Wiesław BROCIEK[1], Robert WILANOWICZ[2], Stefan FILIPOWICZ[1]

Warsaw University of Technology (1), Kazimierz Pulaski University of Technologies and Humanities in Radom (2)

Cooperation of 12-pulse converter with a power system in dynamic state

***Abstract:** The paper presents the results of the analysis of higher harmonics, and total harmonic distortion coefficient in the transformer station 220/15kV on the 15kV side. This transformer supplies the 3kV DC traction substation containing 12-phase converters. The level and the instantaneous waveform on the 15kV side voltage and loading current have been registered and used for the investigation of the influence of the converters on the parameters of the energy of the supplying system. The paper presents the comparison of the real measurements with the results of computer simulation obtained using Microcap.*

***Streszczenie**: Przedmiotem artykułu jest analiza współpracy podstacji trakcyjnej z układem zasilania. Podstacja ta wyposażona jest w prostownik 12-pulsowy i należy do odbiorników nieliniowych o dynamicznie zmieniającym się obciążeniu. Odbiorniki z układami prostownikowymi są źródłami wyższych harmonicznych prądu i napięcia, powodując odkształcenie napięcia w węźle z którego są zasilane. W artykule przedstawiono wyniki pomiarów odkształcenia napięć w stacji transformatorowej 220/15kV. Z szyn 15kV zasilana jest podstacja trakcyjna prądu stałego 3kV wyposażona w 12-pulsowy prostownik. Chcąc opisać wpływ tego układu prostownikowego na układ zasilania, rejestrowano poziom i kształt krzywej napięcia oraz wartości prądu obciążenia po stronie 15kV. Rezultaty otrzymane z pomiarów porównano z wynikami badań symulacyjnych pracy tego układu przeprowadzone w języku MicroCap. (**Analiza współpracy podstacji trakcyjnej wyposażonej w 12-pulsowy prostownik z układem zasilania w stanach dynamicznych**).*

Słowa kluczowe: wyższe harmoniczne napięcia, współczynnik odkształcenia napięcia, układy prostownikowe
Keywords: voltage distortion coefficient, higher harmonics of voltage, 12-pulse converter

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Introduction

Currently, there is a need for experimental studies and new computer programs executing measurements acquired in a real world. This is due to the widespread use and increasing the number of installed non-linear loads of low and high power, and the growing importance of EMC issues at non-linear loads of the power supply systems. Assessment of the quality of electric power systems containing non-linear loads on the basis of experimental and simulation is of practical importance. The paper presents examples of the results of experimental and simulation research of voltage distortion in the system traction power substation equipped with the rectifier circuits.

At present there are the requirements in the field of experimental researches and the new research simulations programs based on the real parameters witch give us possibilities of describing chosen parameters of electrical energy quality in nonlinear systems. It is the result of applications of low and high power nonlinear loads. Very important problems concern the electromagnetic compatibility (EMC) of installed devices. The paper shows results of measurements and numerical calculations concerning distortions of the voltage. Measurements have been carried out in transformer station 110/15kV. This transformer supplies the 3kV DC traction containing 12-pulse converter [1,2,5].

The aim of the measurements is determination of influence of 12-pulse converter on chosen parameters of electrical energy quality of both sides of the transformer 15kV.

The paper shows results of measurements and numerical calculations concerning distortion of current and voltage.

Assessment of the deformation voltage transformer station - measurements

As a result of the measurements followed by their digital processing we can determine: the harmonic currents and voltage coefficient of voltage distortion (THD).

Figure 1 presents the general scheme of supplying 12-pulse rectifier.

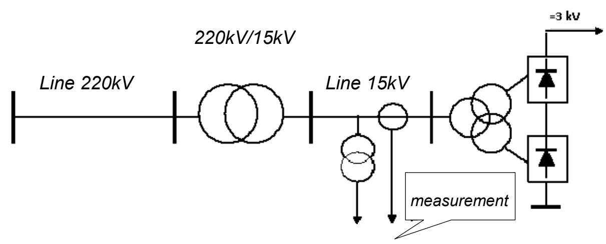

Fig. 1. Schematic diagram of measuring system

The model (Fig. 1) presented below is composed of the following elements:

- the main supplying point (GPZ) 220kV and short-circuit power of S_{zw}=600 MVA,
- 50 km overhead line of 220kV,
- transformer 220/15 kV,
- 1 km supply line 15 kV of 120 mm^2 cross-section,
- transformer Y/d11/y0,
- 12-pulse converter,
- the RL load.

Model contains 15kV bus bars which are supply from 220kV bus bars trough cable line and transformer 220kV/15kV of power S=25MVA. There are equipped with two separate bus bars 3kV DC in traction substation. This transformer supplies the traction substation containing 6-phase rectifiers (diodes) connected in the bridge network – 12-pulse converters – of dynamic load.

Measurements of voltages and currents were performed on terminals of voltage and current transformers installed on the rails 15 kV (Fig. 1).

Each substation, treated as nonlinear load generates typical distortions. Distortions generated by 12-pulse rectifier are the sources of *k*-harmonics

(1) $$k = 4n \pm 1 \text{ where } n = 3,6,9\ldots$$

In the paper [2] results of experimental research and numerical calculation of traction substation equipped with 6-pulse rectifiers have been presented.

According to EN-50160 [3] standard permissible values of chosen electric power quality parameters (defined for 95% of measuring time) for low and medium voltages are equal:

- THD_V coefficient

(2) $$\mathrm{THD}_V = \sqrt{\sum_{k\geq 2}^{n}\left(\frac{U_k}{U_1}\right)^2}\cdot 100\% \leq 8\%$$

where:

k – number of harmonics,
n – number of considered harmonics,
U_k – rms value of k[th] harmonic,
U_1 – rms value of 1[st] harmonic;

- percentage value of 11[th] harmonics

(3) $$\nu_{U_{11\%}} = \frac{U_{11}}{U_1}100\% \leq 3.5\%$$

- percentage value of 13[th] harmonics

(4) $$\nu_{U_{13\%}} = \frac{U_{13}}{U_1}100\% \leq 3\%$$

For 220 kV line THD_V coefficient is equal 3% and the percentage values of 11[th] and 13[th] harmonics are equal 1,5%.

Changes of load current I_{ob} of converter and chosen parameters of quality of energy on 15kV side are shown in Fig. 2 and 3.

- 11[th] and 13[th] harmonics (Fig. 2),
- THDv coefficient (Fig. 3).

The presented results have been obtained based on the registration which has been carried out by using measuring instruments MEMOBOX, according to EN 50160 [3,4] standard (Fig. 2 and 3).

Total value of the load of the current I_{ob} of converters and participation of 11[th] and 13[th] harmonic as a function time (in hours) is shown on Fig. 2.

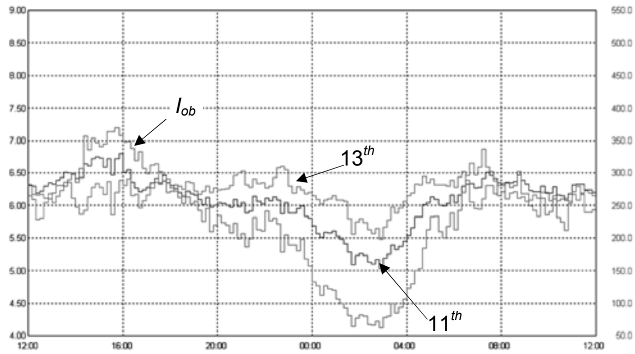

Fig. 2. Changes of load current I_{ob} of converters and 11[th] and 13[th] harmonics on 15kV side

Current load I_{ob} takes the maximum value during the morning rush (6a.m.-9a.m.) and afternoon peak (3p.m.-6p.m.). At low values of short-circuit power on the rails 15 kV, and at high power consumption, THD_V ratio may exceed the limit value during these periods – Fig. 3a. In the so-called valley of the night, the load current decreases three times while THD_V ratio is still within the norm limits:

The exemplary changes of the load current I_{ob} of converters and THD*v* coefficient on 15kV side during 24 hours is shown on Fig.3. The results presented in Fig. 3a, show that THD*v* coefficient exceeds the allowed voltage distortion value (8 %).

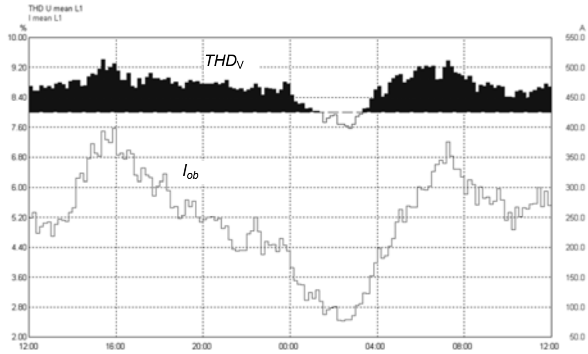

Fig. 3. Changes of load current I_{ob} of converters and THD_V coefficient on 15kV side

In the recorded waveforms of voltages and currents the dominant harmonic are 11[th] and 13[th]

Numerical results

The system shown in Figure 1 were analyzed using a numerical program MicroCap [6]. For a given power circuit 220 kV on the rails, the calculations of propagation of currents and voltages have been simulated in the distribution system shown in Figure 4, assuming short-circuit power S_{ZW220} = 600 MVA. The parameters of the model of supply system (L_S, R_S) have been determined using the following formulas [1,2]

(5) $$X_S = \frac{1{,}1U_p^2}{S_{ZW}} = \frac{1{,}1(220\cdot 10^3)^2}{600\cdot 10^6} = 88{,}7\Omega$$

(6) $$L_S = \frac{X_s}{\omega} = 282\,\mathrm{mH}$$

(7) $$R_S \approx 0{,}1X_S = 8{,}8\Omega$$

The recommended short-circuit power in the power system:

- Voltage 220 kV S_{zw} 220 kV = 400 ÷ 600 MVA
- Voltage 15 kV S_{zw} 15 kV = 150 ÷ 200 MVA

The supplying 220 kV line can be modeled by the 2-port of □ structure and parameters depending on the elementary resistance, conductance and capacitance as well as the length of them [2].

The winding transformer 220/15 kV is ʋ=15/220=0.068, and the parameters of the 220 kV power line with a length of 50 km are equal: R=6.25 Ω, L=65mH, C_1=C_2=224 nF.

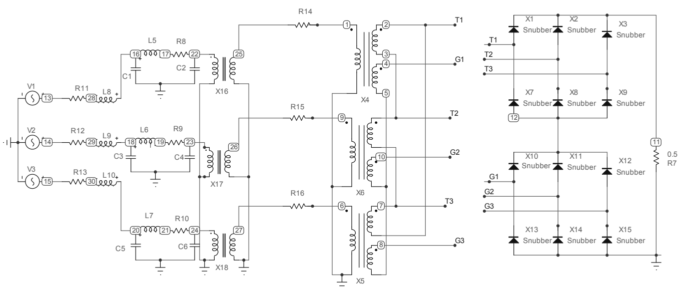

Fig.4. Circuit model of the network with 12-pulse rectifier

The load of the simulated system is formed by the traction engines, converting the electrical energy into mechanical [4,5]. We have applied the RL model of such engine, of the parameters adjusted adequately.

Numerical calculations were made with the data from real system. Figure 5 shows the current and voltage waveforms in a line of 15 kV obtained from simulation tests of the circuit in Figure 4. The current of converters assumed in simulation was 0,8 kA, (the same value as in real).

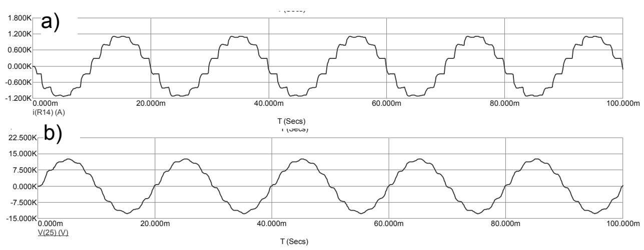

Fig.5. Transient signals of: a) current, b) voltage in 15 kV line

These waveforms are strongly deformed. THD_V value and the percentage of harmonic currents and voltages in the line of 15 kV and 220 kV of the load current are presented in Figure 5a and shown in Table 1. THD_V coefficients are: for line 15 kV - 8.07%, and for the 220 kV line - 4.68%. Both exceed the limits (same as in the measurements). In this case 11^{th} and 13^{th} harmonic have dominated values.

The percentage content of these harmonics exceed the limit values. In such cases, mitigation measures should be taken. One way to reduce the level of harmonics in power systems (traction substations) is the use of passive filters. This issue is widely presented in [2]. The deformed current and voltage waveforms contain also harmonics other than 11 and 13 (for example 23 and 25).

To get the parameters concerning the deformation of the voltage and current in the system we have to know the transient values of the corresponding variables. Fig. 5 illustrates these transients used in further analysis.

Table 1. Percentage value of higher harmonics of current and voltage in 15 kV and 220 kV line for the current converters from Fig. 5a

Number of harmonics	Distortion of current		Distortion of voltage	
	Line 220 kV	Line 15 kV	Line 220 kV	Line 15 kV
	%	%	%	%
11	12,2	7,25	3,87	7,08
13	5,1	5,99	2,6	3,79
23	0,7	2,87	0,3	0,62
25	0,54	2,45	0,2	0,51
THD [%]	13,25	10,13	4,68	8,07

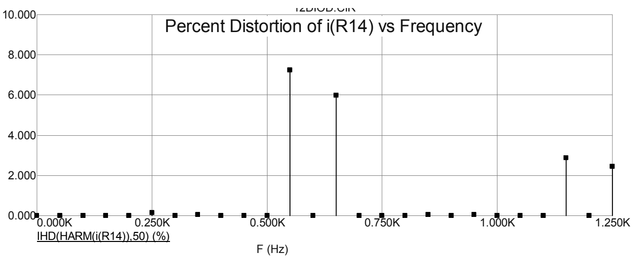

Fig.6. Spectrum of current from Fig. 5a

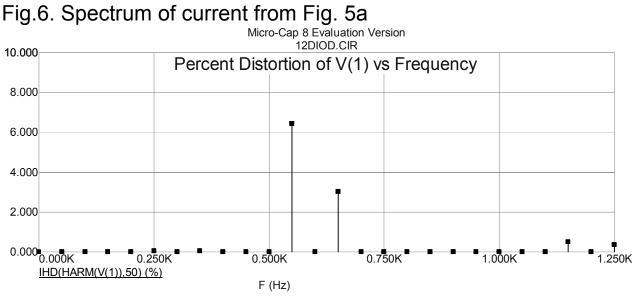

Fig.7. Spectrum of voltage from Fig. 5b

Fig.6 and 7 present spectra of the voltage of 15 kV and the current from Fig. 5a.

Table 2. Percentage value of higher harmonics of current and voltage in 15 kV and 220 kV line for transient signals from Fig.8

Number of harmonics	Distortion of current		Distortion of voltage	
	Line 220 kV	Line 15 kV	Line 220 kV	Line 15 kV
	%	%	%	%
11	9,87	9,67	1,77	1,84
13	3,61	7,02	0,71	0,76
23	0,63	4,3	0,1	0,16
25	0,49	3,69	0,07	0,12
THD[%]	10,54	13,23	1,91	2,01

In conclusion, we may point the agreement between the results obtained from simulation studies and measurements.

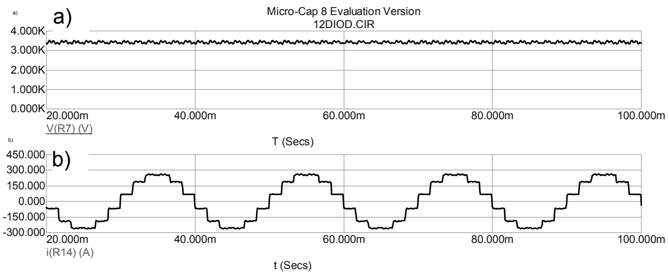

Fig.8. Transient signals of: a) rectified DC current, b) current on 15 kV line

The paper also presents the results of simulation of the system of Figure 4 for the current drawn by the rectifier circuit, where THD_V did not exceed the limit values. Current of the rectifier (about 0.4 kA) and current on the DC (3kV) are side shown in Figure 8.

The percentage of harmonic currents and voltages in the line of 15 kV and 220 kV waveforms of Figure 8, obtained from simulation studies are presented in Table 2. Voltage distortion coefficients and the percentages of the various harmonics do not exceed the limit values. Sample spectrum of 15 kV for this case is shown Fig.9.

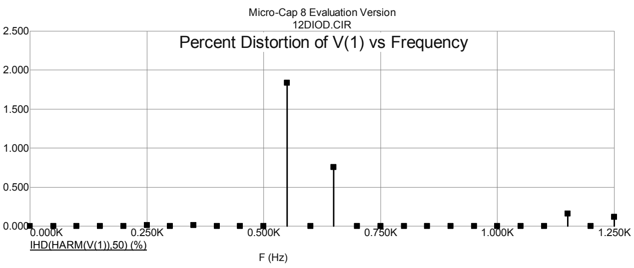

Fig.9. Spectrum of voltage 15 kV from table 2

Developed program allows you to out simulation studies of currents propagation and distribution voltages at different loads and different variants of short-circuit power.

Conclusions

Based on the measurements carried out in traction substation with 12-pulse converters the following conclusion have been worked out:

- distortion of voltage, caused by running the substation is proportional to the load current,
- 11th and 13th harmonics have the main influence on THD_V on 15kV bus bars in registered 15kV voltage.

Additional harmonics generated by the power system have also appeared.

Presented results of measurements allow to simply the defined generation of higher harmonics caused by nonlinear loads and study their influence on power system.

Taking into consideration that the measurements have been carried out in the typical supply system of traction sub-station the obtained results are representative for majority of traction sub-stations.

Results of analysis can also be used to assess the propagation of higher harmonics of the a current and voltage converters.

The paper presents the results of modeling and simulation of the influence of the rectifier network (12-pulses) on the supply sources in the traction systems. The simulation results in the form of higher harmonics of voltage and currents have been compared with the measurements mode in the real substation. The results of comparison confirm good agreement of the developed model with the real measurements.

Development of the numerical methods and computer engineering have great by accelerated the process of analysis of the phenomena in electrical circuits and systems.

The simulated models describe well the most important phenomena occurring in the traction system and its influence on the quality of energy of the power supplying system.

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***Authors**: doc. dr inż. Wiesław Brociek, Warsaw University of Technology, IETiSIP, E-mail: brociek@iem.pw.edu.pl, dr inż. Robert Wilanowicz, Kazimierz Pulaski University of Technologies and Humanities in Radom.*