Lidiia KOVERNIKOVA

Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences

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Active powers at the connection nodes of the non-linear loads to the high voltage network

Abstract*. The paper presents the results of an analysis of harmonic active powers at the nodes connecting the 220 kV supply network to three large-capacity nonlinear loads: an aluminum smelter shop, a paper mill and a traction substation. The equipment of the facilities is the source of harmonics. The measurements were used to calculate active power for harmonics. The calculations show that although the facilities are the sources of harmonics and generate harmonic active powers to the supply network they also receive harmonic active powers from the supply network.*

Streszczenie. *Artykuł przedstawia wyniki analizy mocy czynnej harmonicznych w węzłach łączących sieć 220 kV z odbiornikami dużej mocy, takich jak huty aluminium, papiernie i podstacje trakcyjne. Odbiorniki takie są źródłami harmonicznych. Na podstawie pomiarów obliczono moc czynną harmonicznych. Obliczenia pokazały, że jakkolwiek wymienione odbiorniki generują moc czynną harmonicznych, są one również odbiornikami tych mocy z sieci zasilającej.* ***Moce czynne w węzłach łączących odbiorniki nieliniowe z siecią wysokiego napięcia***

Keywords: harmonic, measurement, harmonic active power.
Słowa kluczowe: Harmoniczne, pomiary, moc czynna harmonicznych.

Introduction

The non-sinusoidal currents and voltages in the electrical networks cause different troubles. For example in [1], the authors discuss additional losses of harmonic active power in electrical networks and equipment, and consider the methods for the estimation of active power losses. The authors of [2] present the harmonics measured in the medical center and their detrimental impact on the work of the medical equipment. In the survey [3], "harmonics were found to be responsible for 5.4% of all power quality costs". The research from [4] poses the problems of potential financial losses of electricity suppliers and consumers in the case of non-sinusoidal currents and voltages. Electricity meters that belong to them measure active energy not only at the first harmonic but also at the other harmonics including those they do not generate. Active power of harmonics for orders n >1 does not perform useful work. Therefore, the suppliers and consumers bear additional expenses when paying the bills for electrical energy.

In [4] the author suggests decomposition of active power in the case of non-sinusoidal currents and voltages into two components: working active power (P_w) and detrimental active power (P_d). Working active power is an active power for the first harmonic, which performs useful work. Detrimental active power is an active power of the harmonics for orders n >1, which is distributed in the electrical equipment and network components, and cause various damages.

This paper demonstrates the results of the estimation and analysis of detrimental active power for harmonics 2-40 under non-sinusoidal currents and voltages at the nodes connecting an aluminum smelter shop, a paper mill and a railway traction substation to the supply network. The analysis is made on the basis of measured non-sinusoidal currents and voltages. The measurements were performed with the aid of the device "OMSK".

Objects of research

The considered facilities receive electrical energy from the 220 kV network and have a large capacity. Their main electrical equipment is a source of harmonics. All facilities are located in one area at a distance of several hundreds of kilometers from one another, but are powered by the 220 kV network of the interconnected power system. Besides the named nonlinear loads, there are other large-capacity nonlinear loads in the 220 kV network, for example, a great amount of traction substations, two aluminum smelters, one more paper mill, etc. Their harmonic currents also spread across the 220 kV network and contribute to the formation of harmonic conditions of the considered facilities.

At the nodes of connection of the facilities to the supply network the device "Omsk" was used to measure currents and voltages in three phases with an interval of 1 minute during 24 hours. Thus, the arrays of phase currents and voltages were obtained for 1440 time instants. All the calculations and the analysis were performed for phase A only. Figure 1 shows the current and voltage oscillograms for phase A at the node connecting the aluminum smelter shop to the supply network.

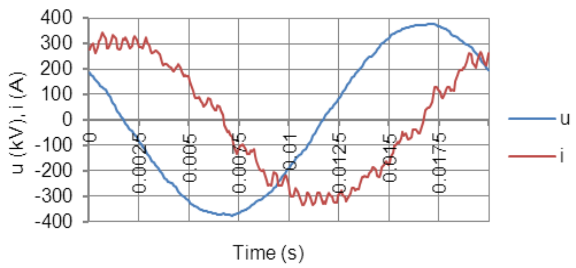

Fig.1. Voltage and current oscillograms

The facilities have different active power curves. They are presented in Fig.2. Active power is calculated by the expression

$$P_{1t} = U_{1t} I_{1t} \cos\varphi_{1t} , \quad (1)$$

where U_{1t}, I_{1t} - effective values of fundamental voltage and current at time instant *t*, φ_{1t} - phase angle between voltage and current at time instant *t*.

The active power of the aluminum smelter shop remains virtually the same throughout the day (Fig.2a). The rectifier circuit determines the harmonic orders and values of harmonic currents of the aluminum smelter shop. The rectification of current is done with a three-phase 12-pulse rectifier circuit.

The active power of the paper mill changes throughout the day because of the shift work (Fig.2b). At the paper mill the sources of harmonic currents are represented by adjustable speed drives. The orders and values of harmonic currents are determined by the rectifier circuits, which are used to feed DC electrical motors.

The active power of the traction substation is abruptly variable (Fig.2c). The traction load determines the harmonic currents of the traction substation. The electric locomotives are the traction load. The DC motors drive electric locomotives. The motors are powered through the single-phase 2-pulse rectifier circuits.

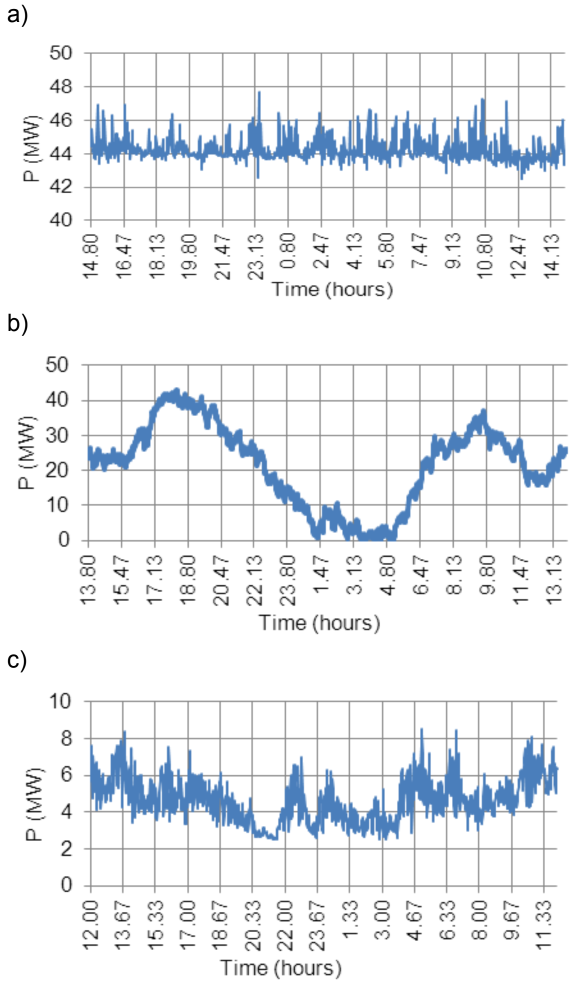

Fig.2. Active power curves of the aluminum smelter shop a), paper mill b), traction substation c)

Table 1 presents the maximum values (max), minimum values (min), average values (aver) and standard deviations (st) for active powers for the first harmonic for one phase. Notations of the Table 1 are: A – aluminum smelter shop, P – paper mill, T – traction substation.

Table 1. Statistical estimates of active powers (MW)

Parameter	A	P	T
max	47.71	42.91	8.50
min	42.49	0.20	2.53
aver	44.21	21.55	4.67
st	0.62	11.70	1.22

Phase shift angles between harmonic voltages and currents

The values of phase shift angles between vectors of harmonic currents and voltages, i.e. $\varphi_n = \varphi_{Un} - \varphi_{In}$, make it possible to determine the directions of active current and power flows with respect to the nodes at which the measurements were made. If φ_n lies in the intervals from 0 to $\pi/2$ or from $3\pi/2$ to 2π, the active current and power are drawn from the supply network to the load. In this case, the node is a load node for the *n*-th harmonic. If the angle φ_n lies in the interval from $\pi/2$ to $3\pi/2$, the active current and power are directed from the load to the supply network. In this case, the node is a generating node for the *n*-th harmonic.

The analysis of the phase shift angles shows that during the measurement period, the angle φ_n took the values in the range from 0 to 2π for most of the harmonics of the aluminum smelter shop and traction substation. The phase shift angles for the harmonics of paper mill also lie in the range from 0 to 2π. However, for some harmonics, they are distributed extremely unevenly among the quadrants of the plane of complex numbers, for example for the 11-th harmonic of the paper mill (Fig.3).

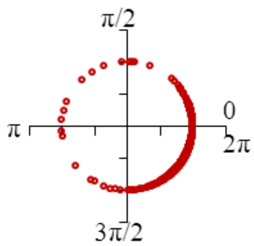

Fig.3. Diagrams of φ_n for the 11-th harmonic of the paper mill

The exceptions could be seen for the 7-th and 11-th harmonics at the connection node of the aluminum smelter shop. The diagrams of angles φ_n for these harmonics are presented in Figs.4a and 4b. At the connection node of the traction substation, the phase shift angles of the 5-th and 7-th harmonics have special diagrams as shown in Figs.4c and 4d.

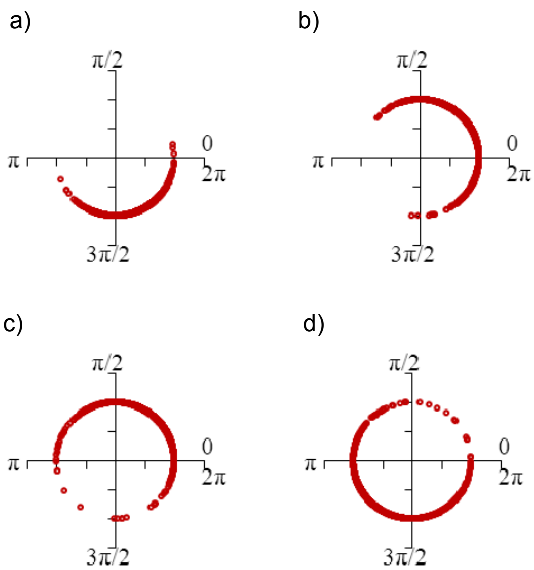

Fig.4. Diagrams of φ_n for the 7-th a) and 11-th b) harmonics of the aluminum smelter shop, for the 5-th c) and 7-th d) harmonics of the traction substation

The presented diagrams show that for some period the harmonic currents are drawn from the supply network to the facilities, and during another period – from the facilities to the supply network. The analysis shows that at one and the same time instant a node can be a generator node for one harmonic and a load node – for another one. Figure 5 demonstrates phase angles φ_n for harmonics 3 and 5, which are characteristic of the traction load. During the 20-minute time interval, the angles φ_n for the 5-th harmonic take the values that correspond to the direction of the 5-th harmonic current from the load to the supply network. They are marked with the red crosses. The angles φ_n for the 3-rd harmonic take the values corresponding to the generator node for the 3-rd harmonic current and are highlighted with the blue crosses, while the angles corresponding to the load node for the 3-rd harmonic current are denoted with the blue circles.

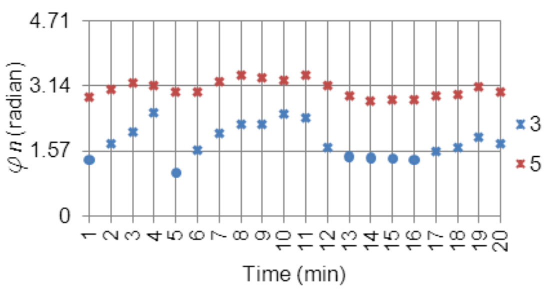

Fig.5. Fragment of the graph φ_n for the 3-rd and 5-th harmonics

Estimation and analysis of detrimantal harmonic active powers

Currents (I_{nt}), voltages (U_{nt}) and phase angle shifts (φ_{nt}) between them for harmonics 2-40 were used to calculate the harmonic active power by the expression

(2) $$P_{nt} = U_{nt} I_{nt} \cos \varphi_{nt} .$$

The analysis of the calculated powers shows that the direction of active power flows for all harmonics during the measurement period varies. However, for some harmonics the predominant direction, i.e. observed for more than 50% of the time of measurement, is the direction from the load to the supply network and for the others – from the supply network to the load. Figure 6 shows the diagrams, which indicate the directions of harmonic active power flows at the connection nodes of the considered facilities in terms of the time it takes for the active powers to flow in a certain direction. Active powers with the "minus" sign ($P_{n(-)}$) are directed to the supply network and with the "plus" sign ($P_{n(+)}$) – to the load. The diagrams show that at the connection node of the aluminum smelter shop, the prevailing directions of harmonic active powers are those from the load to the supply network, whereas the predominant directions for the paper mill and traction substation are the directions from the supply network to the load.

The active power values for even harmonics in both directions are very small and do not exceed 0.1 kW. The considerable active power flows in both directions occur at some odd harmonics. Their orders and statistical data of the active power values are presented in Table 2. The active power values in both directions during the measuring period change in a wide range, i.e. from several tens of kilowatts to several tens of watts. The largest values are observed in active powers for the 11-th and 13-th harmonics for the aluminum smelter shop. At the connection node of the paper mill the greatest value is in the active power of the 3-rd harmonic, directed to the supply network, whereas the largest active power from the network to the load of the facility flows for the 11-th harmonic. At the connection node of the traction substation the largest value is observed in the active power of the 3-rd harmonic in both directions. The power values for odd harmonics, which are not presented in Table 2, do not exceed 0.2 kW.

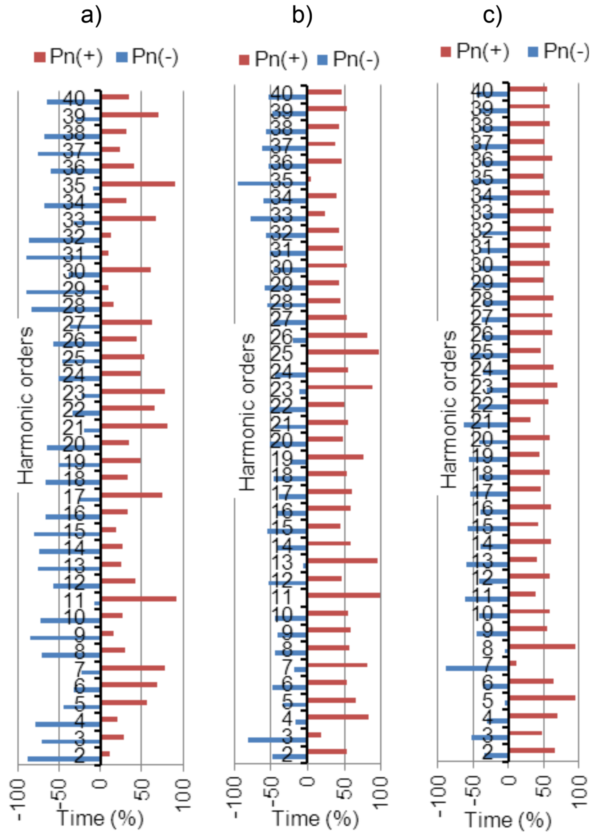

Fig.6. Diagrams of directions for harmonic active powers for the aluminum smelter shop a), paper mill b), traction substation c)

Table 2. Statistical estimates of $P_{n(-)}$ and $P_{n(+)}$ (kW)

Node	n	$P_{n(-)}$				$P_{n(+)}$			
		max	min	aver	st	max	min	aver	st
A	3	1.4	0.0	0.3	0.2	0.9	0.0	0.2	0.2
	5	1.7	0.0	0.3	0.3	1.7	0.4	0.3	0.2
	7	1.3	0.0	0.2	0.2	1.2	0.0	0.3	0.2
	11	17.7	0.0	5.5	4.0	41.5	0.0	17.0	8.1
	13	34.2	0.0	10.9	7.5	17.3	0.0	5.6	3.7
	23	4.0	0.0	0.7	0.7	4.1	0.0	1.0	0.7
	25	2.8	0.0	0.6	0.5	2.4	0.0	0.6	0.5
	35	2.9	0.0	0.7	0.6	4.0	0.0	2.2	1.0
	37	2.7	0.0	1.0	0.6	2.2	0.0	0.4	0.4
P	3	11.5	0.0	0.8	0.7	1.7	0.0	0.2	0.2
	5	1.0	0.0	0.2	0.1	17.3	0.0	0.4	0.7
	7	1.9	0.0	0.4	0.4	1.8	0.0	0.6	0.3
	9	1.0	0.0	0.2	0.1	2.2	0.0	0.3	0.2
	11	0.2	0.0	0.1	0.1	25.2	0.0	22.0	1.5
	23	0.2	0.0	0.0	0.0	8.7	0.0	0.5	0.4
T	3	14.0	0.0	1.2	2.0	7.5	0.0	0.8	1.1
	5	2.0	0.0	0.5	0.5	5.6	0.4	1.3	0.8
	7	2.4	0.0	0.3	0.3	1.2	0.0	0.6	0.2
	9	1.2	0.0	0.1	0.2	0.9	0.0	0.1	0.1

When powered from the source with sinusoidal voltage the load of the facility receives the active power of the first harmonic ($P_{1(+)}$). The electrical equipment to perform useful work P_W consumes large part of this power. The rest of the active power is transformed by the nonlinear equipment into active power of harmonics for orders n > 1. Earlier this power was denoted by $P_{n(-)}$. It is directed from the load to the supply network and in [4] is called reflected active power.

The active power of the first harmonic supplied to the facility from the source can be represented as

(3) $$P_{1(+)} = P_W + P_{n(-)}.$$

The nonlinear loads located in the supply network generate harmonic active powers flowing from the supply network to the load of the facility - $P_{n(+)}$. The orders of harmonics of the active powers $P_{n(-)}$ and $P_{n(+)}$ can be different as they are determined by the operation principle of the nonlinear equipment. Thus, the active power flow going through the node connecting the supply network to the facility from the network to the load is

(4) $$P = P_{1(+)} + P_{n(+)}.$$

The total harmonic active power, i.e. detrimental power is defined as

(5) $$P_d = P_{n(-)} + P_{n(+)}.$$

Based on the expression (5), values P_d were calculated for 1440 measurements of the considered facilities. Table 3 presents the statistical estimates P_d in the units of measurement of active power and in the percentage of working power P_W.

able 3. Statistical estimates of P_d

Node	Value	P_d (kW)	P_d (% P_w)
A	max	61.51	0.14
	aver	32.52	0.07
P	max	17.25	6.59
	aver	4.92	0.08
T	max	54.48	1.07
	aver	3.07	0.08

The Table shows that the maximum power values of paper mill and traction substation differ greatly from the average values. The analysis of arrays P_d for these facilities that consist of 1440 elements showed that there are several elements, which differ from the other elements of the array in value. They give the maximum values of power. Similar elements in literature, for example [5-6], are called abnormal. In certain cases, they are excluded or replaced by the elements calculated by special algorithms. In this case, the abnormal elements are left in the initial form as they are considered by the electrical meters when measuring the electrical energy. Table 3 also shows that the share of detrimental active power as compared to the working active power is not large.

Figure 7 shows P_d calculated for the node connecting traction substation. The abnormal measurements are seen very well.

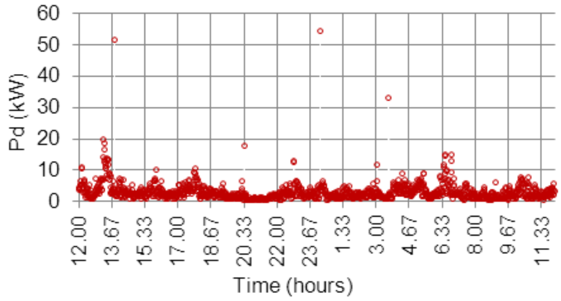

Fig.7. Diagram of P_d at the connection node of traction substation

Conclusions

Phase angles between vectors of currents and voltages for most of the harmonics lie in the interval from 0 to 2π, but are unevenly distributed. For some harmonics of the aluminum smelter shop and traction substation phase angles have special intervals.

Harmonic active power flows at the connection nodes of the aluminum smelter shop, paper mill and traction substation during 24 hours of measurements change the directions. For some period of the time they flow from the load of the facilities to the supply network and for some period of time from the network to the load. Nonlinear loads located at other nodes of the supply network generate the harmonic active powers drawn from the supply network to the load of the considered facilities.

The values of the harmonic active powers lie in the range from several watts to several tens of kilowatts. The largest values are observed in the active powers of the harmonics, which belongs to the characteristic harmonics of nonlinear equipment. The arrays of measured parameters contain abnormal elements.

The values of harmonic active powers that correspond to them differ greatly from the values of harmonic active powers of the other elements

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REFERENCES

[1] Zhezhelenko I.V., Sayenko Y.L., Electric losses, caused by high harmonics in electric power supply systems, *ISNCC*, Łagów, Poland, June 15-18, 2010, Łagów, Poland.

[2] Hartungi R., Jiang L., Investigation of power quality in health care facility, *Proceedings of the International Conference on Renewable Energies and Power Quality*, Granada, Spain, 23-25 March, 2010.

[3] Targosz R., Chapman D., Application note. Cost of poor power quality, *www.leonardo-energy.org/node/141781/.*

[4] Czarnecki L.S., Working, reflected and detrimental active powers", *IET Generation, Transmission & Distribution*, vol. 1, 2012, pp. 1-7.

[5] Irwin J.O., On a criterion for the rejection of outlying observations, *Biometrika*, vol. 17, issue 3-4, 1925, pp. 238-250.

[6] Kobzar A.I., Applied mathematical statistics. For engineers and researchers, 2-nd edition, revised – M.: FIZMATLIT, 2012.

***Authors**: Ph. D., Senior Researcher of Department of Electric Power Systems Lidiia Kovernikova, Energy System Institute of Siberian Branch of Russian Academy of Sciences, 130, Lermontov Str., Irkutsk, 664033, Russian Federation,*
E-mail: kovernikova@isem.sei.irk.ru.