EPQU'09
10th International Conference
ELECTRICAL POWER QUALITY AND UTILISATION
September 15-17, 2009, Lodz, Poland

Electromagnetic Compatibility in the Industrial Electric Power Supply Systems

Igor V. Zhezhelenko, Yuri L. Sayenko, Alexander V. Gorpinich
Electrical Engineering Dept.
Pryazovskyi State Technical University
Mariupol, Ukraine

Abstract—**Over the past years, the problem of electromagnetic compatibility is becoming more and more prevalent among electric utilities' managers and engineering stuff. The main cause is the growing applications of nonlinear, unbalanced and intermittent loads in residential and industrial sectors. The definitions for electromagnetic disturbances, sources of distortions including rectifiers, frequency converters, arc furnaces, welding installations and wind turbines as well as their impact on electrical equipment, protective relaying and automatics are reviewed. Comprehensive analysis of the levels of harmonics, interharmonics, voltage unbalance and flicker in the industrial electric power supply systems is presented. Generalized approach to estimating the levels of electromagnetic disturbances is proposed. Most important passive and active solutions for cleaning up the distortions are discussed.**

Keywords-electromagnetic compatibility, harmonics, voltage unbalance, flicker, passive and active filters

I. INTRODUCTION

Compatibility of different entities, processes, populations, etc. is understood as a comfort existence of all these in the absence of the harmful impact on other entities. In electrical supply systems (ESS), electrical equipment, devices, apparatus and other appliances share common electromagnetic environment, so any of these devices is a source (in other words a generator) of electromagnetic disturbances (ED). At the same time the device is affected by ED from other sources.

Usually ED is defined as an action distorting the main signal and affecting (or being able to affect) one. Main signal is the useful signal characterized by the principle of operation of the electrical receiver, its control or protection system. Propagation of ED can exist either in space (the so called emission disturbances) or in conducting mediums (the so called conducted interference). The latter are representative for industrial ESS and propagate on lines, cables, busbars, conducting constructions, in electrolyte, different melts, etc.

The electric power supply system of an enterprise is the electromagnetic environment where generation, propagation and impact of ED on the electrical receivers occur. Therefore, electromagnetic compatibility (EMC) problem appears in such environment.

Electromagnetic compatibility is the ability of electrical equipment, apparatus and devices to function satisfactorily in its electromagnetic environment without causing intolerable electromagnetic disturbances to any other equipment in that environment.

In 1940s EMC problem has become topical for data-transmission system. Nowadays, its importance is recognized in all areas of generation, transmission and distribution of electric power [1].

In the industrial ESS, special attention is paid to conducted interference considered below. These ED are characterized by different voltage and current waveform distortions as well as effective voltage deviations in the three-phase networks of the industrial electric supply systems. Conducted interference as well as voltage sags and surges do not exhaust all types of disturbances. However, they are prevailing as they make the greatest impacts on the electrical receivers. Their values are usually referred to as EMC indices or power quality indices (PQI).

It is may be argued that power quality is the compliance (or noncompliance) of PQ values to parameters defined in the standards, regulations and another normative documents. PQ problem is an important part of EMC problem. Main aspects of EMC problem in the industrial ESS are considered below.

II. SOURCES AND TYPES OF ELECTROMAGNETIC DISTURBANCES

In the modern industrial enterprises more than half of electric power is used in the transformed form (at iron and steel works - more than 90 %). Widely applied rectifiers, different

978-1-4244-5172-2/09/$26.00 ©2009 IEEE

types of frequency converters, household appliances working both in static and transient modes are powerful ED generators. Nonlinear loads like electric arc furnaces (EAF), electric welding equipment, wind power units, power transformers and motors also generate significant ED. In Table I, ED sources in different branches of industry are presented.

TABLE I. INDUSTRIAL SOURCES OF VOLTAGE DISTORTIONS CAUSING DISTURBANCES IN STEADY-STATE CONDITIONS

Customer	Disturbances (PQI)
Man-made fiber manufacturing, pulp-and-paper industry	Voltage deviations
Machine construction industries with powerful electric welding equipment	Voltage deviations and unbalance, flicker
Ferrous metallurgy industry with electric arc furnaces	Voltage deviations and unbalance, harmonic distortion, flicker
Non-ferrous metallurgy industry (electrolysis)	Voltage deviations and unbalance, harmonic distortion
Enterprises with powerful one-phase electric receivers	Voltage deviations and unbalance
Traction substations of industrial ac electrified railway systems	Voltage deviations and unbalance, harmonic distortion

Valve converters are powerful concentrated sources of higher harmonics. In widely used 6-pulse bridge circuits so called characteristic harmonics are prevailing (5th, 7th, 11th, and so on). Their levels (relative to first harmonic) are reciprocal to harmonic number, i.e. 1/5, 1/7, 1/11, and so on. Theoretically, there is no 5th and 7th harmonics and 11th and 13th harmonics are prevailing if 12-pulse circuit is used. Such converters are installed in the main drive circuits of rolling mills, in electrolysis industry, etc.

Rolling mills operation without special fast-acting compensation system causes significant flicker. For example, flicker severity level about 10.5 can be occurred in 10-kV network of slabbing mill while in 110-kV busbars its value is about 2.2. In blooming mill, the flicker severity level can run to 4 and higher. In cold-rolling mill, the rate of reactive power surges runs to 2000 MVAR/sec at operation mode with metal pickup by rollers. This cause voltage sags with depth up to 10-20 % depending on rated voltage.

Frequency converters are widely used in the iron and steel works, machine construction and light industries. Beside characteristic harmonics, frequency converters generate interharmonics (components that are non-integer multiples relative to fundamental). Fig. 1 shows the block diagram of the frequency converter with DC link.

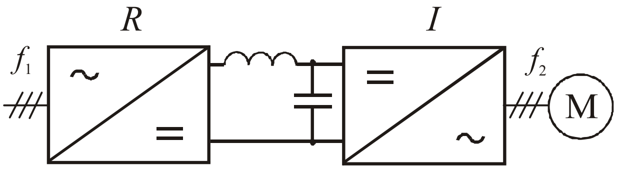

Figure 1. Frequency converter with reactor and capacitor as DC link (frequency converter with voltage inverter)

This frequency converter contains rectifier R, inverter I (usually, voltage inverter) and LC-filter. Input current spectrum is given by

$$f_i = (p_1 k \pm 1) f_1 \pm p_2 n f_2 , \qquad (1)$$

where p_1 and p_2 are the rectifier and inverter ripple, respectively; f_1 and f_2 are the rectifier and inverter frequencies, respectively.

As an example, the frequency spectrum around 7th characteristic harmonics is presented in Fig. 2.

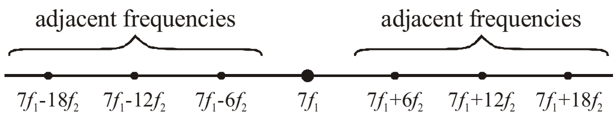

Figure 2. Adjacent frequencies spectrum 7th characteristic harmonics

Usually, $f_1 \neq f_2$; from Fig. 2 it follows that some adjacent interharmonics frequencies are appear around every characteristic harmonics.

Cycloconverters contain two back-to-back rectifiers (Fig. 3). The level of interharmonics varies depending on type of modulating function formed by control system and exceeds the level of characteristic harmonics.

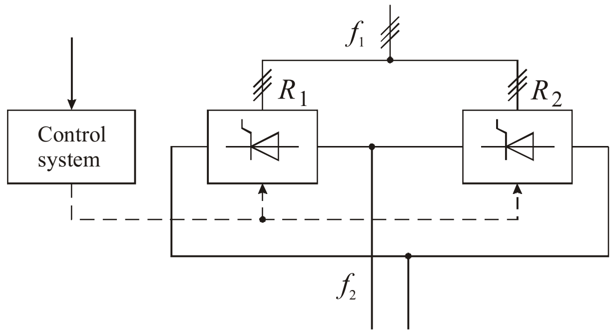

Figure 3. Block diagram of cycloconverter with one-phase output

From data in Table 2, comparative analysis of higher harmonics and interharmonics of the frequency converters with DC link and cycloconverters at different control laws may be executed.

Electric arc furnace is the powerful source of ED such as harmonics and interharmonics, flicker and voltage unbalance. Maximum ED generating is occurred in melting stage. Average harmonic current values generated by EAF, %, are given below

harmonic number	1	2	3	4	5	6	7	8	9
harmonic level	100	2.7	2.3	0.65	2.3	1.3	1.5	1	0.85

TABLE II. LEVELS OF HIGHER HARMONICS AND INTERHARMONICS OF THE FREQUENCY CONVERTERS AT DIFFERENT CONTROL LAWS

Defined parameter	**6-pulse bridge cycloconverter**					***3ph-3ph 6-pulse frequency converter with DC link, f_2 = 30 Hz***
	3ph-1ph at f_2 = 10 Hz				***3ph-1ph at f_2 = 20 Hz and sinusoidal control law***	
	linear control law	***sinusoidal control law***	***triangular control law***	***rectangular control law***		
Effective input current, %	147	208	183	173	128	113
Fundamental input current, %	100	100	100	100	100	100
Effective input harmonic current, %	9	23	24	33	56	42
Effective input interharmonic current, %	107	181	152	138	56	30
Excess of effective input interharmonic current over effective input harmonic current	in 12 times	in 8 times	in 6 times	in 4 times	in 1 times	in 1.3 times

EAF line current waveform is less distorted compared with valve converter one.

In 0-2.5 Hz range, interharmonics with up to 10 % of the fundamental current can appear.

Overall, there is mixed spectrum of EAF current variation containing discrete and continuous components in melting stage. Interharmonics energy for 100 ton- and 200 ton EAF is about 20 % of the whole mixed spectrum energy.

Depending on supply voltage, voltage unbalance on EAF busbars is up to 5-6 % for 6-10-35-kV networks and 3 % – for 110-kV-networks. In these cases, flicker severity level is about 1.5-10.

Electric welding installations (EWI) cause almost all ED such as harmonics, interharmonics, flicker, voltage sags and unbalance. In networks with EWI, voltage unbalance factor is about 1-5 %. For spot welding, interharmonics appear in 35-75 Hz range with amplitude up to 20 % of the fundamental welding current. For all EWI, discrete spectrum energy is about 6-20 % of the whole mixed spectrum energy.

Gas-discharge lamps (fluorescent and mercury arc lamps) are the sources of 3rd, 5th, 7th harmonics [2].

Wind power units are the powerful sources of ED, mainly harmonics and flicker. Long-term severity level up to 5-12, total harmonic distortion is about 5-8 %.

III. IMPACT OF ELECTROMAGNETIC DISTURBANCES ON ELECTRICAL EQUIPMENT, PROTECTIVE RELAYING AND AUTOMATION SYSTEMS

There are many factors that define specific character of the negative impact of ED depending on type of disturbances. In general, ED cause additional power losses in electrical equipment, decrease of its life span and functional reliability. At combined impact of several ED, overall effect is more severe than the one resulting from direct summing up of their values.

The following data show the range of consequences from cumulative impact of ED.

There are more than 700 million induction motors installed in the USA. At an average life of 30 years, motors are replaced at a rate of 23 million units per year. If the existing power quality conditions cause an average additional loss of life about 2 years, this results in the additional failure of 3 million motors per year. Investigations indicate induction motor life decreasing almost 2 times at 10 %-undervoltage.

Voltage unbalance in the industrial ESS is caused by powerful one-phase loads (induction melting furnaces, welding installations, electroslag refining furnaces) as well as three-phase loads continuously operating in unbalanced mode (e.g., EAF). If the enterprise's network is supplied from AC traction substation, three-phase voltage system can be unbalanced. In three-phase networks with voltage unbalance, additional power losses in supply system components, electrical equipment and lamps loss of life, decreasing of economic indices occur.

Voltage fluctuations have an adverse effect on visual perception of objects, components, graphic presentations and in final, labor productivity and eyesight of the employees.

Harmonics in the ESS cause additional power losses in electrical machines, transformers and networks. Voltage waveform distortion activates ionizing processes in the insulation of electrical machines and transformers. In this case, the insulation local defects are propagated causing increase of dielectric losses and decrease of life span. Other undesirable phenomena include aggravating of reactive power compensation, performance degradation of automation, telecontrol, instrumentation and communication systems, etc.

Keeping records of electrical energy in non-sinusoidal modes is accompanied with significant inaccuracies. Their level depends on measuring system of power meter, frequency response, place where the meter is installed (on linear or nonlinear load), etc.

Voltage sags (VS) (Fig. 4) are created by switching operations of powerful electrical receivers, overhead lines tripping during lightning with follow automatic reclosure, short-circuits in electric supply system, etc.

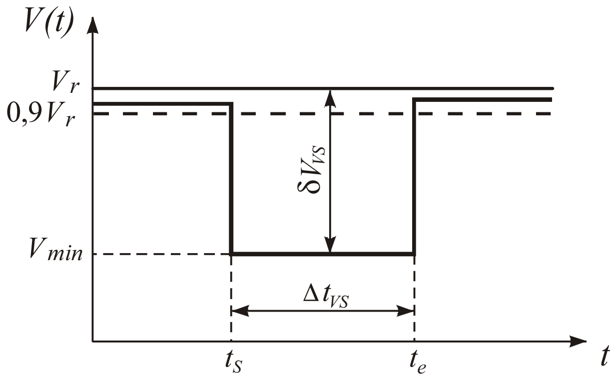

Figure 4. Voltage sag

VS have a most impact on automation, telecommunication and protective relaying systems usually referred to as disturbance sensitive elements (DSE). In some cases, functioning of DSE due to VS causes technological process stoppage. As a rule, permissible power interruption time for industrial customers is about 0.1-0.3 sec.

On rolling mills with microprocessor control system, steady operation is possible only at definite depths of voltage sag depending on its duration. Fig. 5 shows limits for steady operation of DSE of the drawing mill and at the numerical control machine. Programmable controllers, microprocessors and semiconductor relays refer to DSE. Fig. 6 shows its VS sensibility characteristics.

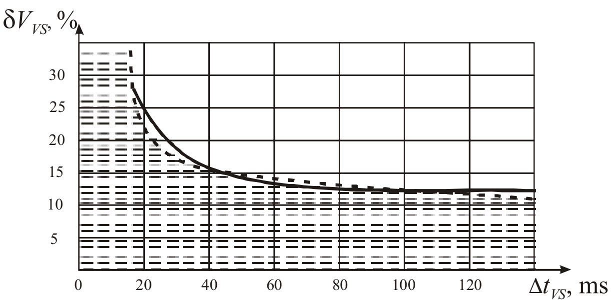

Figure 5. Limits for steady operation of DSE at network VS
— limit for drawing mill T-12;
--- limit for numerical control machine

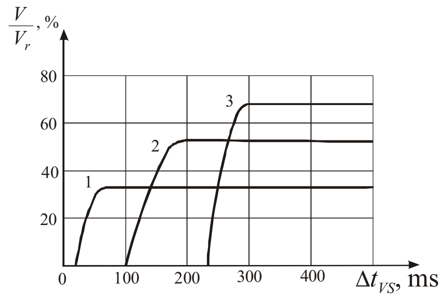

Figure 6. VS sensibility characteristics for programmable controllers (1), microprocessors (2) and semiconductor relays (3)

IV. Estimation of Electromagnetic Disturbances Levels

Estimation of ED levels (PQI values) in the nodes of industrial ESS is carried out by means of linear equivalent circuits that represent ED as driving currents (voltages). In nonsinusoidal modes estimations, ED is represented as harmonic current while impedances of elements are defined taking into account harmonic frequency. Similarly, in unbalanced modes estimations, ED is represented as negative phase-sequence current caused by unbalance while impedances of elements are defined taking into account negative phase-sequence.

Source of voltage fluctuations is represented by driving voltage source with short-term flicker severity P_{St} or long-term flicker severity P_{Lt}. Elements of equivalent circuit are represented as inductances. Types of loads and their characteristics for EMC estimations according to IEEE classification are presented below.

Loads	**Electric characteristics**
Incandescent lamps	Resistance
Fluorescent lamps	Nonlinear
Motors	Inductive
Computers	Nonlinear
Consumer electronics	Nonlinear
Electric heating units	Resistance
Conditioners	Inductive
EAF	Nonlinear
Valve converters	Nonlinear

Fig. 7 shows equivalent circuit for network with load defined as ED source. In general, node impedances of industrial ESS are nonlinear. Its amplitude-frequency responses (AFRs) have zero and pole combinations with number and placement depending on load variations. It is obvious that AFR minimums correspond to voltage resonance mode while AFR maximums correspond to current resonance (i.e., parallel resonance) mode.

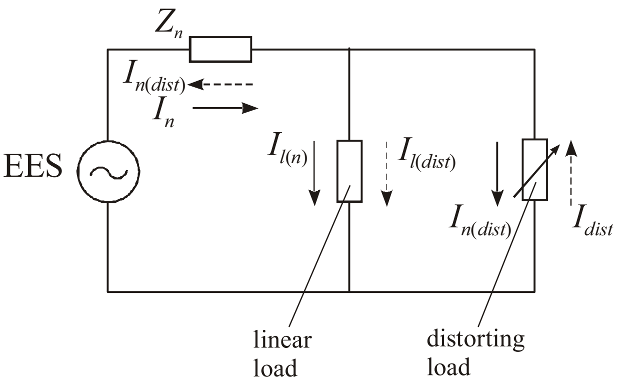

Figure 7. Equivalent circuit for network with load defined as ED source

V. Solutions for Mitigation EMC Problems

One of main techniques for mitigation EMC problems is the sharing of ED source loads (EAFs, rolling mills, EWIs, etc) and other loads (so called constant-power loads, e.g. lighting, motors, household appliances, etc.). The most popular hardware tools for loads sharing are the mutually coupled reactors, transformers with split secondary circuit and three-circuit transformers. Fast-acting static VAR compensators (SVCs) are widely used for mitigating voltage fluctuations. Fig. 8 shows schematic circuit and reactive power waveforms that illustrate the SVC operating principle.

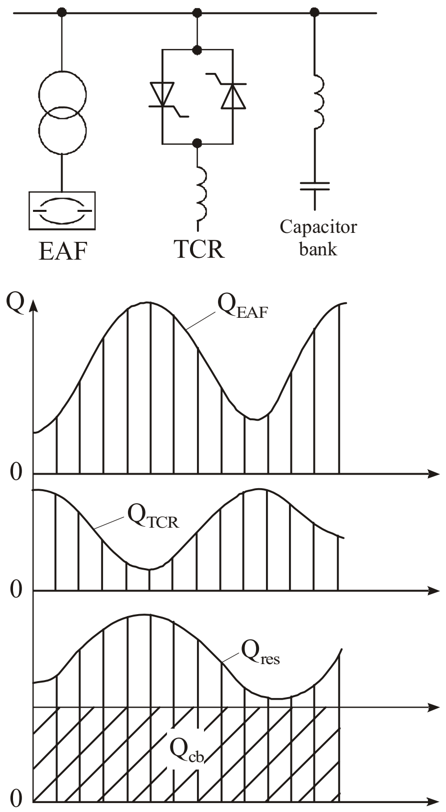

Figure 8. Schematic circuit of indirect acting SVC

The level of compensation of reactive power surges (and thereby voltage fluctuations) depends on control system delay time that must be as minimal as possible. Thyristors used as commutating keys in inductor's circuit generate higher harmonics. To suppress its level, resonant filters are connected to SVC busbars. Thus, SVC is the multifunctional device for suppressing voltage fluctuations, harmonic distortion and in some degree voltage unbalance. In practice, selection of SVC power is based on the reactive power surges with accounting permissible values of P_{St} and P_{Lt}. Second-order resonant filters (so called filter-compensating devices (FCD)) are also multifunctional. These devices are used for harmonics suppression, reactive power compensation and voltage regulation. 5th, 7th, 11th, 13th harmonic order filters and high-pass filter (see Fig. 9) are used in ESS with valve converters. 2nd, 3rd, and so on FCD are installed in electric supply systems with EAFs. The damping FCD is the practical solution for mitigating 2nd and 3rd harmonics as well as interharmonics in case of "dense" spectrum (e.g., at operation of cycloconverter with sinusoidal control law). Such FCD includes capacitor and inductor with the resistor inserted in parallel (Fig. 10).

Active filters (AF) are the increasingly popular solution [3]. Depending on circuits, this approach is used to obtain harmonics and interharmonics suppression, reactive power compensation, decreasing of depth and duration of voltage sags, voltage control on customer's buses. In general, AF is the source of fundamental reactive load current, harmonics and interharmonics to serve for its cleaning. Voltage inverters with thyristor or transistor circuitry are used as AFs. AFs are inserted either in parallel with load (Fig. 11) or in series with line.

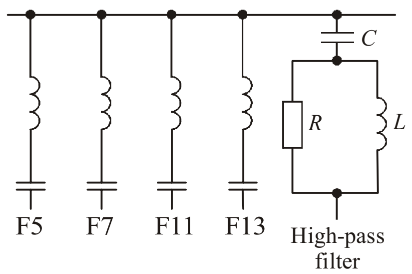

Figure 9. Circuit of the part of ESS with 5th, 7th, 11th, 13th harmonic order filters and high-pass filter

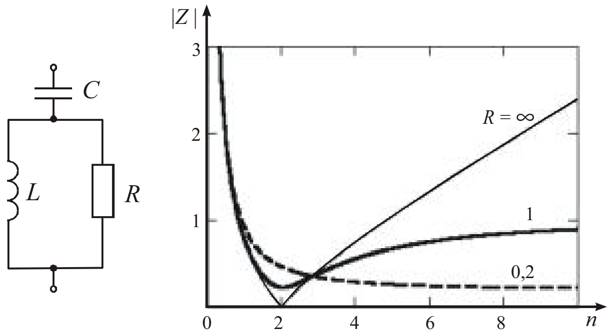

Figure 10. Second order filter and its AFR

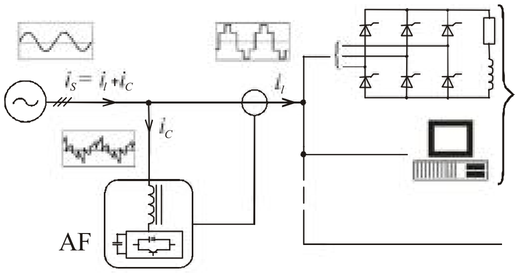

Figure 11. Schematic circuit of parallel AF

According to special algorithm, control device with transfer function $G(j\omega)$ forms control signals which allows AF generate compensating fundamental reactive current i_c, and harmonics' and interharmonics' currents, i.e. $i_S = i_l + i_c$ is theoretically only active current with practically sinusoidal waveform where i_l is the load current. Application of hybrid filters inserted in series or in parallel with FCD is the alternative solution to decrease costs on power quality improving. FCD is tuned to combat large harmonics while AF is used to obtain additional suppression of harmonic distortion. In this case, installed capacity of AF is considerably smaller. Hybrid filter with series and parallel connected AFs is called power quality conditioner. Table 3 characterizes operation of AFs and hybrid filters.

TABLE III. OPERATION OF AFS AND HYBRID FILTERS

Type of AF connection	Problem origin	
	Effect of load on the network	*Effect of network on the load*
Parallel	filtering of current harmonics reactive power compensation current unbalance voltage fluctuations	
Series	filtering of current harmonics reactive power compensation current unbalance voltage fluctuations voltage unbalance	voltage sags/surges voltage unbalance voltage distortion power interruption voltage unbalance
Series-parallel	filtering of current harmonics reactive power compensation current unbalance voltage fluctuations voltage unbalance	voltage sags/surges voltage unbalance voltage distortion power interruption voltage fluctuations

Nowadays, devices for power quality correction using superconductivity effect are being developed.

VI. CONCLUSIONS

The importance of electromagnetic compatibility problem is recognized in all areas of generation, transmission and distribution of electric power. In the industrial electrical supply systems, conducted interference as well as voltage sags and surges are prevailing as they make the greatest impacts on the electrical receivers. The main sources of electromagnetic disturbances are rectifiers, rolling mills, frequency converters, electric arc furnaces and welding installations.

There are many factors that define specific character of the negative impact of electromagnetic disturbances depending on type of disturbances. In general, electromagnetic disturbances cause additional power losses in electrical equipment, decrease of its life span and functional reliability. At combined impact of several electromagnetic disturbances, overall effect is more severe than the one resulting from direct summing up of their values. Voltage sags have a most impact on automation, telecommunication and protective relaying systems usually referred to as disturbance sensitive elements. In some cases, functioning of disturbance sensitive elements due to voltage sags causes technological process stoppage.

Generalized approach to estimating the levels of electromagnetic disturbances can be used. In nonsinusoidal modes estimations, electromagnetic disturbance is represented as harmonic current while impedances of elements are defined taking into account harmonic frequency. Similarly, in unbalanced modes estimations, electromagnetic disturbance is represented as negative phase-sequence current caused by unbalance while impedances of elements are defined taking into account negative phase-sequence.

One of main techniques for mitigation electromagnetic compatibility problems is the sharing of distorting loads. The most popular hardware tools for loads sharing are the mutually coupled reactors, transformers with split secondary circuit and three-circuit transformers. Most important passive and active solutions for cleaning up the distortions are fast-acting static VAR compensators, filter-compensating devices, active filters and power quality conditioners.

REFERENCES

[1] И.В. Жежеленко, Ю.Л. Саенко, Качество электроэнергии и его контроль на промышленных предприятиях, 4-е изд., перераб. и доп., М: Энергоатомиздат, 2005.

[2] И.В. Жежеленко, Высшие гармоники в системах электроснабжения промпредприятий, М.: Энергоатомиздат, 2004.

[3] H. Rudnick, J. Dixon and L. Morán, "Delivering clean and pure power", IEEE Power Energy Magazine, vol. , pp. 32-40, May 2005.