STUDY OF ELECTRIC POWER QUALITY INDICATORS AND THEIR IMPACT ON THE FUNCTIONING OF SPECIALIZED ELECTRICAL EQUIPMENT IN A MEDICAL INSTITUTION

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Abstract—**Electricity quality control issues are becoming increasingly important with the introduction of digital technologies into energy systems and the intellectualization of energy networks. The quality of electricity is not a new problem, but it has received increasing attention in recent years due to an increasingly technologically advanced but electromagnetic world. In this article the main aspects related to the influence of electricity quality violations on the work of electrical equipment, including specialized for medical institutions, are considered. For health-care facilities, while it is important to comply with electricity quality indicators, there are no specific requirements for their monitoring. However, disruptions in the quality of electricity lead to a reduction in the accuracy of the imaging of diagnostic results, leading to study distortions and errors that may in some cases be fatal. For a detailed study of the problem as the object of the study is state autonomous health care institution «Interregional Clinical Diagnostic Center» of Kazan (ICDC). As a result of the conducted study of indicators of electricity quality at particularly responsible facilities of the ICDC deviation of the total coefficient of harmonic component of THDi currents up to 48%. To combat this violation, an active high harmonic filter was chosen and installed, which is a universal means of protection and can perform several functions simultaneously: reduction of the level of higher harmonic components, correction of the power coefficient, reduction of power loss, reduction of flicker, etc. Installation of active high harmonic filter allowed to reduce THDi to 2.5%, which is included into existing international standards.**

Keywords—Higher harmonics, electricity quality indicators, filt-compensating devices, non-linear load, medical electrical equipment

I. INTRODUCTION

Digitalization and widespread automation increase the use of non-linear semiconductor elements in power supply systems, resulting in distortion of electricity parameters. Non-linear load includes: power electronic equipment, AC frequency drives, DC drives, rectifiers, uninterruptible power supplies, elements containing diode bridges, lighting (fluorescent, gas-discharge LED) saturated electromagnetic devices (transformers, motors) etc.

Observation and limitation of electrical phenomena is based on the standardization of electromagnetic compatibility in accordance with GOST 32144-2013 [1] and IEC 61000-xx.

For a long time, the frequency value of the electrical system and the voltage levels in the network nodes were considered the main performance parameters determining the quality of electrical energy (QEE). However, as electrical consumers with non-linear volt-ampere characteristics are introduced into production processes, it is increasingly necessary to take into account the possible asymmetry, non-linearity of the three-phase voltage curve, as well as the highest harmonics of the current curve.

II. OVERVIEW OF THE INFLUENCE OF ELECTRICITY DISTORTION ON THE OPERATION OF ELECTRICAL EQUIPMENT

The most urgent problem is the identification of electrical equipment (consumer) that generates unacceptable distortions of electrical energy. It is proposed to use the results of the measurement of interference spectra to identify loads and, consequently, consumers that generate interference exceeding the QEE. A large number of studies on methods of quality determination and necessary measurements are devoted to this issue [2, 3]. Despite the existence of normative documents on the quality of electricity, the issue continues to be actively discussed.

Higher harmonics can cause adverse phenomena in the power grid [4-8]:

- engine overheating.
- increased engine losses, rapid mechanical wear;
- overheating of wires or neutral tyres;
- increased transformer losses and damage;
- damage to capacitors, which in resonance leads to their explosion;
- switching problems, especially for protective deactivation devices (PDD);
- unintentional (false) disconnection of relay protection devices;
- false operation of electronic devices up to their damage;
- failure to transmit pulsing control signals;
- problems with data transmission and transformation;

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- failure and false alarm of wireless smoke sensors;
- development of interfering noise (up to 16 kHz for human ear);
- stroboscopic effect in lighting systems;
- high-frequency AC shock effects;
- cable fault

Disruption of electricity quality harms electricity consumers and, at worst, can pose a risk to people and property.

In the presence of high-frequency harmonic stratifiers, it is difficult to compensate for reactive power, the insulation life of electrical machines and apparatuses is reduced, and the accident rate in cable networks increases. In these cases, relay protection, automation, telemechanics and communication systems often fail. Higher harmonics of voltage and current influence the power coefficient and torque values of electric motors. A big problem in electrical networks containing high harmonic sources is reactive power compensation with capacitor batteries. The connection of capacitor batteries together with the valve transducers was found to cause resonance phenomena in these networks. In this case, normal operation of capacitor units is not possible without special measures aimed at eliminating capacitor overload.

Failures in the transmission channels over the power circuits in the presence of harmonics cause incorrect commands to control the switching equipment. High harmonic levels can be transferred to adjacent devices on the network, which can cause problems with their performance, especially if they are not protected from harmonic distortions.

Many scholars have presented the reasons for the output of electricity quality indicators for regulatory values, but not all causes and effects have been obtained in practice. At the same time, a large number of new equipment is produced, which has not been investigated for the quality of electrical energy. That is, it is not clear how the new equipment affects the distortion of the QEE, which are indicated in [9, 10], and how the QEE affects the equipment.

III. Electromagnetic Compatibility and Electrical Safety Requirements for Medical Facilities

Modern medical institutions are characterized by:

- operation of a significant amount of very expensive and technically sophisticated equipment;
- high level of electronics and computers;
- the often high but short-term need for electricity in the network;
- the high dependence of patients' lives on the quality of operation of electrical equipment.

All of the above features can be attributed to the Interregional Clinical and Diagnostic Center of Kazan. ICDC is a high-tech medical institution based on the best traditions and long-term experience of the Kazan medical school. The main activities of the ICDC are related to the diagnosis and surgery of cardiovascular diseases. The infrastructure of ICDC is very energy-intensive, a large number of rooms with high-tech medical equipment. ICDC has more than 960 computers, servers and its own security system [11, 12].

The main feature of the power supply of the center is the presence of equipment of the first special category on the requirements of uninterrupted power supply. Also, this institution has rooms with electrical equipment of all possible medical groups. According to GOST 50571.28-2006 (IEC 60364-7-710:2002) the electrical installations of medical premises are divided into groups 0, 1 and 2. Medical premises are the main premises intended for the purposes of diagnosis, treatment, surgery, monitoring and patient care, as well as support facilities for the above functions of the main premises. In other words, this concept includes not only operating and resuscitation, as well as lighting, elevators, economic units, etc.

The most demanding group 2 includes medical rooms in which the contacting parts of electrical equipment (directly in contact with the human body externally or internally) are intended to be used for intracardiac procedures, in the operating theatre for demonstration operations and in other vital medical procedures, when the interruption of the (interruption) of the electricity supply poses a danger to the patient's life. In this case, the primary fault in the power supply chain should not lead to a failure of life support equipment. In the rooms of group 2 there is no automatic disconnection in the event of the first failure of insulation and short-circuit to the body or open conductive parts, as well as during the recording of leakage currents and power outages.

There is a strict requirement for group 1 and group 2 end-user power circuits - circuit breakers for operating tables and fluorographic units must be used with nominal differential response current not exceeding 30 mA. There are also increased requirements for grounding.

In order to protect the electrical equipment of all groups of premises, the use of fuses is prohibited. Protection is provided by circuit breakers of each branch of the electrical circuit with a high degree of selectivity.

In this case, standard circuit breakers are used in the rooms belonging to the zero group for exceeding the permissible current in the controlled power supply circuit.

For the first group, power cables are double-insulated, sources of safe ultra-low voltage, systems of earthed sources of safe ultra-low voltage. Additional measures for this group include the use of redundant electrical circuits and capacity equalization systems.

The highest requirements for electrical equipment at the premises of the second group, namely:

- the use of medical power supply system with isolated neutral;
- application of power supply sources with automatic control of insulation resistance, current level and temperature;
- double insulation of conductive lines;
- ultra-low voltage safety soures;
- systems of earthed sources of safe ultra-low voltage;
- uninterrupted power supplies, the activation time of which does not exceed 0.5 seconds;
- potential equalization system;
- emergency power supply system, including at least 50% of lamps.

Each medical room shall be provided with a system of additional equation of electrical potentials of parts of electrical equipment related to the «patient's environment», namely, protective conductors, third-party conductive parts, screens from external electrical fields (if installed), current conductive floor nets (if installed), metal shell of separating transformers (if any).

The insulation resistance monitoring system of the transformer output winding shall detect a reduction of this parameter to less than 50 kOhm, but without automatically disconnecting the line. The remote control should be installed in enclosures with a protection rating of at least IP54, as wet cleaning and antiseptic treatment are constantly carried out in hospital rooms.

In medical facilities, the following main types of protection against electric shock are used. With direct touch, this is the main insulation, placing the equipment out of range, shell, casing.

The ICU shall have at least 25 per cent of the total illumination powered by a security power source (independent electrical generator or uninterrupted power supply). The third independent power source should maintain power supply for at least 24 hours and be actuated when the voltage is lowered at one of the inputs of the switchgear, service group 2 premises by 10% for a period of more than 3 sec. The requirement to maintain power supply for 24 hours may be reduced to a minimum, 3 hours if the specifics of the medical organization allows the completion of all necessary procedures and evacuation.

For medical institutions, although it is important to meet the electricity quality indicators, there are no specific requirements for their monitoring. However, disruptions in the quality of electricity lead to a reduction in the accuracy of the imaging, which leads to distortions in the images, and therefore increases the number of errors. There are failures in the hard disk drive, which can lead to a long load of the device when turning on or changing modes.

IV. Power consumption characteristic and power quality analysis in the ICDC

All electrical receivers, including specialized medical equipment used in medical institutions, are designed for normal operation with set parameters, electricity supplied to them (regulated frequency, voltage, etc.). When changing the electricity input parameters, there can be no guarantee in the reliability of the results at the output of specialized medical equipment.

At the same time, almost all diagnostic equipment is highly sensitive to violations of electrical energy quality indicators, for which the change of electric power parameters is critical for normal functioning.

Thus, in May 2020, the log of events of uninterrupted power supply «Gamatronic Mega Power» in the interregional clinical diagnostic center was recorded a drop in the level of input voltage with subsequent power outage. As a result, the Edge core switchboard es3628m, the Cisco catalyst switch 2950, four network filters, and the CCTV server motherboard are down. The estimated cost was more than 75000 rubles. The cause of this incident is a violation of the quality of electricity supplied.

As a result of this incident, it was decided to carry out diagnostics of the parameters of the quality of electricity in the ICDC and to identify the sources of its violations.

As shown in figures 1-4, the ICDC has an average electricity consumption of 6500 kW, which is a significant figure for organizations of this type of activity (fig. 2).

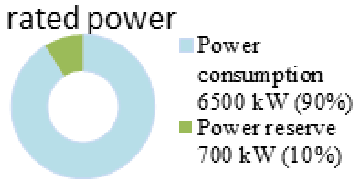


Fig. 1. Map of energy consumption in 2022.

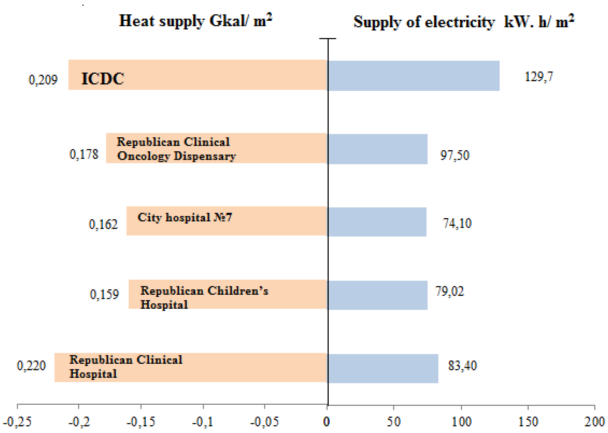
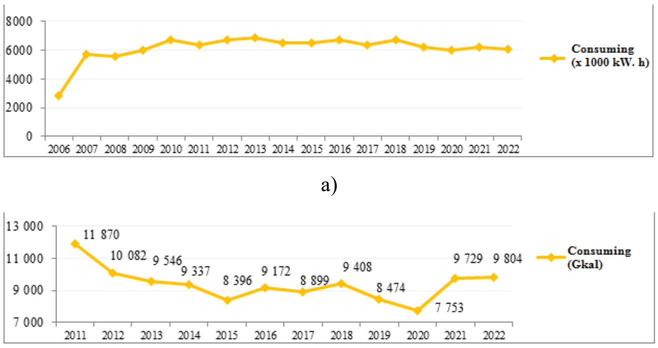


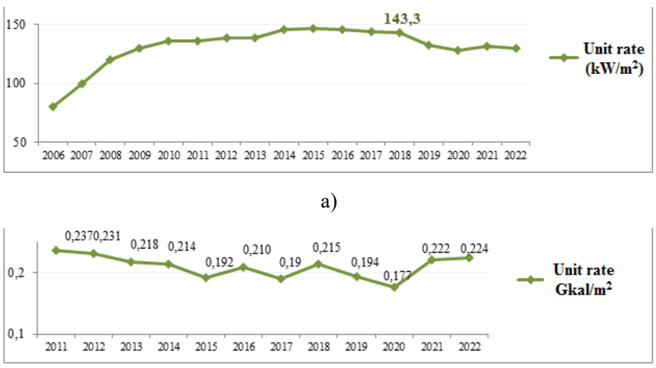
Fig. 2. Comparative characteristics of the specific costs of heat supply and electricity supply of the main energy-intensive medical institutions of Kazan.



a)

b)

Fig. 3. Dynamics of electricity (a) and heat (b) consumption of ICDC from 2006 to 2022.



a)

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Fig. 4. Dynamics of specific consumption of electricity (a) and heat (b) per unit area of ICDC from 2006 to 2022.

One of the most controversial issues related to the quality of electricity is the determination of the actual contribution of each source (consumer) to the quality of electricity at a particular point of total connection [13-19].

The most energy-intensive equipment of ICDC is (fig. 5-6):

- equipment of the data center,
- x-ray computer tomography equipment (CTE),
- x-ray machines,
- magnetoresonance tomograph (MRT),
- equipment of radioisotope laboratory,
- angiographic operating theatre equipment,
- ultrasonic diagnostic laboratories.

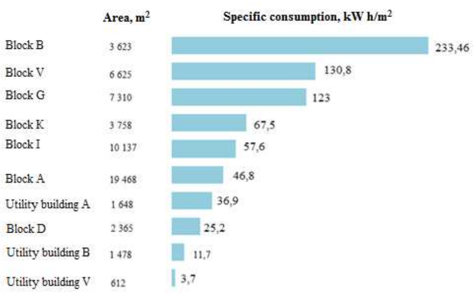


Fig. 5. Specific electricity consumption by ICDC enlarged units 2022.

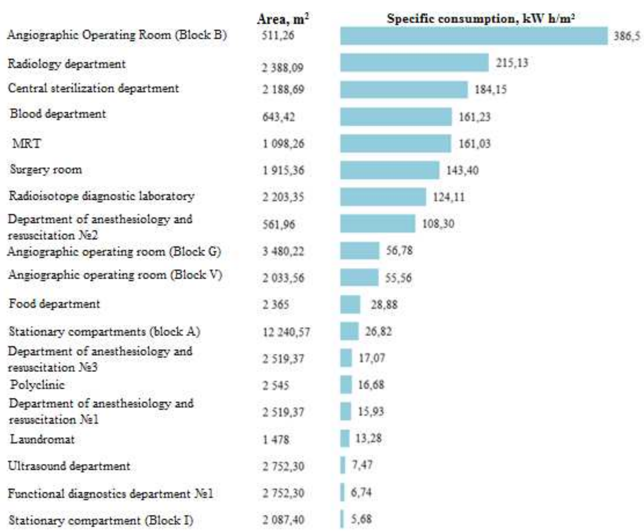


Fig. 6. Specific electricity consumption by ICDC enlarged units 2022.

The main non-linear loads generating harmonic distortion in the ICDC are:

- angiographs,
- CTE and MRT equipment,
- plasmapheresis installations,
- ventilation systems,
- energy saving lighting,
- server racks, etc.

The method of measuring with the help of power quality analyzers is based on finding the true standard value of the measured value. It has long been established that this method is the most accurate tool for measuring electrical values in the presence of distortion of the shape (sine-wave) of current and voltage. Depending on the task and the type of load in the network, the frequency of electrical measurements can vary from once per hour to several times per second.

The Metrel MI2883 power quality analyzer was used to study electrical energy quality indicators at the ICDC. This instrument makes it possible to measure all parameters of the quality of incoming electricity and records the results on an external medium. The recording time interval is set to 30 days. The instrument's connection point was chosen on the input and distribution device of the PKT block G, the server block G, the angiographic operating block G. Based on the results of the measurements, a report is made monthly, the purpose of which was to identify deviations from the standards.

The main results of our measurements of electric energy for January-March 2023 are presented in Table 1. The table presents an analysis of the compliance of the obtained results with the Russian standard and the US standard.

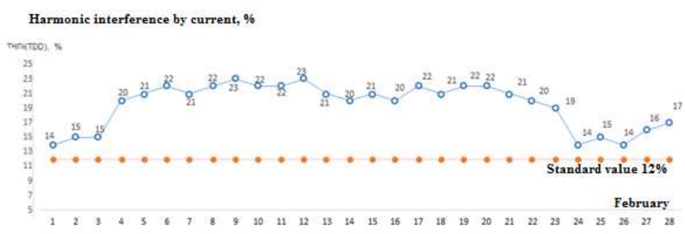
TABLE I. RESULTS OF MEASUREMENTS OF THE PARAMETERS OF THE ELECTRICAL NETWORK FOR JANUARY-MARCH 2023.

Standard / Parameter	Normative parameters for GOST 32144-2013 (Russian Federation)	Normative parameters for IEEE 519 (USA)	Measured value (peaks)	
			deviation	factual meaning
Frequency deviation	± 0.4 Hz	± 0.1 Hz	-0.08 Hz	49.9 Hz
Power failure, less than 1 minute	5% < U < 90%	10% < U < 90%	69%	155 V
Overvoltage	110% < U < 140%	110% < U < 140%	-	-
Voltage interruption	< 5 %	< 10 %	99%	0,02 V
Voltage Deflection	± 10 %	± 10 %	8%	237 V
Asymmetry of voltages	4 %	2 %	1.4%	
THDu (harmonics on voltage)	8%	8%	3.2%	
THDi (TDD) (harmonics on current)	Not normalized	12%	23-48%	
Voltage fluctuations (flicker)	1.38; 1	2	0.28	
Power factor	Not normalized	Not normalized	0.99	

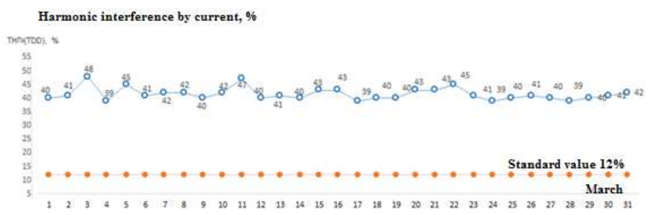
The monthly measurements revealed the following:

- The presence of voltage surges not exceeding the permissible +/-10 per cent of the rated value;
- No deviation of frequency from permissible values was detected;
- One voltage failure (less than 1 minute) was recorded;
- Two power interruptions were recorded during the reporting month. These interrupts refer to «accidental» and are caused by accidents at the supply substation;
- Harmonic distortion of current in the network is 23-48%.

Unlike European and American regulations, GOST 32144-2013 does not regulate currents of higher harmonic components. Only non-sinusoidal voltage is normalized. Although, according to current US standards, harmonic current distortion should not exceed 12%. However, from the graph of changes in the total harmonic coefficient of currents, it is clear that THDi reaches up to 48% (fig. 7).



a)



b)

Fig. 7. Harmonic interference measurements of THDi current (TDD) % for February (a) and March (b) 2023

Unacceptable deviations in the quality of the supply voltage for slow changes of voltage, flicker as a result of the made measurements is not revealed. However, a significant level of high harmonics on the current indicates the nature of the load and possible violations of other parameters of the quality of electrical energy.

High harmonic protection is provided by resonant filtering compensation devices based on capacitors, filtering reactors, inductances and shunt resistors. The main drawback of resonance filters is their limitation to only one resonance frequency.

Currently, active harmonic filters (AHF) [10-12] are gradually replacing the resonance filters. The AHF consists of a power part built on IGBT transistors and a control system. The principle of the AHF operation consists in the active generation of a compensating current in the opposite phase with a current of harmonic load distortion, resulting in the production of a sine wave current. AHF is a versatile tool that can perform several functions simultaneously: reduction of the level of the higher harmonic components, correction of the power coefficient, reduction of power loss, reduction of flicker, etc. AHF are «flexible» devices, this means that AHF parameters vary depending on the mode of operation of network load characteristics. The principle of operation of AHF is to generate the power electronics required harmonic current components to supply nonlinear consumers, so that the shape of the sinusoidal curve has minimal deviations from the norm.

Positive experience of installation of AccuSine PCSN060Y4W20 (Table 2) active filter on transformer substation buses feeding CT scanner Toshiba Aquillion 64, allows to recommend the use of filtercompensating devices for places of concentration of high-tech medical equipment, as well as on tires of supply of ventilation and air-conditioning systems, LED lighting, elevators.

TABLE II. RESULTS OF ELECTRICAL NETWORK MEASUREMENTS ON CTE USING AN ACTIVE HARMONIC FILTER

Standard / Parameter	Normative parameters for GOST 32144-2013 (Russian Federation)	Normative parameters for IEEE 519 (USA)	Measured value	
			filtering enabled	filtering off
Frequency deviation	± 0.4 Hz	± 0.1 Hz	50.0 Hz	49.9 Hz
Power failure	5% < U < 90%	10% < U < 90%	-	-
Overvoltage	110% < U < 140%	110% < U < 140%	-	-
Voltage interruption	< 5 %	< 10 %	-	-
Voltage Deflection	± 10 %	± 10 %	-	-
Asymmetry of voltages	4 %	2 %	to 1.2%	to 2.0%
THDu (harmonics on voltage)	8%	8%	2,2%	3,2%
THDi (TDD) (harmonics on current)	Not normalized	12%	2,5%	40%
Voltage fluctuations (flicker)	1.38; 1	2	norm	norm
Power factor	Not normalized	Not normalized	0.99	0.99

The results of the quality analyzer measurements after the AHF installation revealed the following:

- the non-symmetry of the voltages when the filter is switched on shall be reduced from 2.0% to 1.2%.
- the value of the voltage harmonics when the filter is switched on is reduced from 3.2% to 2.2%.
- the current harmonic value reaches 40% when a computer tamograph is in operation, the filter activated suppresses the interference data up to 2.5%.

We have made a comparative calculation of the required number of active harmonic filters for the protection of medical equipment of ICDC for different manufacturers. The best price indicators and availability for the Russian market have shown filters of Sinexcel (China) (Table 3).

TABLE III. SELECTION OF ACTIVE HARMONIC FILTERS TO PROTECT ICDC MEDICAL EQUIPMENT

№	Installation location - block	Name	Design power (kW)	Quantity (piece)	Total filter load (kW)	Sinexcel (China)	
						Pattern	Cost (rub.)
1.	B	Angiograph	150	1	150	AHF 100A	1 614 200
2.	V	Radiotopical	35	1	35	AHF 50A	899 640
3.		Endoscopy	25	1	25	AHF 50A	899 640
4.		X-ray	88	1	88	AHF 75A	1 424 300
5.		Angiograph	150	1	150	AHF 100A	1 614 200
6.		Computer tamograph-2	110	1	110	AHF 75A	1 424 300
7.		Clinical diagnostic laboratory	238	1	238	AHF 150A	2 421 300
8.	G	Angiograph	150	1	150	AHF 100A	1 614 200
9.		Computer tamograph-1	100	1	100	AHF 75A	1 424 300
10.		MRT	150	1	150	AHF 100A	1 614 200
11.		Functional diagnostics department - 2	40	1	40	AHF 50A	899 640
12.	I	Functional diagnostics department - 1	30	1	30	AHF 50A	899 640
13.		Polyclinic	200	1	200	AHF 150A	2 421 300
14.		Ultrasonography	30	1	30	AHF 50A	899 640
15.	K	Bacteriological laboratory	100	1	100	AHF 75A	1 424 300
		total:	1596	15	1596		**21 494 800**

V. CONCLUSION

Despite the absence of mandatory monitoring of electrical energy quality indicators for health-care facilities of a special group, there is a need for continuous monitoring. This is due to the tendency to change the structure of the load, the emergence of an increasing number of semiconductor non-linear elements inducing interference, entering them into resonance.

Almost all diagnostic equipment is highly sensitive to violations of electrical energy quality indicators, for which the change of parameters of the supply electric energy is critical for normal functioning. Disruptions in the quality of electricity lead to a reduction in the accuracy of the imaging of diagnostic results, leading to study distortions and errors that may in some cases be fatal. These circumstances make the filtering of harmonics of such networks increasingly important.

When choosing a method of reducing the influence of higher harmonics, it is necessary, first of all, to analyze the source and nature of their occurrence, which depend on the factors caused by the operation of electrical equipment.

We offer a method of protection against violation of the quality indicators of electrical energy for the ICDC - the use of active filter compensation devices, which allowed to significantly reduce the asymmetry and the level of high harmonics of voltage and current. AHF is a versatile tool that can perform several functions simultaneously: reducing the level of higher harmonic components, correcting the power factor, reducing power loss, reducing the flicker, etc.

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