

Measurement of currents and voltages non-sinusoidal parameters in power supply systems with rectifier load

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Abstract. The use of frequency-controlled electric drives in industry and municipal services is accompanied by the problem of their negative impact on the distribution network. As examples, the results of measurements of power quality indices in the power supply system of an oil producing enterprise and on the supply input of a railway traction substation are given. It is shown that the voltage subgroup total harmonic distortions (THDS) can exceed their rated permitted values in 100% of the measurement time.

1 Introduction

In industry and municipal services, the use of frequency-controlled electric drives is increasing. Frequency-controlled drives provide operation of own-use mechanisms at power plants, are used in traction substations of electrified transport, oil and gas production facilities, in water and heat supply systems. Their total capacity in the total load of the power supply system of the enterprise can be significant [1]. The application of frequency-controlled drives allows to reduce power consumption and provides advantages in the operation of electric motors. But the use of frequency converters in them, consuming non-sinusoidal current, leads to the power quality deterioration in the power supply system.

Non-sinusoidal voltage is characterized by the voltage subgroup harmonic distortions $K_{U(n)}$ and the voltage subgroup total harmonic distortions (THDS) K_U . The results of the assessment of the power quality state in the electrical grids of the Russian Power System confirm that the highest levels of harmonic distortions are observed in electric grids feeding the electrified railway, oil and gas transportation and mining enterprises, metallurgical and aluminum enterprises [2-5].

Examples of the negative influence of current and voltage harmonics on the electrical equipment, emergency automation devices are given in sources, for example, [6-13].

The purpose of the work is to measure and analyze the current and voltage harmonic components in electrical networks with rectifying converter load and to assess the compliance of the power quality indices (PQI) K_U and $K_{U(n)}$ with the rated values. The measurements

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were performed in the distribution network of the oil producing enterprise and at the 110 kV input of the railway traction substation. During the measurements, BINOM3 specialized devices were used. Devices BINOM3 are certified for compliance with the requirements of standards for measurement methods and norms for power quality [14-18] (registration in the Russia State Register of Measuring Instruments under No. 60113-15).

2 Methods and results

The PQI measurements and statistical analysis algorithms are established in GOST 30804.4.7 and GOST 30804.4.30-2103 [14, 15]. The phase voltages instantaneous values are measured on the main time interval equal to 10 periods of the industrial frequency. Using the Fourier Transform, the r.m.s. values of the 1st- and nth-order voltage harmonics and the nth-order voltage harmonics distortions $K_{U(n)i}$ are calculated:

$$K_{U(n)i} = \frac{U_{(n)i}}{U_{(1)i}} \cdot 100, \% \quad (1)$$

where n – is the harmonics order;

$U_{(n)i}$ – is the r.m.s. value of the nth-order voltage harmonic on the i-th main time interval (harmonic subgroups are applied);

$U_{(1)i}$ – is the r.m.s. value of the 1st-order (fundamental frequency) voltage harmonic on the i-th main time interval (harmonic subgroups are applied).

The voltage harmonic distortions are calculated on the aggregated time interval equal to 10 min, $K_{U(n)}$:

$$K_{U(n)} = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^N K_{U(n)i}^2} \cdot 100, \% \quad (2)$$

where N – is the number of 10-period intervals (main time intervals) in the 10-minute interval ($N = 3000$).

The voltage THDS on the i-th main time interval equal to 10 periods of the industrial frequency, K_{Ui} , is calculated as the ratio of the r.m.s. value of the sum of all the harmonics up to the nth-order to the r.m.s. value of the fundamental frequency voltage:

$$K_{Ui} = \sqrt{\sum_{i=2}^n \left(\frac{U_{(n)i}}{U_{(1)i}} \right)^2} \cdot 100, \% \quad (3)$$

The voltage THDS on the aggregated time interval equal to 10 min, K_U is:

$$K_U = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^N K_{Ui}^2} \cdot 100, \% \quad (4)$$

GOST 32144-2013 [15] establishes rated values for the voltage harmonics distortions and limits the range of harmonics to be considered 40th. PQI measurement devices should provide the measurement of harmonics distortions of voltage and current to 50th-order [15, 19]. The current harmonics levels are normalized in foreign standards [20].

The type of the non-linear electric receiver and its operation modes stipulate the spectral composition of the current being consumed and the voltage spectrum due to the current harmonics flowing along the electrical network elements. The order of the higher harmonics of current consumed by the rectifier converters depends on the circuit and the number of phases of the converter and is determined by the formula:

$$n = kp \pm 1 \quad (5)$$

Depending on the conversion scheme, a number of harmonics are compensated, their orders are determined by the formula:

$$n = \frac{p}{2} (2k - 1) \pm 1, \quad (6)$$

where p – is the number of conversion phases,
 k – is a natural number ($k = 1, 2, 3, \dots$),
 n – is the order of the harmonic.

For example, for a three-phase bridge converter scheme (Fig. 1), $p = 6$ and are characterized by 5 and 7, 11 and 13, 17 and 19, 23 and 25, etc. harmonics in the consumed current.

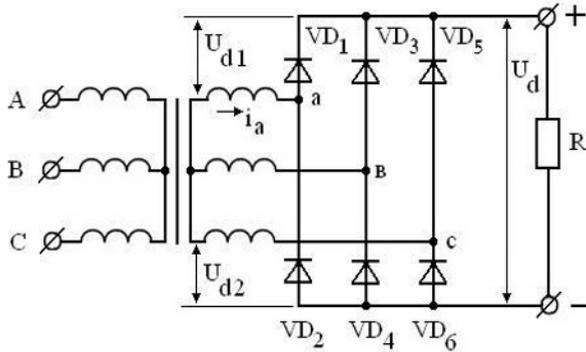


Fig. 1. Three-phase bridge scheme.

From 6 kV switchgear of the gas turbine power plant, 6/0.4 kV transformer substations are supplied. The load of transformer substations includes electric centrifugal pumps used for oil production, which contain frequency-controlled drives with rectifying converters.

The measurements were performed in switchgear 6 kV of the power plant at the line feederbay towards the transformer substations. The odd harmonics of the 5th and 7th, 11th and 13th, 17th-orders, characteristic of the three-phase bridge rectification scheme, are expressed in the spectrum of the current consumption (Fig. 2) in all phases.

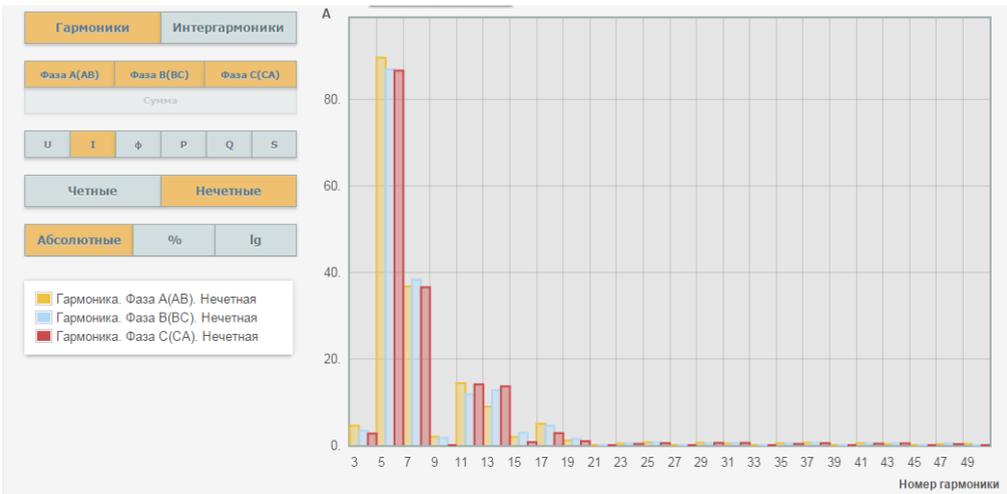


Fig. 2. Spectrum of odd current harmonics $I_{(n)}$, A. R.m.s. values for the main time interval (10 periods), phases A, B, C.

In the voltage spectrum (Fig. 3), harmonics of the same order as in the current spectrum are expressed, and additionally there are 3rd and 15th-orders harmonics.

Based on the results of measurements conducted during the week, it was recorded that in the busbar section of the power plant switchgear in 100% of the measurement time the normative levels of the THDS of voltage were exceeded (Fig. 4 - table 5).

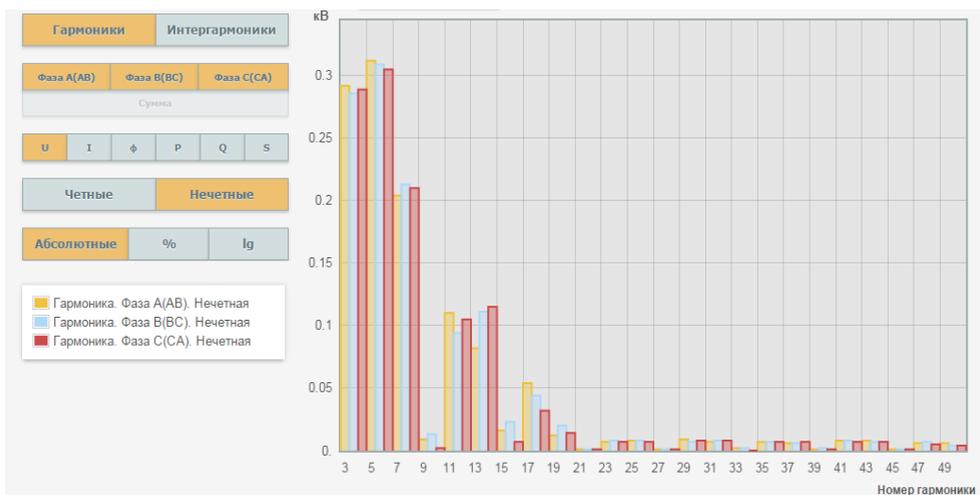


Fig. 3. Spectrum of odd voltage harmonics $U_{(n)}$, kV. R.m.s. values for the main time interval (10 periods), phases A, B, C.

Table 5 - Voltage subgroup total harmonic distortion (THDS) measurement results

Parameter	Phase A (AB)		Phase B (BC)			Phase C (CA)			Standard value	
	Measurement result	T ₁ , %	T ₂ , %	Measurement result	T ₁ , %	T ₂ , %	Measurement result	T ₁ , %		T ₂ , %
$K_{U(95\%)}$, %	14.521	100.000		14.395	100.000		14.391	100.000		5.000
$K_{U(100\%)}$, %	14.552		100.000	14.418		100.000	14.420		100.000	8.000

Table 6 - Voltage harmonic distortion measurement results

n	Measurement result, %												Standard value	
	Phase A (AB)				Phase B (BC)				Phase C (CA)					
	$K_{U(n)}(95\%)$	$K_{U(n)}(100\%)$	T ₁ , %	T ₂ , %	$K_{U(n)}(95\%)$	$K_{U(n)}(100\%)$	T ₁ , %	T ₂ , %	$K_{U(n)}(95\%)$	$K_{U(n)}(100\%)$	T ₁ , %	T ₂ , %	$K_{U(n)}(95\%)$	$K_{U(n)}(100\%)$
2	0.049	0.050	0.000	0.000	0.046	0.048	0.000	0.000	0.055	0.059	0.000	0.000	1.500	2.250
3	8.662	8.690	100.000	100.000	8.405	8.427	100.000	100.000	8.516	8.539	100.000	100.000	3.000	4.500
4	0.052	0.053	0.000	0.000	0.048	0.049	0.000	0.000	0.030	0.031	0.000	0.000	0.700	1.350
5	9.297	9.318	100.000	100.000	9.136	9.169	100.000	100.000	9.008	9.033	100.000	100.000	4.000	6.000
6	0.038	0.039	0.000	0.000	0.029	0.030	0.000	0.000	0.038	0.039	0.000	0.000	0.300	0.450
7	6.066	6.099	100.000	100.000	6.279	6.300	100.000	100.000	6.183	6.207	100.000	100.000	3.000	4.500
8	0.032	0.033	0.000	0.000	0.031	0.033	0.000	0.000	0.026	0.027	0.000	0.000	0.300	0.450
9	0.271	0.277	0.000	0.000	0.399	0.404	0.000	0.000	0.063	0.070	0.000	0.000	1.000	1.500
10	0.028	0.029	0.000	0.000	0.048	0.050	0.000	0.000	0.060	0.062	0.000	0.000	0.300	0.450
11	3.298	3.313	100.000	97.222	2.826	2.849	100.000	0.000	3.122	3.135	100.000	63.889	2.000	3.000
12	0.040	0.042	0.000	0.000	0.032	0.032	0.000	0.000	0.051	0.053	0.000	0.000	0.200	0.300
13	2.496	2.520	100.000	0.000	3.338	3.357	100.000	96.528	3.478	3.503	100.000	100.000	2.000	3.000
14	0.041	0.044	0.000	0.000	0.036	0.037	0.000	0.000	0.032	0.033	0.000	0.000	0.200	0.300
15	0.484	0.489	100.000	34.722	0.711	0.719	100.000	100.000	0.258	0.262	0.000	0.000	0.300	0.450
16	0.048	0.049	0.000	0.000	0.040	0.044	0.000	0.000	0.025	0.027	0.000	0.000	0.200	0.300
17	1.572	1.615	39.583	0.000	1.277	1.312	0.000	0.000	0.937	0.956	0.000	0.000	1.500	2.250

Fig. 4. The Power Quality Tests Report. Voltage subgroup total harmonic distortions, THDS (table 5), and Voltage harmonic distortions (table 6) measurement results, higher and highest values on 10-minutes intervals.

The normative levels of the 5th- and 7th-, 11th- and 13th-, 17th- orders characterizing of the three-phase bridge rectification scheme (Figure 4 - table 6) are violated. These frequencies are present in the currents spectrum, which may indicate the contribution of this load to the deterioration of the power quality of electrical energy. Exceeding the voltage harmonic distortions of the 3rd and 15th-order can be caused by the influence of other distorting receivers connected to the 6 kV busbars.

For the scheme with a series connection of two three-phase bridges (Fig. 5) $p = 12$. There are 11th and 13th, 23rd and 25th, 35th and 37th, 47th and 49th-order harmonics in the current. Such schemes are used in rectifier units of traction substations of the railway.

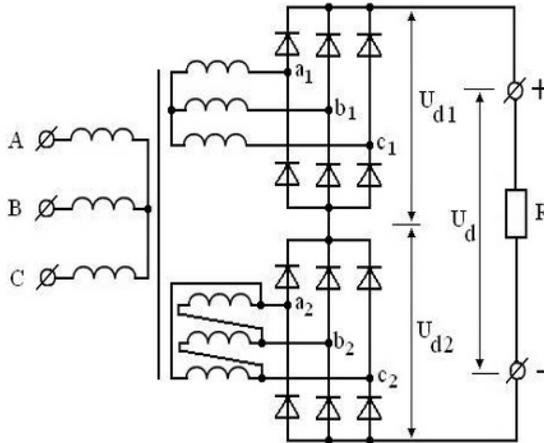


Fig. 5. Scheme with a series connection of two three-phase bridges.

Harmonic distortions are fixed at the 110 kV input of the traction substation. In Fig. 6 and 7 show the spectrums of the current and voltage harmonic distortions in phase A as a percentage of the current and voltage of the fundamental frequency.

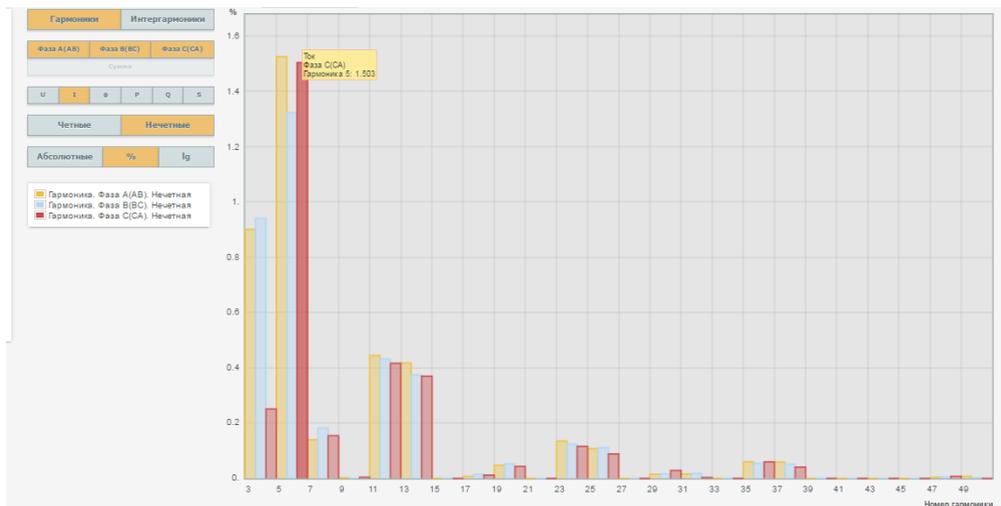


Fig. 6. Spectrum of current harmonics distortions $K_{I(n)i}$, %. R.m.s. values for the main time interval (10 periods), phases A, B, C.

Taking into account formulas (5) and (6), the presence of the corresponding orders harmonics (11th and 13th, 23rd and 25th, 35th and 37th) in the currents and voltages confirms

the presence of a scheme with two three-phase bridges in the rectifier converter in the substation load. The voltage subgroup total harmonic distortions at frequencies present in the current and voltage spectrums go beyond the normative levels (Fig. 8) established in [16]. Harmonic components of 3rd, 5th, 7th order in the current consumed can indicate another distorting load receiving power at the substation input.

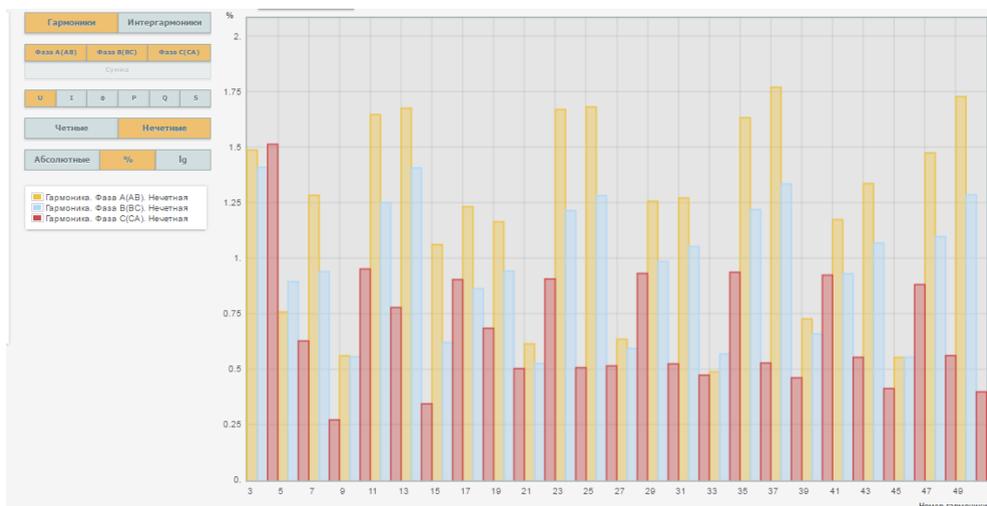


Fig. 7. Spectrum of voltage harmonics distortions $K_{U(n)i}$, %. R.m.s. values for the main time interval (10 periods), phases A, B, C.

Parameter	Phase A (AB)			Phase B (BC)			Phase C (CA)			Standard value
	Measurement result	T ₁ , %	T ₂ , %	Measurement result	T ₁ , %	T ₂ , %	Measurement result	T ₁ , %	T ₂ , %	
$K_{U,(95\%), \%}$	6.870	100.000		5.421	100.000		3.842	100.000		2.000
$K_{U,(100\%), \%}$	7.115		100.000	5.721		100.000	4.008		100.000	3.000

Fig. 8. The Power Quality Tests Report. Voltage subgroup total harmonic distortions (THDS) measurement results.

Based on the results of practical measurements containing arrays of values of the *n*th harmonic components of currents, voltages, and power, the actual contribution of the distorting receivers to the deterioration of the electric power quality at the point of common connection can be determined [21].

3 Conclusions

1. The results of measurements show that rectifier converters consume a current with a characteristic composition of harmonics, depending on the conversion scheme.
2. Using rectifiers reduces the quality of the network voltage. Voltage harmonic distortions can exceed standard and threshold permissible levels during 100% of the observation time.
3. It is necessary to carry out measures to reduce the influence of electric receivers with rectifier converters on the electric power quality

References

1. B.I. Abramov, D.A. Derzhavin, A.M. Churikov, Y.B. Novoselov, M.A. Suslov, Y.V. Shevryev, *Oil Industry*, **01**, 90-92 (2016)
2. L.I. Kovernikova, V.N. Tulsy, R.G. Shamonov, *Electricity. Transmission and distribution*, **2 (35)**, 40–50 (2016)
3. A.I. Artyukhov, I.I. Bochkareva, S.V. Molot, *Collection of proceedings of the international scientific and practical conference "Management of the quality of electrical energy"*, 33–41 (Moscow, 2016)
4. V.S. Borovikov, M.V. Volkov, V.V. Ivanov, V.V. Litvak, V.A. Melnikov, A.I. Pogonin, N.N. Harlow, *Experience of corporate survey of electrical networks of 110 kV of Siberia*, Tomsk, (2010)
5. V.S. Borovikov, M.V. Volkov, V.V. Ivanov, V.V. Litvak, V.A. Melnikov, A.I. Pogonin, N.N. Kharlov, T.B. Akimzhanov, *Regime properties of 110 kV electric networks in the south of Russia in ensuring the efficiency of electric power transmission*, Tomsk, (2013)
6. V.N. Tulsy, I.I. Kartashov, M.G. Simutkin, R.R. Nasyrov, *Industrial Energy*, **5**, 42–47 (2013)
7. M.G. Simutkin, V.N. Tulsy, *Proceedings of the International Scientific and Practical Conference: Power Quality Management*, Moscow, 161–171 (2014)
8. V.N. Gromov, *Proceedings of the International Scientific and Practical Conference: Power Quality Management*, Moscow, 85–93 (2014)
9. O.A. Vasilyeva, *The 8th Scientific and Technical Conference: Metrology. Accounting and quality control of electrical energy. Measurements in intelligent networks*, 153 (2016)
10. O.A. Vasilyeva, *Automation and IT in the energy sector*, **12 (77)**, 27–34 (2015)
11. O.V. Bolshakov, O.A. Vasilyeva, *Automation and IT in the energy sector*, **11 (88)**, 28–37 (2016)
12. M.O. Arsentiev, A.V. Kryukov, O.V. Arsentiev, *Bulletin of the Irkutsk State Technical University (ISTU)*, **12(107)**, 170 (2015)
13. Q.Sh. Vu, N.V. Korovkin, *St. Petersburg polytechnic university journal of engineering science and technology*, **24(02)**, 82–93 (2018), DOI: 10.18721/JEST.240207
14. *GOST 30804.4.7-2013 (IEC 61000-4-7:2009). General guide on harmonics and interharmonics measuring instruments and measurement, for power supply systems and equipment connected thereto.* (2014)
15. *GOST 30804.4.30-2013 (IEC 61000-4-30:2008). Electric energy. Power quality measurement methods.* (2014)
16. *GOST 32144-2013. Electric energy. Power quality limits in the public power supply systems.* (2014)
17. *GOST 33073-2014. Electric energy. Control and monitoring of electric power quality in the public power supply systems.* (2015)
18. *GOST R 8.655-2009. State system for ensuring the uniformity of measurements. Quality factors of electric power measuring instruments. General technical requirements.* (2010)
19. *The Standard of the Organization (JSC «FGC UES»). STO 56947007-29.200.80.180-2014. Measuring instruments for monitoring of the electric power quality indices. Typical technical requirements* (2014)
20. *IEEE 519-1992. IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.* (1993)

21. I.I. Kartashov, V.N. Tulskey, R.G. Shamonov, Y.V. Sharov, R.R. Nasyrov, Power Quality Management (2017)