMS

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Introduction

Identification of the power quality in transmission system is urgently needed in order to formulate properly the contracts and asses suitability of the existing documents. 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). The effect of these measurements is the database which contains, among others, the recorded voltage dips. Using these data the following effects have been investigated: selection of various factors which describe the voltage dip, selection of the dip threshold voltage to which the measuring thresholds are referred, selection of threshold values defining the disturbance; methods for aggregation the measurement results.

Supply network characteristic

Main part of the 110 kV distribution system operated by the PDC is a ring-operated network. 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.

The measuring system

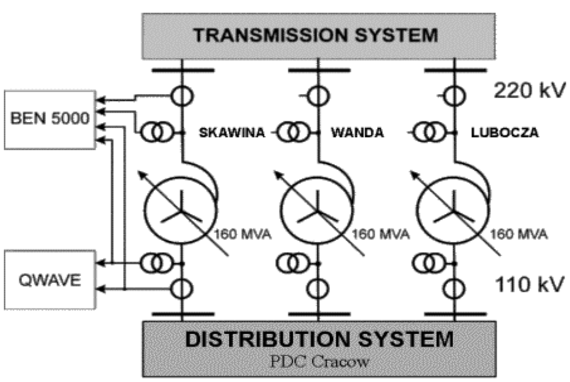

Fig. 1. Block diagram of the PDC Cracow distribution system connections to the transmission system

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, (b) WANDA - predominantly industrial customers, (c) SKAWINA – near to heat and power generating plant - Fig. 1. At these points have been installed instruments for the power quality factors measurement. 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.

Voltage dips and short supply interruptions

Tables 1-11 give a summary of recorded voltage dips and short supply interruptions. Most of the disturbances occur within short time interval.
Analysis shows that use of phase and time (1 min) aggregation significantly reduces the number of disturbances. This does not concern the LUBOCZA, where particularly large number of disturbances occurred in a single phase (L3).

Table 1. Voltage dips without aggregation (WANDA)

Dips [%]	10 - 100ms	100 - 500ms	500 m s- 1s	1 - 3s	3 - 20s	20 - 1min
10- 15	1/3/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
15 - 30	1/0/4	2/3/3	1/1/1	0/0/0	0/0/0	0/0/0
30 - 60	0/1/3	0/0/1	0/0/1	0/0/0	0/0/0	0/0/0
60 - 90	1/1/1	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
90 - 100	1/2/3	0/0/0	0/0/0	0/0/2	2/1/3	0/1/0
Number of recorded voltage dips: 44						

Table 2. 1-minute aggregation (WANDA)

Dips [%]	10 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20s - 1min
10 - 15	4	0	0	0	0	0
15 - 30	2	2	2	2	0	0
30 - 60	1	0	0	1	0	1
60 - 90	1	0	0	0	0	0
90 - 100	0	1	0	0	4	4
Number of recorded events: 25						

Table 3. 3-minute aggregation (WANDA)

Dips [%]	10 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20s - 1min
10 - 15	4	0	0	0	0	0
15 - 30	2	2	2	2	0	0
30 - 60	1	0	0	1	0	1
60 - 90	0	0	0	0	0	0
90 - 100	0	0	0	0	3	4
Number of recorded events: 23						

Table 4. Phase aggregation (WANDA)

Dips [%]	10 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20s - 1min
10 - 15	3	0	0	0	0	0
15 - 30	5	5	1	0	0	0
30 - 60	4	1	1	0	0	0
60 - 90	3	0	0	0	0	0
90 - 100	6	0	0	2	6	1
Number of recorded events: 38						

Table 5. Voltage dips without aggregation (SKAWINA)

Dips [%]	10 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20s – 1min
10 - 15	2/3/2	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
15 - 30	1/1/0	2/4/2	0/1/1	0/0/0	0/0/0	0/0/0
30 - 60	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
60 - 90	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
90 - 100	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
Number of recorded events: 19						

Table 6. 1- and 3-minute aggregation (SKAWINA)

Dips [%]	10 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20s - 1min
10 - 15	3	0	0	2	0	0
15 - 30	2	6	0	2	0	0
30 - 60	0	0	0	0	0	0
60 - 90	0	0	0	0	0	0
91 - 100	0	0	0	0	0	0
Number of recorded events:15						

Table 7. Phase aggregation (SKAWINA)

Dips [%]	10 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20s – 1min
10 - 15	5	0	0	0	0	0
15 - 30	3	4	1	0	0	0
30 - 60	0	0	0	0	0	0
60 - 90	0	0	0	0	0	0
91 - 100	0	0	0	0	0	0
Total of recorded events:13						

Table 8. Voltage dips without aggregation (LUBOCZA)

Dips [%]	10 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20s – 1min
10 - 15	0/0/3	2/2/4	0/0/0	0/0/0	0/0/0	0/0/0
15 - 30	1/0/11	3/2/0	0/0/0	0/0/0	0/0/0	0/0/0
30 - 60	0/1/2	0/1/2	0/0/0	0/0/0	0/0/0	0/0/0
60 - 90	1/0/4	0/0/7	0/0/1	0/0/7	0/0/11	0/0/5
90 - 100	1/0/1	0/0/0	0/0/0	0/0/0	0/1/0	0/0/0
Number of recorded events: 74						

Table 9. 1-minute aggregation (LUBOCZA)

Dips [%]	10 – 100ms	100 – 500ms	500ms- 1s	1 – 3s	3 – 20s	20s- 1min
10 – 15	1	3	0	1	2	0
15 –30	9	1	0	1	0	0
30 – 60	3	1	2	0	0	0
60 – 90	1	5	1	1	6	5
90 – 100	1	1	0	0	1	0
Number of recorded events: 46						

Table 10. 3-minute aggregation (LUBOCZA)

Dips [%]	10 - 100ms	100 - 500ms	500ms- 1s	1 - 3s	3 - 20s	20s - 1min
10 - 15	0	2	0	1	2	0
15 - 30	9	1	0	2	0	0
30 - 60	3	1	2	0	0	0
60 - 90	0	6	1	1	4	2
90 - 100	1	1	0	0	1	0
Number of recorded events: 44						

Table 11. Phase aggregation (LUBOCZA)

Dips [%]	10 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20s- 1min
10 - 15	3	6	0	0	0	0
15 - 30	12	5	0	0	0	0
30 - 60	3	3	0	0	0	0
60 - 90	5	7	1	7	11	5
90 - 100	2	0	0	0	1	0
Number of recorded events: 71						

Table 12. Number of dips depending on the selected threshold value (U_N = 110kV).

Dips	90%	80%	70%	60%
SKAWINA	19	6	6	6
WANDA	44	35	24	21
LUBOCZA	74	59	45	42

Dependence of the number of dips on the selected threshold value, which defines the disturbance is presented in table 12 and in Figure 2. For each location can be seen the reduction of the number of disturbances with an increase in the threshold voltage.

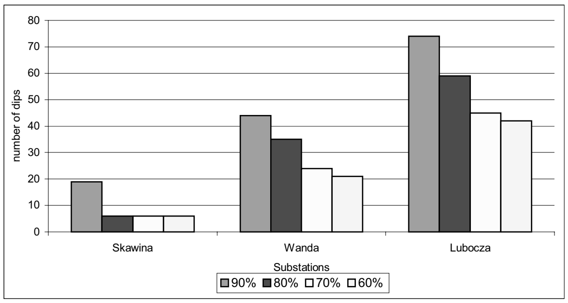

Fig. 2. Dependence of the number of dips on the selected threshold value, which defines the disturbance

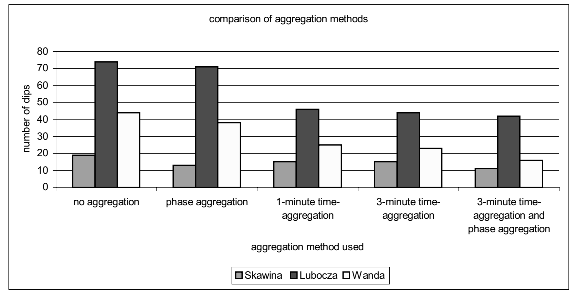

Fig. 3. Dependence of the number of dips on the selected method of aggregation

Figure 3 shows comprehensive comparison of the effect of various types of aggregation on the number of voltage dips for given measurement points.

Aggregated indices for voltage dips

Formulation of aggregated numerical indices for voltage dips is a compromise between the simplicity of calculation, mathematical correctness and representation of the physical complexity of the phenomenon. Regardless, which index will be chosen, it will not reconstruct the whole nature of the disturbance. The indices can only depict an averages situation; information on individual properties of the phenomenon is often lost. Some examples of the proposed methods for description of the disturbance are given below.

Example 1 [3]

The concept of the so-called *qualifying sag* is defined in the contract. This voltage dip occurs when the r.m.s. value of any of the three phase voltages is lower than 75 % of the nominal voltage. Minimal duration of the voltage dip is not defined. The contract provisions include all cases of disturbances conforming the defined class of values, except the voltage dips associated with the system automatic protection and voltage dips occurring in unloaded lines, which cause no effects. The “deepest” voltage dip occurring in 15 min time-interval is regarded as the qualifying. The time of observation starts at the instant of the first dip occurrence and ends at the instant of the end of the last one, or after 15 minutes. The voltage dips, which occur after this time are regarded as belonging to the next observation period. If the residual voltage in one of the three phase voltages: U_A, U_B, U_C is below 75 % of the nominal voltage then, for the purpose of the contract, the so-called *sag score* = $1-(U_A+U_B+U_C)/3$ is determined. It is equal to the average voltage dip in three phases. When in one or two phases a voltage swell occurs instead of the voltage dip then, calculating the *sag score* for these voltages, the value 1 is taken. Also the concept of the so-called *sag score targets* has been introduced. They are determined for a customer, who has several points of recording the voltage dips. The *sag score target* is the sum of *sag score* for all points, and is compared with the value set forth in the contract. Mutual financial commitments are determined at the end of each year, if the *sag score target* of a customer exceeds the value agreed by the contract parties. The difference between the actual value of *sag score* and the value set forth in the contract is multiplied by the agreed compensation rate. Values of the indices for relevant locations are presented in tables 13-15.

Sag score target = 4.880257+3.222527+0.084377 = 8.187161

Table 13. Number of voltage dips in given time-intervals and the sag score (LUBOCZA)

sag score	10 - 500ms	500ms - 1s	1s - 1min	1 - 3min	3 - 15min
0.0833 -0.2	6	3	1	0	0
0.2 - 0.4	3	0	4	2	3
0.4 - 0.6	0	0	0	0	0
0.6 - 0.8	0	0	0	0	0
0.8 - 1	0	0	0	0	0
Number of voltage dips with residual voltage less than 75% - 50 Number of voltage dips after the 15-minute aggregation - 22 *Sag score* – 4.880257					

Table 14. Number of voltage dips in given time-intervals and the sag score (WANDA)

sag score	10 - 500ms	500ms - 1s	1s - 1min	1 - 3min	3 - 15min
0.0833 - 0.2	1	0	2	0	0
0.2 - 0.4	0	1	1	1	0
0.4 - 0.6	0	0	0	0	0
0.6 - 0.8	0	0	0	0	0
0.8 - 1	0	0	2	0	0
Number of voltage dips with residual voltage less than 75% - 29 Number of voltage dips after the15-minute aggregation – 8 *Sag score* – 3.222527					

Table 15. Number of voltage dips in given time-intervals and the sag score (SKAWINA)

sag score	10 - 500ms	500ms - 1s	1s - 1min	1 - 3min	3 - 15min
0.0833 - 0.2	1	0	0	0	0
0.2 - 0.4	0	0	0	0	0
0.4 - 0.6	0	0	0	0	0
0.6 - 0.8	0	0	0	0	0
0.8 - 1	0	0	0	0	0
Number of voltage dips with residual voltage less than 75% - 1 Number of voltage dips after the15-minute aggregation – 1 *Sag score* – 0.084377					

Example 2 [11]

Below are presented the indices developed by EPRI for assessment of supply reliability.

System Average RMS (Variation) Frequency Index$_{\text{Voltage}}$ (*SARFI*$_X$) - Represents the average number of the measured cases of voltage variation (dips, swells, interruptions) of duration from 0.5 cycle to 1 minute, experienced by the customer served from the assessed system.

$$SARFI_X = \frac{\Sigma N_i}{N_T}$$

X - r.m.s voltage threshold (minimum voltage value during voltage dip); possible values for voltage dips can be e.g. 90, 80, 70, 50 or 10 % of the reference voltage,

N_i - number of customers experiencing voltage deviations of the reference value less than *X* % for $X \langle 100$, for *i-th* case,

N_T - number of customers served from the section of the system to be assessed.

If the *SARFI* index is determined for a single customer, then the equation resolves itself into finding the values of aggregated disturbances, determined by the voltage value lower than the specified threshold value.

System Instantaneous Average RMS (Variation) Frequency Index$_{Voltage}$ (*$SIARFI_X$*) – for voltage dips of duration:
0.5-30 cycles and *x* = 90, 80, 70 and 50 %.

System Momentary RMS (Variation) Frequency Index$_{Voltage}$ (*$SMARFI_X$*). Represents the average number of the measured cases of voltage variation of duration: 30 cycles-3 s and *x* = 90, 80, 70, 50 and 10 %, which occurred in a given time in power supply of a given customer.

System Temporary Average RMS (Variation) Frequency Index$_{Voltage}$ (*$STARFI_X$*). Represents the average number of the measured cases of voltage variation of duration: 3-60 s and *x* = 90, 80, 70, 50 and 10 %.
The comprehensive comparison of the indices acc. to EPRI is shown in table 16. The specified indices for the relevant locations are presented in table 17.

Table 16. The comparison of the indices [11]

	0.5 cycle – 60 s	0.5 cycle – 0.5 s	0.5 s – 3 s	3 s – 60 s
< 90 %	$SARFI_{90}$	$SIARFI_{90}$	$SMARFI_{90}$	$STARFI_{90}$
< 80 %	$SARFI_{80}$	$SIARFI_{80}$	$SMARFI_{80}$	$STARFI_{80}$
< 70 %	$SARFI_{70}$	$SIARFI_{70}$	$SMARFI_{70}$	$STARFI_{70}$
< 50 %	$SARFI_{50}$	$SIARFI_{50}$	$SMARFI_{50}$	$STARFI_{50}$
< 10 %	$SARFI_{10}$	$SMARFI_{10}$		$STARFI_{10}$

Table 17. Aggregated indices of voltage dips acc. to EPRI (LUBOCZA/ SKAWINA/ WANDA)

Dips	0.5 cycle – 60 s	0.5 cycle – 0.5 s	0.5 s – 3 s	3 s – 60 s
< 90 %	74/19/44	50/17/33	7/2/4	17/0/7
< 80 %	59/6/35	35/4/24	7/2/4	17/0/7
< 70 %	45/6/24	21/4/14	7/2/3	17/0/7
< 50 %	41/6/18	17/4/9	7/2/2	17/0/7
< 10 %	3/0/14	2/0/7		1/0/7

Example 3 – The index referred to the reference characteristic [10]

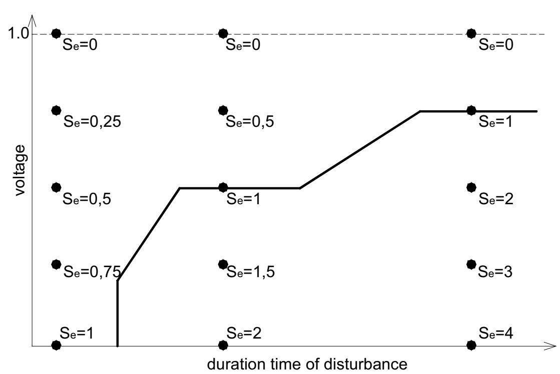

Fig. 4. The index of the voltage dip „severity", referred to the reference characteristic (solid line) for disturbances of various duration and residual voltage

The index (S_e), defined by the relation (1), is determined from the known: the voltage p.u. value and duration of disturbance. In the original proposal the reference characteristic is the CBEMA or ITIC curve.

$$S_e = \frac{1-U}{1-U_{ref}(d)} \qquad (1)$$

where: *U* – residual voltage during the voltage dip of duration *d; $U_{ref}(d)$* - the voltage dip magnitude on the reference characteristic for the disturbance duration *d.* For the disturbances on the curve, the index assumes value 1 – Fig. 4.
For the disturbances above the characteristic, the index value is less than 1, below - greater than 1. For the disturbances of the voltage value (per unit) equal 1, the index assumes the value zero. The longer is the duration of disturbance and smaller the residual voltage, the greater is the index value. As the reference characteristic for calculations has been used the ITIC curve, table 18.

Table 18. Total value of index S_e

GPZ	LUBOCZA	SKAWINA	WANDA	TOTAL
Σ S_e	191.023	11.71262	107.542	310.2776

Example 4 – The energy of voltage dip [2, 4]

Acc. to Thallam the measure of the energy not supplied during a voltage dip is the index E_{VS}: for a single-phase disturbance: $E_{VS} = \left(1 - \frac{U}{U_{ref}}\right)^2 T$; for a three-phase: $E_{VS} = \left(E_{VS-A} + E_{VS-B} + E_{VS-C}\right)$, where U is the voltage value during the dip in [V], T is defined duration of disturbance, and U_{ref} the reference voltage. The greater is the amplitude of a voltage dip and longer its duration, the greater is the index value. Fig. 5 shows illustratively the energy values for the substation SKAWINA.

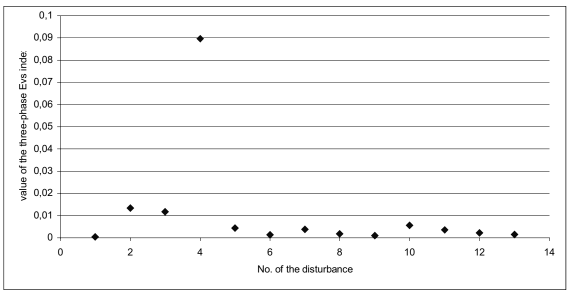

Fig. 5. The energy determined for the three-phase system (SKAWINA)

(acc. to Heydt): The index for a single phase:

$$W = \left(1 - \frac{U}{U_{ref}}\right)^{3.14} T\,;$$

the index for three phases:

$$W = \left(1 - \frac{U_a}{U_{ref}}\right)^{3.14} T_a + \left(1 - \frac{U_b}{U_{ref}}\right)^{3.14} T_b + \left(1 - \frac{U_c}{U_{ref}}\right)^{3.14} T_c\,.$$

Voltage Sag Energy Index - VSEI

Total energy of voltage dips in all disturbances measured at a given point of supply system over the set duration of the measurement: $VSEI = \sum_i E_{VSi}$

Average Voltage Sag Energy Index – AVSEI

Average energy of a voltage dip for all disturbances measured at a given point of supply system over the set duration of the measurement:

acc. to Thallam: $AVSEI = \frac{1}{N}\sum_{i=1}^{N} E_{VSi}$

acc. to Heydt: $AVSEI = \frac{1}{N}\sum_{i=1}^{N} W_i$

It should be noted that this index depends on the instant of beginning the measurement, i.e. on the voltage threshold value. For example, a high threshold value results in recording of a large number of dips (of small energy), thus in a smaller AVSEI value.

Table 19. Values of VSEI and AVSEI indices

LUBOCZA	
acc. to Thallam	*acc. to Heydt*
VSEI	
179.572/0.140264/90.30355	139.3433/0.025394/88.5745
AVSEI	
494055/0.001948/1.254216*	1.935324/0.000353/1.230201*
* LUBOCZA/SKAWINA/WANDA	

Example 5 [9]

System Average Sag Event Frequency Index – SEFI – for all measuring points.
SEFI = (total number of voltage dips)/ (number of points).
The number of voltage dips at individual substations: Lubocza - 74; Skawina -19; Wanda-44. Total – 137. *SEFI* =137/3 = 45.67.

Example 6 [4, 7, 10]

Tables 20 and 21 present the conception of equivalent, weighted voltage dips (calculated on annual basis), which are the basis for determination of mutual financial commitments of the supplier and consumer of electric power. The actual, aggregated voltage dips index, determined on this basis, (total of weighted dips acc. to the table 20 or 21) is subtracted from the value set forth in the contract and the difference is multiplied by the agreed compensation rate.

Table 20. The concept of the voltage dips weighting coefficients [4, 10]

Dips [%]	Weight coeff.	SKAWINA	LUBOCZA	WANDA
0	1	0/0*	4/4	6/6
<50%	1	0/0	38/38	3/3
50-70	0.7	0/0	4/2.8	5/3.5
70-80	0.4	11/4.4	17/6.8	16/6.4
80-90	0.1	9/0.9	11/1.1	4/0.4
TOTAL		**5.5**	**52.7**	**15.8**
* number of dips /weighted dips				

Table 21. The concept of weighting coefficients acc. to [7]

		Duration					
Voltage dip magnitude *u* %		20 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20 - 60s
	Average value	0.06	0.3	0.75	0.875	0.875	0.875
15 > *u* ≥ 10	0.125	0.0075	0.0375	0.0938	0.1094	0.1094	0.1094
30 > *u* ≥ 15	0.225	0.0135	0.0675	0.1688	0.1969	0.1969	0.1969
60 > *u* ≥ 30	0.45	0.0270	0.1350	0.3375	0.3938	0.3938	0.3938
99 > *u* ≥ 60	0.795	0.0477	0.2385	0.5963	0.6956	0.6956	0.6956
0> *u* ≥ 99	0.995	0.0597	0.2985	0.7463	0.8706	0.8706	0.8706

Table 22. Weighted voltage dips acc. to Table 21 (SKAWINA/LUBOCZA/WANDA)

Voltage dip magnitude %		Duration					
		20 - 100ms	100 - 500ms	500ms - 1s	1 - 3s	3 - 20s	20 - 60s
	Average value	0.06	0.3	0.75	0.875	0.875	0.875
15 > u ≥ 10	0.125	0.0525 0.225 0.03	0 0.3 0	0 0 0	0 0 0	0 0 0	0 0 0
30 > u ≥ 15	0.225	0.027 0.162 0.0675	0.54 0.3375 0.54	0.3376 0 0.5064	0 0 0	0 0 0	0 0 0
60 > u ≥ 30	0.45	0 0.081 0.108	0 0.405 0.135	0 0 0.3375	0 0 0	0 0 0	0 0 0
99 > u ≥ 60	0.795	0 0.2385 0.1431	0 1.6695 0	0 0.5963 0	0 4.8692 0	0 7.6516 0	0 3.478 0
0> u ≥ 99	0.995	0 0.1791 0.3582	0 0 0	0 0 0	0 0 1.7412	0 0.8706 5.2236	0 0 0.8706
Aggregated voltage dips index: 0.9571/21.0633/10.0611							

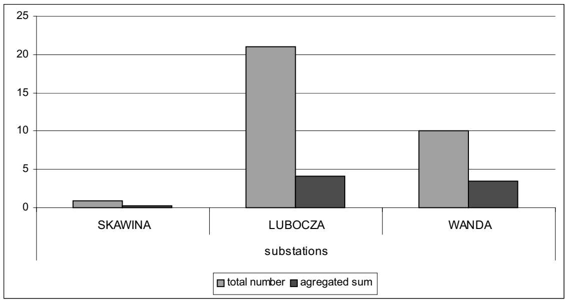

Fig. 6. Total number of voltage dips and aggregated sum of weighted dips

Figure 6 shows total number of voltage dips and aggregated total of weighted voltage dips, for the considered locations.

Conclusions

The paper presents several selected strategies for formulating the issue of voltage dips and short supply interruptions in a contract for the electric power supply. A database, obtained as a result of seven month monitoring of power quality factors at the metering points at the coupling of transmission and distribution system, has been used for illustration of the procedures proposed in bibliography. In the authors' opinion, a large part of the proposed procedures of contractual assessment of voltage dips is weakly founded, excessively complicated, and their practical usefulness has not been recognized yet. Sometimes it is proposed to categorize the voltage dips in transmission systems, taking into consideration only their magnitude (residual voltage), assuming that in most cases the disturbance duration is constant, and results from the settings of short-circuit protection times. The obtained results of measurements do not confirm this thesis.

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