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Correlation analysis of results of measurements in AC power supply of DC traction substations for identification of harmonic disturbances

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Abstract – **The conducted study case, which is presented in the paper, created a basis for identification of the causes for occurrence of voltage distortions and development of proposals solution assuring voltage of appropriate quality parameters, which enabled supplying sensitive loads from the same 15 kV grid as traction substations. With regard to noticeable disturbances in a 15 kV network, observed at non-traction loads and devices of a 3 kV DC traction substation (especially smoothing filters and signalling and control traffic equipment), it was required to perform a set of measurements of voltage quality in a PCC both at the level of 15 and 110 kV. The measurements were performed under various operational conditions and schemes of connection of the supplied loads. An analysis of the correlation between specific harmonics, THD coefficients and the current load was undertaken.**

I. INTRODUCTION

Standards and regulations concerning the problem of quality of electric energy supplied to the receivers from an electric grid impose certain requirements so that operators supply the recipients with energy of appropriate power quality acc. to the "Standard EN-50160:2010. Voltage characteristics of electricity supplied by public electricity networks". The important quality parameters include an admissible level of non-linear distortions – individual harmonics and THD (Total Harmonic Distortion) as well as admissible load fluctuations (due to the instability of loads). Under normal operational conditions, during every week, 95% of samples from the 10-minute values of measurements should not exceed limits. In accordance with the regulations being in law, an obligation to maintain required parameters of the supplied electric energy rests upon the supplier, while an owner of the disturbing load is responsible for reducing its distortion to a defined level. In some cases there appear to be problems in identifying a real cause of disturbances. The issue, although widely studied and well reported is still under consideration, due to large implementation of non-linear loads [1,2,3,4,5,6,7,8,9,10]. Among them disturbing character of traction load on supplying AC lines is significant, still current and under theoretical and in-situ measurement study [11,12,13]. It is possible to read in papers results of research at Italian [14,15,16] and Polish railways [17,18,19,20,21], where 3 kV DC rectifier substations are applied for supplying trains having rated power of 6-8 MW each and equipped with power electronic converters, which are another source of harmonics in a DC catenary [22,23,24,25,26,27]. Application of energy delivery to rectifier substations at the high voltage level may ease the problem of harmonics in AC supply, however in some cases these solutions are very costly and create technical difficulties when to be implemented. So, it is important to pinpoint the problem of disturbances, i.e. finding a source of disturbances before undertaking proper means. The paper presents a case study where from a 110/15 kV PCC (point of common coupling), both traction load (two traction substations - TS1 and TS2 - fig.1) as well as non-traction load (non-railway) (NTN - fig.1) were supplied. Measurements in the PCC at measurement transformers both for voltage at the 15 kV level - A point, as well as at the side of 110 kV voltage from a PUS (public utility system) – B point (fig. 1) were performed to identify the source of disturbances.
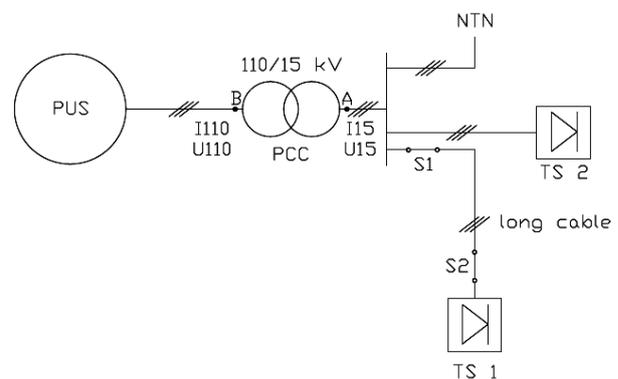

Fig.1. Supply scheme of TS1 and TS2 traction substations and NTN non-traction load from a 110/15 kV PCC.

As it was shown that the application of stochastic and statistical analysis [2,3,4,9,13,14,20,24] of the results may be helpful in identifying the source of disturbances in such a case, in order to find a solution, so a correlation analysis of the measurement results was undertaken.

II. MEASUREMENTS IN A 15 kV NETWORK

In the first stage, the measurements of energy quality at 15 kV bus-bars in a PCC at secondaries of voltage and current measurement transformers were conducted (fig. 1- point A, S1, S2 - closed) with application of a special measurement device dedicated to monitoring and assessment of electrical energy parameters acc. to the EN 50160 standard.

As resulted from the measurements it was found-out that in voltage at 15 kV bus-bars:

- the level of 11th harmonic was above 3.5%, the admissible value limit according to the EN 50160 value (maximum values reached 6.6%), even at night, when it dropped to around 4.2%;
- the level of 13th harmonic was above 3%, the limit according to the EN 50160 value (maximum values reached 5.8%), even at night, when it dropped to around 3.5%,
- the level of 17th harmonic (non-characteristic for 12-pulse rectifiers) periodically was above limit of 2% - maximum values reached 4% on Fridays and Saturdays, but usually during working days the limit was not exceeded;
- value of the THD U reached 10% with limit of 8%.

Therefore, to identify the source of such high values of harmonics in a PCC, from which sensitive loads and TS1 and TS2 substations with 12-pulse rectifiers are supplied, measurements were conducted for five different variants of supply schemes of load from 15 kV bus-bars in the PCC.

A. Measurements for variant 1 of a supply scheme

In this scheme of operation, TS1 and TS2 substations and NTN were supplied from the same 15 kV PCC section (fig 1. - S1, S2 - closed).

Table 1. Coefficients of U_n voltage harmonic correlation versus I15 current for variant 1.

THD U	U5	U7	U11	U13	U17	U19	U23	U25
0.943	0.867	0.793	0.848	0.773	0.921	0.814	0.974	0.921

For analysis of the results of measurements, one used the method of correlation of voltage parameters (higher harmonics 5th to 25th orders and THD U) versus the I15 load current of traction substations. As a result of calculations, one concluded that there is a high correlation between I15 current with THD U and 5th, 17th, 23rd and 25th harmonics, while for 7th, 11th, 13th, and 19th

harmonics the correlation coefficient is lower, but still significant. The results are presented in table 1 and fig. 2÷4. What is interesting is the strong correlation between I15 load current and 5th voltage harmonic, which is not characteristic for 12-pulse rectifiers.
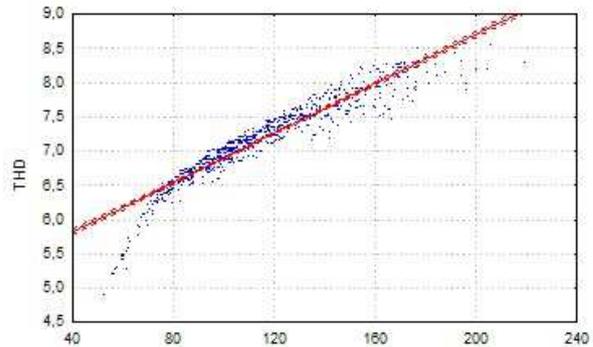

Fig. 2. Correlation of current I15 supplying traction substations with a THD U 15 kV coefficient.
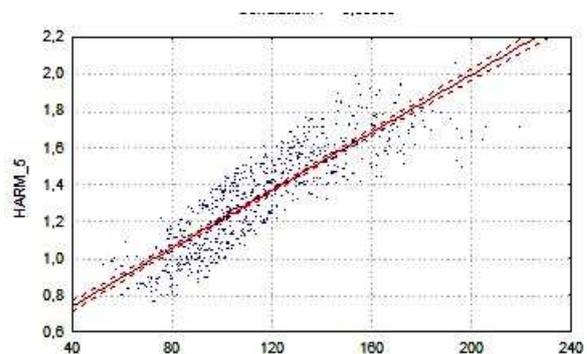

Fig. 3. Correlation of current I15 supplying traction substations with 5th voltage harmonic at the 15 kV level.
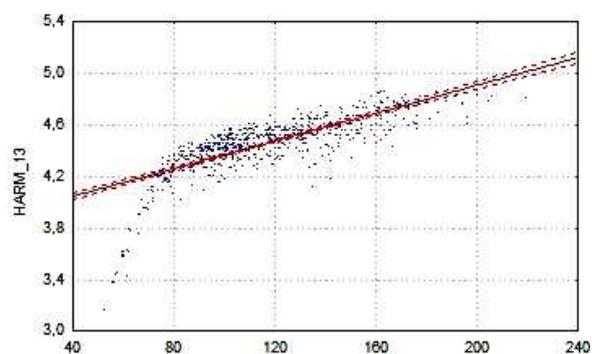

Fig. 4. Correlation of current I15 with 13th voltage harmonic in the 15 kV network.

B. Measurements for variant 2 of a supply scheme

In this variant of a supply scheme, a TS1 substation and non-traction loads (NTS) were supplied from the 15 kV PCC section, while the long cable supplying TS2 was disconnected (S1,S2- opened - fig. 1). The analysis of

correlation of I15 load current with the coefficient of voltage harmonics distortions THD and harmonics 5th to 25th was carried out once again (table 2). As a result of calculations, it turned out that there is a high correlation for THD U (fig. 6) and 11th, 13th (fig. 7), 23rd and 25th harmonics and slightly lower for 17th and 19th harmonics.

On the other hand, for 5th harmonic of voltage there was a low negative correlation (fig.8) and for 7th harmonic - a low positive correlation. As it can be seen from the value of a correlation coefficient for 5th voltage harmonic, switching-off the cable supplying a TS2 substation (variant 2 - switches S1 and S2 –opened, fig. 1) had a significant effect on lowering the value of 5th harmonic (5th and 7th harmonics are not characteristic for a 12-pulse rectifier in a traction substation TS1).
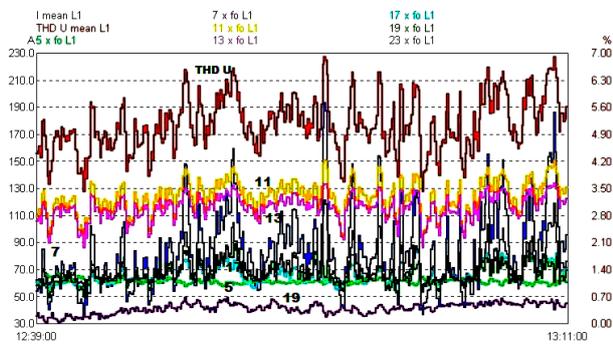

Fig.5. Graph of the THD U and specific voltage harmonics at the 15 kV level for variant 2.

Table 2. Correlation coefficient of U_n voltage harmonics versus I15 current for variant 2.

THD U	U5	U7	U11	U13	U17	U19	U23	U25
0.973	-0.348	0.401	0.947	0.917	0.767	0.775	0.976	0.991

C. Measurements for variants 3 and 4

Furthermore, voltage measurements at voltage transformers at 15 kV bus-bars in a PCC for variants 3 and 4 (comparing with variant 2, one added the supply of long cables supplying TS2, which operates in idle load- S1 closed, S2-opened-fig. 1) were conducted. The difference between variant 3 and 4 was that in variant 3, current load I15 was higher by 40% than in variant 4. The correlation results of the measured values are set and compared in table 5.
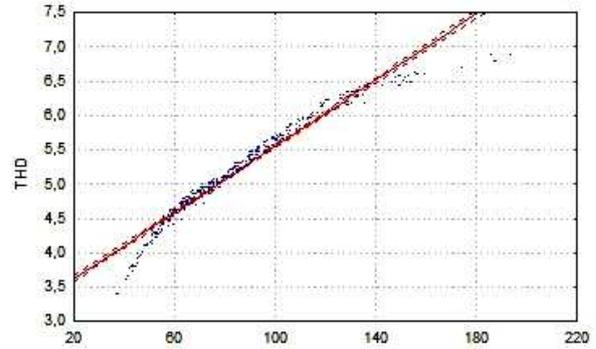

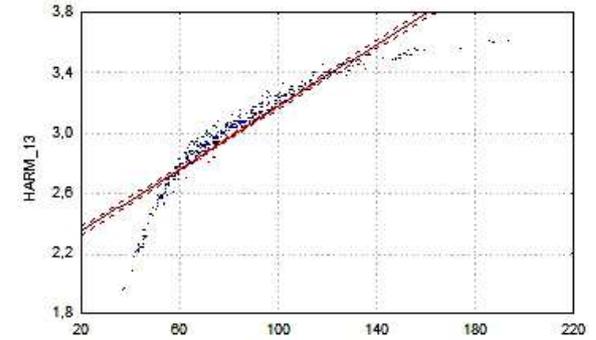*Fig. 6. Correlation of current I15 with THD U coefficient at the 15 kV level.*

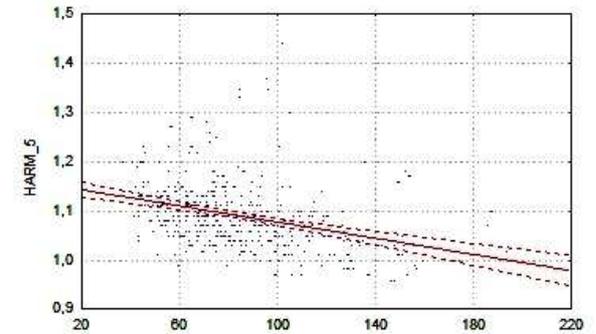*Fig.7. Correlation of current I15 with 13th harmonic of voltage at the 15 kV level.*

Fig.8. Correlation of current I15 with 5th harmonic of voltage at the 15 kV level.

III. MEASUREMENTS AT THE 110 KV VOLTAGE SIDE

In this supply scheme (variant 5 of measurements) TS1 and TS2 substations as well as non-traction needs (NTN) were supplied from the same section of 15 kV bus-bars in a PCC (fig 1- S1, S2 - closed). The measurements were performed on current and voltage measurement transformers on the side of 110 kV supply of a 110/15 kV 25 MVA transformer (point B).

As a result of the measurements, it may be stated that:

- the level of 5th voltage harmonic was above the admissible by the EN 50160 value of 2%, and the admissible value of 2% was not exceeded only by

28% of the measurement period (with required value 95);

- the value of a THD U coefficient was below the admissible limit value of 3%, without exceeding it;
- supplying voltage exceeded the rated value above the admissible 5% (maximum value 8.5%), and period when there was no excess of the admissible value was only 55% of measurement time (required 95%).

Furthermore, one conducted the measurement using a meter of electric energy quality (fig. 9) connected to secondaries of measurement transformers at the 110 kV level (fig. 1 - point B) and instantaneous waveforms of current I110 and voltage U110 by the use of an oscilloscope (fig. 10). As a result of the analysis of FFT waveforms (fig. 11), one observed presence of 5th and 7th harmonics in voltage and current (non-characteristic for the system of 12-pulse traction rectifiers, thus caused by voltage harmonics from a 110 kV network) and 11th and 13th harmonics (characteristic for 12-pulse rectifiers) caused by the current taken by traction rectifiers. It was noticeable that the 13th harmonic amplitude is comparable to the amplitude of 11th harmonic, which may indicate resonance phenomena. It was also confirmed by the value of a THD I coefficient (coefficient of non-linear distortions of current), which for 12-pulse rectifiers should not exceed the value of 13-14% (at low load), and the measured value of a THD I of load (included traction needs and 11 MW non-traction needs) reached 16%.

As a result of the assessment, one recognised a high correlation of 110/15 kV transformer load current with 11th and 13th harmonics voltage. For 23rd and 25th harmonics there was also a high correlation, but due to the very small values of amplitudes of these harmonics, they can be neglected. For 5th, 7th, 17th and 19th harmonics, there was no correlation versus I15 current (i.e. current supplying two traction substations TS1 and TS2). The results of the determined correlation coefficient are presented in table 3. Additionally for this variant 5, one conducted measurements at the 15 kV level of current and voltage waveforms (fig 12) and calculations of I15 current correlation coefficients with the coefficient of THD U, current THD I and for cos ϕ(PF). Calculations show that there is a high correlation of I15 with these coefficients. However, a THD I correlation coefficient is negative, which means that with the increase of I15 current a value of the coefficient THD I decreases. The results of the calculations are presented in table 4 and fig. 13 and 14. Summary of the measurements and analyses is set in table 5.

Table 3. Correlation coefficient of U_n voltage harmonics at 110 kV level versus load current for variant 5.

THD U	U5	U7	U11	U13	U17	U19	U23	U25
0.783	-0.249	-0.057	0.869	0.628	0.107	-0.102	0.955	0.955

Table 4. Correlation coefficients THD U, THD I and PF at 15 kV versus I15 current for variant 5.

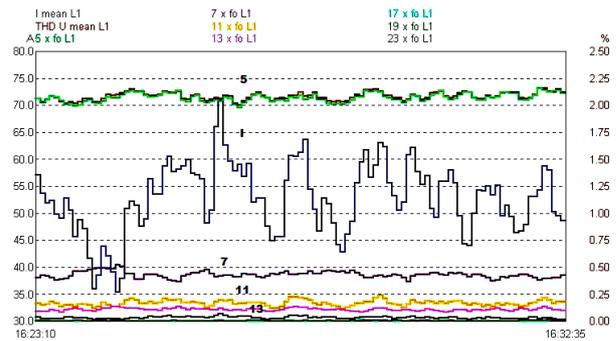| THD U	THD I	cos ϕ(PF)
0.848	-0.953	0.765

Fig.9. Graph of a rms value of current I and voltage harmonics at the 110 kV level for variant 5.
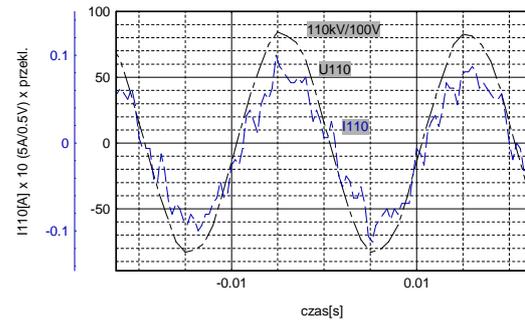

Fig. 10. Current and voltage waveforms (recorded from measurement transformers at the 110 kV voltage, oscilloscope recordings – 10:1).
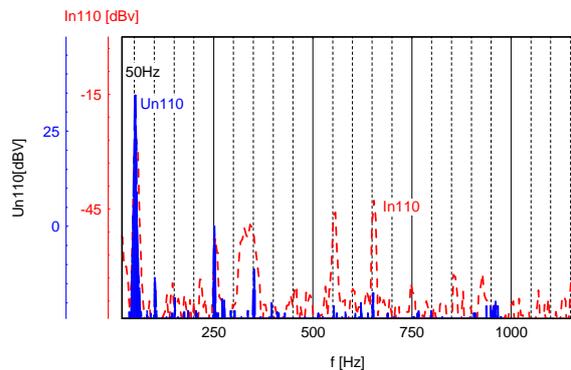

Fig. 11. FFT analysis of current I110 and voltage Un 110 waveforms shown in fig. 10.
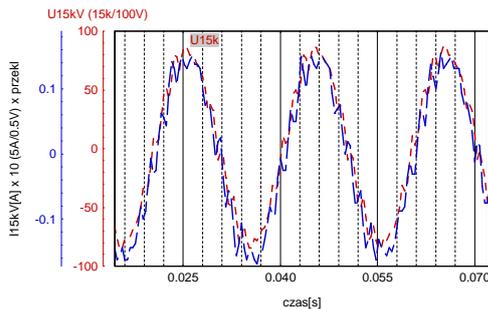
Fig.12. Current and voltage waveforms (measurement transformers measurement at the 15 kV voltage, oscilloscope recordings – 10:1.)
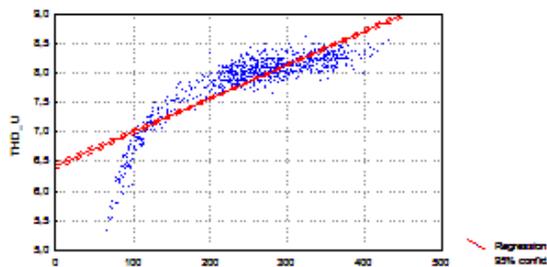

Fig.13. Correlation of THD U at 15 kV busbars with a rms value of current I15 at the 15 kV level of a grid transformer 110/15 kV (variant 5).
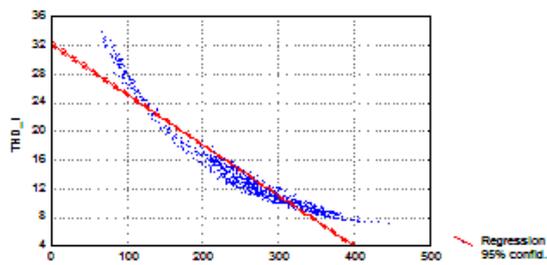

Fig. 14. Correlation of THD I of I15 taken from the 110/15 kV transformer with a rms value of I15 current.

V. COMPARISON OF MEASUREMENT RESULTS

Table 5. The summary of a correlation coefficient THD U and few U_n harmonics versus current for all variants.

Measurement system	THD U	U5	U7	U11	U13
Variant 1	0.943	0.867	0.793	0.848	0.773
Variant 2	0.973	-0.348	0.401	0.947	0.917
Variant 3	0.937	-0.429	0.804	0.953	0.917
Variant 4	0.987	-0.636	0.371	0.978	0.984
Variant 5	0.783	-0.249	-0.057	0.869	0.628

In variant 3 of a supply scheme there is a correlation of 7th harmonic with I15 current, but the value of 7th harmonic is small. For variant 4, there is a correlation of 5th harmonic, but it is a negative one, i.e. with increase of current, the value of 5th harmonic decreases. While measuring current of a 110/15 kV transformer, there was a correlation of current with 11th and 13th harmonics, however, there was no correlation of current with voltage 5th,7th ,17th and 19th harmonics. The highest value of a current correlation coefficient for 5th and 7th voltage harmonics occurred for variant 1. It was a supply scheme, in which TS1 and TS2 substations as well as NTN were supplied. After analysis of all operational schemes, in which the measurements and calculations were performed (tab.5), one can state with a great amount of certainty that the element that creates conditions for the increased current flow of 5th harmonic is the line supplying TS1. The TS1 substation is supplied by a long cable and due to its high capacitance, resonance conditions for 5th harmonic, which is transferred from the side of a 110 kV network, can be created. So it gave a basis for the exclusion of the hypothesis that high values of 5th harmonic were caused by 12-pulse traction substations (load). As it is shown in table 2, in variant 2 there is no correlation of 5th and 7th harmonics versus current I15.

V. CONCLUSIONS

The study presented in the paper concerned a case, where from the same 110/15 kV PCC, both traction load (two traction substations - TS1 and TS2 - fig.1) as well as non-traction load (non-railway) NTN were supplied and significant disturbances in operation of the supplied devices were observed.

At the first approach, the rectifier substations (as a typical non-linear load) were assumed to be the source of disturbances. A set of undertaken measurements both at the 15 kV and 110 kV levels allowed stating with a great certainty that a high value of 5th harmonic at the side of 15 kV voltage was not caused by traction loads but transferred from the 110 kV network. It was possible to indentify it as a result of the conducted analyses with the use of a method of correlation applied to the measurement results taken for various operation schemes of the supplying network. As temporary solutions to reduce high distortions, one proposed the use of inductance for compensation of reactive energy (capacitive) of the cables, and as a final one a separation of a 110/15 kV transformer in the PCC for supply of sensitive loads was suggested.

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