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UNIVERSITY”



**ELECTROMAGNETIC COMPATIBILITY IN ELECTRIC
POWER SUPPLY SYSTEMS**

Confirmed by Ministry of Education and Science of Ukraine as a textbook for students of higher educational institutions studying for the Masters' program

Editorship of the English version and terminology by Professor O.B. Ivanov

Translation from Ukrainian
by S.I. Kostrikska and L.O. Tokar

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The textbook is devoted to electromagnetic processes connected both with conducted and field electromagnetic interferences. Special attention is paid to interharmonic electromagnetic interference. Questions of electromagnetic compatibility in power networks with wind electric sets, problems of voltage dips and voltage impulses are considered. Active filters are considered as a specific problem of electromagnetic compatibility. Influence of electromagnetic fields on biosphere, of electromagnetic ecology, economic and legal problems of electromagnetic compatibility are presented.

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PREFACE

Today the problem of electromagnetic compatibility (EMC) is one of the most important and crucial along with problems of environment, power security and power and resources saving. Annual economic losses resulting from unsatisfactory compatibility level in industry and households are 100 to 500 billion Euros (according to different evaluations).

Works by noted scientists and practical engineers are devoted to solving theoretical and practical problems of EMC. The works find their reflection as in fundamental monographs and publications in scientific and technical journals as in materials of such international organizations as IEC, CENELEC etc. In Ukraine, monographs and other works of such specialists in the field of EMC as A.K.Shidlovski, V.G.Kuznetsov, E.G.Kurenyy and others are widely known. In Russia, a team of authors from MPEI (TU) under the editorship of A.F.Diakov, I.I.Kartashev and others should be mentioned.

Generally, European universities have EMC course in their curricula. Since 2002, the course is professed at technical universities in Russia. Textbooks and study guides on EMC course have been written and published under the editorship of Professor M.V.Kostenko (SPTU), Professor G.Ya.Vagin (Nizhniy Novgorod TU) and a number of others. In 1990 the study guide "Theoretical Background of EMC" was developed in Ukraine. But a textbook on EMC is not available till now. In the existing publications either radiated electromagnetic interferences (EMI) or conducted interference are considered without account of industrial production processes or households peculiarities

Comprehending importance of training specialists possessing knowledge in the field of EMC, authors aimed at creation this textbook for students being taught by the Masters' Program. We believe that EMC course should complete the cycle of professional electrical engineering subjects. It is why the textbook is aimed for the students preparing for the Master's degree.

The text-book considers electromagnetic processes connected both with conducted and field electromagnetic interferences. This material is given in the first two parts of the textbook. The third part is devoted to economic and legal problems of EMC. In the first part special attention is paid to interharmonic EMI which emission depends on performance of variable frequency drive systems. This type of adjustable-speed electric drives is widely used in industry and residences. Questions of EMC in power networks with wind electric sets are considered. Particular attention is paid to comparatively new problems of voltage dips and voltage impulses. Hardware components on the basis of active filters are considered as a specific problem of EMC negative influence compensation.

In the second part of the book modern data concerning influence of electromagnetic fields on biosphere, that is problems of electromagnetic ecology, are presented.

Developing the book authors used available home and world sources including materials of the end of 2008. Personal experience as a result of research and applied

activities carried out at industrial enterprises, municipal facilities and leading design institutions of CIS countries was substantial while the textbook preparation. Materials of doctoral dissertations and doctorate theses recently supervised by the authors (or under active their advising) are used too.

Annexes include some informational and directive materials and topics of Masters' theses which importance, we believe, meet the requirements of EMC theory and practice.

Authors

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PART 1

CONDUCTED INTERFERENCE

CHAPTER 1

IMPORTANCE OF ELECTROMAGNETIC COMPATIBILITY FOR ELECTRICAL ENGINEERING EDUCATION

1.1. Major statements

As a science, electrical engineering covers a number of known divisions, which specific character allows consider them as independent subjects for educational institutions (or faculties) in the field of electrical engineering. Among them are “Electric Power Supply of Industrial Enterprises”, “Electrical annex of power plants and substations”, “High-voltage engineering”, “Electromagnetic transients” etc. In the course of studying electromagnetic processes are considered in compliance with these subjects specificity, including tasks of analysis and synthesis, design features, modes etc. But problems of mutual influence of separate devices, their influence on electromagnetic situation on the whole, on wildlife (biosphere) are beyond focus of interest of the subjects.

The discipline of electromagnetic compatibility of technical devices considers devices and processes, described in traditional courses on Electrical Engineering, from the point of view of electromagnetic disturbances generation, their influence on electrical equipment, extent of automation implementation and the disturbances negative influence compensation.

Give some examples which show specific character of EMC course. Power circuit-breakers, their structure, types, characteristics etc. are studied in the course of electrical annex of power plants and substations. While EMC analyzing the switching processes are investigated: electromagnetic disturbances in the form of switching impulses, surge voltage and other effects. In studying teleautomatics important problem from the point of view of EMC is the problem of electromagnetic disturbances (EMD) in communication channels (mainly, high-frequency). In studying electronic control systems, there are the problems of immunity to noise.

In variable-frequency electric drives one of the most essential sides is influence of EMD on supply networks, especially harmonic and interharmonic EMD.

The wind powered electric sets despite their advantages generate a number of EMD.

Thus, EMC is independent, specific branch of applied electric engineering in which such questions of theory and practice of EMD as generation, influence on electric equipment (EE), and the influence correction are studied.

Electromagnetic compatibility is global problem within which a line of sub-problems are considered. Such ecological problems as compatibility of power industry and noosphere (according to theory of Academician Vernadsky – the sphere of

human thought) are in the forefront of the problem. Tentatively, the problem can be divided into five groups (Fig. 1.1):

- electromagnetic compatibility of power industry with environment (ENV-EMC);
- compatibility with biosphere (BIO-EMC);
- compatibility with extended metal constructions of technosphere (TECHNO-EMC);
- compatibility with informative, computer and radio electronic sphere (E-EMC);
- internal compatibility (IN-EMC), i.e. compatibility of subsystems of the electric power industry.

In the course of operation of different systems (e.g., substations) and subsystems (e.g., transformers) the problems may interweave and partially duplicate each other.

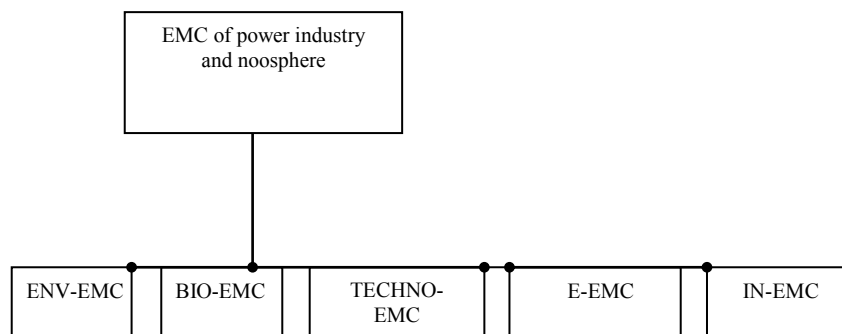


Figure 1.1 Main Groups of EMC in Electric Power Industry

ENV-EMC concerns problems of atmospheric electricity, galvanic corrosion, electromagnetic storms and after-effects of large land areas assignation for power stations and high-voltage transmission lines.

BIO-EMC problems are connected with initiation of dangerous touch and step voltages as well as interfering effects.

Dangerous effects at power frequency and high frequencies belong to the field of TECHNO-EMC.

E-EMC also covers problems of interfering effects (surges, voltage jumps etc.).

IN-EMC studies problems of EMC of different subsystems of electrical power system violation.

1.2. Electromagnetic compatibility: history and development

At the end of 19th century, discoveries in physics and search for serious engineering solution promoted becoming the electrical engineering into one of the most crucial sciences. At the same time further development of electrical engineering and in-

roduction of its results into practice of all branches of technology, and later in households, stipulated development of electrical power engineering which formation in its basic components took place during the period of 1870-1930.

At the beginning of this period after building of first industrial power plants and transmission lines, invention of electrical energy meters and legalization of selling and buying of electric power it became a subject of commodity-money relations that is an article of trade. Like any article of trade the electric power has user value that means its accordance with some, mainly specific, qualitative indices. The indices values (or grades) should not go beyond given (or assumed) limits. Just in the last decades of 19th and the early ones of 20th century the first international organizations as well as normative documents developed by them started up to regulate activities and interaction of the electric power industry subjects. In 1884 the first “Electric Installation Code” - the prototype of current EIC - was introduced in England. In 1904 International Electrotechnical Commission (IEC) was established to coordinate activities in standardization the field of electrical engineering, electronics and related areas of knowledge in Europe. In 1921 an international organization named CIGRE - International Council on Large Electric Systems was established. Its activity aimed was at solving problems of “Great Energetics”. In 1884 was founded the non-commercial association IEEE (The Institute of Electrical and Electronics Engineers). Now, it includes more than 360,000 people from 150 countries.

In CIS countries, different standards, provisions, regulations and other normative documents in the field of electrical engineering and energetics were developed from before the World War II. Nowadays, the standard ГОСТ 13109-97 “Interstate Standard: Quality Standards of Electric Power within general-purpose power supply systems is one of the most important guiding documents.

As far back as in the thirties of previous century, at one of Belgian industrial enterprises was observed that on weekends when power consumption was less than usual, and mains voltage increased (obviously, voltage control was not provided), banks of capacitors strongly got hot and failed after a while. Technical literature of that time classified such cases as lack of electromagnetic compatibility between power network and one of equipment components. It was the first known mentioning of electromagnetic compatibility – EMC.

In the fiftieths and sixtieths of the previous century intensive introduction of power electronic converters (power electronics) into industry as well as use of electronic and microelectronic devices for control and measuring started. Negative consequences of power electronic components influence and interaction inspired concepts of electromagnetic disturbance (EMD), its sources, and, by analogy with radio engineering, disturbance sensing elements (DSE) – receptors perceiving the EMD. As a rule, the interference had harmonic nature and up to the end of previous century harmonics within electric power supply systems were considered as the major type of EMD. Nowadays, due to deterioration and substantial worsening of electric power industry assets state (their deterioration is 70-80% in Ukraine and Russia) more essential became interference due to internal and lightning overvoltage, voltage dips and pulses. By the way, voltage pulses were not mentioned in standards up to 1997.

In 1976 the IEC Technical Body no. 77 adopted such a definition of EMC: “*Electromagnetic compatibility* (between device and its environment or between devices) is the ability of an equipment function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment. According to the above EMC problem has the following two key aspects:

- a) stability of object (or system) under electromagnetic disturbances
- b) emission of electromagnetic disturbances within certain medium, e.g. industrial environment, trade environment, housing environment etc.

It is also mentioned that problem of power quality (PQ) is a component of EMC problem. Such interpretation is formulated in IEC and European standards. For example, EN 61000-33-1995 standard is titled “Electromagnetic Compatibility Limits. Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems for equipment with rated current 3L 16A per phase are not subject to conditional connection”.

However, the power quality problem became so extensive area of activities in electrical engineering and particularly in electric power industry that it can be treated separately equally with other EMC problems.

In the USSR worked task group TK77. It consisted of: Chairman PhD V.N. Niki-forov (VNIIE, Moscow), Vice-Chairman I.V. Zhezhelenko, (ZhdMI, Ukraine), Dr. Yu.S. Zhelezko,(VNIIE), Dr. M.S. Libkin, (Krzhizhanovsky Research Institute ENIN, Moscow), Dr. R.R.Mamoshin, (MIIT, Moscow), Dr. V.G.Kuznetsov, (IED, Kiev).

Interstate standard ГOCT 30352-45 “Electromagnetic compatibility of devices; terms and definitions” determines *EMC of devices* as: “property of the components to function with given quality in a given electromagnetic environment without inadmissible electromagnetic interference against other components”.

Electromagnetic compatibility of devices is one of the most important and independent parts of electrical engineering and electric power engineering. Alongside with electric power networks and systems, high-voltage engineering, power system protection and automatics, it remains one of the most important parts of theory of reliability.

In the further text we will often specify the electromagnetic compatibility of devices as EMC for short.

1.3. Basic concepts and terms

Electromagnetic compatibility of devices is a part of electrical engineering. In wide sense, electrical engineering is extensive area of practical application of electromagnetic phenomena. It is the field of science that study electromagnetic processes and opportunities for use electromagnetic field in practice.

Theoretical fundamentals of electrical engineering (or theory of electrical engineering) study electromagnetic phenomena and processes (as well as their compo-

nents) in electric devices and systems, methods of their analysis and synthesis. This subject is the basis for study special subjects on Electrical Engineering.

Electric power engineering considers problems of generation, power transmission, conversion of electric energy, electricity storing and distribution of electricity. These processes give rise to initiation of definite electromagnetic environment, electromagnetic disturbances generation, their influence on electrical equipment, automatic control systems, monitoring and telecommunication systems.

It is necessary to give definitions of major concepts and appropriate terms. In Europe, terms and definitions concerning EMC given in The International Electrotechnical Vocabulary (IEC 60050) and in the technical report IEC 61000-1-1 are used. As for CIS countries, ГOCT 30372-95 “Interstate Standard. Electromagnetic compatibility of devices. Terms and definitions” and ГOCT 13109-97 (Chapter 3. Definitions, symbols and abbreviations), Standard of Russia ГCTP50397-92 and Ukrainian standards are used. In specific cases we will refer to suitable standard (Appendix 1).

Now give some most common definitions.

Electromagnetic disturbance is electromagnetic phenomenon which may degrade the performance of a device, equipment or system, or adverse effect living or inert matter. Within electric power supply systems (EPSS) electromagnetic disturbances are always available. All components of electrical facilities generate the disturbances (that is, are sources of electromagnetic disturbances emission) being at the same time receptor units (that is, objects of the electromagnetic disturbances influence).

EMC theory and practice consider those of them which influence is substantial from the point of view of power or another type of impact, electric equipment parameters selection etc.

Devices are electrical, electronic or radio-electronic items (equipment, apparatuses or a system) as well as a product which contains electric and/or electronic components (circuits).

Reaction of a device on EMC influence depends on its susceptibility to disturbances (electromagnetic susceptibility) and immunity to interference. By definition, *susceptibility to disturbance* is inability of a device to perform without degradation in the presence of an electromagnetic disturbance; *immunity to interference* is the ability of a device to reduce or reject the effect of interference to electromagnetic disturbances with specified parameters if extra protection equipment against EMI is not available or when the protection equipment do not belong to the device mode of functioning or construction).

Figure 1.2 shows *electromagnetic environment* that is combination of electromagnetic phenomena and/or processes within a given spatial region and/or conducting medium in a frequency range or a time interval.

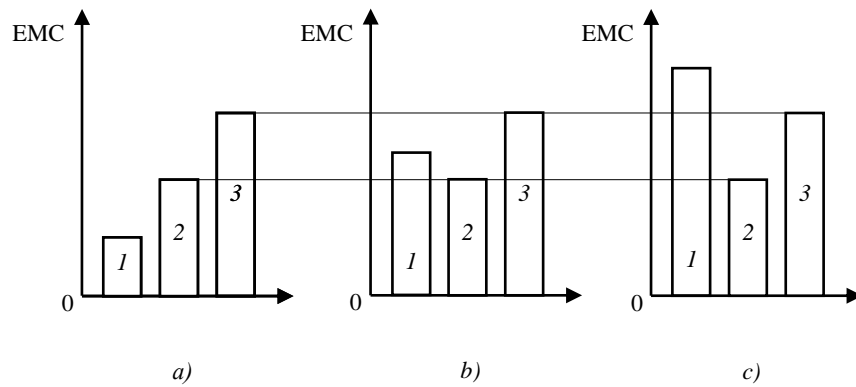


Figure 1.2. Electromagnetic environment:
a – adequate performance of a device; *b* – adequate performance of a device takes place if action of a disturbance is short-time; *c* – adequate functioning of a device is not possible

In Fig. 1.2 are shown levels of electromagnetic disturbances (1) in the point of a device connection to a power network. The device minimum immunity limit (2) and its maximum immunity level (3) unchanged, but electromagnetic disturbance levels in the power network increase. Case *a* corresponds to a required performance of the device. In the case *b* action of EMD was short-time and the device remains capable of operating. In the case *c* the device lose its capability to operate at a required degree of performance.

Limit of disturbance is the maximum permissible electromagnetic disturbance level, as measured in a specified way.

In practice there is diversity of aspects concerning generation and influence of electromagnetic disturbance on electric power system and its components, and objects of influence are so numerous that their classification is rather difficult and highly relative. Hereafter we will proceed from “branch approach” and consider EMC in electric power supply systems of enterprises.

Electromagnetic disturbances may be divided into the two groups. *Natural disturbances* (or *field* ones) are product of lightning discharges and geomagnetic phenomena. Origin of *man-made disturbances* depends on performance of devices, overhead transmission lines, electronic equipment and other control devices. Both types of electromagnetic disturbance are considered in this book.

Depending on medium in which an electromagnetic disturbance propagates *conducted* and *radiated disturbances* are distinguished. The radiated disturbances are propagated in the forms of electric, magnetic or electromagnetic field. These electromagnetic disturbances are also considered in the text-book.

High-frequency and low-frequency electromagnetic disturbances, electromagnetic disturbances with continuous and discontinuous spectrums are considered in chapters devoted to harmonics and interharmonics.

Other types of electromagnetic disturbances are of secondary importance as they are less typical for electric power supply systems of industrial enterprises. Glossary

contains terminology and definitions of electromagnetic disturbances used in theory and practice of EMC.

1.4. Guidelines concerning the course study

The course of electromagnetic compatibility, as a part of Masters' Program, completes the series of subjects on Electrical Engineering forming the up-to-date basis for Masters' of electrical engineering education.

For this reason we hardly recommend to look the manual through at the very beginning of the course study. Pay attention to the questions reflected in the previously studied courses and to be farther considered from the point of view of EMC. For example, drawing attention to questions of EMC of electrical machinery and transformers, it makes sense to refer to synopses or manuals on electric machines where insulation problems are considered. While studying problems of influence of electromagnetic fields on biosphere within EMC course it is expedient to look through questions of electromagnetic field theory from the course of fundamentals of electrical engineering. We believe these two examples bring you to understanding that this subject is synthetic one. Previously mastered electrical engineering courses serve as a basis for it. It is worth saying that the listed courses are notably established and stable. It takes decades to make their essential modifications. It cannot be applied to EMC course which has not been finally shaped yet. Continually new types of electromagnetic disturbances reveal, it is necessary to determine new aspects of their influence on technical devices, develop absolutely new compensating devices (e.g. based on superconductivity etc.) and new computational methods (e.g. on the basis of wavelet-transform etc.) as EMC is dynamic and intensively developing branch of electrical engineering.

That's why we recommend you not limit yourself to this text-book. It is necessary to advert to supplementary sources listed in the text-book, journals, materials of scientific and technical conferences (annually as many as 30 international conferences are held), and to Internet. It is the only way to master EMC course. It is equally important for you to learn to enrich your knowledge by self-study. It goes without saying that your lecturers will help you directing where, when and what kind of extra materials you can find.

Obligatory use of Internet will force you to master English to the needed extent. Undoubtedly, knowledge of mathematical methods used in EMC theory is important. Mainly, you studied them while learning mathematics and other special courses. Annex 2 reminds some of them. Some rarely used methods (e.g. commutation functions) will be explained hereafter.

The handbook contains a list of recommended graduation Masters' Theses. Regard to their preparation seriously from the very beginning of your study.

We believe that cooperation of students and instructors guarantees successful mastering the EMC course.

Test questions

1. What is EMC?
2. What is importance of consideration of electromagnetic disturbances effect on industrial enterprises power supply system?
3. What is conducted disturbance?
4. Define a concept of power quality.

Topics for essay

1. Emergence and development of electromagnetic compatibility theory and practice.
2. Mathematical methods in the theory of electromagnetic compatibility.
3. Interdependence between electromagnetic compatibility and electrical engineering.
4. Conducted and radiated disturbances.
5. Economic aspect of the electromagnetic compatibility problem.

2.1. Standardization of indices

Normalization of figures of electromagnetic compatibility (or figures of power quality) is one of the key items of electromagnetic compatibility problem.

As a rule, process of voltage variation within electric power supply systems of industrial enterprises is random: voltage $U(t)$ variation is rather slow in power networks with surgeless loads, and it is rather quick process in networks with sharply varying (impact) loads. It is expedient to use mathematical tools of spectral theory of random processes for obtaining sufficient estimators of electromagnetic disturbance effect on electric equipment and the power system dynamics. As electromagnetic disturbance has energetic meaning, figures of EMC (figures of power quality) are estimated by means of ratio of electromagnetic disturbance power spectrum $G(t)$ to the rated fundamental frequency voltage. Fig. 2.1 shows qualitatively the curve of the voltage power spectrum $G_U(f)$.

According to ДСТ 13109-97 standard the system of power quality figures at supply from three-phase power networks consists of the voltage deviation δU_s ; range of voltage deviation δU_t (in our case, it is values of the voltage fluctuation); intensity(dose) of flicker P_t ; distortion factor K_U ; n th harmonic ratio $K_{U(n)}$, voltage unbalance factors of negative sequence K_{2U} and zero-sequence K_{0U} ; duration of

voltage dip Δt_d ; voltage pulse size U_p ; factor of temporary overvoltage K_{ou} ; frequency deviation Δf .

Frequency band within 0–10 Hz characterizes the voltage deviation; range of voltage deviation δU_t is determined with the help of the expression (within frequency intervals $f_2 \leq f \leq f_4$ and $f_3 \leq f \leq f_1$):

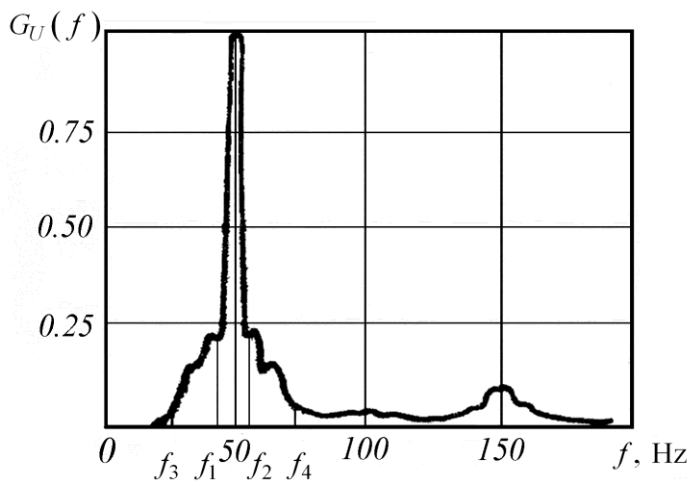


Figure 2.1. Curve of voltage power spectrum

$$\delta U_t = \sqrt{\frac{\int_{f_2}^{f_4} G_U(f)df + \int_{f_3}^{f_1} G_U(f)df}{\int_0^{\infty} G_U(f_0)df}}$$

$$\frac{\sqrt{\int_{f_2}^{f_4} G_U(f)df + \int_{f_3}^{f_1} G_U(f)df}}{U_r}$$

The interval $f_1 \leq f \leq f_2$ corresponds to voltage deviation that equals to:

$$\delta U_s = \sqrt{\frac{\int_{f_1}^{f_2} G_U(f)df - \int_0^{\infty} G_U(f_0)df}{\int_0^{\infty} G_U(f_0)df}} = \frac{\sqrt{\int_{f_1}^{f_2} G_U(f)df - U_r^2}}{U_r}$$

Distortion factor and voltage unbalance factor are

$$K_U = \frac{\sqrt{\int_{f_4}^{\infty} G_U(f)df}}{U_r}, K_{2V} = \frac{\sqrt{\int_0^{\infty} G_U(f)df}}{U_r}$$

Known expressions to determine figures of power quality (FPQ) according to ДСТ 13109-97 follow from represented expressions.

Principles of normalization of power quality with respect to the voltage are based on technical-and-economic approaches and are as follows:

a) Figures of power quality in regard to the voltage have energetic meaning, i.e. they characterize power (energy) of voltage curve distortion. The degree of the negative effect of distortion energy on electrical equipment and production processes are compared with the figure of power quality.

b) Limiting values of power quality figures are selected proceeding from technical and economic reasons.

c) Power quality indices are valuated within definite period of time with preset expectancy to obtain true enough and comparable values

d) Accepted values of a power quality index are pointed out on terminals of using equipment (UE) and in network nodes.

System of power quality indices based on these preconditions may also be used for design practice. It permits to execute wholesale measurement assurance of the power quality control with the help of relatively simple and cheap devices as well as implementation measures and methods of power quality assurance.

In CIS countries Standard ДСТ 13109-97 "Quality Standard of Electric Power within Supply Systems of General Duty" was adopted. Admissible values of power quality figures established by the Standard mainly in regard to EMC meet recommendations of IEC to be implemented in National Standards.

In Europe and in particular in EU countries the regulatory base for using equipment EMC assessment includes widely known standards as:

– European Standard EN 50160 "Voltage characteristics of electricity supplied by public distribution systems" (1994);

– IEC standard IEC 1000-2-6:1995 “Electromagnetic compatibility (EMC). Environment. Assessment of the emission levels in the power supply of industrial plants as regards low-frequency conducted disturbances”.

The Standard specifies requirements concerning EMC within power networks of enterprises. Using equipment of enterprises belongs to the three classes of EMC levels depending on levels of equipment used:

Class 1 Susceptible electrical equipment (computers, computer centers, systems of automatics and telecommunications etc.);

Class 2 Using equipment which does not produce significant electromagnetic disturbance (lighting, metal-cutting equipment etc.);

Class 3 Converters of current and frequency, abruptly variable load, electric welding etc.

Such loads as arc furnaces and rolling mills belong to separate class.

Comparison of requirements to EMC established by these standards shows that requirements of ДСТ 13109-97 concerning deviations of the voltage and frequency, and distortion factor is 2-3 times tougher to compare with the two mentioned above standards. Standards of IEC and EU establish levels of EMC at different points of power network to which different using equipment is connected. As for ДСТ 13109-97 some indices are standardized for the network, and others – on terminals of using equipment.

In all mentioned standards, values of every index of power quality are pointed out without regard to possible influence of other power quality indices. This problem has to be solved in the course of the following study.

Countries of North and South America as well as some African countries had adopted American standard IEEE Standard 519 which sets limitations concerning harmonics. Unlike European Standards, values of the load current harmonics produced by the load nonlinear part in a point of general connection are limited.

Standard ДСТ 13109-97 determines two types of norms concerning power quality - *normally allowable* values and *maximum allowable* values. Assessment of conformity of a power quality index with specifications is performed within estimated time equal to 24 hours.

2.2. Power quality standards

Quality of electricity should meet requirements of ДСТ 13109-97.

Following indices of power quality are normalized by the Standard ДСТ 13109-97 put in force from 01.01.1999.

Steady voltage deviation δU_s :

$$\delta U_s = \frac{U_{av} - U_r}{U_r} 100, \%$$

where U_{av} is averaged voltage value (V, kV) within a minute interval; U_r is rated voltage;

$$U_{av} = \sqrt{\frac{\sum_{i=1}^N U_i^2}{N}}$$

where U_i is voltage value of the i th observation, V, kV; N is number of observations.

Number of observations within a minute time interval should not be less than 18.

According to ГСТ 13109-97 allowable deviation across terminals of using equipment should be within limits of $\pm 10\%$ of U_r during 24 hours, and 95 % of the 24 hours voltage deviation should be within $\pm 5\%$ of U_r .

Both allowable and maximum allowable values of steady voltage deviation in the points of consumer connection to power networks should be stipulated in agreements for use of electricity between a power supplier and a consumer with account of necessity to meet the requirements of standard on terminals of using equipment.

Non-sinusoidal voltage waveform

The voltage waveform is characterized by the following indices:

- the distortion factor of the voltage curve K_U , %
- the n th voltage harmonic ratio $K_{U(n)}$, %.

These indices are determined by the expressions

$$K_{U(n)} = \frac{U_n}{U_r} 100$$

$$K_U = \sqrt{\sum_{n=2}^{40} U_n^2} \frac{100}{U_r}$$

where U_n is rms value of the n th voltage harmonic, V, kV.

Both allowable and maximum allowable values of the voltage distortion factor in the points of general connection to power networks are shown in Table 2.1.

Table 2.1

Values of distortion factor of voltage curve, %

| Allowable Values | | | | Maximum Allowable Values | | | |
|------------------|------|-----|---------|--------------------------|------|-----|---------|
| U_r , kV | | | | U_r , kV | | | |
| 0.38 | 6–20 | 35 | 110–330 | 0.38 | 6–20 | 35 | 110–330 |
| 8.0 | 5.0 | 4.0 | 2.0 | 12.0 | 8.0 | 6.0 | 3.0 |

Allowable values of the n th voltage harmonic ratio in the points of connection to power networks with rated voltage U_r , for networks of 0, 38 kV and 6–20 kV are giv-

en in Table 2.2.

Table 2.2

Values of voltage harmonic ratio, %

| Harmonics | n | U_r, kV | |
|--|-----|-------------------------|--------------------------|
| | | 0.38 | 6-20 |
| Non-multiple of 3 odd harmonics at rated voltage U_{nom} , kV | 5 | 6.0 | 4.0 |
| | 7 | 5.0 | 3.0 |
| | 11 | 3.5 | 2.0 |
| | 13 | 3.0 | 2.0 |
| | 17 | 2.0 | 1.5 |
| | 19 | 1.5 | 1.0 |
| | 23 | 1.5 | 1.0 |
| | 25 | 1.5 | 1.0 |
| | >25 | 0.2+ | 2.2+ |
| | | $13 \cdot \frac{25}{n}$ | $0.8 \cdot \frac{25}{n}$ |
| Odd harmonics multiple of 3 at rated voltage U_r , kV (for single-phase systems) | 3 | 5.0 | 3.0 |
| | 9 | 1.5 | 1.0 |
| | 15 | 0.3 | 0.3 |
| | 21 | 0.2 | 0.2 |
| | >21 | 0.2 | 0.2 |
| Even harmonics at rated voltage U_r , kV | 2 | 2.0 | 1.5 |
| | 4 | 1.0 | 0.7 |
| | 6 | 0.5 | 0.3 |
| | 8 | 0.5 | 0.3 |
| | 10 | 0.5 | 0.3 |
| | 12 | 0.2 | 0.2 |
| | >12 | 0.2 | 0.2 |

Note: n is the number of the voltage harmonic; the allowable values given for n equal to 3 and 9 relate to single-phase system. In three-phase three-wire power systems the values are half as much as indicated in the Table.

Maximum allowable value of the n th voltage harmonic ratio is determined by the formula:

$$K_{U(n)\max} = 1.5K_{U(n)\text{norm}}$$

where $K_{U(n)\text{norm}}$ is normally allowable value of the n th harmonic ratio.

Voltage unbalance

Voltage unbalance is characterized by:

- The factor of voltage unbalance of negative sequence K_{2U} , %;
- The factor of voltage unbalance of zero-sequence K_{0U} , %.

These factors are determined according the expressions:

$$K_{2U} = \frac{U_{2(1)}}{U_r} 100$$

$$K_{0U} = \frac{U_{0(1)}}{U_r} 100$$

where $U_{2(1)}$ is rms value of the voltage negative sequence of the three-phase voltage system fundamental frequency, V, kV; $U_{0(1)}$ is the same for zero-sequence of the fundamental frequency, V, kV, and U_r is rated value of the line-to-line voltage, V, kV.

Both allowable and maximum allowable values of the voltage unbalance factor by the negative sequence in the common points of connection are 2.0% and 4.0 % accordingly.

The allowable and maximum allowable values K_{0U} of four-wire systems with the rated voltage of 0.38 kV are equal to 2.0% and 4.0 % accordingly.

Frequency deviation Δf (Hz) is determined by the expression

$$\Delta f = f_{av} - f_r$$

where f_{av} is the mean frequency value within 20s time period; f_r is the rated frequency, Hz. According to ДСТ 13109-97 normally allowable and maximum allowable values of the frequency deviations are ± 0.2 and ± 0.4 Hz.

2.3. Standardization of voltage fluctuation

The fluctuation is rapid variation of rms voltage value having speed of 1-2% per second or more.

The voltage fluctuation on terminals of using equipment occurs due to rapid variations in power consumption by consumers with rapidly varying consumption. Such consumers are:

- arc furnaces;
- rolling mills;
- installations for arc and contact welding;
- electric saws;
- rolling machines;
- pressure pumps;
- compressors;
- lifts;
- cranes and winches;

- x-ray units;
- refrigerators;
- air conditioners etc.

Fluctuation of load caused by such consumers is either of determined nature or of random one. Accordingly, the voltage fluctuation in a power network may be either determined (rarely) or random (more often). The voltage fluctuation caused by changeable load, first of all by the industrial ones, transferred over the network giving rise to the fluctuations on terminals, including terminals of quiet loads. Also they are transferred into household electric mains affecting performance of many consumers and electrical equipment as well as peoples' sight and human body as a whole.

As a result of light flux flickering of an optical source fast fatigue of vision occurs. Light flickering is the main and common criterion of negative effect of voltage fluctuation. So, ergonomic approach was used for the fluctuation standardization. Evidently, people in view of individual differences absolutely variously perceive oscillations of light flux. That is why in seventies technical body no.77 of IEC introduced *the standard characteristics*:

- Fluctuation of light flux (flicker) is assumed to be in the shape of a meander.
- Dependence of range (amplitude) of oscillations on repetition frequency are given as curves of allowable values.
- Amplitude-frequency characteristic (AFC) of visual analyzer (receptor) fits the curve (or curves) of allowable values.

The voltage fluctuation is characterized by the amplitude (range of fluctuation) δU_t , by frequency f and time intervals between the following each other voltage variations Δt_k , and by intensity of incandescent lamps flickering which irritates the human vision that is called the intensity of flicker (IF) or the voltage flicker (VF).

The value of IF also called "*dose of flicker*" (DF) is related with the power of voltage fluctuation and determined by integral

$$P_t = \frac{k}{\theta} \int_{t-\theta}^t dt \int_0^{35} g^2(f)G(f, t)df$$

where $g(f)$ is amplitude-frequency characteristic of visual analyzer; $G(f, t)$ is energy spectrum of process of voltage variation at the instant t ; θ is averaging time interval taking into account the effect of perception memory, $\theta = 300 \text{ ms}$.

Factor k in the formula is chosen so that the value $P_t = 1$ meets the threshold of flicker perceptibility.

The voltage flicker characterizes the power of voltage fluctuation taking into account character of human visual and brain perception of an incandescent lamp flux flicker intensity that is similar to the voltage fluctuation. The incandescent lamps are the most widely spread loads that are more sensitive to the voltage fluctuation than TV-sets, computers, electronic and microelectronic control devices. The flicker intensity is expressed by means of dimension-

less units. Ordinates of the standard curve of the voltage fluctuation allowable values $\delta U_t(f)$ (Fig. 2.2) correspond to the value of flicker intensity equal to $P_{st} = 1$ that is determined during 10 minutes with probability of 99 %.

Figure 2.2 shows a curve of allowable voltage fluctuation range depending on the repetition frequency.

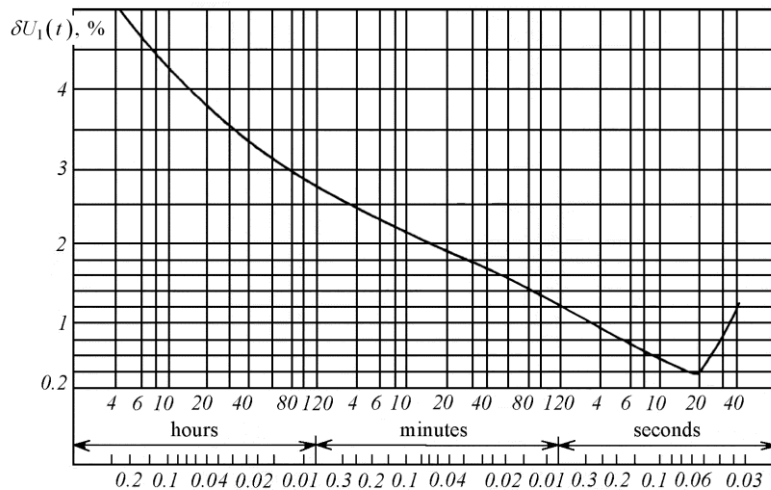


Figure 2.2. Curve of allowable values of $\delta U_t(f)$

The curve is plotted for the case of voltage fluctuation having a shape of meander. The quantity P_{st} is also called *the short-term flicker intensity*. This statement is taken by IEC as the basis for standardization of voltage fluctuations.

Process of visual perception under the voltage fluctuation is simulated on the basis of theory of compound signal passage through a non-linear dynamic system. Experimental investigations executed for many years made possible to determine the amplitude-frequency characteristic (AFC) of the visual analyzer (Fig. 2.3) adopted by IEC. Maximum limit of the voltage fluctuation frequency which influence the vision, with account of an incandescent lamp filament time constant, is about 35 Hz at $\delta U_t(f) \leq 10\%$.

Value of intensity of flicker reflects sufficiently human response on any type (form) of light flux variations independent from disturbance source.

Choice of *observation time* is important. It may be chosen according to duration of the equipment, producing the voltage fluctuation, operational cycle. It would be desirable to specify it independently from a source of fluctuations. The most suitable period is 10 minutes. Intensity of flicker at 10 minute interval is denoted as P_{st} .

The suggested period of 10 minutes may be used to determine intensity of flicker caused by rolling mills, pumps and home appliances. If general effect of the voltage fluctuation is stipulated by a number of sharply variable loads characterized by random nature of their operation (welding, electric motors etc.) intensity of flicker P_{Lt} within considered period can be found on the basis of a set of 10-minute values:

$$P_{Lt} = \sqrt[3]{\frac{1}{N} \sum_{k=1}^N P_{stk}^3}$$

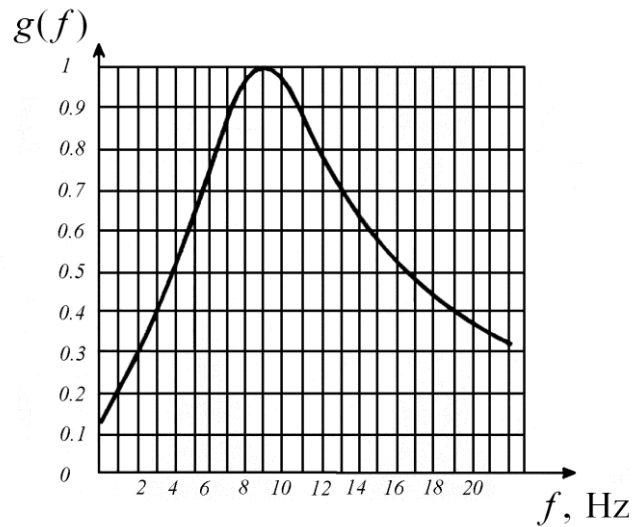


Figure 2.3. Amplitude-frequency characteristic of visual analyzer

If the shape of voltage fluctuations differs from meander, the intensity of flicker is limited by the values of $P_{st} \leq 1.38$ and $P_{Lt} \leq 1.0$. Short-term value of the intensity is determined within 10-minute interval, and the long-term – for the time interval of 2 hours. Value of the flicker intensity in the points of mutual connection of consumers containing incandescent lamps is limited separately: $P_{st} \leq 1.0$; $P_{Lt} \leq 0.74$. These valuations determine EMC level.

2.4. Standardization of interharmonics

Standardization concerning the interharmonics is in the stage of knowledge accumulation.

Voltage level of interharmonics equals to 0.2 % is widely used. This value is taken proceeding from the sensitivity of receivers in the system of control data transfer within power networks. Its application in other cases without taking into consideration possible physical after-effects may require implementation of cost-intensive normalizing devices, e.g. expensive passive filters. Look through the norms given below that have been taken from different documents makes obvious that common approaches are not available, and there is substantial disagreement.

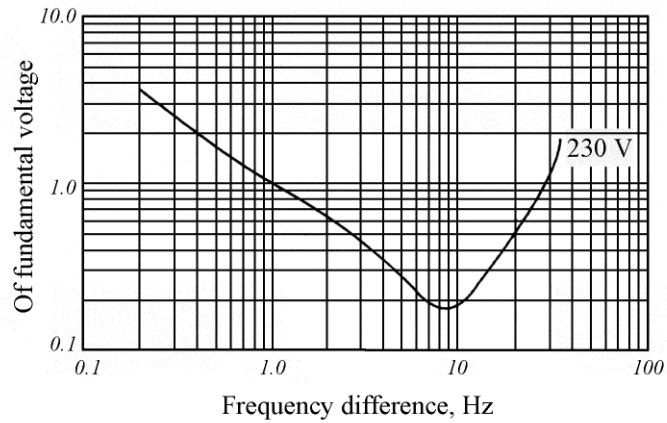


Figure 2.4. Compatibility levels for interharmonics causing light flickering

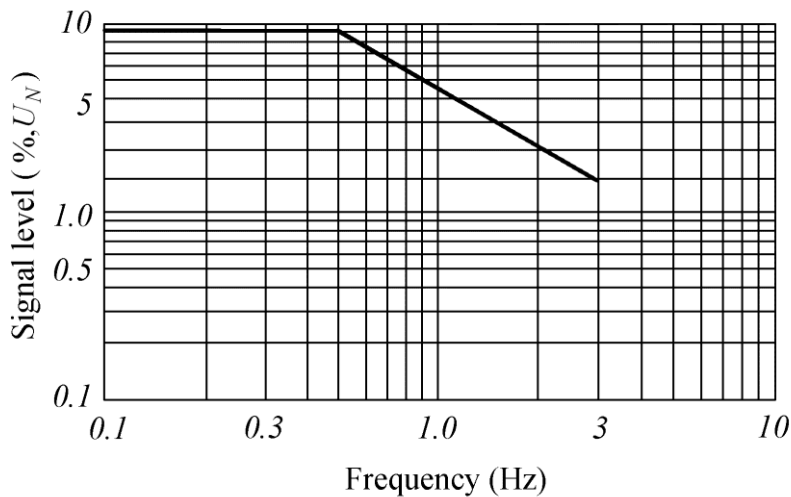


Figure 2.5. Meister Curve for interharmonic signals used in general purpose power networks (from 100 to 3000 Hz)

Table 2.3

Allowable levels of interharmonics in accordance with CENELEC (ENS0160)

| Frequency of subharmonic or interharmonic, Hz | <80 | 80 | 90 | $90 < f < 500$ |
|--|-----|-----|-----|----------------|
| Voltage distortion, % of the fundamental component | 0.2 | 0.2 | 0.5 | 0.5 |

In the Standard project test immunity levels for interharmonics are given for different frequency ranges. Depending on equipment type, the voltage values are within

1.5 % in the bounds of the frequency range of 1000÷2000 Hz. Test levels for interharmonics with frequency over 100 Hz are within 2–9 %.

Another IEC document formulates compatibility levels only for the case when frequency of interharmonics is close to the fundamental component. As a result, the supply voltage is modulated causing light flicker. Fig. 2.4 shows compatibility level for a separate voltage interharmonic (in % of amplitude of the fundamental) as a function of

the frequency difference, which interaction is integrated by the interharmonic.

The characteristic is called the intensity of flickering ($P_{st} = 1.0$ for incandescent lamps at 230 V).

Detailed recommendations concerning boundary values of signals of interharmonics at data transfer and control used in power systems are described below.

1. Low-frequency control systems. Level of the interharmonics cannot exceed odd not multiple of three harmonics of the same frequency range. For existing systems this value is within 2–5 % U_r .

| | | | | | |
|--|---|---|-----|----|---------------------|
| Harmonic order..... | 5 | 7 | 11 | 13 | $17 \leq n \leq 49$ |
| Rms value of harmonic (% of the fundamental harmonic)..... | 6 | 5 | 3.5 | 3 | $2.27(17n) - 0.27$ |

2. Systems of medium frequency. The value of signal is not more than 2 % of U_r .

3. System of radio-frequency signals. Compatibility levels are ascertained but must not be more than 0.3 %.

In Great Britain it is accepted that for data transfer and control in power systems, control at supply voltage is not applied. Consumers may connect electric installations without preliminary estimation of admissibility of their individual interharmonics emission in regard to the values listed in Table 2.3. Allowable values for any separate interharmonic in the frequency range between 80 and 90 Hz may be linearly interpolated on boundary values given below.

4. Guidelines concerning supply voltage. Manufacturers of equipment should guarantee themselves its compatibility with the environmental conditions. Some countries formally use so called Meister curve (Fig. 2.5).

According to the Standard **CENELEC EN50160**, values of voltage signal averaged over a period of three seconds during 99 % of 24-hours should be either less or equal to values from Fig. 2.6.

IEC Standards

According to IEC recommendations interharmonics of voltage are limited within frequency range to value of 0.2% of component obtained at frequency lower than 2 kHz.

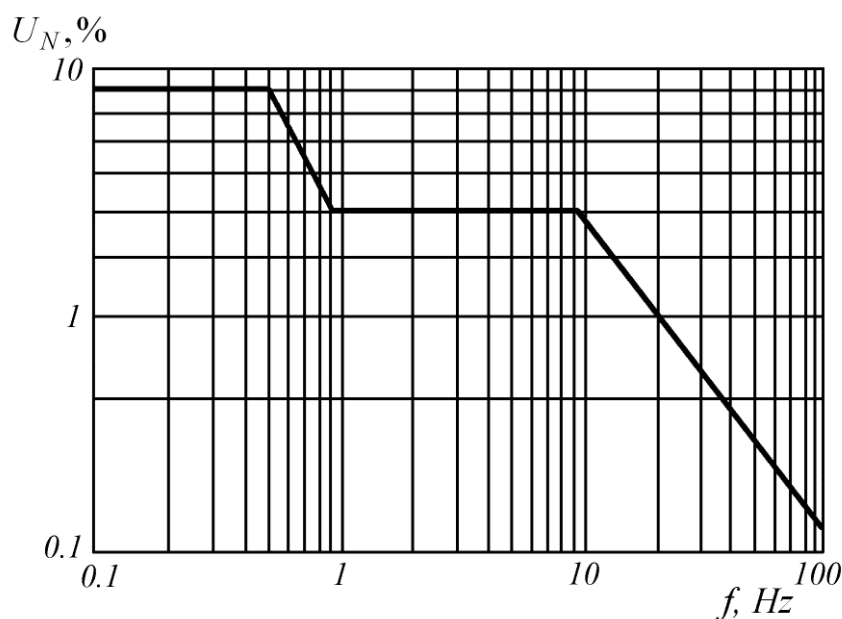


Figure 2.6. Frequency dependence of signal voltage level used in general purpose power distribution networks of medium voltage

2.5. Voltage pulses and dips

Voltage pulses also called transient overvoltage may appear in curves of voltage instantaneous value. Fig. 2.7, *a* shows half-waves of a network voltage instantaneous values on which voltage pulse (surge) takes place. Fig. 2.7, *b* shows idealized pulse as well as its characteristic quantities.

According to ГOCT 13109-97 pulse voltage is called the voltage variation after which it either returns to the start value or approximates to it within several milliseconds. Lightning voltage pulses and switching voltage pulses are recognized. Voltage pulse is characterized by the following values:

- 1) pulse voltage U_p ;
- 2) pulse amplitude U_{pm} ;
- 3) pulse duration Δt_p ;
- 4) duration $\Delta t_{p0.5}$ of existence of the instantaneous value of a pulse voltage $U_p > 0.5U_{pm}$.

To determine the voltage pulse duration $\Delta t_{p0.5}$ in the limits of which its instantaneous value is not less than 0.5 of its peak value, the voltage pulse with the peak value of U_{pm} is selected (Fig.2.7,*b*). Start moment $t_{st0.5}$ and end moment $t_{end0.5}$ correspond to points of crossing the curve of the voltage pulse with horizontal line drawn on the level of $0.5U_{pm}$. The duration $\Delta t_{p0.5}$ is determined by the expression

$$\Delta t_{p0.5} = t_{end0.5} - t_{st0.5} .$$

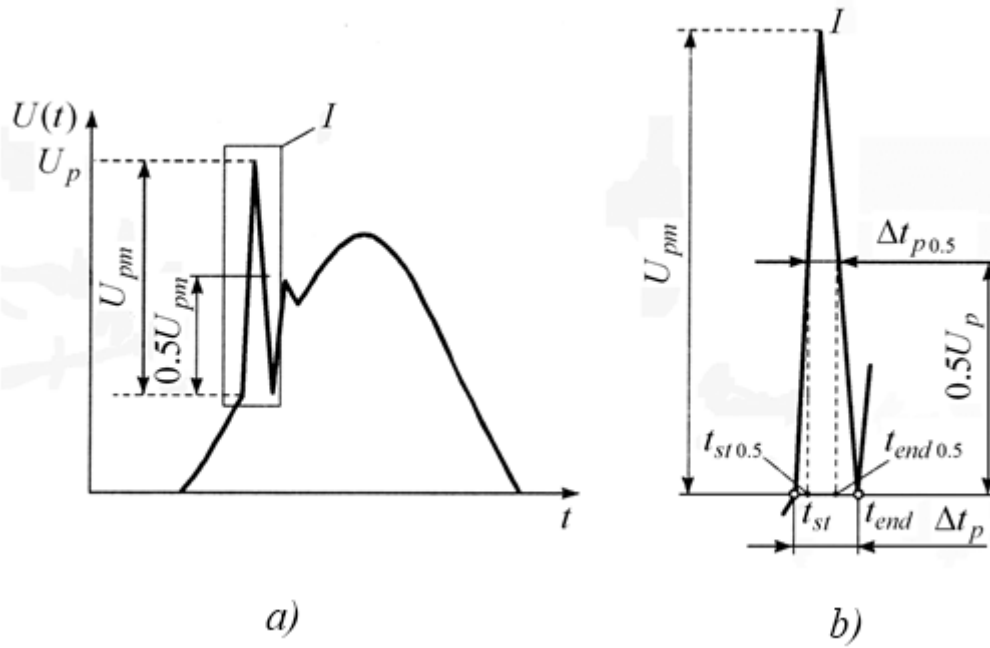


Figure 2.7. Parameters of voltage pulse

Approximate values of phase pulse voltages on transformer terminals are:

| Network | U_p kV |
|--------------|-------------|
| 6 kV | 34 |
| 10 kV | 48 |
| 35 kV | 140 |
| 110 kV | 350 |
| 220 kV | 660 |

Switching impulse voltages
within network:

| Network | U_p kV |
|---------------|-------------|
| 0.38 kV | 4.5 |
| 3 kV | 15.5 |
| 6 kV | 27 |
| 10 kV | 43 |
| 20 kV | 85.5 |
| 35 kV | 148 |
| 110 kV | 363 |

Voltage dip is sudden reduction of the voltage in a power supply system to some minimum value during the time not less than half-cycle (usually 10ms) followed by voltage recovery up to initial or close to it level.

According to ДСТ 13109-97 and similarly to EN50160 the voltage dip starts from sudden voltage reduction less than $0.9U_r$ and lasts from 10 milliseconds up to several dozen seconds till the instant when the voltage reaches $0.9U_r$ or close to this value again (Fig. 2.8).

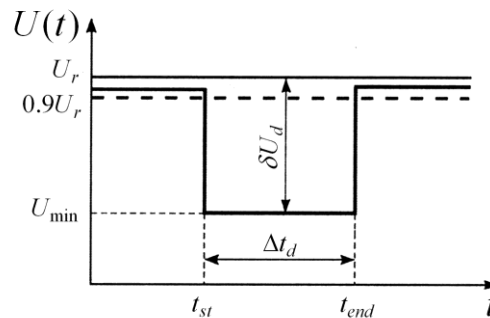


Figure 2.8. Voltage dip

Voltage dip is characterized by the two parameters:

- dip depth δU_d , %
- time (duration) Δt_d .

Table 2.4

Statistical data of voltage dips according to UNIPEDE

| No | $\Delta t_d, s$ $\delta U_d, \%$ | $0.02 \leq$ | $0.1 \leq$ | $0.5 \leq$ | $1 \leq$ | $3 \leq$ | $20 \leq$ | $60 \leq$ |
|----|--|-------------------|-------------------|-----------------|-----------------|------------------|------------------|-------------------|
| | | \div < 0.1 | \div < 0.5 | \div < 1 | \div < 3 | \div < 20 | \div < 60 | \div < 180 |
| 1 | $90 > \div \geq 85$ | 541 | 61 | 24 | 25 | 53 | 51 | 10 |
| 2 | $85 < \div \geq 70$ | 1532 | 203 | 136 | 20 | 7 | 1 | 1 |
| 3 | $70 < \div \geq 40$ | 1146 | 225 | 38 | 26 | 8 | 1 | 1 |
| 4 | $40 < \div \geq 1$ | 97 | 424 | 31 | 28 | 5 | 1 | 3 |
| 5 | $1 > \div \geq 0$ (interruptions of power supply) | 2 | 20 | 7 | 27 | 27 | 6 | 10 |

ДСТ 13109-97 specifies one more parameter – frequency of dips occurrence. The indicated parameters are determined by the expressions:

$$\delta U_d = \frac{U_r - U_{min}}{U_r}$$

$$\Delta t_d = t_{end} - t_{st}$$

Below you can find results of statistical treatment of voltage dips during a year according to UNIPEDE (Table 2.4) and DCT 13109-97 (Table 2.5).

Table 2.5

Statistical data of voltage dips according to DCT 13109-97

| No | $\Delta t_d, s$ | 0.01-0.1 | 0.1-0.5 | 0.5-1.0 | 1.0-3.0 | 3.0-20 | 20-60 | Total, % |
|----|--|----------|---------|---------|---------|--------|-------|----------|
| | $\delta U_d, \%$ | | | | | | | |
| 1 | 10-30 | 19.0 | 17.0 | 4.0 | 1.0 | 0.5 | – | 41.5 |
| 2 | 30-60 | 8.0 | 10.0 | 3.0 | 0.5 | – | – | 21.5 |
| 3 | 60-95 | 1.0 | 4.0 | 2.0 | 0.5 | – | – | 7.5 |
| 4 | 100 (interruptions of power supply) | 1.0 | 4.0 | 17.0 | 2.0 | 1.5 | 4.0 | 29.5 |
| 5 | Total | 29 | 35.0 | 26 | 4.0 | 2.0 | 4.0 | 100 |

2.6. Electromagnetic compatibility characteristic quantities measurement

Maximum allowable errors of electric power quality characteristic quantities metering are the following:

- 1) voltage deviation: absolute error is $\pm 0.5 \%$;
- 2) range of voltage deviation: relative error is $\pm 8 \%$;
- 3) flicker dose: relative error is $\pm 5 \%$;
- 4) distortion factor: relative error is $\pm 10 \%$;
- 5) n th harmonic ratio: relative error is $\pm 5 \%$;
- 6) voltage unbalance factor by negative sequence: absolute error is $\pm 0.3 \%$;
- 7) voltage unbalance factor by zero-sequence: absolute error is $\pm 0.5 \%$.

Voltage fluctuation measuring

Gage for level of lamp flickering called *flickermeter* may be used under any law of voltage variation. Virtually it measures the degree of light flux of incandescent lamps flickering.

In this process the three main elements can be considered:

- 1) source of the voltage fluctuation;
- 2) human eye being a receptor, that is the sensing element;
- 3) Human brain with its nonlinear (as a function of frequency) reactions.

Only the first component is available to measure the voltage fluctuation. The rest should be simulated, in other words it is necessary to find proper conformity between voltage variations of different form and level of human irritation.

Fig. 2.9 shows the simplified structural diagram of a flickermeter consisting of five separate units.

Unit 1

Within the unit information about instantaneous voltage fluctuation is extracted out of the signal varying proportionally to rms. value of the source voltage. Mean value of the voltage variations corresponds to mean rms of the voltage determined within a minute interval.

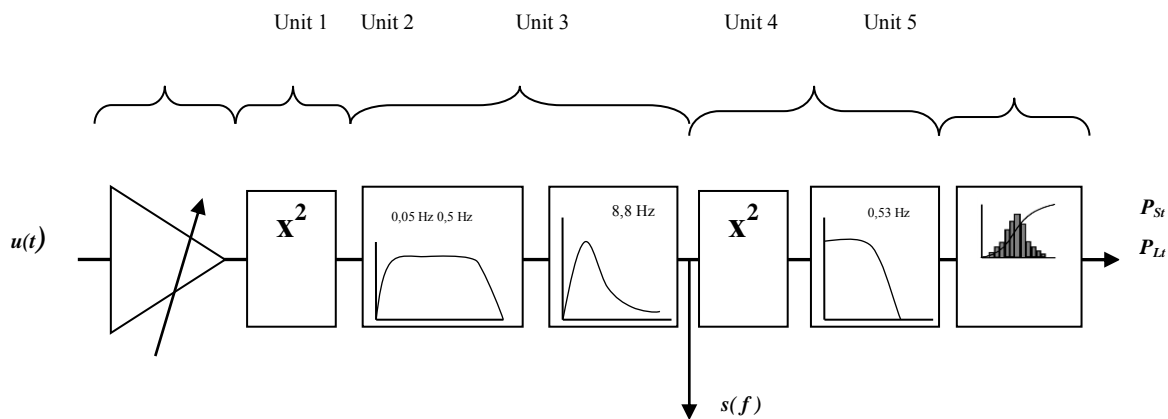


Figure 2.9. Simplified structure of flickermeter

Unit 2 (demodulator)

Instantaneous voltage variation value is the input signal. This signal is superimposed onto fundamental frequency of 50 Hz. Then the signal is squared with the help of quadratic demodulator.

Unit 3 consists of several filters. Frequency response of the set, including incandescent lamp and a human eye, is reconstructed with the help of wide-band fourth-order filter represented by means of frequency characteristic shown in Fig.2.10 and the dependence:

$$H_{230V} = \frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1^2} \frac{1 + \frac{s}{\omega_2}}{\left(1 + \frac{s}{\omega_3}\right) \left(1 + \frac{s}{\omega_4}\right)}$$

where $k = 1.74802, \lambda = 2\pi 4.05981, \omega_1 = 2\pi 9.15494, \omega_2 = 2\pi 2.27979, \omega_3 = 2\pi 1.22535, \omega_4 = 2\pi 21.9$.

The expression as well as a type of frequency response characteristic is true for 230V/60W incandescent lamps. Other types of expression should be used for other light sources (for example, fluorescent lamps).

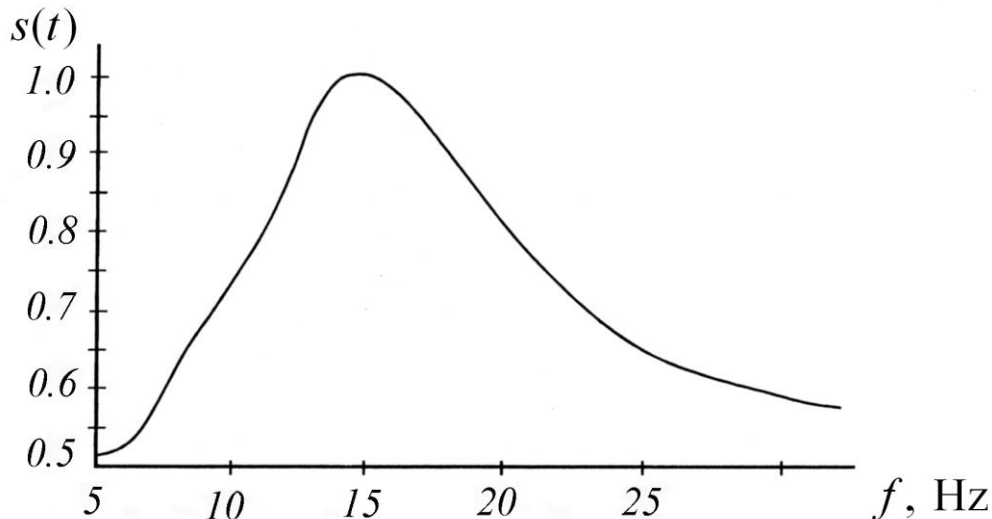


Figure 2.10. Frequency response characteristic of wide-band filter of the fourth order

Unit 4 is a model of nonlinear reaction of human brain on light flux fluctuations. The output of *unit 4* is instantaneous level of the voltage fluctuation. The two statistical values are obtained: values of the short-term and long-term flicker (P_{St} and P_{Lt}). $P_{St} = 1$ value corresponds to threshold of perceptible flicker boundary which should not be exceeded.

Unit 5 performs statistical estimation of the flickering intensity.

Measurement of distortion and voltage unbalance

Today combined (unit-type) measuring devices for measurement of several indices of power quality are used (higher harmonics, K_U , voltage unbalance, fluctuation and deviation); in some cases the devices make possible to measure active and reactive power, phase voltage and line-to-line voltage, currents of fundamental frequency and other parameters. Consider measurement of power quality index on the example of measuring of harmonics and unbalance.

Values of the current and voltage harmonics and K_U are made with the help of set of instantaneous values of voltage and current measured at definite time instants (or the signal phase values).

The measuring device consists of the three main functional parts: device for measurement of the voltage and current instantaneous values which performs according to certain measurement algorithms; data processing device which performs according to specified algorithms of the power quality indices computation (e.g., the algorithm of the distortion factor computation); facilities to display and store the results obtained.

The main problems to be solved in the course of the gage for the distortion factor measurement development on the basis of PC or Micro-PC are choice and estimation of optimum algorithms of distortion factor determination by instantaneous values of the current and voltage; development of optimum measurement algorithms which

guarantee minimum estimation error; development of high-precision measurement technology for the instantaneous values performing according given measuring algorithms and, finally, realization of algorithms in high-level programming languages as well as development of user-friendly graphical interface.

The structural diagram of a power quality gage on the basis of PC is given in Fig.2.11.

The voltage matching device fulfills electrical isolation, the signal level normalization as well as the input signal switching-off from the measurement channel when the gage is de-energized (that is necessary for its input circuit protection). The current matching device performs similar functions, it has additionally a converter of current to voltage.

The analog-to-digit converter realizes the described below measurement algorithm. The comparator following transition of the analogue voltage signal in phase A through zero value enables and stops timer counters. It gives ability to calculate values of signal cycle and its frequency if frequency of the master oscillator is known. After the period has been determined, the values stored in the timer counters are divided by the number of sampling points.

In such a way, the interval of instantaneous values reading is specified.

The obtained sets of instantaneous values are processed with the help of computer and are displayed on the monitor graphically and digitally and may be printed out.

When distortion is measured the algorithm of K_V computation is executed in the device as it is indicated below.

1. Computation of the voltage rms value is performed by the expression:

$$U = \sqrt{\frac{1}{m} \sum_{i=0}^{m-1} u^2(t_i)}$$

Where m is number of the samples within the period; $u(t_i)$ is measured instantaneous value of voltage corresponding to time instant t_i .

2. Computation of the voltage quadrature components is made by the formulae:

$$U_x = \frac{2}{m} \sum_{i=0}^{m-1} u(t_i) \cos \omega t_i$$

$$U_y = \frac{2}{m} \sum_{i=0}^{m-1} u(t_i) \sin \omega t_i.$$

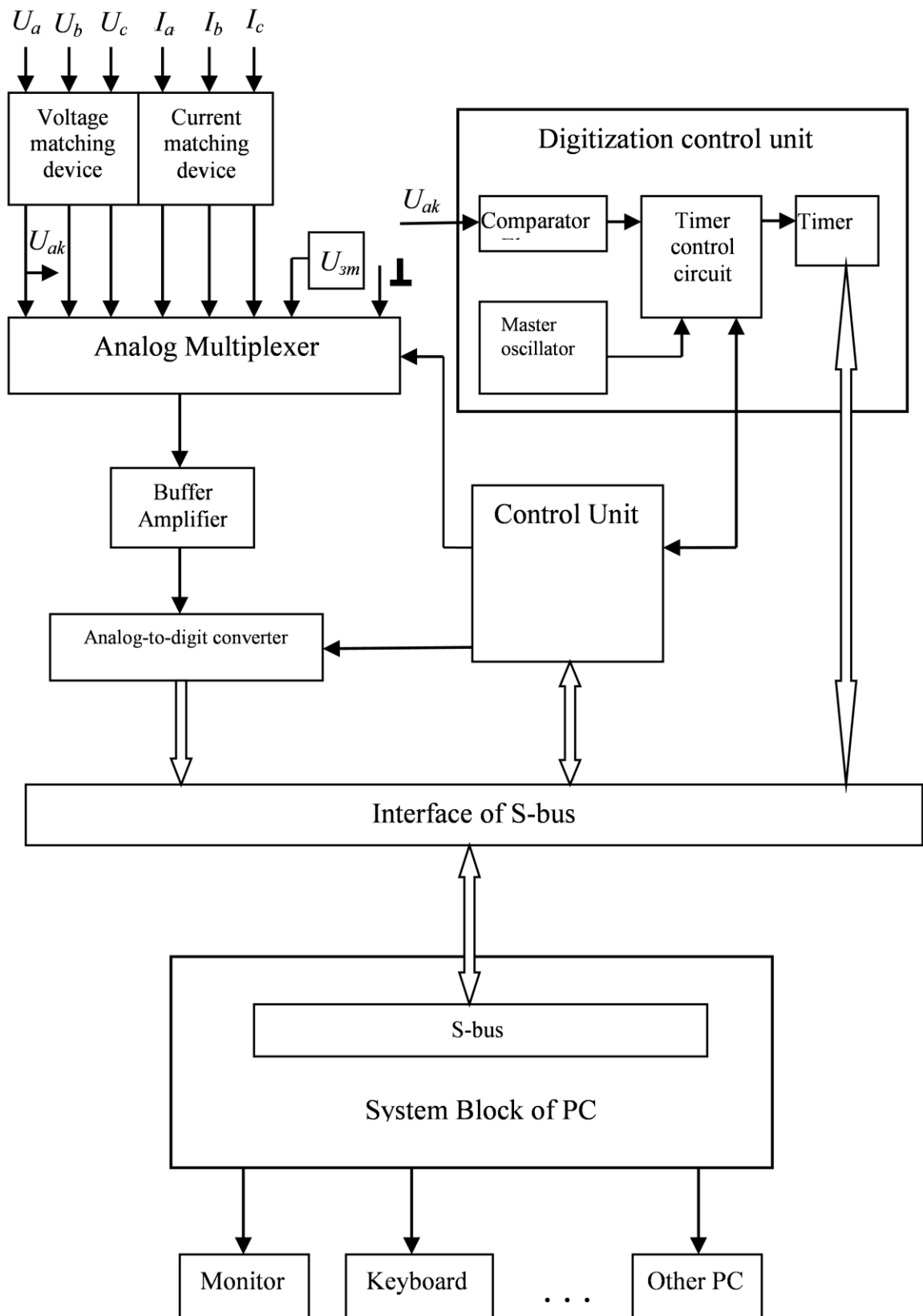


Figure 2.11. Block diagram of power quality measuring instrument on the basis of personal computer

3. For computation of rms value of the voltage fundamental component the following expression is used:

$$U_1 = \sqrt{\frac{U_x^2 + U_y^2}{2}}.$$

4. Computation of the voltage curve distortion factor, %, is performed as

$$K_U = \frac{\sqrt{U^2 - U_1^2}}{U_1}.$$

Algorithm of the n th voltage harmonic ratio computation is executed as follows:

1. Computation of quadrature components of n th harmonic:

$$U_{nx} = \frac{2}{m} \sum_{i=0}^{m-1} u(t_i) \cos n\omega t_i$$

$$U_{ny} = \frac{2}{m} \sum_{i=0}^{m-1} u(t_i) \sin n\omega t_i.$$

2. Calculation of rms value of n th harmonic:

$$V_n = \sqrt{\frac{V_{nx}^2 + V_{ny}^2}{2}}.$$

3. Computation of the fundamental quadrature components:

$$U_x = \frac{2}{m} \sum_{i=0}^{m-1} u(t_i) \cos \omega t_i$$

$$U_y = \frac{2}{m} \sum_{i=0}^{m-1} u(t_i) \sin \omega t_i.$$

4. Computation of rms value of the fundamental:

$$U_1 = \sqrt{\frac{U_x^2 + U_y^2}{2}}.$$

5. Computation of n th voltage harmonic ratio, %:

$$K_{U(n)} = \frac{U_n}{U_1}.$$

For unbalance measurement the following algorithm is used:

1. Calculation of quadrature voltage components of A , B and C phases:

$$U_{Ax} = \frac{2}{m} \sum_{i=0}^{m-1} u_A(t_i) \cos \omega t_i$$

$$U_{Ay} = \frac{2}{m} \sum_{i=0}^{m-1} u_A(t_i) \sin \omega t_i$$

$$U_{Bx} = \frac{2}{m} \sum_{i=0}^{m-1} u_B(t_i) \cos(\omega t_i - 120^\circ)$$

$$U_{By} = \frac{2}{m} \sum_{i=0}^{m-1} u_B(t_i) \sin(\omega t_i - 120^\circ)$$

$$U_{Cx} = \frac{2}{m} \sum_{i=0}^{m-1} u_C(t_i) \cos(\omega t_i + 120^\circ)$$

$$U_{Cy} = \frac{2}{m} \sum_{i=0}^{m-1} u_C(t_i) \sin(\omega t_i + 120^\circ)$$

2. Calculation of quadrature voltage components of negative sequence:

$$U_{2x} = \frac{1}{3} (U_{Ax} + U_{Bx} + U_{Cx})$$

$$U_{2y} = \frac{1}{3} (U_{Ay} + U_{By} + U_{Cy})$$

3. Computation of negative sequence voltage

$$U_2 = \sqrt{\frac{U_{2x}^2 + U_{2y}^2}{2}}.$$

4. Computation of the voltage unbalance factor by negative sequence:

$$K_{2U} = \frac{U_2}{U_r}$$

Factor of voltage unbalance by zero-sequence is measured on similar algorithm (in expressions for quadrature components the phase difference is equal to 0).

2.7. Measuring of network nodes amplitude-frequency characteristics

Lately a number of methods have been developed to study frequency responses of power networks. The simplest method is based on study of steady state before and after connection a load to the given node having linear voltage-current characteristic (e.g., capacitor bank CB).

By this method the load (CB) is switched on and off, and amplitudes and initial phase angles of voltage harmonics in the point of load connection, and of current flowing through the load, at the instants before and after the load commutation are varied. Impedance of the network is determined according to the expression

$$\underline{Z}_{gr,n} = \frac{U_{n1}}{I_n} - \underline{Z}_n$$

where \underline{U}_{n1} is voltage of n -th harmonic before load connection, V; I_n is current of n -th harmonic flowing through the load, A; \underline{Z}_n - the load impedance at frequency of n -th harmonic, Ohm.

Impedance \underline{Z}_n is determined by the dependence:

$$\underline{Z}_n = \frac{U_{n2}}{I_n}$$

Where \underline{U}_{n2} is voltage of n -th harmonic after load connection, V.

The method disadvantage consists in necessity of powerful load use for obtaining the desired precision, absence of nonlinear elements in the load, great number of the load switching, and lack of stable voltage harmonics levels during all the time of measuring. Measuring is possible only for frequencies of harmonics available in the supply voltage.

Frequency response characteristic of power network may also be determined by means of analysis of the voltage waveform distortion caused by connection of load being a source of higher harmonics (e.g., thyristor converter).

In this case, to determine the network impedance magnitude, initial phases of voltage and current harmonics in the point of the non-linear load connection are varied. The network impedance is determined according the expression:

$$\underline{Z}_{gr,n} = \frac{U_{n1} - U_{n2}}{I_n}$$

where $\underline{Z}_{gr,n}$ is the network impedance at the frequency of n th harmonic, Ohm; U_{n1}, U_{n2} are voltage of n th harmonic in the network node when the load is connected and disconnected, V; I_n is the current of n th harmonic flowing through the network element having nonlinear voltage-current characteristic, A.

Accuracy of the obtained data depends upon values of current harmonics generated by their source (the element with nonlinear voltage-current characteristic). Measurements are possible only for the frequencies at which the currents harmonics are generated.

It is of interest methods of electric networks frequency response characteristic determination that are based on insertion into the network signals having frequencies non-divisible by the fundamental frequency of the network. One of modifications of measuring system implementing this principle is as follows. The system consists of a power unit controlled by PC, and a measurement unit. The control computer forms incoming signals for power unit which provide flowing the current through it, that includes the non-divisible by 50 Hz harmonics (175 Hz, 225 Hz, ..., 2525 Hz). The power unit is a three-phase bridge assembled of turn-off thyristors that is loaded by inductance. The unit provides flowing the current up to 150 A at voltage of 0.46 kV.

The measurement unit performs measuring of instantaneous values of the voltage in the point of device connection as well as the current flowing through the device. Measurement results may be examined with the help of PC and recorded for further study. Method of orthogonal correlation is used to increase measurement accuracy.

Test questions

1. List the main indices of electric power quality according to GOST 13109-97 Standard.
2. What are the principles of the electromagnetic interference standardization?
3. Give explanations for response characteristic of the main power quality indicators.
4. Describe features of the national standards which define requirements to power quality indicators.
5. What is the flicker of voltage?
6. What are technical regulations concerning electromagnetic compatibility?
7. From what structural units does the flickermeter consist?
8. Describe the principles of unbalance and wave form distortion measurement.

9. On what principles is measuring of network nodes amplitude-frequency characteristics based?
10. Name the known to you principles of interharmonics standardization.
11. With what parameters are the voltage dips characterized?

Topics for essay

1. Substantiation of electromagnetic compatibility standardization principles.
2. Standardization of voltage and current harmonics wave form distortion.
3. Special features of voltage pulses and dips normalization.
4. Special features of voltage fluctuation normalization.
5. Application of IEC recommendations at standardization.

3.1. Valve inverters

More than 50% of electric power is used at modern industrial enterprises in the converted form (at metallurgic plants the converted electric power takes more than 90 %). Widely used valve converters, different types of frequency converters, household devices and home appliances working in both static and transient conditions are powerful generators of electromagnetic disturbances.

Such nonlinear loads as electric arc furnaces and electric welding equipment, wind power stations, power transformers and motors also generate important great disturbances.

Table 3.1 shows the above indicated sources of electromagnetic disturbance at enterprises of different industrial branches.

Table 3.1

Industrial sources of voltage distortion causing interferences at steady-state operation

| <i>Consumer</i> | <i>Disturbance</i> |
|---|--|
| Production of chemical fiber, pulp-and-paper industry | Voltage deviation |
| Machine-building enterprises with powerful welding units | Voltage deviation and fluctuation, voltage unbalance |
| Ferrous metallurgy with electric arc furnaces | Voltage deviation, fluctuation and non-sinusoidal curve shape, voltage unbalance |
| Nonferrous metallurgy industry enterprises (electrolysis) | Voltage deviation, fluctuation and non-sinusoidal curve shape |
| Enterprises with powerful single-phase consumers | Voltage deviation and unbalance |
| Railway substations | Voltage deviation, harmonics and unbalance |

Valve converters are powerful concentrated sources of harmonic interference. In the most often used three-phase six-ripple bridge circuits, harmonics of the 5th, 7th, 11th and 13th order are prevalent. Their magnitudes are inversely proportional to their numbers, and they are called the characteristic harmonics. When twelve-pulse

circuits are used, the 5th and 7th harmonics are not theoretically available, and the 11th and 13th ones prevail. Such converters are applied for circuit designs of main drives of roll mills, for electrolysis etc. Under impact loading conditions (e.g., in rolling) voltage dips and fluctuations arise within supply networks.

Electric drive of modern papermaking machine consists of 20-30 and sometimes larger number of electric motors which speed is strictly coordinated. Thyristor converters are commuted in accordance with six-ripple bridge circuit and are used for energizing one or a group of electric motors. Steady-state currents of 5th, 7th, 11th and 13th harmonics are 90, 60, 38 and 30 A respectively. Levels of harmonics have the same order as in converters of mills of modern powerful rolling mills.

When twelve-ripple circuits are realized, levels of 5th, 7th, 11th and 13th harmonics are 38, 30, 0.8 and 0.6 A.

Under rolling mills operation, if special fast compensating devices are not available, sizeable voltage fluctuations occur. Thus, dose of flicker in a power network of 10kV of a slab mill is 10.5; on 10kV buses it is 2.2. Within blooming mill mains the flicker dose value exceeds 4.

Reactive power surge while metal picking up by rolls at cold rolling mill is 2000 Mvar. It results in voltage dips up to 10-12% depending on rated voltage and short circuit power.

Valve converter operating in the network with unbalance of line-to-line voltages is also a source of negative-sequence current

$$I_2 = 0.5K_{2U}I_1$$

where K_{2U} is the factor of voltage unbalance for the negative sequence; I_1 is the fundamental of the converter line current under balanced condition.

The phase of current I_2 equals

$$\arg I_2 = \varphi_2 + \alpha$$

where φ_2 is phase displacement between current vectors I_2 and I_1 ; α is the converter delay angle.

Today *frequency converters* are widely used in metallurgy, machine-building, light industry. They are sources of electromagnetic disturbances in the form of harmonics and interharmonics. Interharmonics frequency lies between frequencies of characteristic harmonics.

Most commonly frequency converters are applied with direct-current link and direct frequency converters – cycloconverters.

3.2. Frequency converters with direct-current link

Frequency converters with direct-current link are widely used – from drives of rolling mills up to roller beds, mechanical aids and fans. These frequency converters with

a direct-current link as well as direct frequency converters are powerful sources of characteristic harmonics and interharmonics. Double energy conversion taking place within the frequency converters with a d. c. link rather decreases their efficiency. But a number of important advantages of the converters provide their dominance in modern electric drive. Their average pay-back period is not more than 1.5 years.

The converter with a direct-current link (Fig. 3.1) consists of the two valve systems - rectifier and inverter (as a rule, the voltage inverter). Direct-current link includes the inductance L_d and the capacitance C . Both, the rectifier and the inverter may be either controllable or uncontrollable. Correspondent control systems (if they are available) may be either independent or interrelated. Powerful frequency converters with a DC link are equipped with smoothing reactor L_d to reduce the current i_d ripples. In low-power converters connection between the rectifier and the inverter is carried out only with the help of the capacitor C . Anyway frequency converters with DC link are connected directly to power network, that is without a transformer.

For analysis of electromagnetic compatibility of the converter and the supply network the principle of superposition is used. The processes stipulated by the rectifier and inverter operation are considered independently. Their superposition is made with the help of commutation (switching) functions. As the commutation function K_I for current, the equation of right-angle step function of the current consumed by the rectifier from the supply network is taken that is possible due to direct connection of the converter with a direct-current link to the network.

The network current is a sum of the rectifier current harmonics i_{bn} and the inverter current interharmonics i_{in} scaled on the side of rectifier unit with the help of commutation function K_I :

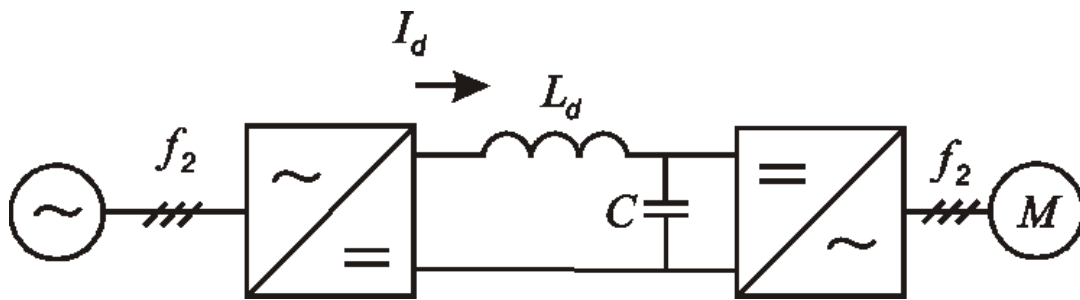


Figure 3.1 Structure of converter with direct-current link

$$i_{gr,n} = i_{rect,n} + K_I i_{inv,n}$$

Curve of the network current contains harmonics with the frequencies

$$f_{in} = (kp_1 \pm 1)f_1 \pm p_2 n f_2; \quad k = 0, 1, 2, \dots; \quad n = 0, 1, 2, \dots$$

The first summand determines the frequencies of characteristic harmonics and the second – the frequencies of interharmonics non-multiple of input frequency f_1 .

Equation of the commutation function is classical series expansion of the network current curve consumed by 6 (or 12)-pulse rectifier:

$$K_I = \frac{2\sqrt{3}}{\pi} \left(\sin \omega_1 t - \frac{1}{5} \sin 5 \omega_1 t - \frac{1}{7} \sin 7 \omega_1 t + \dots \right).$$

The pulsating current component of the inverter includes, besides the rectified current I_d , also the sum of 6th, 12th, 18th, and so on harmonics which amplitudes decrease notably with the harmonic number increase. Restricted to amplitude of 6th harmonic of I_{6u} , it may be presented as:

$$I_{6u} = \frac{U_{d6}^{(u)}}{Z_6 \left(\frac{\omega_2}{\omega_1} \right)}$$

where $U_{d6}^{(u)}$ is amplitude of 6th harmonic of the inverter rectified voltage; $Z_6 \left(\frac{\omega_2}{\omega_1} \right)$ is impedance of the inverter direct current link from the inverter side.

The value of $U_{d6}^{(u)}$ is found with the help of graphic charts or tables as a function on the inverter delay angle β .

Relative value of the interharmonic is:

$$\delta = \frac{I_{6m}}{I_{1m}} \cong \frac{U_{d6}^{(u)}}{Z_6 \left(\frac{\omega_2}{\omega_1} \right)} = \frac{U_{d0}^{(u)} \cos \beta \cdot K_{d6}^{(u)}}{Z_6 \left(\frac{\omega_2}{\omega_1} \right)}$$

where $K_{d6}^{(u)}$ is relative value of amplitude of the 6th harmonic of the inverter rectified voltage.

Characteristic harmonics of the network current

In practice of different valve inverters type harmonics estimation, a rectifier is considered as a source of characteristic current harmonics which level is inversely proportional to the harmonic number. It corresponds to the case when inductance of the DC circuit is $L_d = \infty$, and inductance of commutation circuit is $L_{com} = 0$. Curves of line currents are of rectangular stepped shape with 120 electrical degrees time duration. In actual practice, particularly in the frequency converters with a reactor in the DC circuit, the curves are deformed owing to presence of pulsating component. The indicated curves deformation depends on relation between L_d and L_{com} (Fig. 3.2).

The ripple (Fig. 3.2) influences the value of characteristic harmonics. Depth of the current ripple is characterized by the current ripple factor λ_I :

$$\lambda_I = \frac{I_{6m}}{I_d}$$

In Fig. 3.3 relationship between magnitudes of four network current characteristic harmonics and of two DC current harmonics as functions of the ratio $\frac{L_d}{L_k}$ are presented.

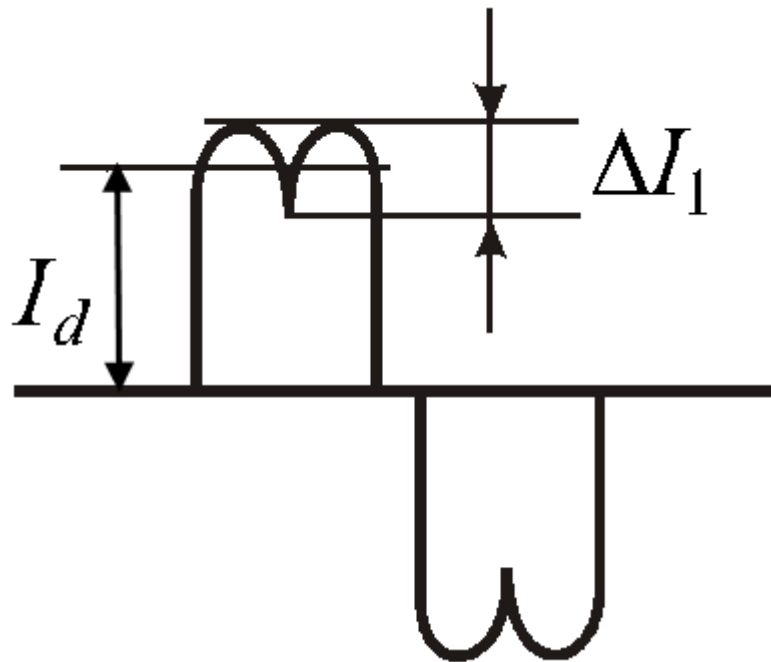


Figure 3.2 Curve of rectifier line current

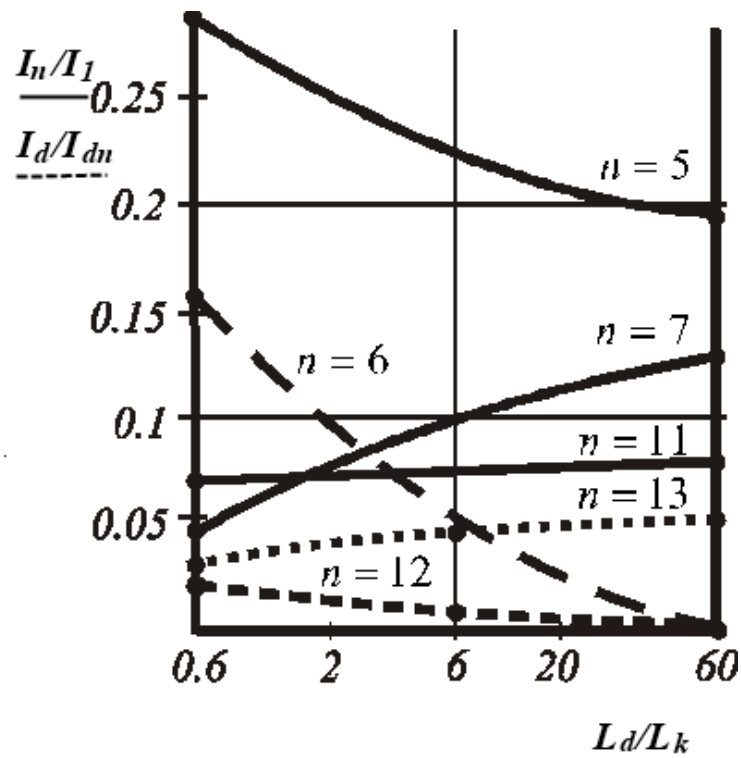


Figure 3.3 Dependence of network current and load current harmonics on inductance ratio

Curves in Fig. 3.3 show that, when inductance of DC current link decreases, level of the 5th network current harmonic increases significantly. At the same time the 7th harmonic level decreases. Levels of the 11th and 13th harmonics vary insignificantly. Under the same conditions, increase of the 6th current harmonic in the DC circuit results in similar increase of interharmonic in the network current curve.

Under the given λ_I values relative magnitudes of characteristic rectifier harmonics $I_{rect,n}^*$ is determined by the expressions:

| | | | | |
|--------------------|--------------|-----------------|------|------------------|
| n | 5 | 7 | 11 | 13 |
| $I_{rect,n}^*$... | 0.2+0. | 0.14- | 0.09 | 0.076 - |
| | $9\lambda_I$ | $0.21\lambda_I$ | 1 | $0.087\lambda_I$ |

Estimations of interharmonics level when a reactor or a capacitor is available in the circuit of rectified current

In the first case the impedance of DC current link determined from the inverter side is

$$Z_n \left(\frac{\omega_2}{\omega_1} \right) = \sqrt{r^2 + \left(n \frac{\omega_2}{\omega_1} X_d \right)^2}$$

where r and X_d are resistance and reactance of the reactor.

As $X_d \gg r$ then

$$Z_n \left(\frac{\omega_2}{\omega_1} \right) = n \frac{\omega_2}{\omega_1} X_d.$$

For $n = 6$

$$Z_6 \left(\frac{\omega_2}{\omega_1} \right) = 6 \frac{\omega_2}{\omega_1} X_d$$

Assuming $U_{d0}^{(rect)*}$ at relative value of the reactance X_d^* obtain:

$$\delta = \frac{\cos\beta \cdot K_{d6}^{(u)}}{6 \left(\frac{\omega_2}{\omega_1} \right) X_d^*}.$$

Relative value X_d^* may be determined as depending on the rectified current ripple factor λ_I as:

$$X_d^* = \frac{K_{d6}^{(rect)}}{6\lambda_I}$$

In some cases, the voltage ripple factor λ_U is used. It is evident that

$$\lambda_U = \lambda_I X_d^*$$

For instance, $K_{d6}^{(rect)} = 0.18$ if the delay angle is $\alpha = 30^\circ$ and $\lambda_I = 0.15$. Then

$$X_d^* = \frac{0.18}{6 \cdot 0.15} = 0.2.$$

In this case the ripple factor $\lambda_U = 0.15 \cdot 0.2 = 0.03$ or 3% that is less than allowable value of 5%. For example, if $f_2 = 30$ Hz, $X_d^* = 0.14$ and $\beta = 30^\circ$, we obtain

$$\delta = \frac{0.86 \cdot 0.18}{6 \cdot \frac{30}{50} \cdot 0.2} = 0.21.$$

3.3. Direct frequency converters

Frequency converters without DC link are direct frequency converters. They are specific load type which generates interharmonics of noticeable magnitude into pow-

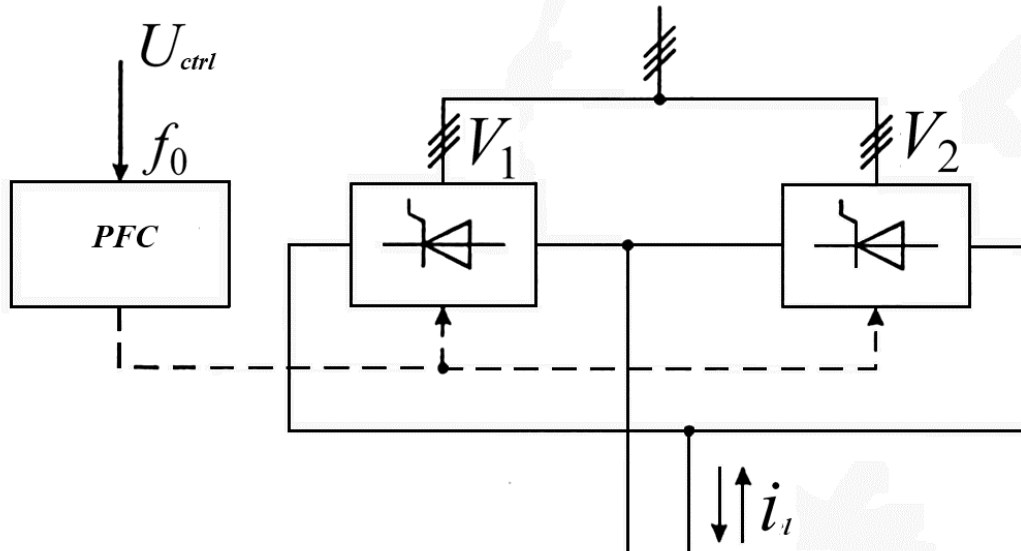


Figure 3.4 Three phase – single phase direct frequency converter with self-commutation

er supply networks. There are many types and circuits of the frequency converters used in practice. One of most widely spread type of frequency converters are the self-

commutated converters called the cycloconverters. Fig. 3.4 shows a simplified circuit of a three-single-phase self-commutated direct frequency converter. The circuit includes two similar valve sets B_1 and B_2 conducting load current of different sense. The load current fundamental frequency f_2 is determined by the system of pulse position control.

Cycloconverters with external commutation are improved type of frequency converters. Converters with external commutation are set up according to the same schematic diagrams as cycloconverters with self-commutation but they have extra component/components providing external commutation.

Today there are the following areas of cycloconvertes application: controlled AC electric drives, power sources with constant output and variable input frequency, controlled sources of reactive power for AC systems, interconnection of ac current systems to control power interchange between them.

According to the principle of operation, cycloconverters of any type are devices which synthesize the given form of a curve. Output voltage curve with expected frequency and amplitude is formed by means of consecutive supply the input voltage through power switches to the output terminals at the appropriate time intervals determined by the system of pulse position control. Thus curves of the output voltage consist of sections of the input voltage curves. The input current curves are formed of the output current curves sections. Features of the output voltages as well as the input currents formation cause presence interharmonics in them. These interharmonics are distorting components. The spectra of the output voltage and the input current are discontinuous ones. Such spectra nature is stipulated by operating principle of the self-commutated frequency converter. In actual operating conditions, different disturbances resulting in disruption of prescribed algorithm of valve control occur in input and output of the self-commutated frequency converter. The disturbances are caused by random change of input power parameters, such as random fluctuations in load, in the self-commutated frequency control system parameters and other factors. All the disturbances cause extra distortions in the curves of output voltage and input current which spectra in this case will consist of discrete and continuous parts.

Study of output voltage and input current of CC is made with the help of switching (commutation) functions which represent laws of power converter switches commutation. It is convenient to apply commutation functions in the form of a trigonometric series to estimate the spectral response. Then curves of output voltage and input current may be expressed mathematically as sums of sum harmonic components with frequencies being usually sums and differences of numbers multiple of source frequency and expected output frequency.

In the general case output voltage of a direct frequency converter having d input phases and m output phases may be determined according to the expression

$$\mathbf{u}_{\text{out}}(t) = \mathbf{H}(t)\mathbf{u}_{\text{in}}(t) \quad (3.1)$$

where $\mathbf{u}_{in}(t)$, $\mathbf{u}_{out}(t)$ are column matrices of input/output voltage with dimension of n and m -vector accordingly; $\mathbf{H}(t)$ is matrix of switching functions with dimension of $m \times d$.

As an example, consider a direct frequency converter with three-phase input and single-phase output. With it three-phase output of the direct converter may be formed of three independent single-phase systems.

In this case, expression (3.1) for the three-phase/single-phase direct frequency converter will be as follows:

$$\mathbf{u}_{out}(t) = [h_1(t) \quad h_2(t) \quad h_3(t)] \begin{bmatrix} u_{in1}(t) \\ u_{in2}(t) \\ u_{in3}(t) \end{bmatrix} \quad (3.2)$$

where $h_i(t)$ are switching functions; $u_{in,i}(t)$ are instantaneous values of source voltage of i th phase, $i = 1, 2, 3$.

The source voltage is

$$u_{out}(t) = U_{1ph,m} \sin \left[\omega_{in} t - (i - 1) \frac{2\pi}{3} \right] \quad (3.3)$$

where $U_{1ph,m}$ is amplitude value of phase voltage at frequency ω_{in} .

The switching functions depend on the converter circuit type. For three-phase bridge converter the switching functions may be represented as the following harmonic series:

$$h_i(t) = \frac{4}{\pi} \sum_{k=1,3,5,\dots}^{\infty} \frac{1}{k} \sin \frac{k\pi}{6} \cos k \left[\Omega t \mp (i - 1) \frac{2\pi}{3} \right] \quad (3.4)$$

where Ω is the switching function frequency (modulation frequency).

In expression (3.4) the upper sign « \leftarrow » corresponds to positive phase sequence and lower sign « \rightarrow » - to negative one. Under positive sequence, phase sequence of switching functions is the same as the source phase sequence, under negative sequence it is reverse.

Modulation is the first and key stage of frequency conversion. The output ac voltage of needed frequency may be obtained by means of proper modulation of switching functions temporal parameters (the repetition frequency, the pulse duration, etc.). Herewith, modulation of repetition frequency of the switching functions relative to the average frequency ω_{in} will be observed. Mathematically, it may be taken into account by means of substitution of $\Omega t = \omega_{in} t \pm M(t)$ for the case of positive phase sequence or $\Omega t = -\omega_{in} t + M(t)$ for the case of negative phase sequence to expression (2.4). Here $M(t)$ is modulation function which type defines both form and characteristics of output voltage curve. Then, despite of phase sequence, expression (3.4) will be

$$h_i(t) = \frac{4}{\pi} \sum_{k=1,3,5,\dots}^{\infty} \frac{1}{k} \sin \frac{k\pi}{6} \cos k \left[\omega_{in} t \pm M(t) - (i-1) \frac{2\pi}{3} \right]. \quad (3.5)$$

Substitution of (3.3) and (3.5) into (3.2) gives the following *expression of output voltage for three-phase/single-phase 6-pulse direct frequency converter* assembled in a bridge circuit:

$$u_{out}(t) = \frac{-3U_{1m}}{\pi} \sum_{s=-\infty}^{\infty} \frac{(-1)^s}{6s+1} \sin[6s\omega_{in}t \pm (6s+1)M(t)] \quad (3.6)$$

where U_{1m} is amplitude of the line-to-line voltage.

In expression (3.6) the upper sign «+» corresponds to voltage curve of positive type, and the lower sign «-» to voltage curve of negative type. It should be noted that if the phase sequence is negative, it is possible to obtain only voltage curve of negative type. Thus, frequency content of output voltage will depend on modulation function sign.

The input current curve is formed in a similar way to the output voltage curve, that is of sections of curve (curves) of single-phase or polyphase load in output. Hence the curve of input current may be described with the help of the same system of switching functions as the curve of output voltage. With it

$$\mathbf{i}_{in}(t) = \mathbf{H}(t)^T \mathbf{i}_{out}(t)$$

where $\mathbf{i}_{in}(t), \mathbf{i}_{out}(t)$ are column matrices of input/output current; $\mathbf{H}(t)^T$ is transposed matrix of switching functions.

For three-phase/single-phase bridge converter, the current in a phase of power line is equal to difference of two currents when load is connected alternatively to line voltages (for example, for phase A – to u_{AB} and u_{CA}). Then the system of input currents may be represented as

$$\begin{bmatrix} i_{inA}(t) \\ i_{inB}(t) \\ i_{inC}(t) \end{bmatrix} = \begin{bmatrix} h'_1(t) \\ h'_2(t) \\ h'_3(t) \end{bmatrix} i_{out}(t) \quad (3.7)$$

$$\begin{bmatrix} h'_1(t) \\ h'_2(t) \\ h'_3(t) \end{bmatrix} = \begin{bmatrix} h_1(t) - h_3(t) \\ h_2(t) - h_1(t) \\ h_3(t) - h_2(t) \end{bmatrix} \quad (3.8)$$

where $h_1(t), h_2(t), h_3(t)$ are switching functions caused by (3.5); $i_{out}(t)$ is output current (load current) of the direct frequency converter.

Structure of input currents expressions stipulated by (3.7) will be the same. Therefore, it is quite enough to consider the input current of one of the phases. For

other phases input currents may be obtained by means of suitable *phase displacement* introduction. Then for phase *A*

$$i_{in}(t) = h'_1(t)i_{out}(t)$$

where, taking into account (3.5) and (3.8),

$$h'_1(t) = -\frac{2\sqrt{3}}{\pi} \sum_{q=-\infty}^{\infty} \frac{(-1)^q}{6q+1} \sin \left[(6q+1) \left(\omega_{in}t \pm M(t) - \frac{2\pi}{3} \right) \right].$$

As it has been indicated above, the modulation function may be either linear function or periodic one. To form a curve of output voltage with the required frequency ω_{out} the following modulation functions are used:

1. Linear

$$M(t) = \omega_{out}(t) + \psi$$

where ψ is an arbitrary phase angle.

2. Sinusoidal

$$M(t) = \mu \sin(\omega_{out}(t) + \psi)$$

where μ is depth of output voltage control (modulation depth), $0 \leq \mu \leq 1$.

3. Triangular

$$M(t) = \arcsin[\mu \sin(\omega_{out}(t) + \psi)].$$

4. Rectangular

$$M(t) = \begin{cases} +\pi/2 & -\psi \leq \omega_{out}t < \pi - \psi \\ -\pi/2 & \pi - \psi \leq 2\pi - \psi \end{cases}$$

Curves of the output voltage (input current) of a direct frequency converter as well as their frequency contents depend greatly on modulation function. Fig. 3.5 – 3.8 show calculated curves of the output voltage under different types of function $M(t)$ and their spectrums obtained by means of fast Fourier transform for the voltage curves. Relative values U^* of amplitudes in all the cases (Fig. 3.5 – 3.8) are determined concerning amplitude of main component of output voltage under linear modulation function.

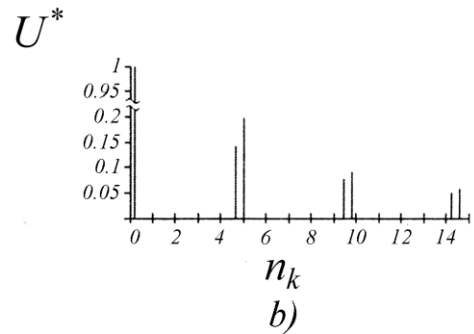
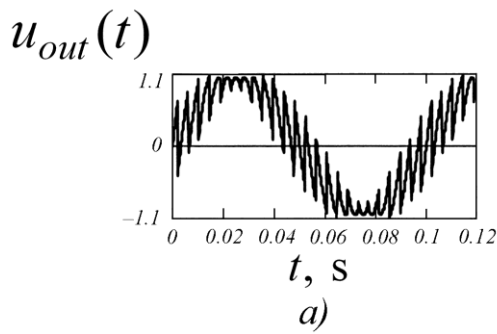


Figure 3.5 Output voltage of negative type (a) and its amplitude spectrum (b) for three phase – single phase bridge 6-pulse direct frequency converter under linear modulation function and output frequency $f_2 = 10$ Hz

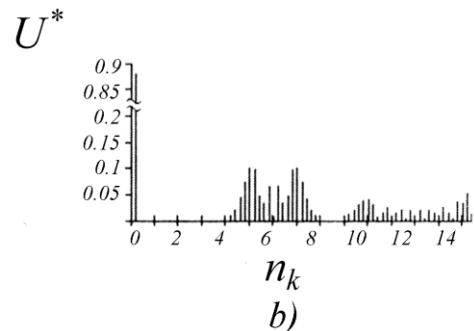
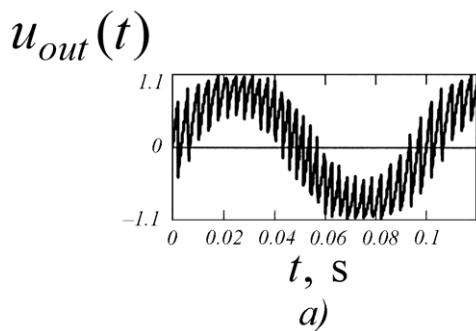


Figure 3.6 Output voltage of negative type (a) and its amplitude spectrum (b) of three phase – single phase bridge 6- pulse direct frequency converter under sinusoidal modulation function, $\mu = 1$ and output frequency $f_2 = 10$ Hz.

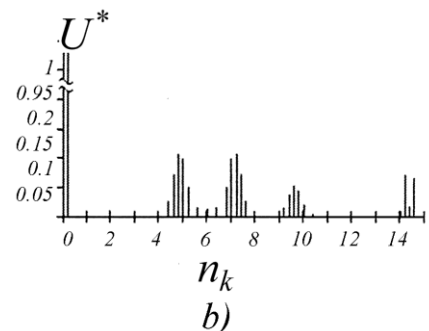
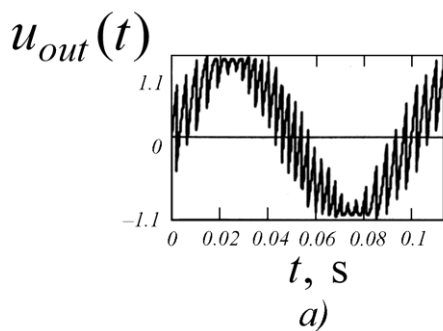


Figure 3.7 Curve of output voltage of negative type (a) and its amplitude spectrum (b) of three phase – single phase bridge 6- pulse direct frequency converter under triangular modulation function, $\mu = 1$ and output frequency $f_2 = 10$ Hz

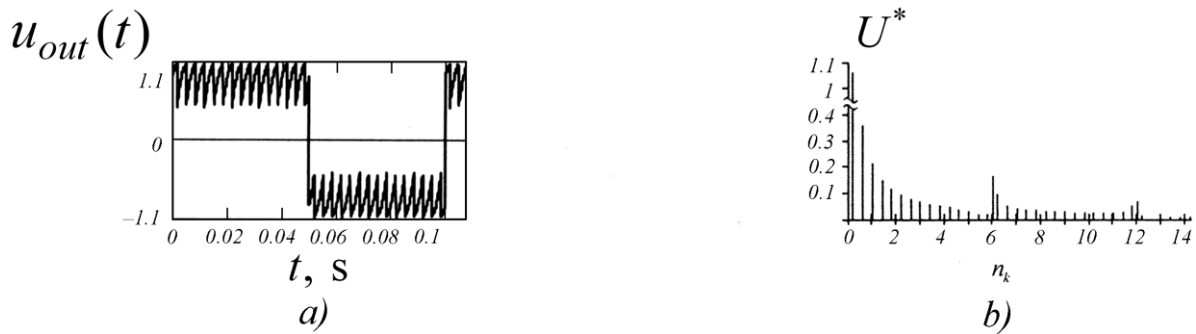


Figure 3.8 Output voltage of negative type (a) and its amplitude spectrum (b) of three phase – single phase bridge 6- pulse direct frequency converter under rectangular modulation function and output frequency $f_2 = 10$ Hz

Data from Table 3.2 give ability to compare level of harmonics and interharmonics of a frequency converter under different control laws.

Table 3.2
Level of harmonics generated by frequency converter under different control laws

| Parameter | Bridge 6- pulse direct frequency converter | | | | | 3ph-3ph 6- pulse frequency converter with direct-current link $f_2 = 30 \Gamma\text{H}$ |
|---|--|------------------------|------------------------|-------------------------|---|--|
| | 3ph-1ph at $f_2 = 10$ Hz | | | | | |
| | Linear control law | Sinusoidal control law | Triangular control law | Rectangular control law | 3ph-3ph at $f_2 = 20$ Hz and sinusoidal control law | |
| Rms value of input current, % | 147 | 208 | 183 | 173 | 128 | 120 |
| Fundamental of input current, % | 100 | 100 | 100 | 100 | 100 | 100 |
| Rms value of input current harmonics, % | 9 | 23 | 24 | 33 | 56 | 29 |
| Rms value of input current interharmonics, % | 107 | 181 | 152 | 138 | 56 | 44 |
| Excess of rms value of interharmonics over rms value of input current harmonics | 12 times | 8 times | 6 times | 4 times | 1 time | 1,5 times |

3.4. Induction inverter cascade

Schematic diagram of induction inverter cascade is shown in Fig. 3.9.

The line current contains harmonic components of the following frequencies:

1. Characteristic harmonics produced by converter C2:

$$(p_2 k \pm 1) f_1, \quad k = 0, 1, 2, \dots$$

2. Interharmonics caused by the dc link which pass into the feeding line by means of converter C2 as side components of its characteristic harmonics.

From the line supplying the transformer appear components having frequencies:

$$f_{n,1} = (k p_2 \pm 1) f_1 \pm p_1 n f_2 = (k p_2 \pm 1) f_1 \pm p_1 n s f_1,$$

$$n = 0, 1, 2, \dots, \quad k = 0, 1, 2, \dots$$

where s is the slip; p_1 and p_2 are pulses number of converters C1 and C2.

For $n = 0$ successive values of coefficient k mean frequencies of characteristic harmonics for the given structure of converter C2. For $n \neq 0$ successive values of k represent frequencies of interharmonics that are side components around harmonics of the bridge C2.

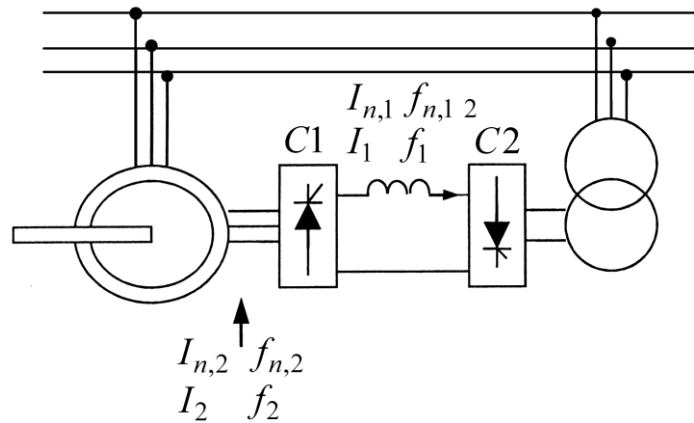


Figure 3.9 Induction inverter cascade

3. Harmonic components which availability is caused by transformation of rotor harmonics to the stator side. Components of rotor currents with frequency $f_{n,2}$ forming symmetrical three-phase system arise in the stator with frequency $f_{n,1}$:

$$f_{n,1} = f_{n,2} \pm \Delta f_1 = f_{n,2} \pm f_1(1 - s) = s f_1(k p_1 \pm 1) \pm f_1(1 - s) = f_1(s k p_1 \pm 1).$$

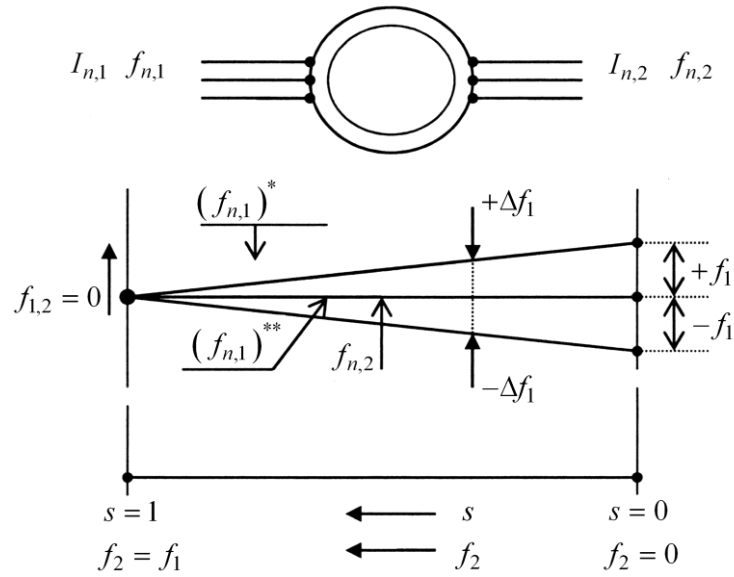


Figure 3.10 Transformation of rotor harmonics to the side of stator in the induction cascade

Sign before Δf_1 depends on whether rotor harmonics form system rotating in accordance to (+) or opposite with (-) the stator field.

Unbalance of three-phase system for a given harmonic of the rotor current causes availability of pair of interharmonics in the stator: $f_{n,1} = f_{n,2} \pm \Delta f_1$. Typical for a rectifier harmonics are rather important for cascade units. Usually extra components being side ones do not exceed 3% of the fundamental (for 12-pulse rectifiers). Interharmonics transferred into rotor circuit by means of rotating rotor field have even smaller amplitudes.

3.5. Thyristor-controlled switches

By this method, the current flowing through a semiconductor switch during several periods is provided. The current either is sinusoidal or is not available. Fig. 3.11 represents the case of control in three-phase circuit. Henceforth common in practice single-phase load will be considered. Control of definite conduction periods is selection of N current periods of their total number M . Selecting the ratio N/M the average value of power given to the consumer is controlled. Such method of control is called the integral method. Current consumed by the load may be described with the relationship:

$$i_0 = \sqrt{2}I_0 \sin(M\omega t) \Big|_0^{2\pi(\frac{N}{M})} + 0 \Big|_{2\pi(\frac{N}{M})}^{2\pi}$$

where I_0 is rms current, and Mf^{-1} is the repetition period.

In this case coefficients of Fourier series are:

$$a_k = \frac{1}{\pi} \int_0^{2\pi \frac{N}{M}} i_0(M\omega t) \cos(k\omega t) d\omega t = \sqrt{2}I_0 \frac{M}{\pi(M^2-k^2)} \left(1 - \cos \frac{2\pi kN}{M}\right), \quad (3.9)$$

$$b_k = \frac{1}{\pi} \int_0^{2\pi \frac{N}{M}} i_0(M\omega t) \sin(k\omega t) d\omega t = \sqrt{2}I_0 \frac{M}{\pi(M^2-k^2)} \left(-\sin \frac{2\pi kN}{M}\right), \quad (3.10)$$

$$c_k = \sqrt{a_k^2 + b_k^2}.$$

Hence it follows:

$$c_k = \frac{\sqrt{2}I_0 M}{\pi(M^2-k^2)} 2 \sin \frac{\pi kN}{M}. \quad (3.11)$$

For $k=1$ expressions (3.9) ÷ (3.11) describe the subharmonic being the current component of lowest-frequency $(1/M)f$. For example given in Fig. 3.12 where $N=2$, $M=3$, its value is $\frac{1}{3}$ of the source voltage frequency. Frequency of other components is multiple of it.

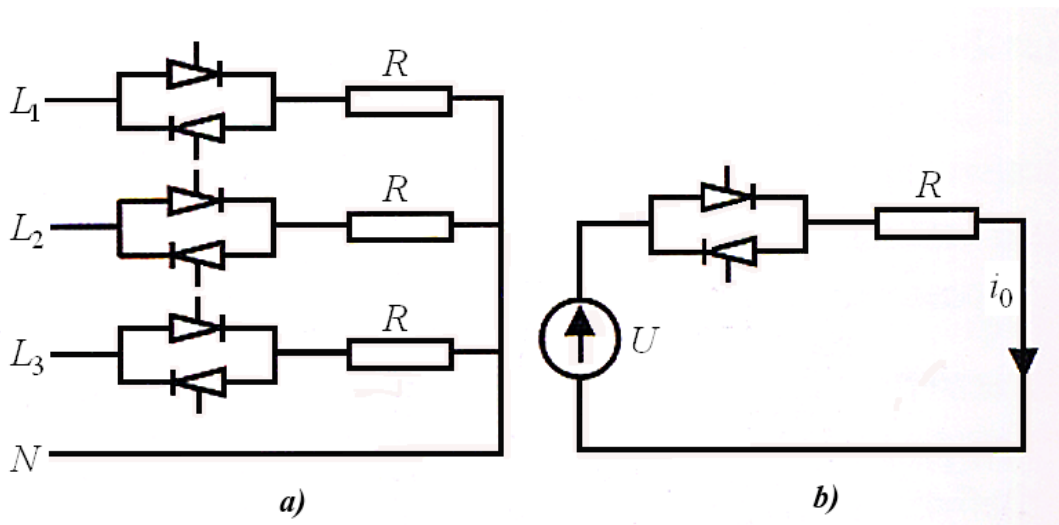


Figure 3.11 Alternating current control in three-phase (a) and single-phase (b) devices

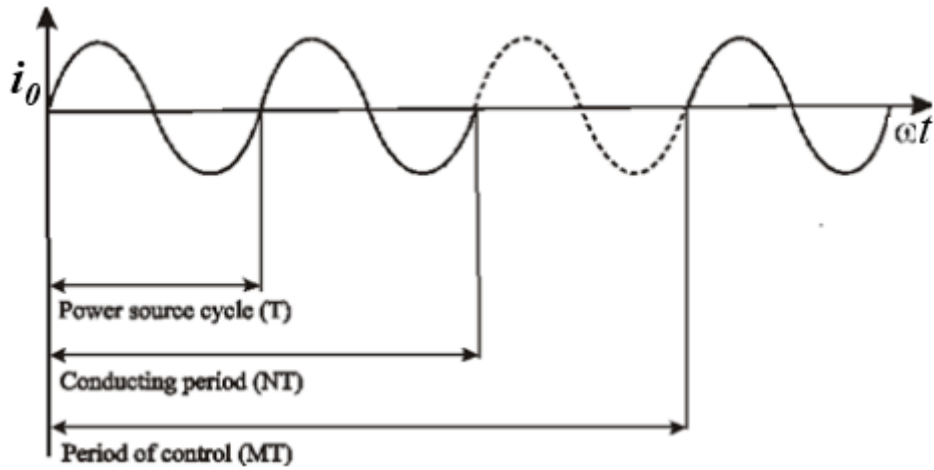


Figure 3.12 Load current under integral control at $N=2, M=2$

Dependence (3.12) permits to determine amplitudes of other components in per cent of the current amplitude I_m :

$$\frac{I_k}{I_m} = \left| \frac{2M \sin\left(\frac{N}{M}k\pi\right)}{\pi (M^2 - k^2)} \right| \quad (3.12)$$

where k is the harmonic number.

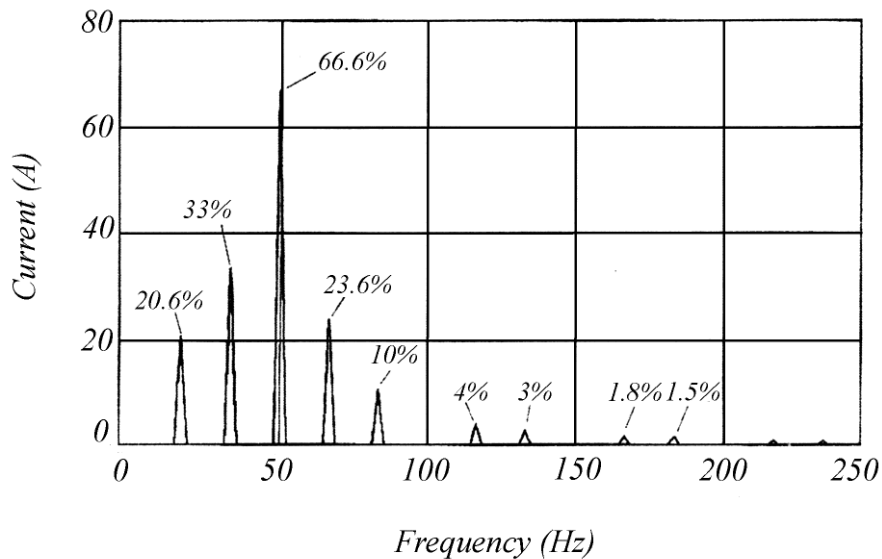


Figure 3.13 Current spectrum at $N=2, M=3$

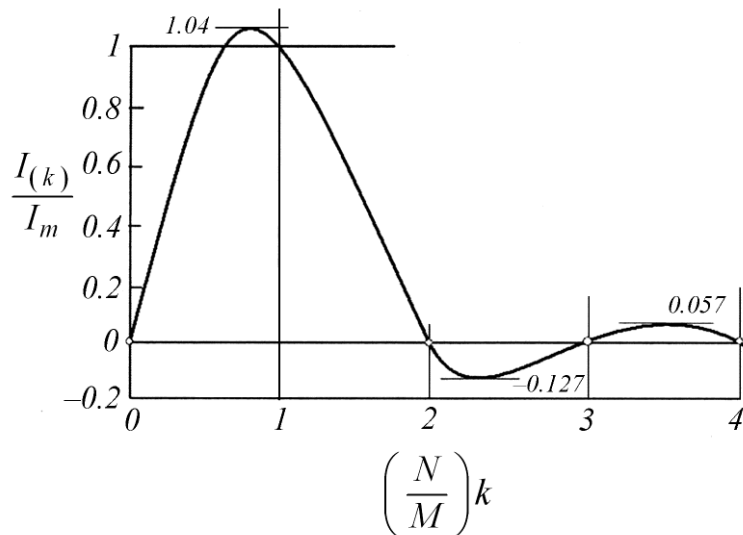


Figure 3.14 Subharmonic amplitudes at integral consumer control

This method of control is a source of subharmonics (that is components with frequency being lower than basic one) and interharmonics but is not a source of harmonics. If $N=2$, $M=3$, as in Fig. 3.12, amplitudes of harmonics are equal to zero for $k=6, 9, 12, \dots$. Current spectrum for this case is shown in Fig. 3.13. As it is seen, the component with frequency of supply voltage and the subharmonic under $k=2$ having frequency of $(2f)/3$ prevail in the amplitude spectrum. Using Fig. 3.14, correspondent amplitudes of interharmonics in considered control device may be determined.

For $N=1$, $M=2$ and $f=50 \text{ Hz}$, the fundamental frequency equals 50 Hz , $k=1$. Table 3.3 gives relative values of subharmonics.

Table 3.3

Frequencies and values of successive amplitudes for $N=1$, $M=0$

| Component serial number (k) | $f, \text{ Hz}$ | Relative amplitude value $I_{(k)}/I_m$ | Order of component $f_{(k)}/f$ |
|---------------------------------|-----------------|--|--------------------------------|
| 1 | 25 | 0.42 | 1/2 |
| 2 | 50 | 0.5 | 1 |
| 3 | 75 | 0.25 | 3/2 |
| 4 | 100 | 0 | 2 |
| 5 | 125 | 0.06 | 5/2 |

Control and data transfer signals within power systems. Despite the fact that electric grids are intended for consumers electric power supply, they are also used for transmission signals to control definite category of consumers (illumination of streets, tariff shift, consumer tele-switching, etc.) or for data transmission. Industrial networks are not used to transmit signals employed by private consumers. From a technical point of view, the transmitted signals are sources of interharmonics with dura-

tion of 0.5–2 s and the sequences repetition period of 6–180 s. In most cases impulse lasts 0.5 s, and the pulse train duration is 30 s. The signal voltage and frequency are previously agreed, and the signal is sent at the assigned time.

IEC 61000-2-1 Standard defines the four main categories of the signals:

- *Low frequencies* - sinusoidal signals within 110–2200 (3000) Hz, and, as a rule, 110–500 Hz in new systems. They are mostly used in professional electric systems (sometimes in industrial ones) at levels of low, medium and high voltage. Amplitude of the signal voltage is within 2–5 % of nominal voltage (it depends on local practice). It may increase up to 9 % under conditions of resonance

- *Medium frequencies*: sinusoidal signals within 3–20 kHz, mainly 6–8 kHz. They are mostly used in professional electric systems. Amplitude of signal is up to 2% of U_r .

- *Radio frequencies*: 20–159 (148.5) kHz (up to 500 kHz in some countries). They are used in professional, industrial and municipal electrical systems as well as for commercial use (telecontrol of different devices etc.)

- *Marks on supply voltage* - non-sinusoidal patterns on harmonic voltage diagram in the form of:

- extended voltage impulses up to 1,5–2 ms
- short voltage impulses up to 20–50 mcs
- impulses with 50 Hz frequency and width equal to the period of circuit voltage or its half.

Fig. 3.15 shows example of voltage spectrum for system of data transfer at frequency of 175Hz. The spectrum contains also other interharmonics generated as a result of interaction with characteristic harmonics. Harmonics of higher than second order are not important. They cannot interfere with the power consumer. But interharmonics which frequency is less than 200 Hz may be problematic.

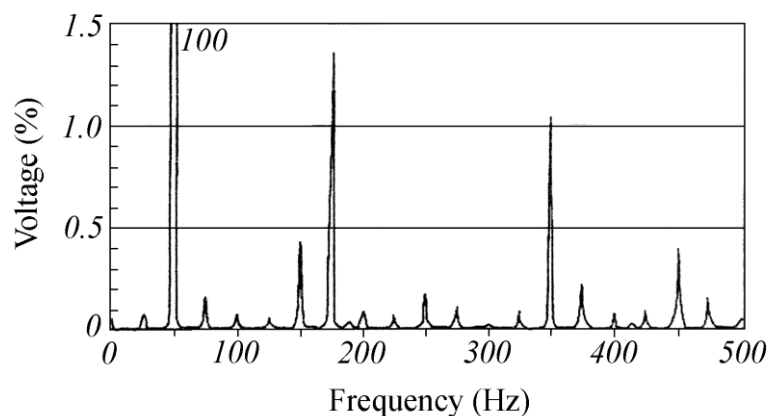
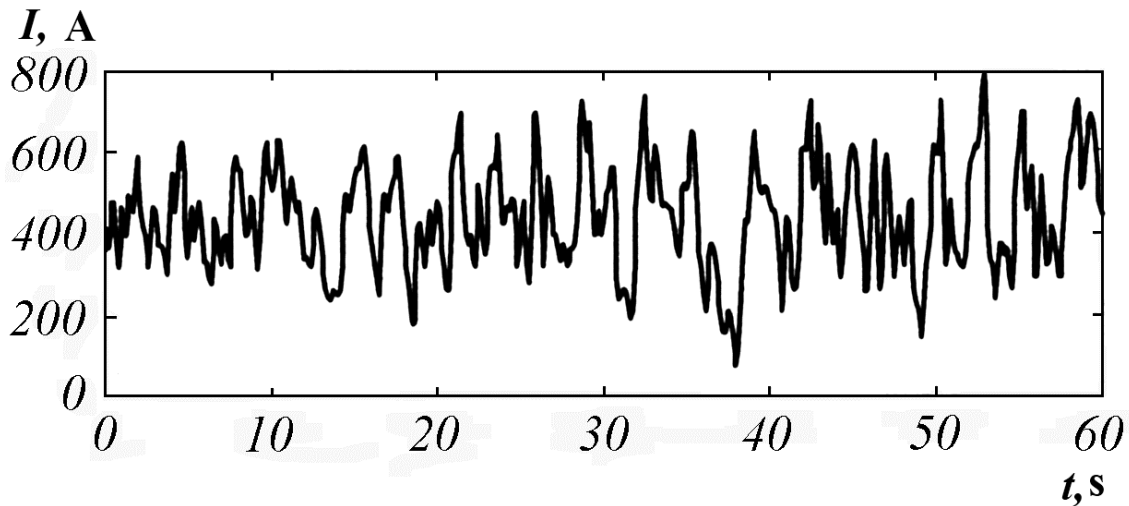


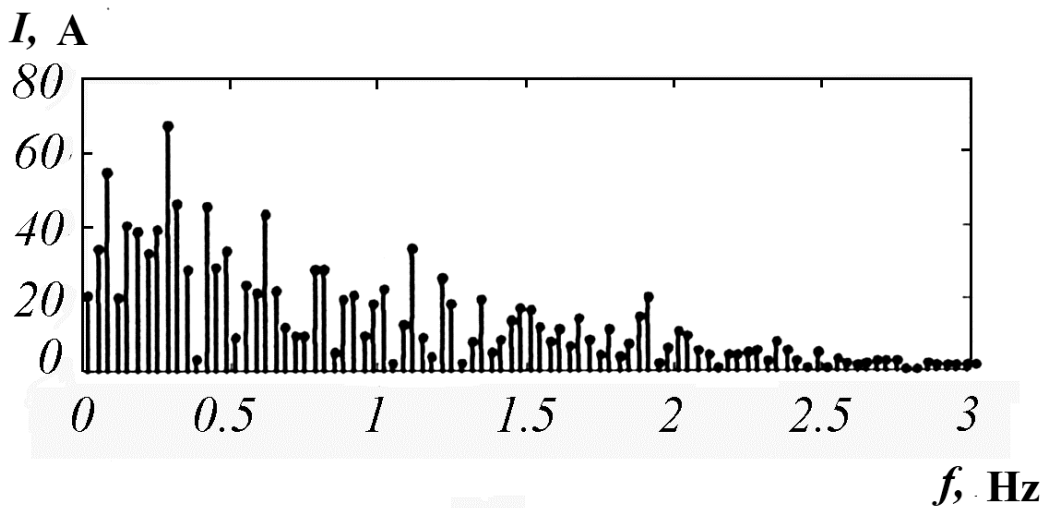
Figure 3.15 Result obtained by means of fast Fourier transform for voltage in the process of signal transduction

3.6. Arc steel furnaces, electric welding and other equipment

Arc steel furnace is considerable source of electromagnetic disturbances such as harmonics and interharmonics, voltage fluctuation and unbalance. Mainly generation of electromagnetic disturbances takes place during melt-down period. Averaged values of current harmonics in % generated by ASF-200 furnace are:



a)



b)

Figure 3.16 Graph of phase B load current for ASF-100 (a) and its amplitude spectrum (b)

| Harmonic number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----------------|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

| | | | | | | | | | |
|---------------------------------|-----|-----|-----|------|-----|-----|-----|-----|------|
| Value (level) of harmonic | 100 | 2.7 | 2.3 | 0.65 | 2.3 | 1.3 | 1.5 | 1.0 | 0.85 |
| | | | | | | | | | |

Curves of line currents of ASF are distorted much less to compare with valve inverter currents. Fig. 3.16 shows graphs of behavior of phase B current of ASF -100 during time of stationary operation (60 s) and amplitude spectrum of rms current within the frequency range of 0-2.5 Hz obtained with the help of fast Fourier transform.

Analysis of the line spectrum indicates that interharmonics which levels are up to 10% of the current fundamental emerge within the band of 0-2.5 Hz. As a whole spectrum of ASF current deviations during melt-down period is compound as it consists of discrete and continuous components. Interharmonics power for ASF-100 and ASF-200 is about 20% of the whole power of the compound spectrum.

Voltage unbalance on ASF buses may be 5–6 % for 6–10–35 kV networks depending upon source voltage and 3 % for 110 kV networks. For the same cases, dose of flicker is as a rule within 1.5-10.

Electric Welding Equipment (ЭЦВ) practically generates all electromagnetic disturbances which characterize the power quality: harmonics, unbalance, voltage dips and deviation, etc.

Harmonics of butt welding machine currents are determined on the expression:

$$I_n = S_r k_{l,typ} \sqrt{CDF_{typ}} / (n^2 U_r)$$

where S_r is nominal (rated) load of the welding equipment; $k_{l,typ}$ and CDF_{typ} are the average typical load factor and the cycle duration factor respectively; $n = 3, 5, 7$.

Variation range of current harmonics of dc electric welding machines is 12-30 % for $n = 3$, 4–15 % for $n = 5$ and 2–8 % for $n = 7$.

Harmonics currents of direct-current welding machines and welding rectifiers commutated on 6-pulse circuit are estimated on similar expression

$$I_n = S_r k_{l,typ} \sqrt{CDF_{typ}} / (\sqrt{3} n^2 U_r)$$

where $n = 5, 7, 11$.

Unbalance factor in networks supplying electric welding machines is 1–5 %.

Like ASF, electric welding equipment is a sources of interharmonics too. Under spot welding interharmonics are within 35-75 Hz and have amplitudes up to 20 % of welding current fundamental. Fig. 3.17 shows amplitude spectrum of current of multi-spot welder. It is seen that interharmonics range covers the band of 0-20 Hz under relative values of amplitudes up to 6 %.

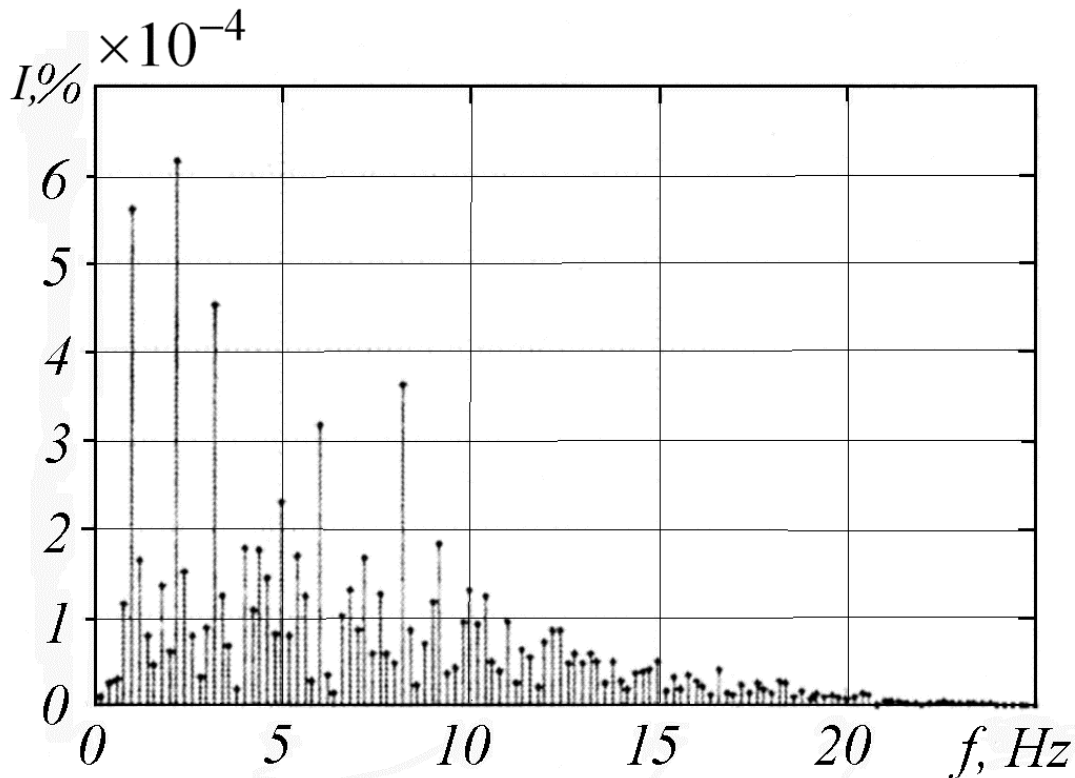


Figure 3.17 Current amplitude spectrum under performance of multi-spot welder

For all electric welding equipment, power of discrete spectrum is 6–20 % of total energy of the compound spectrum.

Parameters of voltage dips produced by some types of electric welding equipment are as follows:

| Machine type | $S, \text{ kV}\cdot\text{A}$ | Depth of voltage dips, % | Duration of voltage dips, s |
|-------------------------|------------------------------|--------------------------|-----------------------------|
| Stationary spot welders | 75 | 1.2 | 0.18 |
| Butt welders | 750 | 13 | 0.7 |
| Multi-spot welders | 63 | 16.3 | 0.36 |
| Arc welding | 60 | 1.0 | 27 |

Gas-discharge lamps (fluorescent and mercury-arc) are sources of harmonics. Relative values of currents of the 3rd and 5th harmonics are 16–21 % and 0.9–3 % for fluorescent lamps with inductance-capacitance ballast, and 18% and 5.8-7.2% for mercury-arc lamps with compensation. The n^{th} harmonic current

$$I_n = 0.25S_r/(n^2U_r)$$

where S_r is the lamp rated power.

Wind power installations (WPI) are intensive source of electromagnetic disturbances, mainly of harmonics and voltage deviation. Fig. 3.18 and 3.19 show typical circuit of powerful wind power installations and power network diagram in which nodes measurement of long-lasting flicker dose P_{Lt} and sinusoidal voltage curve distortion factor K_U were made.

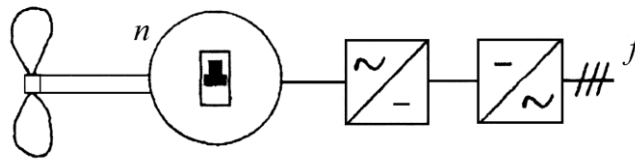


Figure 3.18 Typical circuit of powerful wind installation

Some measurement results cited below confirm rather considerable level of deviations. Values of K_U in some nodes are also great. Voltage deviations differ in different phases, therefore difference in values of K_U is smaller.

| Section I | | | Section II | | | | |
|-----------|------|------|------------|----------|------|------|------|
| Phase | A | B | C | Phase | A | B | C |
| P_{Lt} | 3.15 | 3.9 | 3.03 | P_{Lt} | 8.55 | 6.81 | 8.00 |
| K_U | 1.76 | 1.85 | 1.82 | K_U | 2.95 | 3.13 | 3.28 |

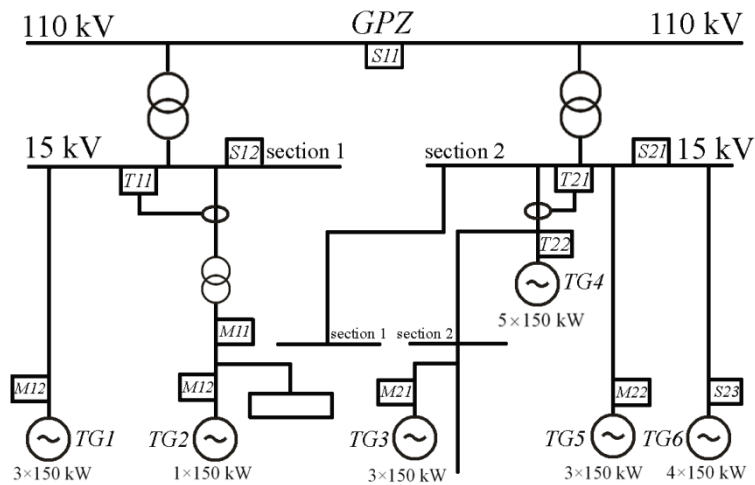


Figure 3.19 Power network of wind power station

3.7. Interference in trolley lines of electric transport

Interference in trolley lines are characterized by complexity and diversity. In low-frequency part of spectrum the interference intensity is the largest, and it reduces at frequency increase. The source of impulse disturbances is sparking taking place in the course of electric equipment performance such as disconnect switches, electric machines etc. Intensity of electromagnetic disturbances when electric locomotives move greatly depends on state of a trolley line and rails, material of the line and a current collector, their design, electric locomotive velocity and state of the line insulation. Improper suspension of the trolley line, availability of jags and projections, inadequate state of rail joints affect it negatively too. Negative consequences of the above factors are especially considerable in the case of steel instead of copper contact wire use. The matter is that, with the course of time, the wire undergoes corrosion, and on its surface jaggings appear. Bad contact between wheels and railing on dirty rail track especially while braking or slipping is also a source of electromagnetic interference.

On lines with voltage of 35 kV, arresters generate *impulse disturbances* with duration about 1 μ s in the time of lightning storms. It results in interference in wide spectrum of communication band. Filters of communication equipment change shape and amplitude of impulses and increase their duration.

Disturbances caused by expulsion-type arresters while lightning stipulate complicated false response of high-frequency communication system relays. In grids of 6-10 kV blowing of high-voltage fuses at short circuits causes surges which multiple is $(4,5 \dots 7)U_{ph}$. These surges may produce impulse electromagnetic losses which de-range telecommunication equipment.

Valve inverters of traction substations are the main source of harmonic electromagnetic disturbances. As a rule, thyristor 6-pulse valve inverters are used. Their performance originates a quantity of ac components of current having different frequency and amplitude. The largest amplitude belongs to ac component with frequency of 300 Hz under performance on 6-pulse circuit ($50 \cdot 6 = 300$ Hz). In addition to 300 Hz frequency, harmonics 600 Hz, 900 Hz etc. arise which level decreases with the frequency increase.

At some frequencies significant bursts of electromagnetic disturbances level due to resonance in circuits of the traction substation.

Test questions

1. Name types of electromagnetic disturbances you know.
2. Why do valve inverters belong to the most powerful sources of electromagnetic disturbances?
3. What is the interharmonic?
4. Compare generation of interharmonics by frequency converters of different types.

5. What types of electromagnetic disturbances do arc steel furnaces generate?
6. What types of electromagnetic disturbances does electric welding equipment generate?
7. What types of electromagnetic disturbances do wind power installations generate?
8. Compare levels of electromagnetic disturbances stipulated by performance of fluorescent and mercury-arc lamps.
9. What kinds of electromagnetic disturbances are available in the networks of electric transport?
10. Compare levels of harmonics and interharmonics of frequency converters at different control laws.

Topics for essay

1. Amplitude spectra of valve converters and arc steel furnaces.
2. Frequency converters harmonic and interharmonic spectra.
3. Thyristor controlled converters impact on network power supply.
4. Amplitude spectra of frequency converters with direct current link.
5. Current spectra of electric welding equipment.

CHAPTER 4 INFLUENCE OF ELECTROMAGNETIC DISTURBANCES ON ELECTRICAL EQUIPMENT, CONTROL AND COMMUNICATION SYSTEMS

4.1. Influence of electromagnetic disturbances on electrical equipment, protection and control systems

Negative influence of electromagnetic disturbances, which are indicators of electric power quality, is multifactorial and manifests itself differently depending on the type of disturbance. But increase in electric equipment losses, service life and functional reliability decrease are common features for all types of interference caused by the electromagnetic disturbances. Under combined action of several electromagnetic disturbances their impact is greater than simple sum of impacts caused by each disturbance separately.

The following data confirm large scale after-effect of electromagnetic disturbances joint impact. There are about 700 mln motors installed in the USA. At average motor life of 30 years it is necessary to replace annually 23mln of motors. Under available power quality a motor service life is reduced by 2 years, and it results in necessity of extra replacement of 3 mln motors a year.

Voltage deviations in electric power supply system take place mainly due to load variation which is caused by:

- power consumers operating conditions;
- variation in number of connected consumers;
- routine switching;
- network operating irregularities.

Voltage deviations are closely related with voltage falling and its control in networks. At the network load variation in time the sources voltage falling (deviation) varies too. Value of voltage deviation δU_t in the specified point of a network is a function of many variables, that is:

$$\delta U_t = f(U_{gr}, P, Q, Z, Y, \sum \delta U^{ad})$$

Where P and Q are the consumed active and reactive power in the considered network; U_{gr} is the voltage of the supply grid (e.g., on buses of a substation); Z and Y are impedance and admittance of the network elements; $\sum \delta U^{ad}$ is a sum of “additions”-extra voltages (e.g., in a transformer or in transformers of the supply network).

Influence of voltage deviations on the consumed active and reactive power may be shown with the help of steady-state power-voltage curve (Fig. 4.1).

Under considered range of voltage deviations productivity of the consumer reduces and specific energy consumption increases. Under positive voltage deviations the productivity increases and specific energy consumption reduces. Specific energy

consumption of a thyristor converter increases considerably at $\delta U_t > 0$ and reduces a little at $\delta U_t < 0$.

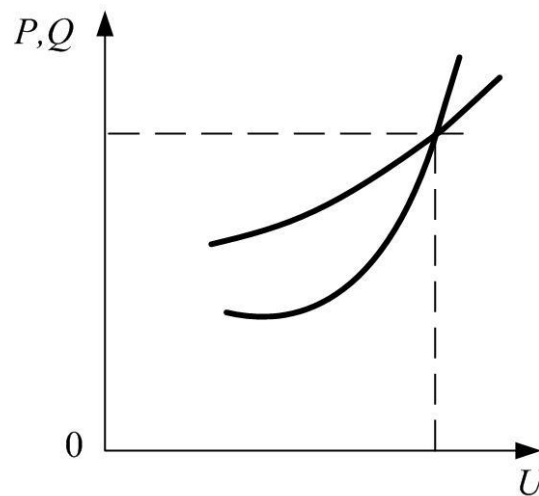


Figure 4.1 Steady-state power-voltage curves

Under voltage reduced below the rated voltage, decrease in light flux produced by lighting equipment is typical. Thus, if voltage is $0.9U_r$, light flux of an incandescent lamp is 40% less. If voltage is $1.1U_r$, light flux increases similarly but the service life decreases by 4 times.

Fluorescent lamps and lamps of ДПЛ-400 type are less sensitive to voltage variation, but starting of a fluorescent lamp becomes impossible at voltage of $0.8U_r$ or less.

Voltage unbalance of industrial power supply systems is caused by availability of powerful single-phase loads (induction melting and heating furnaces, welding sets, electro-slag refining furnaces) as well as three-phase loads working continuously under unbalanced conditions (e.g., arc steel furnaces). Three-phase voltage system may be unbalanced if enterprise network is energized from a traction ac substation.

Additional losses in components of the power networks, decrease of service life of lamps and decline in economic performance take place due to voltage unbalance.

In ac machines magnetic fields rotating with the synchronous speed in the direction of the rotor revolving and with double synchronous speed in the opposite direction are produced. As the result, the braking electromagnetic torque, as well as additional heating of machines active parts (mainly of rotor) by currents of double frequency, arise.

In induction motors at the unbalance factor by negative sequence taking place in practice ($K_{2U} \leq 0.05 \dots 0.06$) decrease of the torque is small. More considerable are additional losses due to heating machines active parts by currents of double frequency and insulation service life reduction.

Dangerous vibrations as a result of alternate torque and tangential forces pulsating with double network frequency may occur in synchronous motors together with extra losses and rotor and stator heating under power network voltage unbalance.

If unbalance is significant vibration may happen to be dangerous, especially in the case of insufficient strength or availability of welding defects. As a rule, dangerous overstressing in structural components does not arise if current unbalance does not exceed 30%.

Extra power losses in synchronous motors under unbalanced load cause local heating of the field winding. It requires to reduce the field current and hence to decrease the reactive power given to the network. In such a case, it may result in necessity to decrease the generator active load or torque on the synchronous motor shaft.

Voltage fluctuations have negative impact on visual perception of subjects, details, graphic drawings and, as a result, on labor productivity and human vision.

As it is known, physiological basis of visual perception is the visual analyzer functioning, one of the main components of which is the receptor. Its main function is to convert energy of the acting irritant into neural process. The light energy is the visual analyzer irritant. Processes taking place in a visual analyzer of a biological system, like all natural phenomena, have energy basis, and the process of visual perception is of energy nature. The visual analyzer has certain energy characteristics.

Besides energy characteristics, the analyzer has temporal characteristics (Fig. 4.2). They are defined by means of time necessary for appearance of visual perception. Latent period of visual reaction, critical flickering frequency and adaptation time are the temporal characteristics.

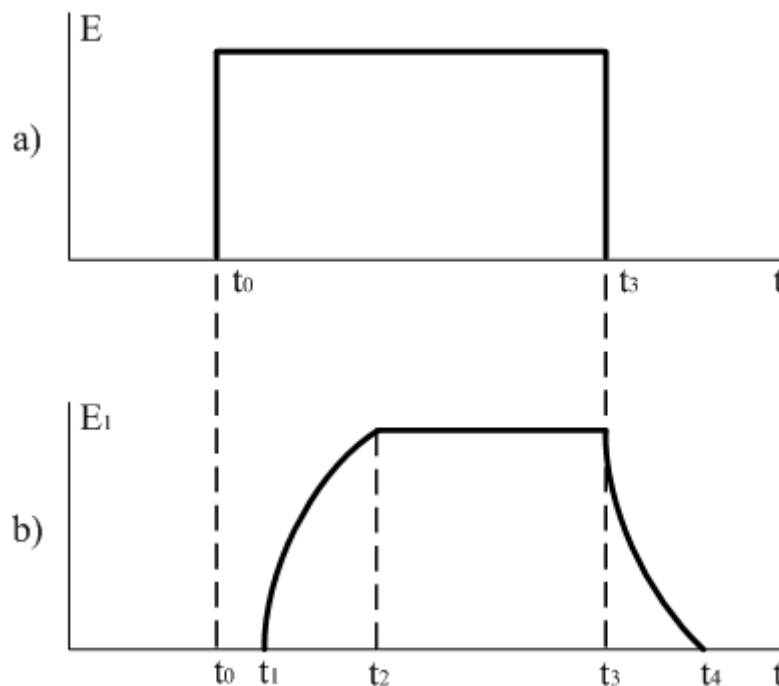


Figure 4.2 Time chart of visual analyzer signals: a) input signal; b) output signal

The characteristics of visual analyzer in a great degree influences on the voltage fluctuation to vision. Their study makes possible to prove mathematical model of vision and to develop normalization procedure for the voltage fluctuation..

Proceeding from Fig. 4.2, it is possible to come to the conclusion that visual analyzer is aperiodic lag unit. The time delay (or latency time) is time t_1-t_0 which depends on signal intensity. It reduces in the course of time. Mean value of latency time is 160—240 ms. Time intervals t_1-t_2 and t_3-t_4 characterize visual inertia. Therefore, if duration of illumination pulses flickering is shorter than inertia time, effect of flicker will be smaller to compare with the case when pulse duration is longer than inertia time. At this, intensity of the signal perception will be as many times less as actual pulse duration less than inertia time.

Visual perception is characterized by means of time during which the perception is retained (0.2 – 0.5s). Effect of pulses flickering depends on their traveling period. If a pulse traveling time is longer than time perception retaining, then every next exposure superposes residual pulse. Therefore, its effect will be greater to compare with the case when pulses are of the same amplitude but have the period less than the time of perception retaining.

Study of the visual analyzer temporal characteristics as well its frequency response makes possible to give its mathematical description. The visual analyzer is a dynamic unit with time delay having complicated frequency-response characteristics which depend on frequency range of actuating signal, its intensity and character. Fluctuation of illumination is perceived with eye as energy caused by the signals (voltage fluctuations) of different frequencies. Having certain frequency-response characteristics, the visual analyzer “weighs” energy according to own frequency characteristics, and then its transformation into energy of nerve process takes place.

Influence of flicker depends on lamps type. Under equal voltage fluctuation, negative effect an incandescent lamp is much greater than of fluorescent ones. If $\delta U_t > 10\%$, extinctions of fluorescent lamp take place. At $\delta U_t > 15\%$ contacts of magnetic starters may break. Under such fluctuations, capacitors and valve inverters failure may takes place. If $\delta U_t > 12\%$, spoilage of high-frequency heating installations production and breakdown of induction melting furnaces cores occur, systems of synchronous motors operational mode automatic control are switched off.

Under voltage fluctuations, productivity of electrolysis plants reduce, their service life shortens due to increased electrode wear. At the plans of chemical fiber synthetic threads either break or have variations in thickness due to speed of induction motors driving bobbin machines oscillation. It results in defects or shortage of outputs. When resistance furnaces are energized by valve inverters, oscillations of load current as well as unstable mode of automatic temperature control system occurs.

Short-time voltage fluctuation during the electric arc welding have not practically effect on welding seam quality owing to inertia of thermal processes in metal. Fluctuations and voltage deviation in power networks energizing contact welding equipment seriously influence spot welding quality.

The voltage amplitude and, in greater degree, its phase fluctuations result in motors, mechanical constructions and pipeline fittings vibrations. The latter causes metal endurance strength and its service life reduction. So when the voltage fluctuates with frequency of 1 Hz, the pipeline service life is shortened by 5-7% due to pressure pulsation.

In the case of harmonics in electric power supply system availability, extra losses in electric machines, transformers and power networks appears; reactive power compensation with the help of capacitor banks becomes more difficult; service life of electric machines and equipment reduces; performance of automation facilities, tele-mechanical and communication systems and signal worsens, etc.

The power factor and torque on shaft of induction motors operating at non-sinusoidal voltage decrease insignificantly. Therefore, harmonics influence on power factor of induction motors may not to be taken consideration. The same is true for the torques caused by current harmonics as these torques do not exceed several tenths of per cent of the torque developed current fundamental having frequency of power line.

Capacitor banks may perform for a long time under overloading by current harmonics not more than by 30 % at the voltage increase not more than 10 %. But under the conditions their service life decreases. As a rule, in power supply systems of industrial enterprises the capacitor banks operate in condition close to current resonance at the frequency of one of harmonics. In such a case they can fail due to current overload.

Energy measuring under non-sinusoidal operating conditions results in occurrence of significant errors. Their values depend upon measuring system of an energy meter as well as on its frequency response characteristic, place of its installation (linear load or nonlinear load) and other factors.

When power of nonlinear load P_{nl} is measured, two flows of power takeplace: the power flow of fundamental frequency P_1 and the power flow of higher order harmonics $\sum_{n=2}^{\infty} P_n$. Nonlinear load is a source of harmonics. Therefore

$$P_{nl} = P_1 - \sum_{n=2}^{\infty} \Delta P_n.$$

For linear load the power equals

$$P_l = P_1 + \sum_{n=2}^{\infty} \Delta P_n.$$

The expressions are easily transformed into

$$P_{nl} = P_1(1 - \gamma_m) \text{ and } P_l = P_1(1 + \gamma_m)$$

where $\gamma_m = \sum_{n=2}^{\infty} \Delta P_n / P_1$ is total of error of the meter at the harmonic frequencies..

If $n > 1$, the frequency error of an induction-type meter is negative, hence $\gamma_m < 1$. The latter expressions help to conclude that there is electric energy overestimation at nonlinear loads and underestimation if loads are linear.

Practice shows that at $K_U = 7 \dots 10 \%$ and 5th to 13th harmonics prevalence electric energy overestimation consumed by thyristor converters may reach 4–6 %. Mainly it depends upon influence of 11th and 13th harmonics as in this case frequency errors of induction-type meters are significant ($\gamma_m = 0.8 \dots 0.9$).

Electronic and digital energy meters have positive frequency error. Therefore, at their use electric energy underestimation

takes place in power networks with nonlinear loads and overestimation under linear loads.

Effect of harmonics on systems of phase-pulse control may result in so called harmonic instability. It consists in occurrence of high voltage of even or multiple of three harmonic on busses of multi-pulse semiconductor converter. In such a case commutation failure is possible under inverter conditions of the converter. Operation of the phase-pulse control system may also become unstable. Harmonic instability may occur at the valve inverter connection to a power system which short-circuit power is commensurable with power of the converter if other harmonic sources, such as power transformers, and non-symmetry of pulses of phase-pulse system are available.

There were cases when auto-oscillations within control systems of valve converters arose as a result of 30th-40th current harmonics penetration into the phase-pulse control system. With it significant load current oscillations as well as emergency disconnection of valve converters took place.

Harmonics of grid current and voltage worsen performance of telematics equipment if power circuits are used as communication channels between subsets of control center and remote station, impede the remote control through power distribution networks with use of harmonics. Current harmonics in overhead transmission lines worsen operation of communication channels.

Current harmonics penetrating into circuits of power systems result in deterioration of performance high-frequency communication and automation systems and give rise to false response of some protection equipment. The most impact of harmonics takes place on equipment comprising semiconductor devices.

Harmonics of voltage and current force influence of other types of electromagnetic disturbances. Under sharp voltage decrease in power network probability of failure of switching systems under the conditions of non-sinusoidal modes considerably increases.

Currents of interharmonics cause voltage distortion depending upon amplitude of current components and resistance of power-supply system at relevant frequency. The more range of frequencies of the current components the higher is risk of undesirable resonance effects which may increase the voltage distortion and cause overloading of using equipment and its operating irregularity. The most widespread interharmonics consequence are heating of equipment, low-frequency oscillations of mechanical systems, problems in performance of fluorescent lamps and electronic equipment, disturbances to protection and control signals in wires of mains, overloading of passive harmonic filters, interference in telecommunication devices, acoustic effects, saturation of instrument transformers.

Variations of rms voltage value and flickering are the most commonly encountered interharmonics effects.

Voltage dips appear under commutation of powerful using equipment, disconnection of overhead lines at thunderstorm periods with following automatic reclosure, under short circuits in power supply systems, etc.

Table 4.1 shows examples of voltage dips distribution of by reasons causing failure in power grids of Belarus metallurgical works at voltage of 110kV.

Table 4.1

Distribution of voltage dips by reasons in 110kV power grid of Belarus
Metallurgical Works

| Depth of dips, % | Share of dips, % | | | Total number of dips, % |
|------------------|------------------|-----------|--------------|-------------------------|
| | Three-phase | Two-phase | Single-phase | |
| 0 – 10 | 23.7 | 27.17 | 17.34 | 68.21 |
| 10 – 25 | 22.54 | 4.05 | 0 | 26.59 |
| 25 – 35 | 2.31 | 0 | 0 | 2.31 |
| 35 – 60 | 2.89 | 0 | 0 | 2.89 |
| 60 – 100 | 0 | 0 | 0 | 0 |
| Total, % | 51.44 | 31.22 | 17.34 | 100 |

The most negative impacts of voltage dips effect automatic installations, telecommunication equipment, and protection devices. They are called sensitive to interference elements. In some cases operation of protective devices caused by the electromagnetic interference leads to interruption of manufacturing process. As a rule the allowed duration of power systems functioning break for industrial consumers is in the bounds of 0.1 – 0.3 s.

For rolling mills where microprocessor control systems are widely used sustainable operation is possible only at definite small dips depth which depends on their duration. Fig. 4.3 shows boundaries of stable operation of sensible element of a drawing mill and of a machine tool with numerical control. Fig. 4.4 shows boundary of stable performance of a mill when a capacitor bank is connected to its terminals.

Programmable controllers, microprocessors unit and semiconductor relays are interference sensitive components. Characteristics of their sensitivity to voltage dips are given in Fig. 4.5 (see above). The stable operating area of a computer depending upon δU_d is shown in Fig. 4.6.

Susceptibility of some using equipment to voltage dips at their duration of $\Delta t_d \geq 0.02$ s is characterized by the following data:

| | |
|---------------------------------------|---|
| Electromagnetic contactor..... | $\delta U_d \geq 15\%$ and $\Delta t_d \geq 0.02$ s |
| Electronically controlled motors..... | $\delta U_d \geq 15\%$ and $\Delta t_d \geq 0.02$ s |
| Under-voltage relay..... | $\delta U_d \geq 20\%$ and $\Delta t_d \geq 0.5$ s |
| Medical diagnostic units..... | $\delta U_d \geq 25\%$ and $\Delta t_d \geq 0.07$ s |
| High-pressure discharge lamps..... | $\delta U_d \geq 20\%$ and $\Delta t_d \geq 0.05$ s |
| Auxiliary motors of power plants..... | $\delta U_d \geq 55\%$ and $\Delta t_d \geq 1.5$ s |

Value of *stability threshold* of electronic control systems when interference sensitive component failure takes place is determined by means of the expression

$$L_s = \delta U(\Delta t)^\beta$$

where $\beta = 2.5 \dots 3.5$.

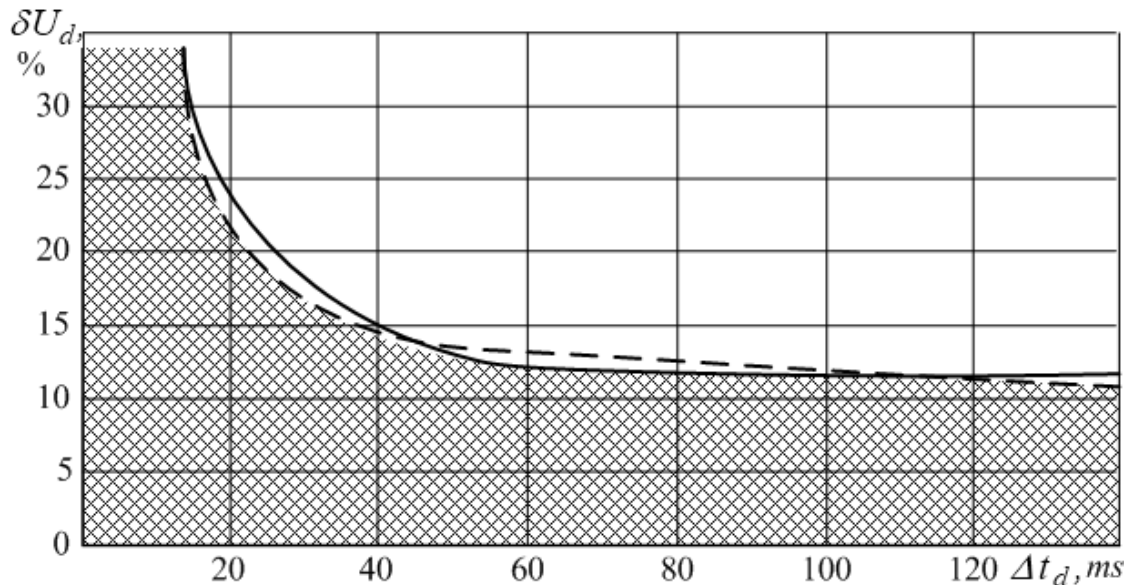


Figure 4.3 Stable operation boundaries of sensible element of a drawing mill and of a machine tool with numerical control:— drawing mill T-12 of 21/200 type; ---numerically controlled machine-tool ПМФ4 of IP-500 type

Thus for elements of control systems of some types of frequency converters

$$L_s = \delta U^{3.5} \sqrt{\Delta t}.$$

The voltage drop is electromagnetic component of damage caused by low power quality. It is defined by total loss caused by separate electromagnetic disturbances without taking into account their mutual influence that somewhat reduces total loss.

Negative impact of electromagnetic disturbances on receiving remotely operated equipment depends on the passband width of the receiving subset. The wider it the greater is acting value of electromagnetic disturbance voltage.

In communicating devices both commutation and atmosphere interferences are audible in earphones as continuous buzz with frequency of 300Hz. It may be explained by modulation of all high-frequency interferences with fundamental component of 300 Hz.

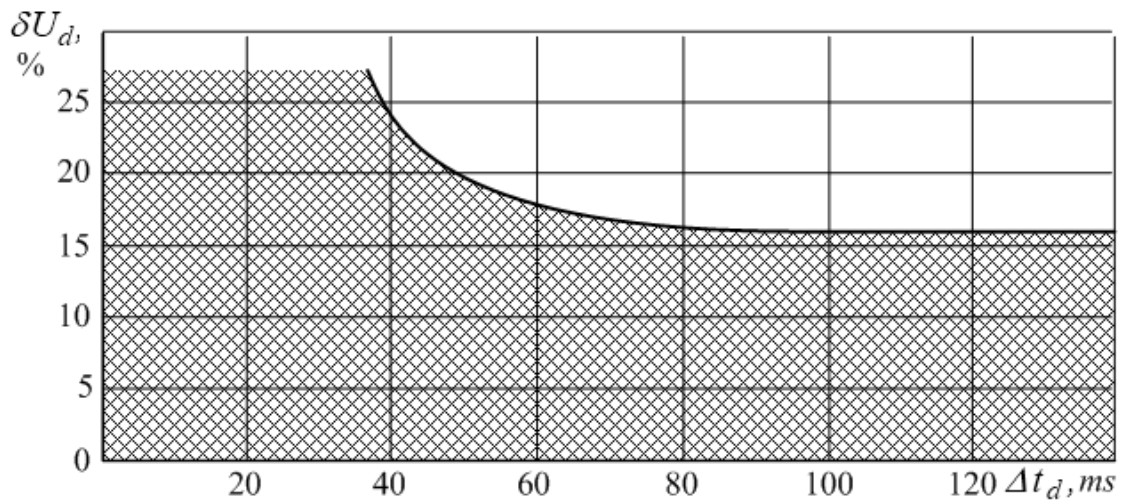


Figure 4.4 Boundary of stable performance of a mill when a capacitor bank is connected to its terminals: — drawing mill boundary of stable performance; under the boundary is stability area of drawing mill performance

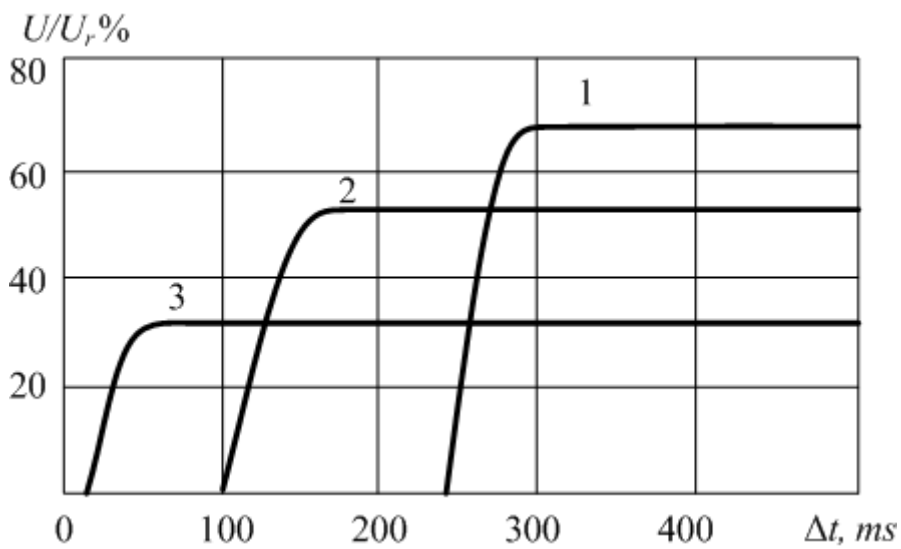


Figure 4.5 Characteristics of sensitivity to voltage dips of programmable controllers (1), microprocessors (2), semiconductor relays (3)

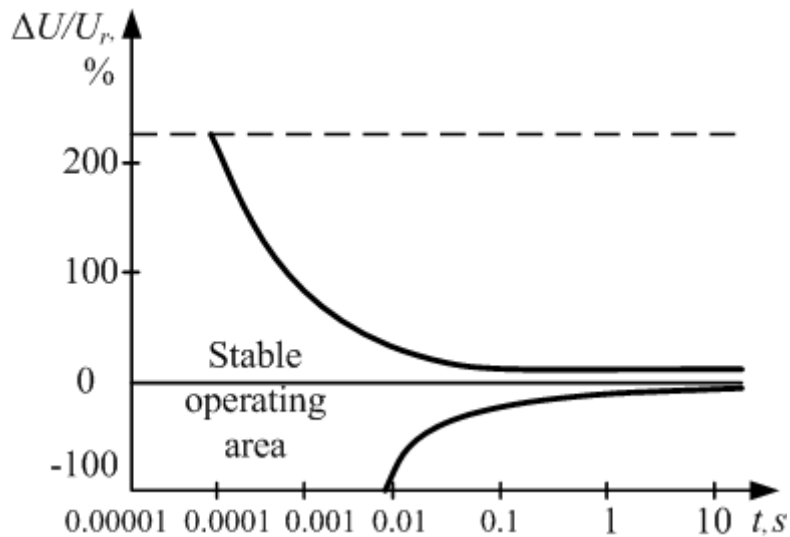


Figure 4.6 Stable operation area of computer under power supply interruptions

4.2. Losses of active power

Structure of extra losses under electromagnetic interference

Extra active power losses in components of electric equipment occur if electromagnetic interference takes place. As a rule, they are defined as total loss resulting from separate electromagnetic interferences (i.e. indexes of power quality) without taking into account their mutual influence that causes the losses understatement.

Each kind of electric equipment (generator, motor, transformer, and capacitor) is roughly considered as indivisible physical body that, on one hand, essentially simplifies the losses calculation but at the same time adds considerable error into the losses estimation which may reach 10 – 12 %.

Structure of expressions for these losses estimation is as follows:

- At voltage deviation:

$$\frac{\Delta P_{\delta U_s}}{\Delta P_r} \cong 2\Delta U$$

- At voltage unbalance:

$$\frac{\Delta P_{(2)}}{\Delta P_r} = k_e^{(2)} K_{2U}^{(2)}$$

where factor $k_e^{(2)}$ depends on type of electric equipment and its parameters;

- At available harmonics and interharmonics:

$$\frac{\Delta P_n}{\Delta P_r} = \sum_{n_{min}}^{\infty} k^h(n) \left(\frac{U_n}{U_r}\right)^2$$

where the factor $k^h(n)$ depends upon kind of equipment, its parameters and order of the harmonics and interharmonics;

- At voltage fluctuation

$$\frac{\Delta P_{\delta U_t}}{\Delta P_r} = k^f D$$

where the factor k^f depends upon type of equipment and its susceptibility to voltage fluctuations; D is the process dispersion.

Losses of active power resulting from unbalance

Extra losses of active power $\Delta P_{IM}^{(2)}$ in an induction motor are determined by the expression

$$\Delta P_{IM}^{(2)} = 2.4 \Delta P_r I_{st}^2 K_{2U}^2$$

Where ΔP_r is the stator copper loss under the rated load; I_{st} is the starting current ratio.

For synchronous machines extra losses are

$$\Delta P_{SM}^{(2)} = k_{SM} K_{2U}^2$$

Value of the factor k_{SM} is assumed equal: for turbo-generators $k_{SM} = 1.856$, for salient pole machines with damper winding $k_{SM} = 0.681$ and for machines without damper winding $k_{SM} = 0.273$; for synchronous compensators $k_{SM} = 1.31$.

Extra losses in transformers at $K_{2U} \neq 0$ are

$$\Delta P_{TR}^{(2)} = \frac{\Delta P_{sc}}{u_{sc}^2} K_{2U}^2$$

Here ΔP_{sc} is short-circuit losses (rated value); u_{sc} is impedance voltage in relative units.

In capacitor banks extra losses of active power if unbalanced operating conditions are

$$\Delta P_{CB}^{(2)} = Q_r \tan \delta K_{2U}^2$$

where Q_r is rated reactive power of the capacitor bank; $\tan \delta$ is the dielectric dissipation factor for fundamental frequency.

For overhead lines

$$\Delta P_{OL}^{(2)} = 3I_2^2 R$$

where R is resistance of the overhead line phase for fundamental frequency.

Losses at harmonic frequencies

Extra loss in an induction motor caused by current of n th harmonic equals:

$$\Delta P_{IM}^{(n)} = 3I_n^2 (R_{st,n} + R'_{rot,n})$$

where $R_{st,n}$ and $R'_{rot,n}$ are the stator resistance and the rotor referred resistance at the harmonic frequency. For high-voltage induction motors it may be assumed that $R_{st,n} = R'_{rot,n}$.

At higher frequencies the skin effect in stator and rotor windings becomes apparent, therefore

$$R_{st,n} = R_{st,n} \sqrt{n}, \quad R'_{rot,n} = R'_{rot,n} \sqrt{n}.$$

Expression for total loss will be the following:

$$\Delta P_{IM\Sigma}^{(n)} = \Delta P_{R,r} k_{sk}^2 \sum_{n=2}^m \left(\frac{U_n}{U_1} \right)^2 (\sqrt{n} + \sqrt{n \pm 1}) = \Delta P_{R,r} \sum_{n=2}^m k_{incr,n}. \quad (4.1)$$

where $\Delta P_{R,r}$ is rated loss in the stator copper; $k_{incr,n}$ is the factor taking into account increase in copper losses owing to n th harmonic (including interharmonics).

Active power losses caused by harmonics current in transformers are defined with the formula:

$$\Delta P_{TR,n} = 3 \sum_{n=2}^m I_{n,TR}^2 R_{sc} k_{n,TR}$$

where $I_{n,TR}$ is current of n th harmonic flowing through the transformer; R_{sc} is resistance the transformer short-circuit resistance for industrial frequency; $k_{n,TR}$ is the factor taking into account increase in short-circuit resistance for harmonics as a result of skin and proximity effects. It may be assumed that for power transformers $k_{5,TR} = 2.1$, $k_{7,TR} = 2.5$, $k_{11,TR} = 3.2$, $k_{13,TR} = 3.7$.

Power losses in capacitor banks are determined at assumption that dielectric dissipation factor $\tan \delta$ has the same value for harmonics up to the 13th inclusive:

$$\Delta P_{CB\Sigma} = 3\omega C \tan \delta \sum_{n=1}^{13} n U_n^2 \quad (4.2)$$

where U_n is voltage of n th harmonic (as well as interharmonics) on buses after connection of the capacitor bank having capacity C .

Losses in filter-compensating devices caused by n th harmonic or interharmonic include mainly losses in the choke and the capacitor bank at frequencies to which the device adjusted and at the fundamental wave frequency

$$\Delta P_{fc} = 3I_n^2 R_{ch} \sqrt{n} + 3n\omega C U_n^2 \tan \delta$$

where I_n is current of n -th harmonic passing through the filter; $R_{ch} \sqrt{n}$ is resistance of the choke for n -th harmonic under assumption that skin effect appears strongly.

Power losses caused by voltage deviation

Nowadays a number of methods for assessment loss of power and energy in power supply systems stipulated by voltage deviation are known. In calculations the assumption, that negative voltage deviations cause increase in consumed current ΔI , is accepted. At this, extra losses of active power are:

$$\Delta P_{\delta U} = 6I \Delta I R_{PSS}$$

where R_{PSS} is effective resistance of a power supply system.

Relative increase in losses to compare with losses ΔP_r under rated voltage $U = U_r$ is

$$\frac{\Delta P_{\delta U}}{\Delta P_r} = \frac{2\Delta I}{I}$$

Total loss in an industrial enterprise power supply system due to worsening power quality is determined as sum of the losses specified separately by worsening of each the power quality indicator. It is assumed that value of each of power quality factors does not depend on values of others.

Additional losses due to voltage fluctuation

Assess additional power losses caused by voltage on elements of electric network fluctuation for the case of electric arc furnace (Fig.4.7).

Suppose that the current component of the furnace caused by fluctuation of the voltage is driving current $I_{dr} = I_{ASF} \sqrt{D_I}$ where I_{ASF} is the current determined without taking the fluctuations into account; D_I is dispersion of current fluctuations in relative units.

The driving current I_{dr} stipulates the voltage drop (the voltage disturbance U_{dst}) for the network with reactance X_{sc} equal

$$U_{dst} = \sqrt{3} k_{TR} I_{ASF} \sqrt{D_I} X_{sc} = \sqrt{3} I_1 \sqrt{D_I} X_{sc}$$

where k_{TR} is the furnace transformer voltage ratio; I_1 is the primary current of the transformer.

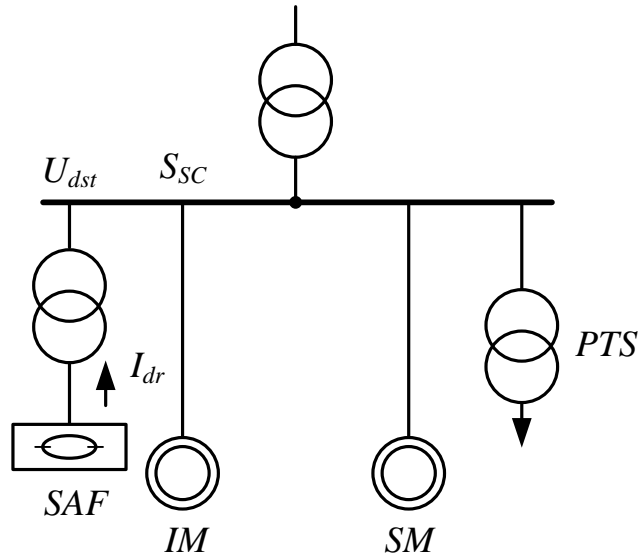


Figure 4.7 Circuit of network section with arc steel furnace

Additional losses of active power ΔP_{dst} in elements of electric power network (motors, transformers, cable lines etc.) by electromagnetic interference are equal to

$$\Delta P_{dst} = 3I_{el,dst}^2 R_{el}$$

where R_{el} is effective resistance of the element, $I_{el,dst}$ is its current component defined by with the interference (the voltage fluctuation) and being equal to

$$I_{el,dst} = \frac{U_{dst}}{\sqrt{3}X_{el}} = \frac{I_1 \sqrt{D_I} X_{sc}}{X_{el}}$$

where X_{el} is the electric element reactance.

Additional power loss is

$$\Delta P_{dst} = \frac{3I_1^2 D_I X_{sc}^2}{X_{el}^2} R_{el}.$$

Active power loss in the element of network under rated voltage (rated losses) equals

$$\Delta P_{dst} = 3I_r^2 R_e = \frac{U_r^2}{X_{el}^2} R_{el}.$$

The loss in relative units is

$$\Delta P_{dst}^* = \frac{\Delta P_{dst}}{\Delta P_r} = \frac{3I_1^2 D_I X_{Sc}^2}{U_r^2}.$$

As $X_{Sc} = \frac{U_r^2}{S_{Sc}}$ where S_{Sc} is the power of short-circuit, obtain:

$$\Delta P_{dst} = \frac{3I_1^2 U_r^2}{S_{Sc}^2} D_I = \frac{S_{FTR}^2}{S_{Sc}^2} D_I$$

where S_{FTR} is power of the furnace transformer.

The short-circuit power S_{Sc} is limited by breaking capacity of switching devices. It may be within 100÷500 MV·A for networks of 6–10 kV and 500÷1000 MV·A for networks of 35 kV. Dispersion of furnace current fluctuation is in the bounds of 0.01÷0.12 relative units and depends on the furnace power. In this less dispersion values correspond to more powerful furnaces and vice versa.

Thus, proceeding from actual correlation between the furnace transformer power, the short-circuit power and dispersion of the furnace current fluctuations it may be concluded that maximum additional loss of active power caused by voltage fluctuations for single running furnace may be equal to 0.1 % of the rated loss. For a group of running furnaces additional losses of active power cannot be more than 1 % of total rated loss in elements of the network even if their functioning is coordinated. Random process of the node voltage fluctuation is determined by the sum of random processes of each separate source voltage fluctuations that is the sources of electromagnetic disturbances are considered as independent ones.

Above indicated values of additional losses are determined for the case when fluctuation sources and “quiet” load are connected to one section of buses. In practice, circuits with separate feeding of “quiet” load and of sources of distortion from different sections of buses of a transformer with split winding or a three-winding transformer. In this case additional losses turn out to be less. Distribution of the fluctuation is considered on the assumption of linearity of parameters of power supply system elements.

In general the additional losses of active power caused by voltage fluctuations at rapidly varying load may be determined according to the expression:

$$\Delta P_{dst}^* = \frac{k}{S_{Sc}^2} \sum_{i=1}^n S_{nl,i}^2 D_{nl,i}$$

where $S_{nl,i}$ is apparent power of i th nonlinear rapidly varying load; $D_{nl,i}$ is its dispersion of fluctuation in relative units; k is a factor depending upon probability of coincidence of fluctuation sources performance conditions ($k \leq 1$).

Compare additional power losses resulting from the voltage fluctuations and its deflection of sine wave form. Levels of harmonics generated by an electric arc furnace are insignificant to compare with the fundamental. As calculations show, addi-

tional losses resulting from availability of harmonics and voltage fluctuations are comparable. For example, at the furnace ДСП-100 operation additional losses in the supply transformer TM-2500/35 fed from the same section of buses ($S_{sc} = 1000 \text{ MV} \cdot \text{A}$) connected with harmonics are 0.3 % of rated loss, and the losses resulting from voltage fluctuations are 0.1 %. It should be noted that when a furnace operation the loss component caused by harmonics is always appears greater. Thus, the additional losses caused by voltage fluctuation at an electric arc furnace operation may be neglected.

If roll mills are sources of interference additional losses of active power as a result of voltage fluctuation are not also more than 1 % (dispersion current fluctuation is $D_I < 0.1 \%$). But the component of additional losses arising due to available harmonics may considerably exceed the component of losses caused by voltage fluctuations. So in 6-pulsevalve inverters of roll mills additional loss caused by harmonics can reach 10% of rated loss. That is, they are dozens times more to compare with loss resulting from voltage fluctuations. The excess is quite less for 12-pulse inverter (by 2-3 times).

Studies of actual electric power networks show that additional losses of active power resulting from voltage fluctuation are not more than 1 % of rated losses. Hence, additional loss component connected with voltage fluctuation may be not taken into account at the losses in power networks evaluation. It should be noted that the conclusion is valid for any electric power networks independently availability of capacity banks or their absence.

4.3. Insulation service life decrease

Additional losses due to electromagnetic interference result in extra electric equipment heating causing its temperature increase, decrease of service life of insulation (as well as electric equipment on the whole) by $\Delta T_{sl} = T_{sl} - T_{sl}^{dst}$ where T_{sl} and T_{sl}^{dst} are service life of power supply system elements in absence and presence of electromagnetic interference. *Service life of insulation* is determined by Montzinger's formula:

$$T_{sl} = Ae^{-0.086\tau}$$

where A is a factor depending on insulation type; 0,086 is Montzinger's parameter based on the assumption that 8° temperature rise reduces service life of insulation by half (so called eight-degree rule); τ is temperature of insulation heating.

Relative decrease in service life of electric equipment insulation is

$$\Delta T = \frac{T_{sl} - T_{sl}^{dst}}{T_{sl}} = 1 - e^{-0.086\Delta\tau} \cong 0.086\Delta\tau + \left(\frac{0.086\Delta\tau}{2}\right)^2. \quad (4.3)$$

As it has been noted, abovementioned approach is approximate since relationship between $\Delta\tau$ and additional loss is found under assumption that electric equipment, transformers and other elements of power supply system are solid physical bodies.

The temperature rise of electric machines under non-sinusoidal voltage may be determined according to the expression:

$$\Delta\tau = \Delta\tau_1 \frac{\Delta P_{cn}}{\Delta P_{c1}}$$

Where ΔP_{c1} are copper losses under sine voltage; ΔP_{cn} are copper losses caused by harmonics; $\Delta\tau_1$ is the temperature under sine voltage.

For induction motors the following expression is true:

$$\frac{\Delta P_{cn}}{\Delta P_{c1}} = \frac{\sum_{n=2}^n I_n^2}{I_1^2} = \sum_{n=2}^n k_{in}^2$$

where I_1 and I_n are the motor currents of the fundamental and n^{th} harmonics; $k_{in} = I_n/I_1$.

Additional rise of power transformer winding insulation temperature may be found according to the empirical expression

$$\Delta\tau_T = 0.6\tau_T \sum_{n=2}^n k_{in}^2 k_{rn}$$

where k_{in} is relative (as a fraction of fundamental harmonic current) value of n^{th} harmonic of current flowing through the transformer; k_{rn} is a factor taking into account increase in winding resistance due to skin and proximity effects; approximately, it may be accepted that $k_{rn} = \sqrt{n}$; τ_T is temperature of insulation overheating under sine current.

Additional temperature rise of induction motor windings under condition of unbalance is determined by the expression:

$$\Delta\tau \cong 500K_{2U}^2$$

For synchronous machines it is found as

$$\Delta\tau \cong \tau_{rot,r} \frac{\Delta P_{add}}{\Delta P_{fr}} \quad (4.4)$$

where ΔP_{add} are additional losses due to negative-sequence current; ΔP_{fr} are losses in the field winding at rated conditions; $\tau_{rot,r}$ is temperature of the rotor body excessive heating under rated balanced load.

Additional temperature rise of power transformers under unbalance is determined with the help of the expression:

$$\Delta\tau \cong \infty K_{2U}^2$$

where α is a factor depending on electromagnetic and design transformer parameters.

For capacitor banks it is

$$\Delta\tau \cong \tau_r K_{2U}^2$$

4.4. Refined calculations of electromagnetic interference influence

Consider problems of electric equipment insulation ageing at availability of electromagnetic interference in more detail.

Power transformers

Reduction in transformers lifetime at worsening power quality takes place as the result of extra windings insulation temperature rise caused by additional loss of active power appearing as a rule due to flowing in them the currents of negative sequence and currents of harmonics. Therefore, common approach to evaluation of service life of power transformers under non-sinusoidal and unbalanced voltage is based upon determination of active power additional losses that correspond with of winding temperature increase (it is considered as proportional to additional losses) and calculations of service life according to empirical expressions.

The additional loss under voltage unbalance are determined as total of additional-no-load and short-circuit losses. Additional loss due to eddy currents is also taken into account under non-sinusoidal voltage. As a rule, this part of loss is small and being on average about 5 % of a transformer short circuit loss. But the additional loss sharply increases when currents of harmonics flow through the windings and may reach up to 30 – 50 %.

The additional power loss caused by current harmonics are

$$\Delta P_n = 1.291 \frac{P_{sc}}{u_{sc}^2} \sum_{n=2}^N \frac{1 + 0.05n^2}{n\sqrt{n}} K_{U(n)}^2$$

where u_{sc} is the impedance voltage in relative units; no-load additional loss due to harmonics is neglected.

Under voltage unbalance the additional loss in a transformer are determined by the formula:

$$\Delta P_{(2)} = \frac{P_{sc}}{u_{sc}^2} K_{2U}^2$$

where $K_{2U} = U_2/U_r$ is the voltage unbalance factor of negative sequence equal ratio of the negative sequence voltage U_2 to the rated voltage U_r . Additional loss of no-load due to voltage unbalance may be not considered in practical calculations.

Mostly, *method of temperature of a transformer winding most heated point determination* is used to calculate additional temperature growth. It is found as the sum of the winding overheating temperature above the oil temperature, the oil upper layers overheating temperature above the ambient cooling environment temperature and the ambient temperature. Many National Standards normalize this method.

At determination of combined influence of voltage harmonics and unbalance on extra temperature rise of a transformer it is assumed that their mutual effect is not available. As a rule, cooling means temperature has permanent value.

It is known that the following relationship is valid for transformers:

$$\tau_{exc} = \Delta P^m \quad (4.5)$$

where τ_{exc} is the upper oil layers temperature excess above temperature of the cooling medium; ΔP^m is total power loss in the transformer; m is the exponent.

Rated power losses

$$\Delta P_r = P_{nl} + P_{sc} = P_{nl} \left(1 + \frac{P_{sc}}{P_{nl}} \right) = P_{nl}(1 + d)$$

where $d = \frac{P_{sc}}{P_{nl}}$.

The loss under short circuit condition at rated current I_r :

$$P_{sc} = 3I_r^2 R_T$$

where R_T is effective short-circuit resistance.

If the current has non-rated value ($I \neq I_r$):

$$P_w = 3I^2 R_T$$

where P_w is the windings resistance loss;

$$\frac{P_w}{P_{sc}} = \frac{3I^2 R_T}{3I_r^2 R_T} = \left(\frac{I}{I_r} \right)^2 = \left(\frac{S}{S_r} \right)^2 = S_*^2 = k^2$$

where S_r is the rated apparent power of a transformer.

Hence,

$$\Delta P_r = P_{nl} + P_{sc} S_*^2.$$

Taking into account equation (4.1), obtain:

$$\frac{\tau_{exc}}{\tau_{exc,r}} = \left(\frac{1+dk^2}{1+d} \right)^m, \quad \tau_{exc} = \tau_{exc,r} \left(\frac{1+dk^2}{1+d} \right)^m$$

where $\tau_{exc,r}$ is value of τ_{exc} under rated load.

For the transformer windings temperature excess over the oil upper layers the following expression is valid:

$$\tau_{int} = P_w^N$$

where N is the exponent which value depends on type of the cooling system;

$$\frac{\tau_{int}}{\tau_{int,r}} = \left(\frac{P_w}{P_{sc}} \right)^N, \quad \tau_{int} = \tau_{int,r} \left(\frac{P_w}{P_{sc}} \right)^N = \tau_{int,r} k^{2N}$$

where $\tau_{int,r}$ is value of τ_{int} under rated load.

Table 4.2

Parameter values according to GOST 14209-97

| Parameter | Distribution transformers | Transformers of medium and high power capacity | | |
|----------------|---------------------------|--|-----------|-----------|
| | <i>ONAN</i> | <i>ON</i> | <i>OF</i> | <i>OD</i> |
| <i>m</i> | 0.8 | 0.9 | 1.0 | 1.0 |
| <i>N</i> | 0.8 | 0.8 | 0.8 | 1.0 |
| $\tau_{int,r}$ | 23 | 26 | 22 | 29 |
| $\tau_{exc,r}$ | 55 | 52 | 56 | 49 |

In Table 4.2 the following designations of cooling systems are used:

ONAN – natural (gravity) circulation of air and oil;

ON – forced air circulation and natural circulation of oil;

OF – with forced circulation of air and oil;

OD – with natural circulation of air and forced circulation of oil.

Thus,

$$\tau = \tau_{exc,r} \left(\frac{1+dk^2}{1+d} \right)^m + \tau_{int,r} k^{2N}. \quad (4.6)$$

Expression (4.5) is valid only for transformers with *ON* cooling system.

Extra heating of transformer insulation due to harmonic currents as well as negative-sequence currents, if mutual influ-

ence of voltage non-sinusoidal waveform and unbalance does not take place, is equal to

$$\Delta\tau = A \left(\frac{K_2^2 U}{u_{sc}^2} + \frac{1.291}{u_{sc}^2} \sum_{n=2}^N \frac{1+0.05n^2}{n\sqrt{n}} K_{U(n)}^2 \right) \quad (4.7)$$

where A is invariable depending on electromagnetic and design parameters of the transformer:

$$A = \frac{m\tau_{exc,r}P_{sc}}{P_{sc}+P_{nl}} + N\tau_{int,r}.$$

Depending upon temperature rise equation of Montzinger or “eight-degree” rule is used to estimate service life of insulation of power transformers. Also, empiric expressions based on of Vant Hoff's - Arrhenius equation which establishes relationship between the service life and inverse to Kelvin temperature.

International Electrotechnical Commission recommends accept six-degree rule for assessment of A class of insulation ageing. The rule is as follows: service life of insulation varies twice due to its temperature variation by six degrees. According to equation of Montzinger, service life of insulation of power transformers under rated temperature $\tau_r = +98^\circ\text{C}$ is

$$T_r = M e^{-\alpha\tau_r}.$$

Expression for relative insulation service life is

$$T_* = \frac{T}{T_r} = e^{-\alpha(\tau-\tau_r)}.$$

From that, service life of insulation of a transformer is

$$T = T_* T_r = T_r e^{-\alpha(\tau-\tau_r)} = T_r e^{-\alpha(\tau+\tau_c-\tau_r-\tau_{cr})}$$

where τ is temperature excess above the coolant temperature τ_c ; $\tau_r = 78^\circ\text{C}$ is rated winding temperature rise above the coolant temperature $\tau_{cr} = 20^\circ\text{C}$.

Then

$$T = B e^{-\alpha(\tau-\tau_r)} = B e^{-\alpha\Delta\tau}$$

where B is the constant depending upon insulation life under nominal temperature

$$B = T_r e^{-\alpha(\tau_c-\tau_{cr})}. \quad (4.8)$$

Relative decrease of insulation service life

$$\Delta T_* = \frac{T - T_{lq}}{T} = 1 - e^{-\alpha \Delta \tau} \quad (4.9)$$

where T_{lq} is service life of low-quality insulation.

Fig. 4.8 shows dependences of relative decrease of insulation service life for TM-630/10 type transformer on voltage waveform distortion factor K_U plotted under different values of demand factor k_l . The dependences are given for the case of six-pulse converter is a part of the load (harmonic components of voltage are not indicated here).

Fig. 4.9 shows effect of voltage unbalance on decrease of insulation service life of TM-630/10 type transformer.

If demand factor is $k_l \geq 0.7$, availability of voltage unbalance and high content of harmonics in network voltage curve may result in significant decrease of service life of transformer due to insulation thermal deterioration.

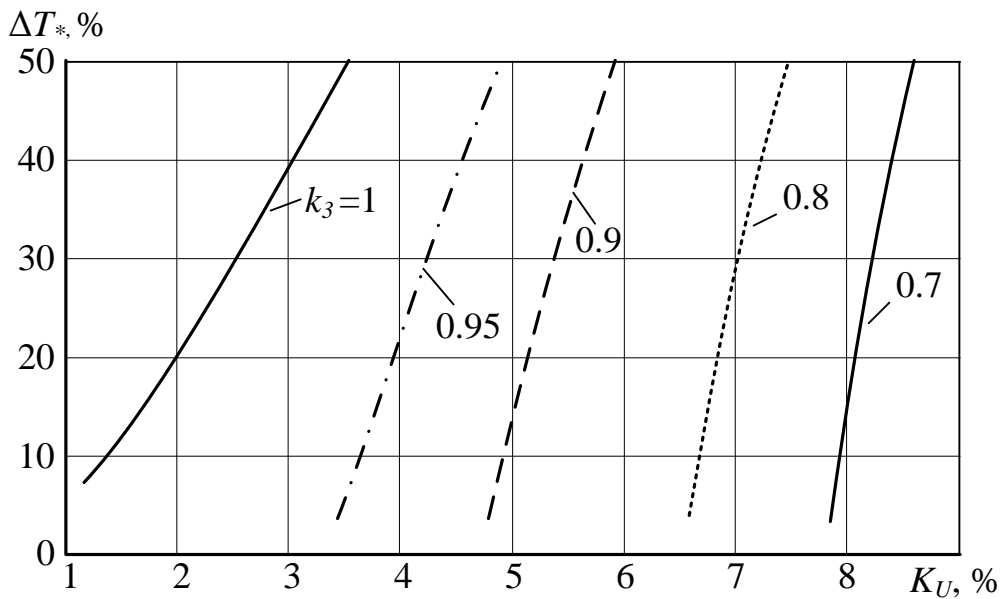


Figure 4.8 Impact of non-sinusoidal wave form on shortening of service-life for transformer TM-630/10

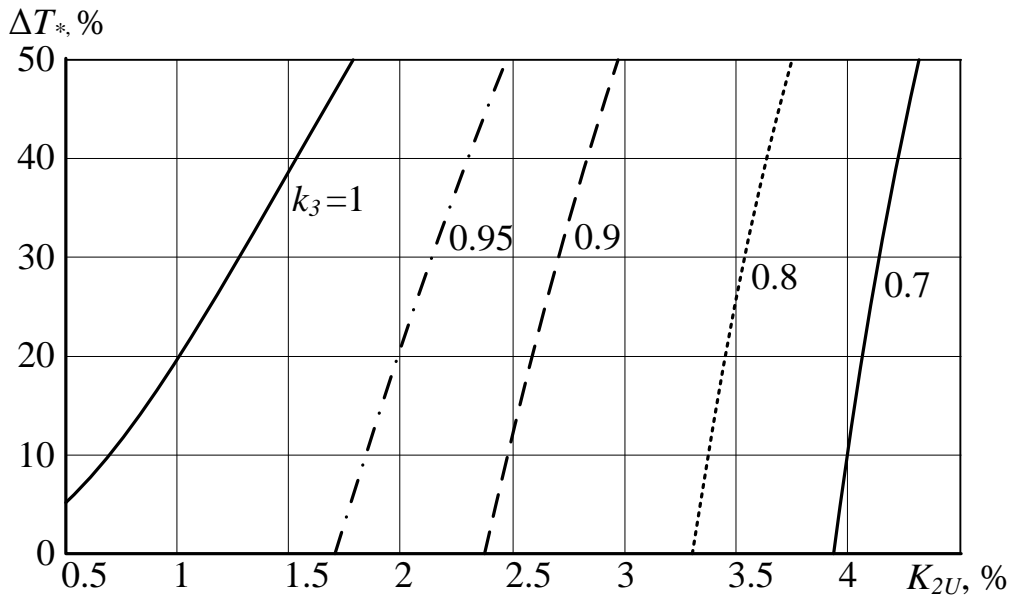


Figure 4.9 Impact of voltage unbalance on shortening of service-life for transformer TM-630/10

As a rule, appreciable problems with electric equipment running are not available if parameters of power quality are in accordance with DST 13109-97. In many cases negative impact of poor power quality does not appear explicitly as it takes place in the case of harmonics which cause equipment service life shortening due to accelerated insulation ageing. With it ageing appears as functional reliability reducing.

For analysis of power transformers reliability under lowered power quality, the normal distribution law for failure-free time and for $\Delta\tau$ is applied. In this case the reliability function is:

$$R(t) = \frac{0.5 + \Phi\left(\frac{m_T - t}{\sigma_T}\right)}{0.5 + \Phi\left(\frac{m_T}{\sigma_T}\right)} \quad (4.10)$$

where $\Phi(t) = \frac{1}{\sqrt{2\pi}} \int_0^t e^{-\frac{t^2}{2}} dt$ is the probability integral; m_T and σ_T are the mathematical expectation and mean-square deviation of the transformer service life the power quality reduction,

$$m_T = B \exp\left(-\alpha m_{\Delta\tau} + \frac{\alpha^2}{2} \sigma_{\Delta\tau}^2\right), \quad (4.11)$$

$$\sigma_T = m_T \sqrt{\exp(\alpha^2 \sigma_{\Delta\tau}^2)} \quad (4.12)$$

where $m_{\Delta\tau}$ and $\sigma_{\Delta\tau}$ are the mathematical expectation and mean-square deviation of extra temperature rise of transformer insulation accordingly; B is a constant determined on expression (4.7).

Below the results of calculation of the function for insulation of transformer TM 630/10 supplied from a network with parameters of the waveform $m_{K_U} = 6.2\%$ and $\sigma_{K_U} = 0.05m_{K_U}$ at different parameters of unbalanced operating conditions.

| | | | | | | |
|--------------------------|-------|-------|-------|-------|-------|-------|
| $m_{K_U}, \%$ | 2 | 2.5 | 2.75 | 3 | 3.25 | 3.5 |
| $\sigma_{K_U}, \%$ | 0.2 | 0.25 | 0.275 | 0.3 | 0.325 | 0.375 |
| $R(t)$ | 0.938 | 0.384 | 0.724 | 0.559 | 0.397 | 0.145 |

At calculations it was assumed that mutual influence of voltage unbalance and non-sinusoidal wave form is not available. It is obvious, that simultaneous effect of unbalance and harmonics results in appreciable decrease of $R(t)$ to compare with the case when just one type of electromagnetic interference is available. So, in the absence of harmonics and $\sigma_{K_U} = 2\%$ it turns out that $R(t) \cong 1$, that confirms economic feasibility of GOST 13109-97 norms.

Similar dependences are also valid for other types of electric equipment – generators, induction and synchronous motors etc.

Under continuous effects of unbalance and harmonics which parameters are the boundary value allowed according to GOST 13109-97, service life of 10 MV·A, 35/6 kV transformer is reduced by 25–30%. Under these parameters mean values the service life is reduced by 8–10 %.

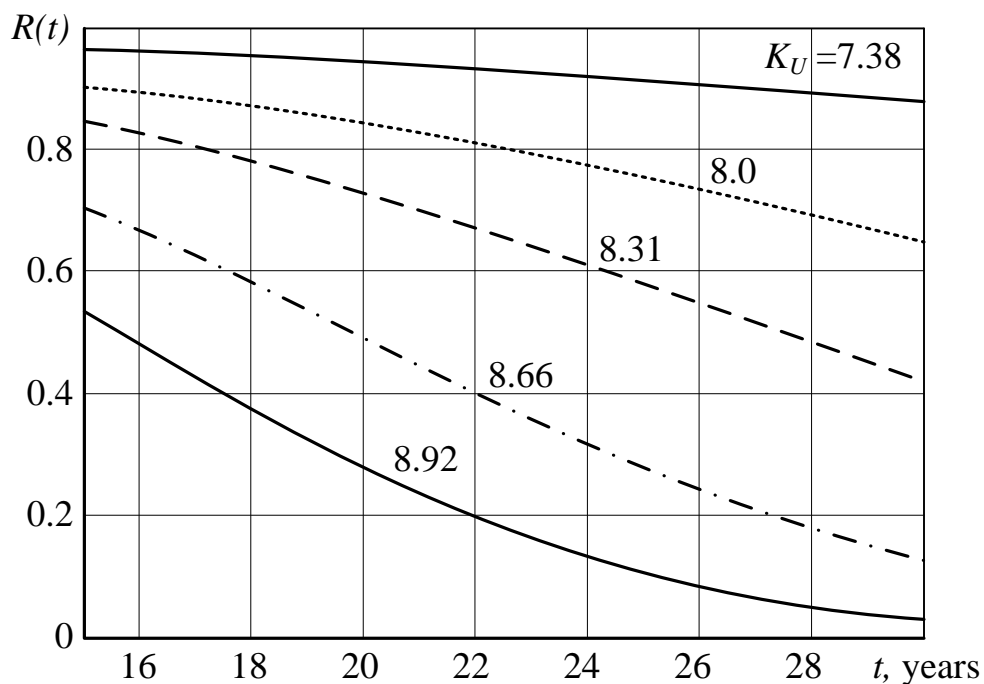


Figure 4.10 Curves of reliability function of TM-630/10 type transformer under different values of distortion factor $K_U, \%$

The calculations of reliability function $R(t)$ for transformer of TM-630/10 type were performed at 70% of the rated load assuming that mutual effect of voltage wave form and voltage unbalance is absent. It is also provided that transformer loading is

70% of nominal one. The charts of the reliability function are shown in Fig. 4.10 and 4.11.

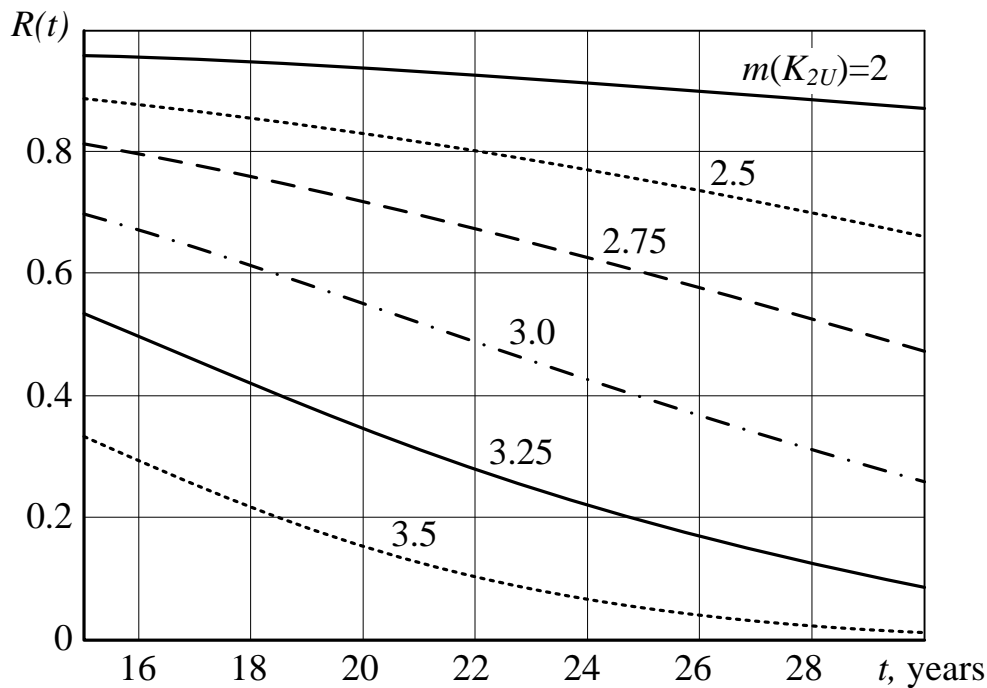


Figure 4.11 Curves of reliability function of TM-630/10 type transformer under different values of mathematical expectation of voltage unbalance factor by negative sequence $m(K_{2U})$, %

Calculation results show that reliability decrease under non-sinusoidal and unbalanced voltage may become considerable even if a transformer is loaded with less than rated load. Besides, impact of voltage wave form is greater.

Induction motors

Decrease in service life of induction motors under non-sinusoidal voltage, unbalance and voltage deviations is also associated thermal ageing of insulation due to stator winding temperature increase.

For induction motors thermal calculations detailed thermal model is used as a rule, and the motor is not considered as solid body. Most researchers are inclined to think that that the motor temperature is a non-linear function of the power loss. It should also take into account that motors are manufactured with thermal margin in rated conditions in the range of 7 – 10 °C. Therefore, the temperature estimation should be performed taking into account design features of specific induction motor types.

Most of all, temperature of stator winding is determined with the help of equivalent thermal circuits. In the majority of cases three-phase model is used on the assumption that motor operates with rated load at constant temperature of cooling medium.

Service life of induction motors under decreased power quality is determined by empiric relationships depending upon stator winding temperature rise. According to the relationships some temperature rise value $\Delta\tau$ depending on temperature class decreases insulation service life twice. Then

$$T = T_r e^{-\beta\Delta\tau} \quad (4.13)$$

where T is the insulation service life at temperature τ ; T_r is the insulation service life at the rated temperature τ_r ; $\Delta\tau = \tau - \tau_r$ is the stator winding overheating temperature; $\beta = \frac{\ln 2}{\Delta\tau} = \frac{0.693}{\Delta\tau}$ is the factor of insulation ageing. For class B insulation $\Delta\tau$ is 10°C .

American researchers use expressions obtained according to investigation carried out especially for induction motors. Sometimes, Van-Hoff's-Arrhenius equation is used to determine service life of induction motors insulation.

Relative decrease in insulation service life (by analogy with expression (4.5)) is

$$\Delta T_* = \frac{T - T_r}{T} = 1 - e^{-\beta\Delta\tau} \cong \beta\Delta\tau - \frac{1}{2}\beta^2\Delta\tau^2 + \frac{1}{6}\beta^3\Delta\tau^3. \quad (4.14)$$

To determine overheating of stator winding insulation under non-sinusoidal voltage and its unbalance the generalized thermal model of the induction motors may be used (Figure 4.12). In such a case the following designations are used: τ_1 is average temperature rise of the induction motor stator winding; $\Delta P_1, \Delta P_2, \Delta P_3$ are the electric losses in the stator and rotor winding, and the steel loss accordingly; R_{11}, R_{12}, R_{13} are the generalized thermal resistances of equivalent thermal circuit. Friction losses in bearings as well as rotor friction on air may be neglected as they have insignificant influence on thy motor heating. But stray losses assumed equal to 1% of rated power are taken into consideration and added when loss in the rotor winding is determined.

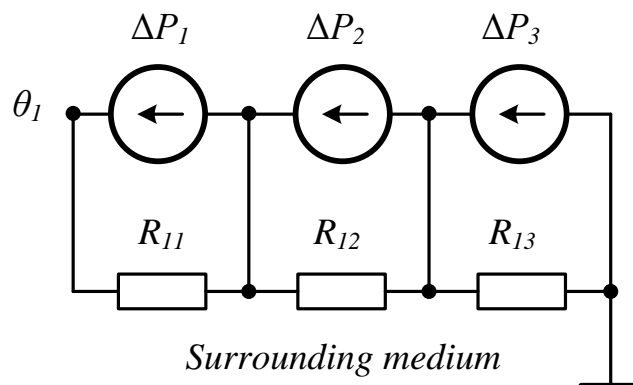


Figure 4.12 Generalized thermal model of induction motor

The equivalent thermal circuit (Fig.4.12) provides estimation only the average temperature increase of an induction motor stator winding as it is this temperature

that determines thermal conditions of motor from the point of view of reliability, expected service life and overloading capacity.

Thus,

$$\tau_1 = R_{11}\Delta P_1 + R_{12}\Delta P_2 + R_{13}\Delta P_3. \quad (4.15)$$

Unknown thermal resistances in equation (4.11) are determined with the help of three experiments, one of which is similar to no-load test and two others - to short-circuit tests. Calculations are based on accurate measurements of the stator winding temperature increase and losses in the induction motor at these tests; accuracy of calculations by this method is $2 - 3^\circ\text{C}$.

Thermal resistances may be determined with the help of the empiric expressions:

$$R_{11} \cong \frac{K}{D_{a1}l_1}, \quad R_{12} \cong R_{13} \cong 0.6R_{11}$$

where D_{a1} is outside diameter of the stator core, cm; l_1 is length of the stator core, cm; K is a factor equal to 27 for 0.5÷10 kW induction motors and 35 for 11÷250kW motors.

Calculation results for 4A series motors are given in Table 4.3.

Table 4.3

Results of heat calculations

| Induction motor type | Rated power, kW | Average winding overtemperature, $^\circ\text{C}$ | |
|----------------------|-----------------|---|------------------|
| | | Generalized heat model | Heat calculation |
| 4A80A4Y3 | 1.1 | 72.4 | 73.1 |
| 4A90L4Y3 | 2.2 | 77.7 | 77.6 |
| 4A100S4Y3 | 3 | 77.2 | 74.8 |

According to GOST 183-74, the coolant temperature of $+40^\circ\text{C}$ specifies difference ($\tau_{1M} - \tau_1$) which is accepted not equal for different temperature classes. Hence, use of the considered heat model of induction motor makes possible determination of relative decrease of insulation service life by expression (4.10).

Induction motor overheating due to currents harmonics (if the steel loss caused by harmonics may be neglected) is

$$\Delta\tau_n = \Delta P_1 R_{11} \sum_{n=2}^N \sqrt{n} I_{n*}^2 + \Delta P_2 R_{12} \sum_{n=2}^N \sqrt{n \pm 1} I_{n*}^2 \quad (4.16)$$

where $I_{n*} = I_n/I_r$ is relative value of current of the n th harmonic.

In presence of voltage unbalance induction motors overtemperature is determined as

$$\Delta\tau_n = \frac{2K_{2U}^2}{100} \tau_1 \quad (4.17)$$

where K_{2U} is the voltage unbalance factor by negative sequence, %. An induction motor over-temperature caused by voltage deviation is

$$\Delta\tau_{vd} = 60\delta U_{vd} \quad (4.18)$$

where δU_{vd} is the voltage deviation, relative units.

Generalized thermal model is used to determine influence of current harmonics, the voltage unbalance and deviation on decrease of service life of 4A80A4Y3IM type induction motor having power 1.1kW (Fig. 4.13 and 4.14). Current harmonics frequency content is given in Table 4.4. It is accepted that motor operates under the rated load. Influence of the voltage unbalance and deviation was taken into account assuming that their mutual effect is absent.

Table 4.4

Values of current harmonics and current distortion factor K_I , %

| n | Frequency contents | | | | |
|-------|--------------------|------|------|-----|-----|
| 5 | 19.2 | 17.5 | 12.1 | 7.5 | 5.5 |
| 7 | 13.2 | 11.1 | 8.3 | 5 | 3.5 |
| 11 | 7.3 | 4.5 | 4.6 | 2.5 | 2 |
| 13 | 5.7 | 2.9 | 3.6 | 2 | 1.5 |
| 17 | 3.5 | 1.5 | 2.2 | 1.5 | 1 |
| 19 | 2.7 | 1 | 1.7 | 1 | 0.8 |
| K_I | 25.5 | 21.5 | 16 | 9.7 | 7.1 |

Analysis of the obtained dependencies (Fig.4.13 and 4.14) show that considerable decrease in induction motors service life takes place at $K_I > 10\%$, $K_{2U} > 2\%$ and $\delta U_{vd} > 5\%$.

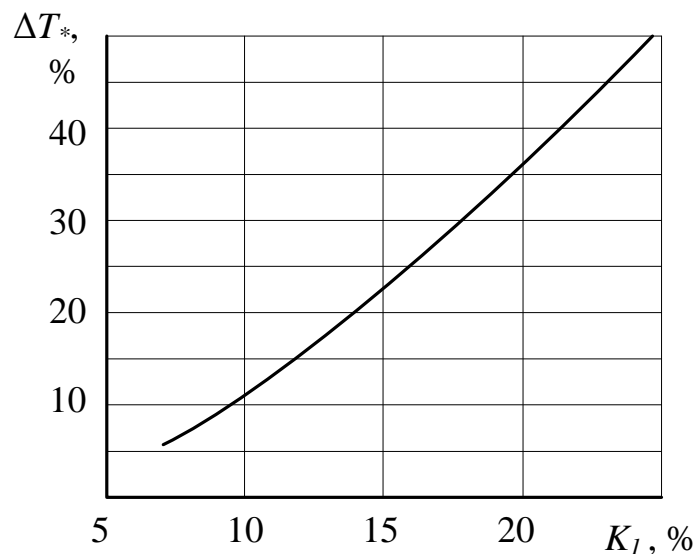


Figure 4.13 Effect of current wave form on decrease of service life of 4A80A4B3 type induction motor

To assess induction motors reliability at reduced power quality the same approach is used as for supply transformers.

Results of calculations concerning values of reliability function $R(t)$ for induction motors of 4A80A4Y3 type under voltage deviations are given below ($T = 20$ years). It is assumed that the motor works under the rated load (Fig. 4.15 and 4.16).

It may be concluded that considerable decrease of induction motors reliability takes place under the voltage deviations exceeding 10%.

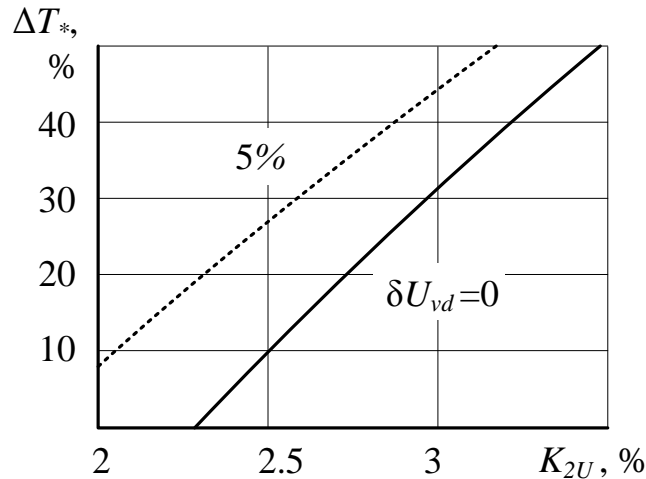


Figure 4.14 Effect of unbalance and voltage deviations on decrease of service life of 4A80A4B3 type induction motor

To avoid overheating and premature failure of induction motor at considerable harmonics level, unbalance and voltage deviation it is necessary to reduce their loading.

Power cables

Harmonics influence greatly on decrease in service life of cable lines. Ageing of cable insulation is accelerated as the result of more intensive heating and ionization processes causing its service life decrease.

Service life of cables under non-sinusoidal voltage:

$$T_{n-s} = T_r \exp \left[-K_a \left(\frac{1}{\tau_r} - \frac{1}{\tau_{n-s}} \right) \right]$$

where τ_r is insulation temperature under rating conditions, K; τ_{n-s} is insulation temperature at harmonics availability, K; K_a is a factor being proportional to the activation energy;

$$K_a = \frac{E_a}{R}$$

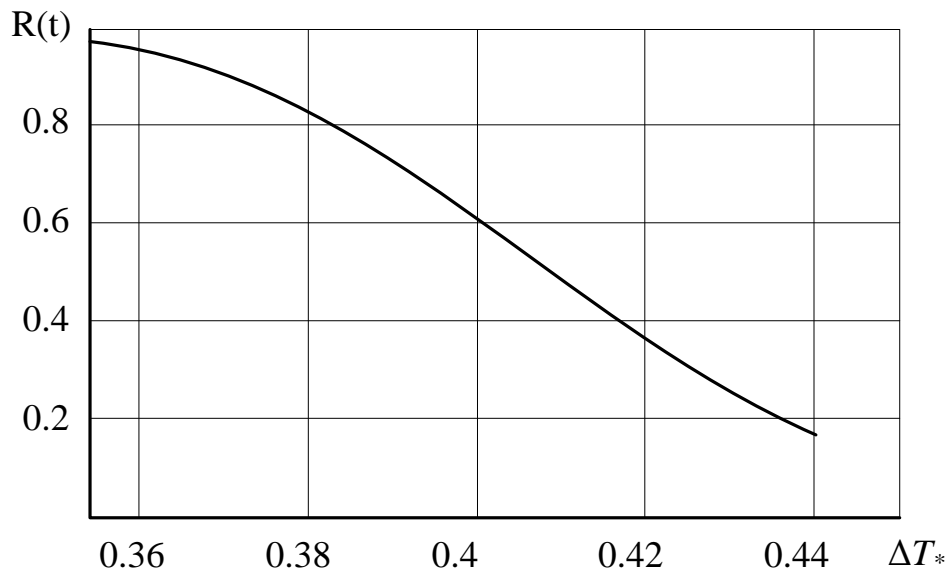


Figure 4.15 Dependence of reliability function of 4A80A4B3 type induction motor on ΔT_* , relative units; $T = 20$ years

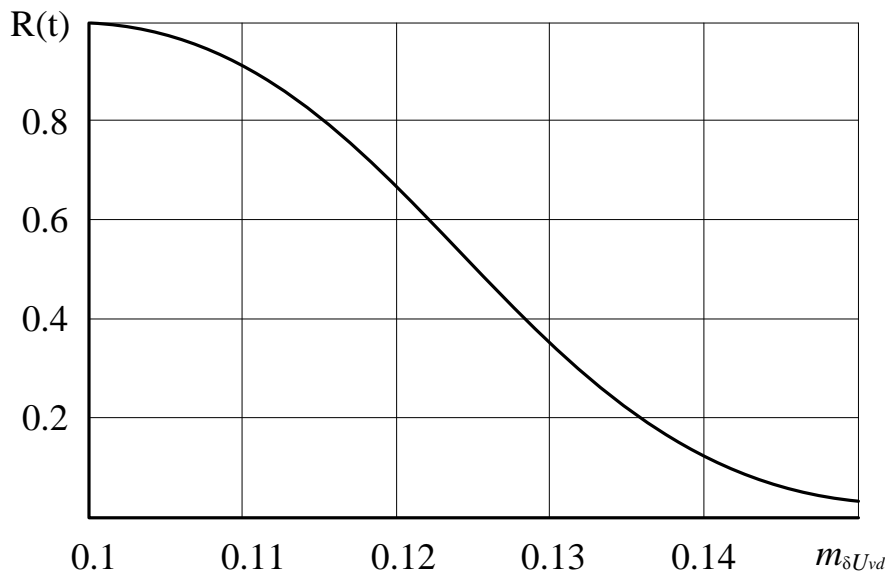


Figure 4.16 Dependence of reliability function of 4A80A4B3 type induction motor on $m_{\delta U_{vd}}$, relative units; $T = 20$ years

where E_a is activation energy, J/mole; R , J/(K·mole), is absolute gas constant.

Expression for T_{n-s} within operating temperature range may be determined with sufficient accuracy approximated by expression (4.12) at $\beta = 0.0866^\circ\text{C}$. If cable insulation overheating is determined at non-harmonic voltage, expression (4.12) permits to determine service life of cables with impregnated-paper and with polyvinylchloride elastron isolation. Relative decrease in a cable line insulation service life may be determined on (4.13).

To calculate insulation overheating for cables of medium voltage, three-core cable thermal equivalent circuit at non-sinusoidal voltage shown in Figure 4.17 may be applied. According to designations in Figure 4.17 τ_c , and τ_{amb} are the cable conductor and ambient temperatures; P_c , and P_{ins} are losses in the conductor and in the insu-

lation; S_{ins} , S_{pc} and S_{gr} are heat-transfer resistance of the insulation, protective coating and ground.

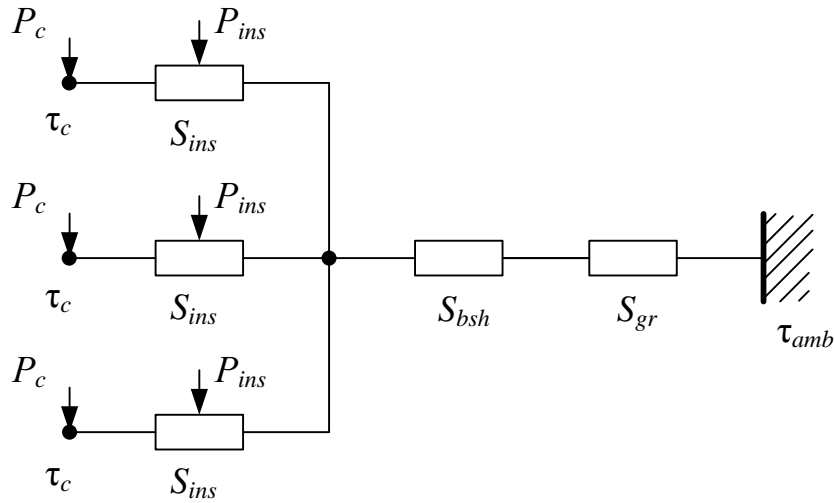


Figure 4.17 Thermal equivalent circuit of three-core cable buried in the ground

Difference of temperatures of conductors and ambient temperature in accordance with Fig. 4.17 equals

$$\theta_c = \tau_c - \tau_{amb} = 3P_c(S_{ins} + S_{pc} + S_{gr}) + 3P_{ins}(S_{ins}/2 + S_{pc} + S_{gr}). \quad (4.20)$$

Insulation thermal resistance equals

$$S_{ins} = \frac{\sigma_{ins}}{6\pi} G$$

where σ_{ins} is the specific insulation thermal resistance; G is geometric coefficient.

Cable overheating due to current harmonics is

$$\Delta\tau_n = \tau_{exc,r} \sum_{n=2}^N I_{n*}^2 (0.187 + 0.532\sqrt{n}) \quad (4.21)$$

where $\tau_{exc,r}$ is temperature increase caused by losses cable in a cable wire under rating conditions:

$$\tau_{exc,r} = 3P_{c,r}(S_{ins} + S_{pc} + S_{gr}) = 3I_r^2(S_{ins} + S_{pc} + S_{gr})$$

where $P_{c,r}$ are cable losses at rated current I_r .

Active resistance of the cable wire at frequency of the n -th harmonic is

$$R_{c,r} = R_c(0.187 + 0.532\sqrt{n}).$$

Fig. 4.18 shows decrease in service life of cable insulation due to influence of the harmonics.

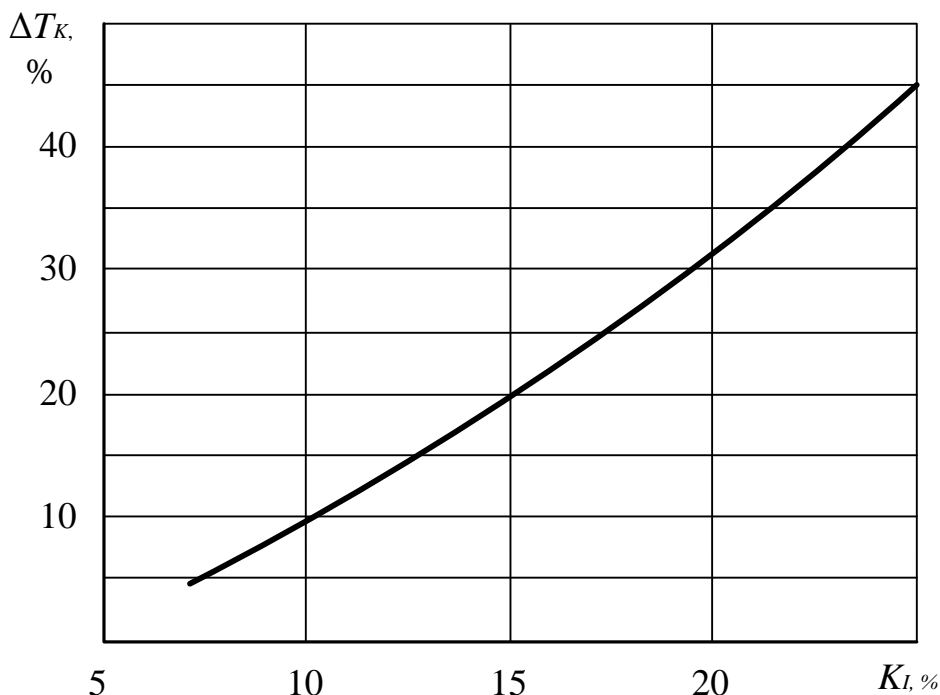


Figure 4.18 Effect of current wave form on decrease of service life of АПВЭВ-6/10-1 (3×95) type cable

Effect of currents harmonics on decrease of the considered cable service life is similar to that of general-purpose induction motor of 4A80A4B3 type.

Approach similar to the used for power transformers and induction motors may be used evaluation of cable lines reliability in presence of the harmonics..

Fig. 4.19 shows graphs of reliability probability of АПВЭВ-6/10-1(3×95) cable depending on time of operation under non-sinusoidal current. The dependences had been obtained for the case when the load includes 6-pulse inverters (harmonics content is not given here).

As a rule, electric insulation ageing is not taken into consideration while determining impact of voltage wave form on electric equipment service life.

At the same time dominant impact of non-sinusoidal voltage magnitude on insulation ageing is observed. Results of long-term observations of voltage curves form in electric power supply systems of industrial enterprises confirm that. In many cases harmonics stipulate sharper form of the voltage curves in comparison with the sine curve. Therefore, availability of harmonics leads to accelerated ageing of insulation of transformers, electric machines and cables.

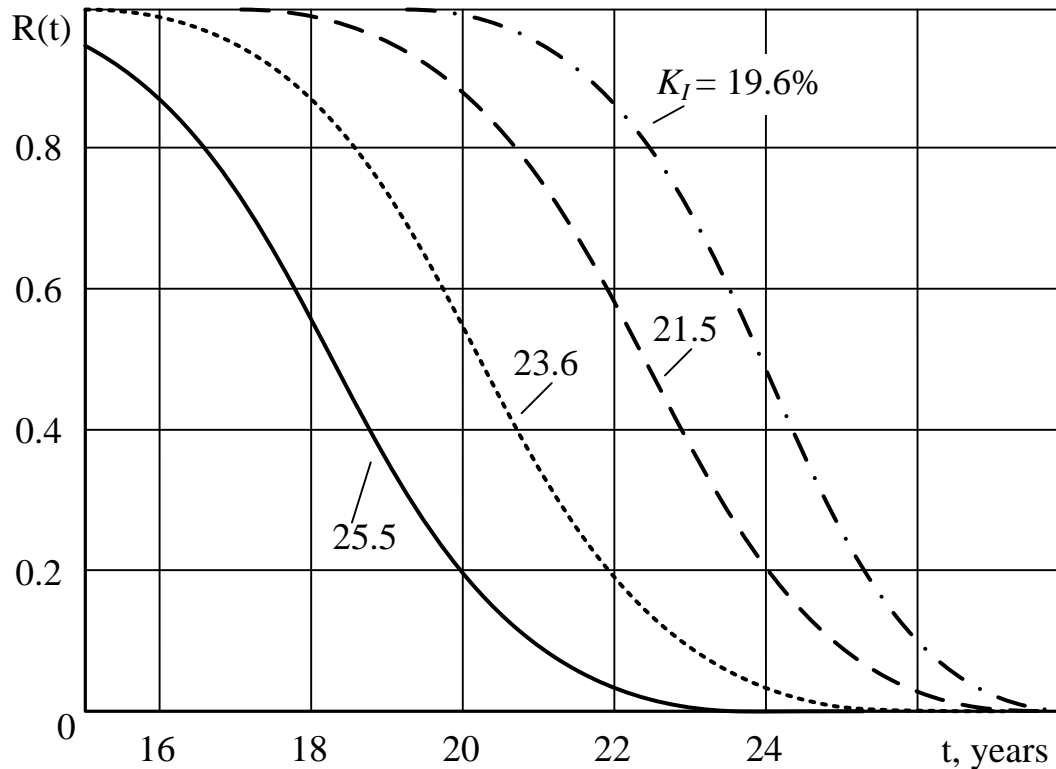


Figure 4.19 Curves of АПВЭВ-6/10-1(3×95) type cable reliability under different values of current distortion factor K_I , %

Test questions

1. How do the voltage deviations influence on consumption of active and reactive power?
2. Give examples of decrease in service life and reliability of electric equipment as the result of voltage deviations.
3. How can the voltage unbalance influence on service life of electric equipment insulation?
4. How can the voltage wave form effect on service life of electric equipment insulation?
5. What are the reasons of the voltage dips occurrence?
6. Illustrate consequences of the voltage dips influence on electric equipment.
7. Compare levels of additional power losses caused by different types of electromagnetic interference.
8. How does transformer reliability vary depending on wave form of the supply grid voltage?
9. What transformer uptime distribution law is used at the reliability analysis?

10. What maximum power loss can occur at voltage fluctuation in a network comprising an electric arc furnace?

Topics for essay

1. Major aspects of electromagnetic disturbances effect on electric power equipment.
2. Major aspects of electromagnetic disturbances effect on systems of relay protection and automatics.
3. Performance of the visual analyzer at voltage fluctuation.
4. Electric energy metering under availability of electromagnetic disturbances.

5.1. Overvoltage resulting from switches operation

Commutation process is accompanied by initiation and extinction of electric arc in a circuit-breaker. In vacuum and air circuit-breakers, widely used in power supply systems; arc is not stable under small current. Interruption of the arc in vacuum takes place before the current cut off at its passage through zero (Fig. 5.1). At this overvoltage may result from the current cutoff, repeated re-ignitions and three-phase simultaneous switching off. Such voltage surges, called the commutation overvoltage, cause electric equipment insulation fault. Power transformers with 6 and 10kV rated insulation voltage are intended for impulse overvoltage with 23kV and 34kV peak values respectively.

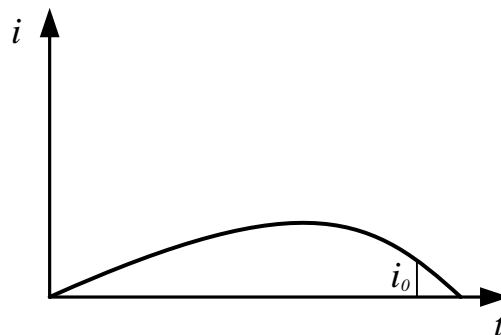


Figure 5.1 Current cutoff

The greatest danger of commutation overvoltage is made up for electric motors having larger insulating strength compared to transformers but lowered impulse strength to influence of waves with sharp edge. The motors wave impedance is twice lower to compare with transformers. Therefore, overvoltage under normal current cut-offs also significantly less. At the same time connection of electric motors or switching off their starting current is, as a rule, accompanied with multiple repetitive arc ignitions and formation of overvoltage waves with sharp edge. At this, it is possible gradual increase in wave maxima and reaching up to fivefold values of the motor phase voltage.

If necessary, vacuum circuit-breakers are used at frequent commutations (electric arc furnaces etc.) and at active-inductive load. At capacitive load (capacitor banks, filtering-compensating devices, static compensators of reactive power) sulfur hexafluoride circuit-breakers are used.

At large currents switching off (>100 A) the arc extinction takes place under natural passing the current through zero. In this case, dangerous overvoltage does not occur and the restored voltage does not exceed doubled amplitude of the network voltage.

Under small current disconnection (< 25 A) the current cutoffs, that is, premature current breaking in any point of the sine wave, often occur. Such a case takes place, for instance, at a transformer no-load disconnection (or at disconnection of a shunt reactor). No-load current of transformers is within unities or tenths of amperes. Capacitance of transformers is very small, and their leakage inductance is rather large: $\sqrt{L/C} = 10 \dots 100$ Ohm, $U = I\sqrt{L/C} = 4 - 5$ relative units.

At capacitor banks disconnection the processes behavior is similar.

Parameters of circuit-breakers widely used in enterprises power supply systems are presented below.

| | Connection Time, s | Disconnection Time, s |
|---|-----------------------|--------------------------|
| Dead tank oil circuit-breaker... | 0.3–0.5 | 0.08 |
| Live-tank oil circuit-breaker... | 0.3–0.4 | 0.12–0.17 |
| Air circuit-breakers... | 0.1–0.3 | 0.04–0.12 |
| Sulfur hexafluoride circuit-breakers... | 0.08–0.3 | 0.03–0.075 |
| Vacuum circuit-breakers... | 0.08–0.3 | 0.05–0.075 |

The data show that commutation time of air, sulfur hexafluoride and vacuum circuit-breakers is essentially shorter to compare with oil circuit-breakers. For this reason, switching is accompanied by impulses of overvoltage and current having sharp, almost abrupt edge.

5.2. Commutation overvoltage

Commutation overvoltage in power networks of enterprises are connected with operational and emergency commutations of various network elements.

Disconnection of inductive loads, such as non-loaded transformers, reactors, electric motors result in overvoltage in them as well as in breakers and cable line between them. The overvoltage nature consists in transition of electromagnetic energy $\frac{Li^2}{2}$, stored in the induct-

ance, into electric energy $\frac{CU^2}{2}$. As a rule, the overvoltage values do not exceed $(2.0 \div 2.5)U_{ph}$.

Large overvoltage occur at switching on transformers at the instant of peak-switching current flowing through the switch, that is, in a short time after turning on, and also in cases of switching off braked high-voltage induction motors.

Overvoltage at electric motors commutation

High-voltage motors are considerable part of load at the enterprises.

Switching off electric motors is accompanied by overvoltage due to break of the current (it is similar to disconnection of excitation currents of transformers and reactors).

At a motor operation in its leakage inductance the magnetic energy is accumulated:

$$W_M = \frac{L_s}{2} i_{cutoff}^2$$

where L_s is the motor leakage inductance; i_{cutoff} is the current cutoff.

Conversion the energy from magnetic to electric form (and vice versa) is accompanied by overvoltage having the form of high-frequency oscillations.

The overvoltage is determined by the expressions:

$$U_{ov} = Z_s i_{cutoff}, \quad Z_s = \sqrt{L_s / C_{ecv}}$$

where L_s is the leakage inductance of the motor; C_{ecv} is equivalent capacitance of the system including the cable and the motor.

The largest overvoltage is produced by motors of comparatively small power having great values of the wave impedance.

Feature of motors is variation of their parameters with the rotor slip change:

$$s = 1 - \frac{\omega_2}{\omega_1}$$

where ω_1 is the magnetic field angular velocity, determined by the three-phase grid voltage; ω_2 is the rotor velocity.

The motor impedance at stationary rotor ($s = 1$) is in the main determined by resistance and leakage reactance of the stator and rotor windings. Under synchronous speed ($s = 0$) it is practically equal to impedance of the magnetizing circuit. Ratio of the rotor referred impedance Z'_s to impedance under stationary rotor Z'_{sc} is

$$\frac{Z'_s}{Z'_{sc}} = \frac{\sqrt{1 + \left(\frac{s_{cr}}{s}\right)^2}}{\sqrt{1 + s_{cr}^2}}$$

Fig. 5.2 shows a curve of the ratio $\frac{Z'_s}{Z'_{sc}}$ as a function of $\frac{s}{s_{cr}}$ for the case of $s_{cr} = 0.1$. It follows that motor impedance which determines the rotor referred current is sharply decreases at small the slip growth. Under $s = 4s_k$ the rotor current is only by 2.5% less than initial starting current.

Under comparatively small slip increase the referred rotor current becomes practically inductive and is substantial part of the total starting current. As a result, great share of cutoff current is defined by inductance.

Large overvoltage up to $5U_{ph}$ occur at switching off the motor with motionless rotor as energy accumulated in the inductance is directly proportional to square of the current. Switching off motors with stationary rotor takes place in the cases of

self-starting, the protection system operation in the course of starting etc.

Overvoltage caused by commutation of filtering-compensating devices

Tuned harmonic filters are widely used to decrease distortion of voltage curves in industrial power supply systems. At commutation of filtering and compensating devices transient overvoltage may arise.

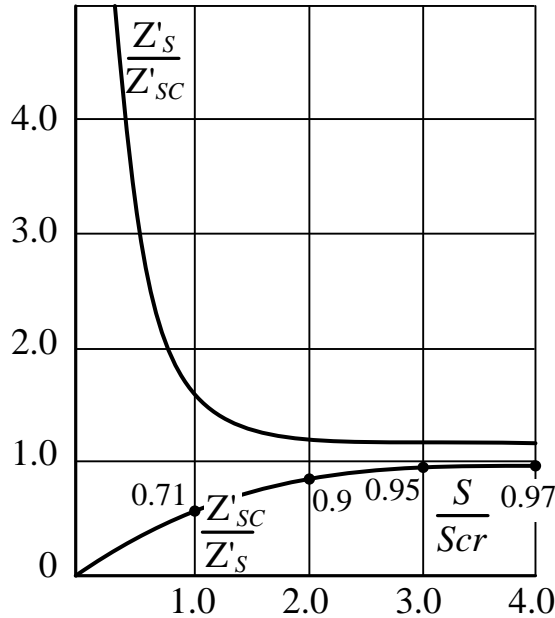


Figure 5.2 Ratio of impedances against $\frac{S}{S_{cr}}$

Equivalent circuit being used at transient calculation is shown in Fig. 5.3.

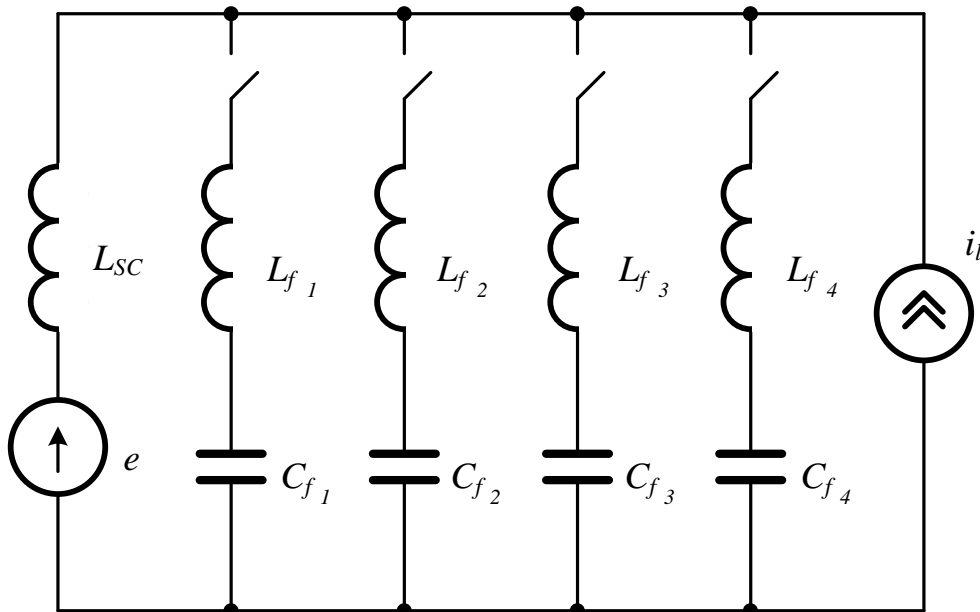


Figure 5.3 Equivalent circuit for calculation of transient over voltages in networks provided with filters

Valve inverters are commutated with use either 6- or 12-phase circuits (either ac-

tual or conditional). Short circuit inductance L_{sc} takes into account parameters of both power system and high-voltage motors if they are fed from the substation.

Study of transient in the circuit shows, that connection of the first filter causes maximum overvoltage on capacitors and reactors not exceeding double amplitude of the network rated voltage. Maximum value of transient current flowing through the filter exceeds the rated current amplitude by number of times some greater the number of harmonic to which the filter is tuned.

Connection of the second filter causes maximum overvoltage on capacitors and reactors which not also exceed double amplitude of the network rated voltage. The inrush transient current ratio is some greater than the number of harmonic to which the filter is tuned.

Transients in compensating filters caused by sharp voltage changes give rise to appearance of great transient currents in them. Short-term overloading by current of the compensation filtering devices may reach 50-75 %. Voltage on the capacitors reaches the voltage of a supply network that is by 5-10 % more than the voltage on busses. If voltage margin of the capacitors is small, regular increase the voltage may result in their fault. Hence, from the point of view of the filters reliability, it is desirable to limit the voltage fluctuations with value of ± 3 %.

Duration of transients in a power system equipped with the compensation filtering devices does not exceed 0.1s. As a rule, time interval between load swings is more than 0.1s. Therefore it may be assumed that any disturbance appears in electric power supply system under its stationary state.

5.3. Overvoltage arising at single phase-to-earth faults

There are several theories of arc overvoltage development caused by single phase-to-earth faults.

According to the theory of Peters-Slepian, the arc interruption takes place at the current of working frequency passing zero value. Iterative ignitions are represented in the form of metallic ground fault and repeat at every period under maximum voltage value in each the phase. At every repeated ignition the arc duration equals half a period of the working frequency. The arc interruption takes place under each current of working frequency passing zero value. The faulted phase voltage after the arc interruption is recovered smoothly at fundamental frequency. The overvoltage sign remains invariable.

According to the theory of Petersen, repeated ignitions of the grounding arc are also taken the form of metallic ground faults. But features of the arc volt-ampere characteristic are not taken into consideration. By the Petersen theory, repeated ignitions take place in each the half-period. Despite current value as well as its rate of change increase at each the period, arc duration after every iterative ignition is equal to half-period of the free oscillations. Each arc interruption in the network is followed by rising of direct bias voltage. The restored voltage on the fault phase after the arc interruption is of oscillatory character.

According to the theory proposed by N.N. Beliakov, the arc interruption for a long time takes place when the first high-frequency maximum of the restored voltage on the faulted phase (the quenching peak) becomes less than value of breakdown strength of fault area during half-period of free oscillations. The theory is in intermediate position between the theories of Petersen and Peters-Slepian. According to Petersen, arcing process should terminate during the very first passing the current of oscillations through zero. According to Peters and Slepian, it should terminate at passing through zero of the working frequency current. By the Beliakov's theory, the two key conditions should coincide within one cycle of the arc ignition-quenching-ignition.

As studies of a number of authors (e.g., F.A. Likhachiov) show, in each specific case may take place one or another mechanism of quenching.

The process of overvoltage development as well as its amplitude in networks with insulated and with compensated neutral differ.

According to the theory of Beliakov, peak overvoltage values are:

For 6 kV network

$$U_{ov} = 2.88U_{ph}.$$

For 10 kV network

$$U_{ov} = 2.84U_{ph}.$$

On the faulted phase the overvoltage may be:

For 6 kV network

$$U_{ov} = 2.19U_{ph}.$$

For 10 kV network

$$U_{ov} = 2.11U_{ph}.$$

Not always design parameters conforming to networks actual are used to determine maximum possible over voltages. As a rule, studies do not take into account losses in the circuit (resistance, electrical conductance of leaks, losses in insulation) as well as conductance of voltage transformers through which high-voltage winding the electrical charges conforming to the bias voltage U_{bias} run down to the ground.

Use of the ground-fault neutralizers for capacitive currents reduction decrease the overvoltage value and its occurrence probability at arc short-circuit to the ground.

Under resonance adjustment, the overvoltage value does not exceed $2.1U_{ph}$, that is only slightly exceeds the overvoltage at metallic grounding.

The foregoing is valid only for networks with balanced values of phase capacity.

As a rule, cable networks are balanced, although unbalance may be determined by worsening of one of the phase insulation. Capacitance unbalance of phases is observed at use of main transmission lines which length is often more than a kilometer. In the networks operating in condition of resonant adjustment or at under-compensation, the overvoltage at phase capacitive unbalance is 30-40% higher to compare with balanced networks. Even if insignificant under-compensation is available, the overvoltage value may turn out to be much greater. In networks with increased voltage distortion factor, the number single phase-to-ground faults considerably increase (up to 30-40%) to compare with the networks where the distortion factor meets the required specified value.

5.4. Ferro-resonance overvoltage

High power intensity of metallurgic, machine-building plants and some other industries stipulates availability of large number of transformer substations, cable lines, current distribution networks and different using equipment in their power supply systems. Complexity of manufacturing processes needs changes in line pattern as well as its parameters. It often results in occurrence ground-faults, transformers and cable lines damage due to ferro-resonance. Ferro-resonance in power supply systems is accompanied with insulation flashover on bushings, breakdown of transformers, cables and other equipment insulation. Voltage transformers are damaged most of all. Often, neutral displacement arising due to ferro-resonance in networks with insulated neutral results in false earth warning and unreasonable de-energizing of consumers.

Ferro-resonance is an oscillating process being a result of capacitance and non-linear reactance interaction.

In power supply systems the interacting parameters are the network capacity and non-linear inductance of transformers. All other network elements parameters do not considerably influence the process. Ferro-resonance processes in power supply systems and overhead lines do not differ essentially. But different values of the network parameters cause peculiarities of the processes. So various length of overhead lines is the reason of various combinations of capacitive and inductive reactance resonating on definite power source harmonic frequency. In this case transformer may be the source of higher harmonics. Under definite conditions Ferro-resonance may be self-maintained. There is no necessity to disturb conditions of the system to develop Ferro-resonance as natural resonance process arises in the system. *The two key types of Ferro-resonance* are typical for power systems of 6–10 kV: in the first case it is the result of a supply transformer open-phase operating conditions, in the second case it is the result of open-phase condition of a voltage transformer. Physical nature of the process is similar but their development takes place under different conditions and different parameters of network. So, Ferro-resonance generated by supply transformer open-phase conditions is typical for extensive networks with great ratio of their capacitive reactance to resistance. This problem belongs more to cable grids and in less degree to the grids with overhead lines. For appearance of Ferro-resonance to which voltage transformers are involved it is necessary that capacitance of the grid or its section was small. The latter is more typical for networks with overhead lines.

As a rule, Ferro-resonance effects are rather durable. Ferro-resonance effects take place rarely to compare with arc surges and commutation surges but their damage is significant.

Consider physical nature of Ferro-resonance effects in 6-10kV electric networks. Distinctive feature of the Ferro-resonance circuit is that the transformer operating at saturation area has inductance varying with time. Magnetizing curve of such a transformer varies within each period of supply source voltage. Every value of inductive reactance x_μ resonates with capacitive reactance x_C . There is probability of resonance occurrence in each period. Increase of the network voltage may result in the transformer core saturation. With it, the transformer inductance reduces till the value of leakage inductance. The transformer inductance variation produces terms of Ferro-resonance arising at frequencies multiple of the network frequency.

The transformer magnetization curve has some typical areas. As an example consider magnetization curves of voltage transformers. The curve of a transformer may be conventionally divided into three areas (Fig. 5.4):

- The area where the curve is slightly deviated from vertical axis and the curve is nearly linear. This area corresponds to non-saturated state of the transformer core. The inductive reactance of a transformer is maximal.
- For the area of the curve bending till it transition into horizontal line the inductance varies most appreciably.
- At horizontal area the reactance is very small being roughly equal to reactance of the winding which does not have a core.

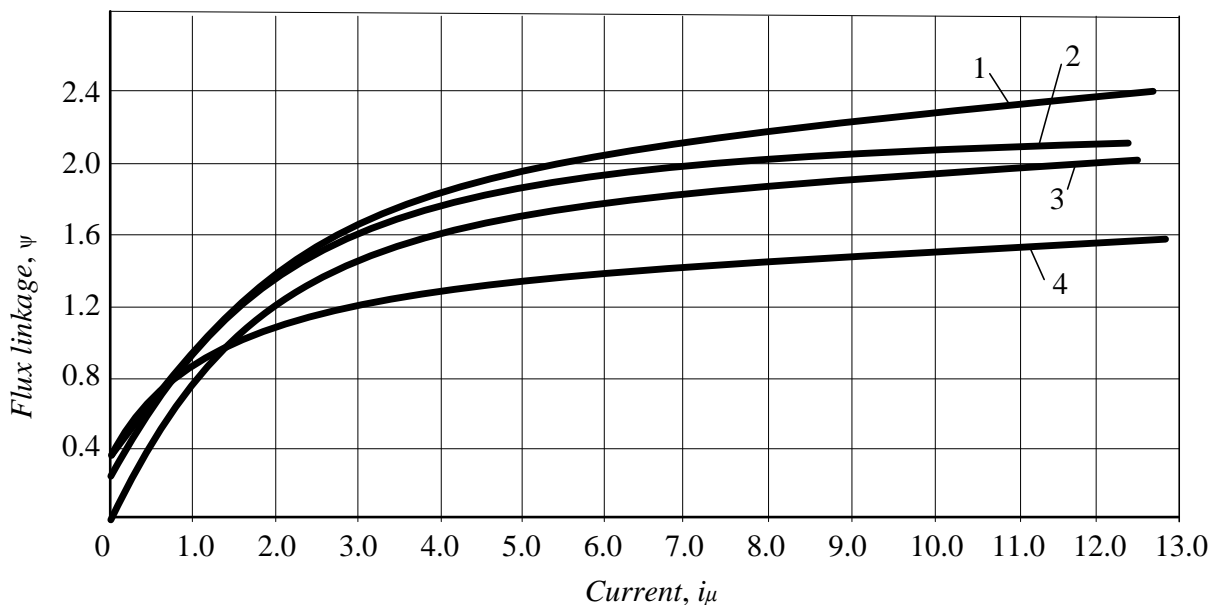


Figure 5.4 Magnetization Curves of Potential Transformers on Instantaneous Magnitudes of Magnetic Linkage and Current:

1 – HOM-6/10/; 2 – HOM-35; 3 – 3HOM-15/35-54/; 4 – НТМИ-6/10/-66

As an example, consider Ferro-resonance effect within electric power supply network using a single-phase equivalent circuit (Fig. 5.5). Under a transformer with ferromagnetic core and a capacitor parallel connection, the parallel Ferro-resonance can take place.

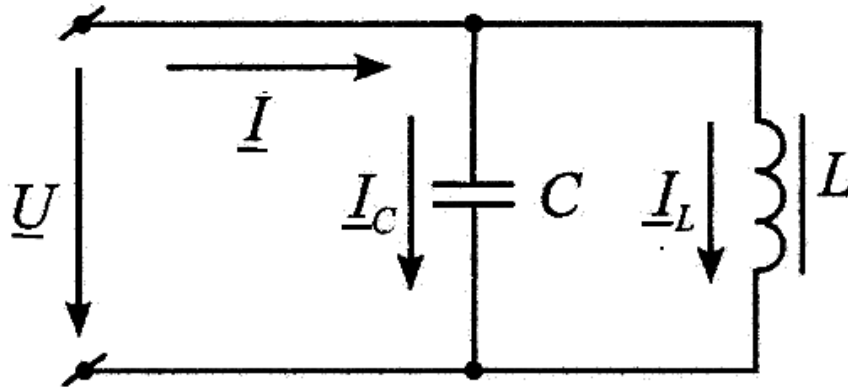


Figure 5.5 Single-phase equivalent Ferro-resonance circuit

Fig. 5.6 shows voltage-current curves of a transformer $U(I_L)$ and of a capacitor $U(C)$. If loss in the circuit and harmonics caused by nonlinear nature of the transformer characteristic are neglected, the primary current of the transformer and current in the capacitor are in opposite phase one to another, and the current of the unbranched part of the circuit equals the absolute value of the parallel paths currents difference, defined by their volt-ampere curves. Ferro-resonance takes place under voltage U_{res} at which the transformer inductive reactance equals the capacitive reactance, and their currents have the same magnitude and are in opposite phase compensating one another. In the case of a capacitor and a nonlinear inductance parallel connection, resonance may be obtained by means of the applied voltage variation.

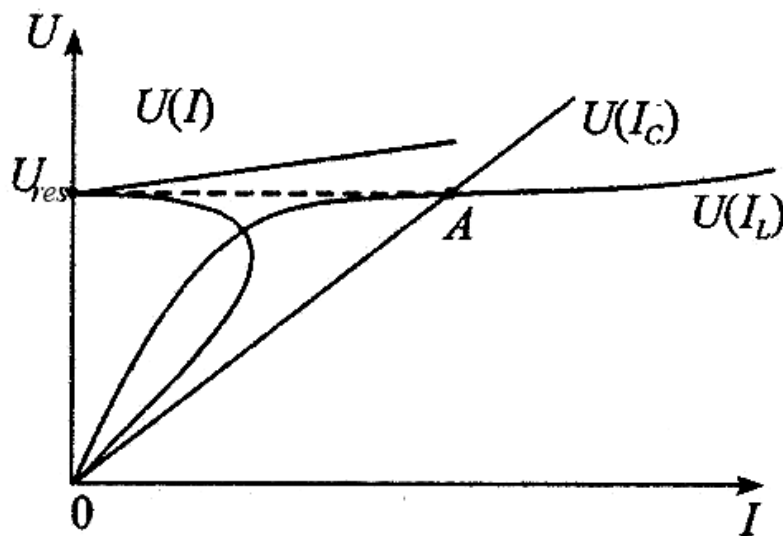


Figure 5.6 Idealized voltage-current characteristics of a capacitor and a transformer

Taking into account previously neglected loss in the circuit and harmonics, find that the resonance current I in the unbranched circuit does not equal to zero. Actual volt-ampere curves of the circuit are given in Fig. 5.7. Section 5 – 2 of the curve presents the area of the circuit unstable state. At the current increase from zero, the operating point moves along the volt-ampere curve by the path 0-1-2-3-4. At the current decrease from a value defined by point 4, the operating point moves along the path 4-3-5-1-0. Therefore, smooth current increase can cause the voltage stepwise increase.

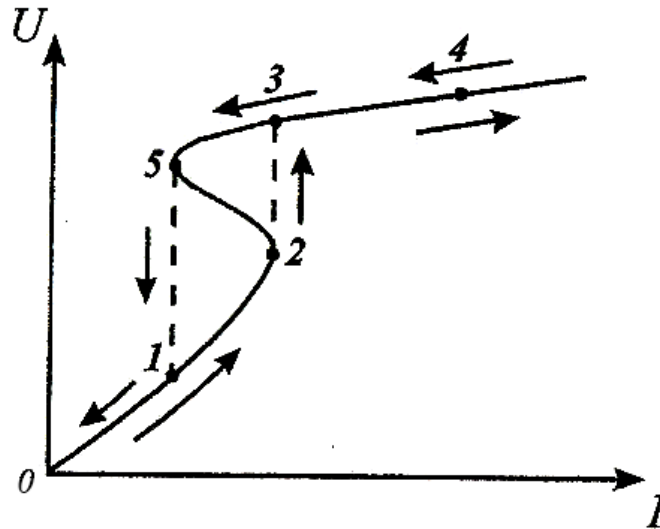


Figure 5.7 Actual volt-ampere curves

For appearance of Ferro-resonance in a voltage transformer at least one of its phases must be saturated. The resonating phase may be easily determined by comparison of current rushes in the phases. Maximum current rush takes place in the saturated phase, and minimum one – in the phase that was short-circuited to the ground before.

Superposing the positive sequence voltage to the phase voltage system distorts their shape and causes overvoltage. In the transformer neutral considerable current rushes are observed. Such rushes reach the value of 3 A. Polarity of current rushes in phases corresponds with polarity of current rushes in the neutral. Their frequency equals the frequency of Ferro-resonance oscillations. Maximum values of the rushes may reach 10 A that is greater than the rated current by thousands times. Ferro-resonance at frequencies of 16.6, 25 and 100 Hz is accompanied with overvoltage till $1.7U_{ph}$. The overvoltage at frequency of 50 Hz may reach $2U_{ph}$ and at frequency of 150 Hz $3.5U_{ph}$.

Listing of measures on protection against internal over voltages is given in Table 5.2.

Table 5.2.
Measures on protection against internal overvoltages

| Protection Events | | |
|--|--|--|
| Against arc overvoltage | Against commutation overvoltage | Against ferro-resonance overvoltage |
| Arrangement of arc- | Arrangement of excess- | Balanced connection of |
| Arrangement of excess-voltage suppression- | Arrangement of valve-type | Using of damping active load |
| Arrangement of valve-type | Using of protective capacitors | Detuning resonance-circuits |
| Using additional in- | Use of damping re- | Arrangement of excess |
| Grounding the neutral | Adjustment of breaking | Installation of switch close |
| Selective switching | Improvement of circuit | Insulation preventive |
| Improvement of pre- | Using of thyristor | Grounding the transformer neutral through resistor |
| | Breaking delta-connected | |
| | Improvement of preventive insulation maintenance | Selection of voltage transformers taking into account the short-circuit to |

Test questions

1. List reasons of commutation overvoltage.
2. In what cases does overvoltage occur in a power supply system?
3. Describe receptivity of electronic equipment to disturbances that appear in power supply systems at transient conditions.
4. Assess overvoltage levels under single phase-to-ground faults.
5. In what cases does commutation overvoltage appear?
6. What overvoltage levels take place under commutation in power compensating and filtering devices?
7. What is the voltage fluctuations danger?
8. What are the types of Ferro-resonance processes in power supply system?
9. What are the causes of Ferro-resonance occurrence?
10. What are the features of transients in power compensating and filtering devices at network voltage deviation?

Topics for essay

1. Features of modern switching devices impact on voltage and current pulses generation.
2. Influence of commutation overvoltage on electric equipment.
3. Ferro-resonance in industrial enterprises power networks.
4. Reason and sources of commutation pulses appearance.
5. Conditions of Ferro-resonance overvoltage arising.

6.1. Starting statements

Estimation of electromagnetic interference (EMI) levels (values of electricity quality) within the nodes of electric power supply system of an enterprise is fulfilled on the basis of linear equivalent circuits in which EMI are presented as driving currents (voltages). At non-sinusoidal conditions calculation modes are calculated the electromagnetic interferences are presented as higher harmonics currents. At this, impedances of system elements of electric power source elements are taken with account the higher harmonics frequencies. Similarly, while calculating non-symmetrical conditions EMI is presented as negative-sequence current resulting from the unbalance; impedance of network elements is taken with account of negative phase sequence.

Negative-sequence current of a valve inverter $I_2^{(VI)}$ depending upon positive-sequence current $I_1^{(VI)}$ as well as unbalance factor of line-to-line voltage of the work K_{2U} is determined on the expression $I_2^{(VI)} = 0.5K_{2U}I_1^{(VI)}$, its phase is $arg I_2^{(VI)} = \psi_{21} + \alpha$. Here ψ_{21} is phase displacement between vectors $I_2^{(VI)}$ and $I_1^{(VI)}$; α is valve inverter delay angle. Impedance of valve inverter negative sequence is $Z_2^{(VI)} = 2Z_1^{(VI)}$, where $Z_1^{(VI)}$ is valve inverter resistance under $K_{2U} = 0$.

Table 6.1

Electrical characteristic of load

| <i>Loads</i> | <i>Electrical Characteristics</i> |
|-----------------------|-----------------------------------|
| Filament lamps | Resistance |
| Luminous lamps | Nonlinear |
| Electric Motors | Inductive |
| Computers | Nonlinear |
| Consumer Electronics | Nonlinear |
| Electric heaters | Resistance |
| Air conditioners | Inductive |
| Electric arc furnaces | Nonlinear |
| Valve inverters | Nonlinear |

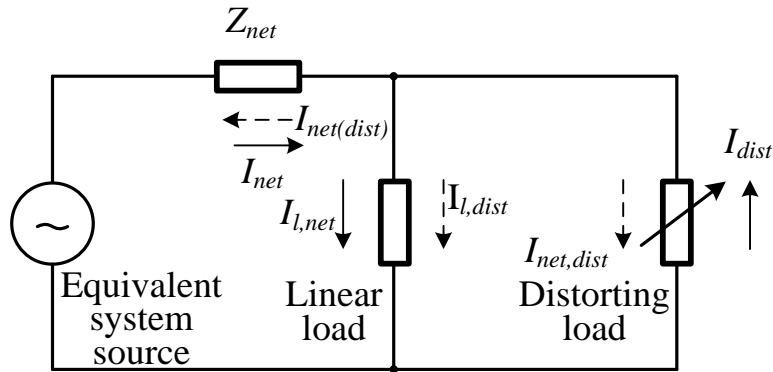


Figure 6.1 Equivalent circuit for network loaded with source of EMI

Source supply voltage fluctuation is shown as driving voltage source. Such a source is P_{St} or P_{Lt} . Elements of equivalent circuits are presented as inductances. Load types as well as their electrical characteristics within EMC computation according to IEEE (American Institute of Electrical and Electronics Engineers) classification are given in Table 6.1.

Equivalent circuit of network loaded with the source of electromagnetic interference (nonlinear load) is shown in Fig. 6.1.

In an industrial enterprise power supply system node resistances are as a rule non-linear. Their amplitude-frequency characteristics (AFC) contain zeros and poles which number and position greatly depend on load alternations (Fig. 6.2 and 6.3). It is obvious that in the case under consideration minima of AFC correspond to series resonance conditions, and their maxima – to parallel resonance.

As an example of negative consequences of parallel resonance is the single phase-to-earth fault in enterprise compensated power supply system. If the system is tuned on resonance on fundamental frequency of 50 Hz harmonics current can increase considerably, and its magnitude may exceed capacitive current of the fundamental frequency that often results in the defective cable burning.

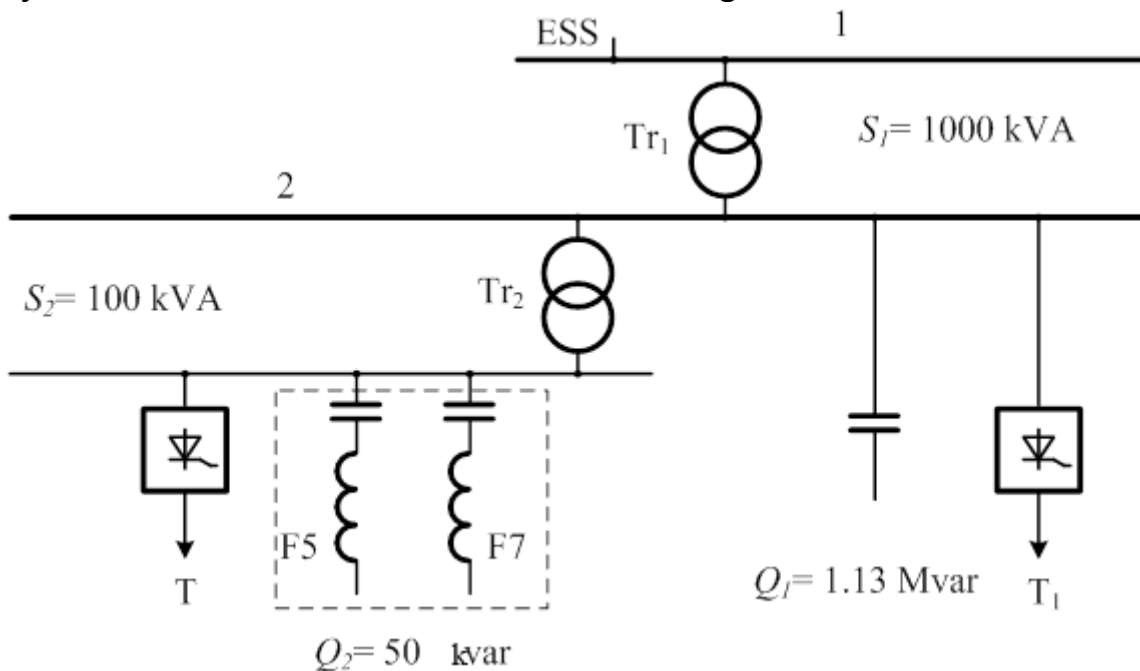


Figure 6.2 Consumer electric power supply circuit

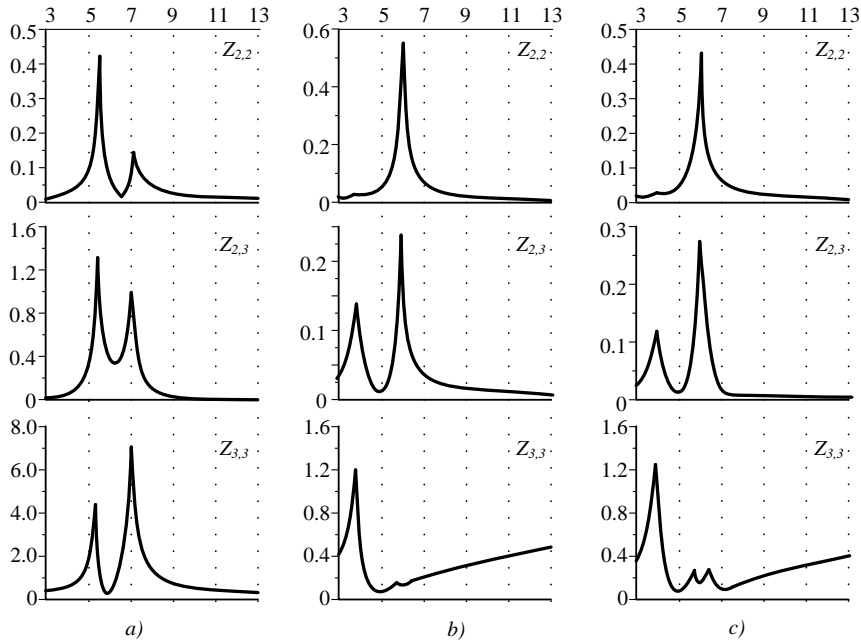


Figure 6.3 AFC of load node for the cases of connection only capacitor bank CB (a), capacitor bank CB and filter F5 (b), capacitor bank CB and filters F5 and F7 (c)

The frequency characteristic of the network node 110–220–330 kV, to which the enterprise power supply system is connected, is also nonlinear, that is worth considering at calculations.

6.2. Computation of voltage deviations

Voltage deviations are determined for specific points of an enterprise electric power supply system: on 6, 10, 35 kV buses of deep input substations (DIS) or main step-down substations (MSDS) supplied through electrical pathways or long overhead lines and also on buses 0.38 – 0.66 kV of shop transformers and distribution centers. The voltage deviations are calculated for maximum and minimum load of a power supply center.

The voltage deviation is determined by the expression:

$$\delta U_{h(l)} = \delta U_{+(-)} + \delta U_g - E_{ad} \quad (6.1)$$

where $\delta U_{u(l)}$ is upper (lower) voltage deviations limit, %; $\delta U_{+(-)}$ is the upper (lower) voltage deviations limit on the consumer terminals according to GOST 13109-97, %; δU_g is voltage reduction at the grid section from the supply node to terminals of the consumer, %; E_{ad} is voltage additive by the local voltage control means, %.

Besides voltage deviations compatibility in the different conditions of 24 hour load is assessed by the condition

$$\delta U_h > \delta U_l$$

where $\delta U_{h(l)}$ is the minimum (maximum) of all voltage deviations determined by (6.1) at of maximum (minimum) load.

If the condition is not fulfilled for one of 24 hour loading periods, taps of the distribution transformer and local means of voltage control are used to decrease the voltage reduction in distribution networks.

While compatibility examination it is necessary to determine both upper and lower limits of the voltage-control range in the supply center under specific conditions of load:

$$\delta U_{u(l),s-c} = \frac{1}{2} (\delta U_{(u),s-c,\max(\min)} - \delta U_{(l),s-c,\max(\min)})$$

where subscripts *max (min)* mean maximum and minimum loading conditions.

Consider method of calculation for cases specific for the industrial power supply networks: on buses of the main step-down substation with deep input, for radial grids of enterprises and simple double-ended ring mains.

Calculation of voltage deviations on buses of a main step-down substation is carried out without taking into account the control device, installed in the supply center, dead band for the two bounds of load condition – for maximum and minimum loads and for two power consumers - the closest one and the most remote electrically. With it the voltage drops in every network elements are taken into account. Of two values of δU_{s-c} the greater one is selected.

The upper limit of the allowable voltage deviation on buses of the main step-down substation under minimum load is determined for a high-voltage motor and power consumer with voltage up to 1kV closest to the substation buses. With it transformation ratio for the substation supplying the closest power consumer is assumed the greatest, and voltage drop on network elements are determined for conditions of minimum load:

$$\begin{aligned} \Delta U'_{s-c+} &= (0.05U_r + \Delta U_{trs})k_{tr} + \Delta U_{10(6)kV} \\ \Delta U''_{s-c+} &= 0.05U_r + \Delta U_g \end{aligned}$$

where ΔU_{trs} is voltage drop in the transformer of the substation..

Of the two values of $\delta U_{s-c,+}$ the less one is chosen (more severe condition).

Consider determination of the voltage deviations within radial grids and for sections of double-ended ring mains.

Voltage deviations within any network point for a fixed instant is:

$$\delta U = \sum_{i=1}^m E_{adi} - \sum_{l=1}^n \Delta U_l$$

where $\sum_{i=1}^m E_{adi}$ is algebraic sum of added voltage produced by regulating means; $\sum_{l=1}^n \Delta U_l$ is total voltage drop for radial grids within the considered section; for double-ended ring mains – on all circuit sections under consideration.

The voltage drop on a network section is

$$\Delta U_l = \frac{Pr + Qx}{10U_r^2}$$

where P and Q are active and reactive power, kW; r, x are resistance and reactance of the section, Ohm, U_r is rated voltage, kV.

Voltage drop in the transformer is determined by the simplified expression:

$$\Delta U_{tr} = (u_{act} \cos \varphi + u_{react} \sin \varphi) S/S_r$$

where u_{act} and u_{react} are active and reactive components of the impedance voltage, %; φ is the load phase angle; S_r and S are the rated and actual power of the transformer.

When voltage drops in networks with different voltages are determined their parameters are referred to the basic voltage:

$$r_b = R \left(\frac{U_b}{U_r} \right)^2 ; \quad x_b = X \left(\frac{U_b}{U_r} \right)^2 .$$

6.3. Calculations of voltage unbalance

Calculation of the voltage unbalance is based on use of equivalent circuit of the network for negative sequence.

Equivalent circuit for the negative-sequence currents is similar to circuit for positive sequence. All circuit elements are presented by their negative sequence parameters. Unbalanced load is represented as negative-sequence current source. Negative-sequence current I_{2q} in the q -th branch produced by the negative sequence current source I_{2p} available in the p -th branch is determined by means of the expression

$$I_{2q} = \underline{K}_{2pq} I_{2p}$$

where \underline{K}_{2pq} is distribution factor of the negative-sequence currents between p -th and q -th branches of equivalent circuit.

If several sources of unbalance are connected to various network nodes, the following is valid:

$$I_{2q} = \sum_{p=1}^S \underline{K}_{2qp} I_{2p} .$$

Nodal-voltage method is more expedient for the latter case. In the matrix form nodal voltage system looks as

$$\mathbf{G}_2 \mathbf{U}_2 = \mathbf{I}_2$$

Here \mathbf{G}_2 is matrix of transfer conductance between nodes of the negative sequence equivalent circuit; \mathbf{U}_2 and \mathbf{I}_2 are matrices of node voltages and currents of the negative sequence.

It should be noted that direct recalculation of K_{2U} values for network nodes, if its value is known for the node, where unbalanced source is available, using the above-mentioned procedures is impossible.

The key stage of the calculation is determination of negative sequence voltage U_2 according to the expression:

$$U_2 = I_{2\Sigma} Z_{2\Sigma}$$

where $I_{2\Sigma}$ is equivalent current of the negative sequence caused by unbalanced loads; $Z_{2\Sigma}$ is the network negative sequence impedance.

Under connection of three different single-phase loads to line-to-line voltages AB , BC , CA negative-sequence current I_2 and its initial phase φ_{I_2} are

$$I_2 = \frac{\sqrt{3}}{3} \sqrt{I_{AB}^2 + I_{BC}^2 + I_{CA}^2 - I_{AB}I_{BC} - I_{BC}I_{CA} - I_{CA}I_{AB}}$$

$$\varphi_{I_2} = \tan^{-1} \frac{\sqrt{3} I_{AB} + I_{BC} - 2I_{CA}}{I_{AB} - I_{BC}} - \varphi_l$$

Or if the apparent power is given

$$I_2 = \frac{\sqrt{3}}{3U_r} \sqrt{S_{AB}^2 + S_{BC}^2 + S_{CA}^2 - S_{AB}S_{BC} - S_{BC}S_{CA} - S_{CA}S_{AB}}$$

$$\varphi_{I_2} = \tan^{-1} \frac{\sqrt{3} S_{AB} + S_{BC} - 2S_{CA}}{S_{AB} - S_{BC}} - \varphi_l$$

When single-phase loads with displacement angle φ_H are connected on two of the line-to-line voltages, the negative-sequence current initial phase φ_{I_2} is within bounds:

| | |
|---------------------|---|
| AB and BC | $30^\circ - \varphi_H \leq \varphi_{I_2} \leq 150^\circ - \varphi_H$; |
| BC and CA | $150^\circ - \varphi_H \leq \varphi_{I_2} \leq 270^\circ - \varphi_H$; |
| CA and AB | $270^\circ - \varphi_H \leq \varphi_{I_2} \leq 30^\circ - \varphi_H$. |

Relative value of module $Z_{2\Sigma^*}$ (as a fraction of positive sequence impedance) as well as phase angle of equivalent negative sequence impedance for buses section (system) are:

$$Z_{2\Sigma^*} = \frac{\sqrt{(\sum_{i=1}^n S_{ri} \cos \varphi_i)^2 + (\sum_{i=1}^n S_{ri} \sin \varphi_i)^2}}{\sqrt{(\sum_{i=1}^n S_{ri} y_i \cos \varphi_i)^2 + (\sum_{i=1}^n S_{ri} y_i \sin \varphi_i)^2}} \quad (6.2)$$

$$\arg Z_{2\Sigma^*} = \tan^{-1} \frac{\sum_{i=1}^n S_{ri} y_i \sin \varphi_i}{\sum_{i=1}^n S_{ri} y_i \cos \varphi_i} \quad (6.3)$$

where S_{ri} , y_i , φ_i are rated apparent power, relative value of the negative sequence admittance and phase angle of i -th connection of linear (nonlinear) part of the load.

Table 6.2

Expressions for determination of negative sequence reactance of power supply system elements

| Load type | Expressions for negative sequence parameters | Note |
|---|--|--|
| Synchronous motors | $X_{2s} = U_r^2 X_{2^*} / S_r$ | $X_{2^*} = 1/k_{st}$ if catalogue data are not available k_{st} is starting current ratio e_{sc^*} is relative value of impedance voltage, which is accepted equal to $e_{sc^*} = 0.1$ if catalogue data are not available. For reactors X_{R^*} is taken instead of e_{sc^*} X_* is relative winding reactance |
| Induction motors | $X_{2I} = U_r^2 X_{2^*} / S_r$ | |
| Two winding transformers and reactors | $X_{2tr} = U_r^2 e_{sc^*} / S_r$ | |
| Three-winding transformers with split coils, mutually coupled reactors for each winding | $X_{2R} = U_r^2 X_* / S_r$ | |
| Capacitor bank | $X_{2CB} = U_r^2 / Q_{CB}$ | |
| Valve inverter | $Z_{2VI} = 2U_r^2 / S$ | S is inverter load apparent power, $\underline{Z} = Z \cos \varphi + jZ \sin \varphi$ where $\cos \varphi$ is power factor of loaded valve inverter |
| Electric arc furnace | $Z_{2F} = U_r^2 / S$ | The same |
| Lighting load | $R_L = U_r^2 / P$ | P is load power |
| Power supply system | $X_{2PSS} = U_r^2 / S_{sc}$ | S_{sc} is short-circuit power |

Expressions for determination of negative sequence parameters of power supply system elements are presented in Table 6.2.

Unbalanced load is a source of negative sequence current.

Example

Determine K_{2U} on a plant buses of 10 kV and 110 kV. Diagram of power supply system is shown in Fig. 6.4. The vacuum arc furnace with power of 6 MVA, $y_1 = 0.42$, $\cos \varphi_1 = 0.85$, the electroslag melting furnace with $Q_{CB} = 8$ Mvar, $y_2 = 1$, $\cos \varphi_2 = 0$ and the load 5 MVA, $y_3 = 5$, $\cos \varphi_3 = 0.8$ are connected to node 1. To node 2 the load with power of 12 MVA, $Z_2 = 0.5 + j0.55$. Power of short-circuit on buses 110 kV is 1600 MVA. The current of negative sequence, caused by connection to node 1 the single-phase electroslag melting furnaces having power of 5 MVA, equals $I_2 = 1.5$ relative units. The elements admittance y_1, y_2, y_3 is also given in relative units.

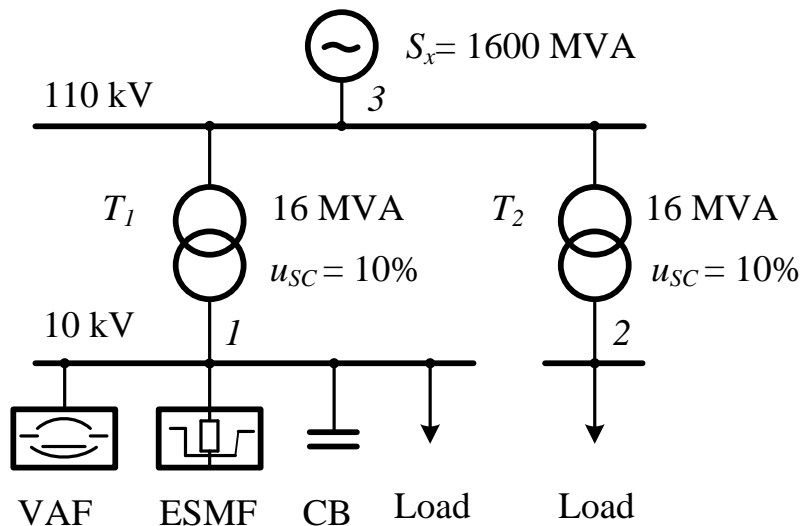


Figure 6.4 Thermal electric plant power supply circuit diagram

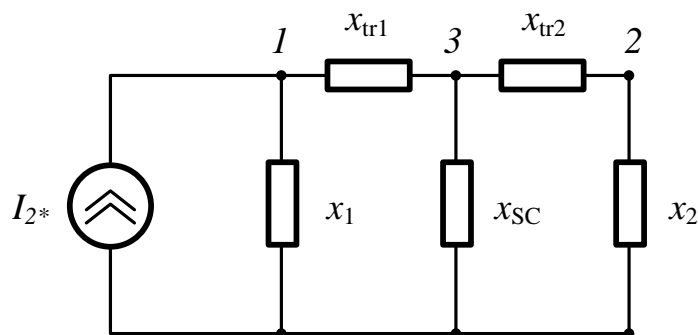


Figure 6.5 Equivalent circuit of negative sequence for network shown in Fig. 6.4

Solution

According to (6.2), modulus of negative sequence impedance in relative units for 10kV bus section in the node I is:

$$|\underline{z}_2| = \frac{\sqrt{(6*0.85+5*0.8)^2+(6*0.53-8*1+5*0.6)^2}}{\sqrt{(6*0.85*0.42+5*0.8*5)^2+(6*0.53*0.42-8*1*1+5*0.6*5)^2}} = 0.39.$$

Argument of impedance \underline{z}_2 is determined by (6.3):

$$\varphi_2 = \arctan \frac{8.33}{22.14} = 20.6.$$

For convenience take basic power equal the total load power $S_6 = 9,28\text{MVA}$. Then, complex negative sequence impedance of 10kV bus section in node I , relative units, is

$$\underline{z}_{2(1)} = 0.37 + j0.14.$$

In further calculations of the network elements parameters only their reactive components will be taken into consideration.

The transformer resistance is

$$x_{tr1} = x_{tr2} = \frac{u_{sc}}{100} \frac{S_b}{S_r} \frac{10}{100} \frac{9.28}{16} = 0.058.$$

The system reactance is

$$x_{sc} = \frac{S_b}{S_{sc}} = \frac{9.28}{1600} = 0.0058.$$

10kV buses negative sequence impedance in node 2 is

$$\underline{z}_{2(2)} = (0.5 + j0.55) \frac{9.29}{12} = 0.39 + j0.43.$$

The Current of negative-sequence source is

$$I_2 = 1.5 \frac{5}{9.28} = 0.81.$$

Node 1

Negative sequence equivalent impedance

$$\underline{Z}_{2\Sigma(1)} = \frac{\underline{Z}_{2(1)} \left(jx_{tr1} + \frac{(jx_{tr2} + \underline{Z}_{2(2)})jx_{sc}}{jx_{tr2} + \underline{Z}_{2(2)} + jx_{sc}} \right)}{\underline{Z}_{2(1)} + jx_{tr1} + \frac{(jx_{tr2} + \underline{Z}_{2(2)})jx_{sc}}{jx_{tr2} + \underline{Z}_{2(2)} + jx_{sc}}} = 0.0085 + j0.059 = 0.06e^{j82^\circ}.$$

Unbalance factor equals

$$K_{2U} |\underline{Z}_{2\Sigma(1)}| I_2 = 0.064 \cdot 0.81 = 0.047 = 4.7 \%$$

Node 3

Negative sequence impedance equals

$$\underline{Z}_{2\Sigma(3)} = \frac{(jx_{tr2} + \underline{Z}_{2(2)})jx_{sc}}{jx_{tr2} + \underline{Z}_{2(2)} + jx_{sc}} = 3.31 \cdot 10^{-5} + j5.76 \cdot 10^{-3} = 0.0057e^{j89.7^\circ}.$$

The negative-sequence current in transformer T1:

$$I_{2(T1)} = I_2 \left| \frac{\underline{Z}_{2(1)}}{\underline{Z}_{2(1)} + jx_{tr1} + \frac{(jx_{tr2} + \underline{Z}_{2(2)})jx_{sc}}{jx_{tr2} + \underline{Z}_{2(2)} + jx_{sc}}} \right| = 0.81 \frac{0.4}{0.43} = 0.77.$$

The negative sequence factor equals

$$K_{2U} = |\underline{Z}_{2\Sigma(3)}| I_{2(tr1)} = 0.0057 \cdot 0.77 = 0.0044 = 0.44 \%$$

Node 2

The negative sequence impedance is

$$\underline{Z}_{2\Sigma(2)} = \underline{Z}_{2(2)} = 0.39 + j0.43 = 0.58e^{j48^\circ}.$$

The negative-sequence current in transformer T2 equals

$$I_{2(tr2)} = I_{2(tr1)} \left| \frac{jx_{sc}}{jx_{sc} + jx_{tr2} + \underline{Z}_{2(2)}} \right| = 0.77 \frac{0.0058}{0.63} = 0.0071.$$

The negative sequence factor equals

$$K_{2U} = |\underline{Z}_{2\Sigma(2)}| I_{2(tr2)} = 0.58 \cdot 0.0071 = 0.0041 = 0.41 \%$$

6.4. Calculations of harmonics and interharmonics

Calculations of harmonic levels of voltage and current, K_U , amplitude-frequency characteristics and other parameters of non-sinusoidal conditions is done on the basis of equivalent circuits, valid separately for each harmonic. Nonlinear loads are presented as current sources (driving currents) or rarer as voltage sources of harmonics. Equivalent circuits of a non-linear load as voltage source and internal reactance $x_{int n}$ are used in the case when resonance or near resonance conditions arise at frequency of n th harmonic. In power supply systems of industrial enterprises controlled valve inverters are mainly used. Current of n th harmonic I_n for $n \leq 13$ is rather accurately determined on the formula

$$I_n = \frac{I_1}{n} \cong \frac{I_{VII}}{n}$$

where I_{VII} and I_1 are load current of the inverter and its fundamental.

Initial phase of the current I_n is

$$\varphi_n = (\alpha + \gamma/2) n$$

where α and γ are delay and commutation angles.

For other nonlinear loads (electric arc furnaces, welding sets) value of harmonic currents are mainly determined by means of experimental data averaging for specific type of electric equipment.

Table 6.3

Impedance of electric power supply system components to harmonic currents

| Consumer | Formula for determination of network impedance to n th harmonic, Ohm | |
|--|--|----------------------------------|
| | 6 kV | 10 kV |
| Synchronous (asynchronous) motor, turbo-generator with S_r , MVA, rated power | $\frac{6}{S_r} n$ | $\frac{17}{S_r} n$ |
| Loaded transformer of shop substation with S_r , MVA, rated power | $\frac{12}{S_r} n$ | $\frac{34}{S_r} n$ |
| Double-winding transformer for coupling with power system with rated power S_r , MVA | $\frac{0.4 u_{sc} \%}{S_r 100} n$ | $\frac{11 u_{sc} \%}{S_r 100} n$ |
| Capacitor bank with power Q_{CB} , kvar | $\frac{40}{Q_{CB} n}$ | $\frac{110}{Q_{CB} n}$ |

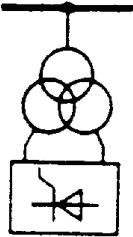
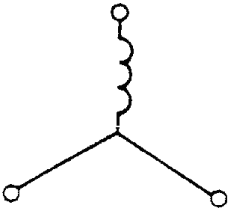
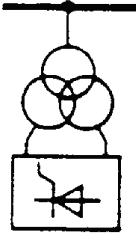
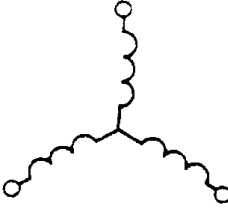
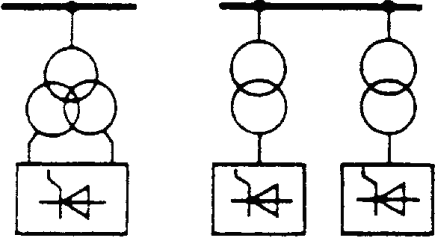
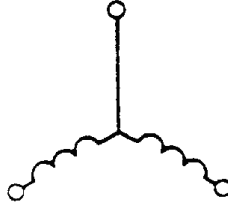
Impedance of a power supply system elements at harmonic frequencies for networks with $U_{\text{HOM}} \geq 6$ kV is mainly inductive. Taking into account their active component is necessary when values of voltage and current harmonics are estimated under resonance conditions. At this it is assumed that skin effect appears sharply the resistance increase in direct proportion to \sqrt{n} .

Approximate values of the impedance which are widely used in design work of CIS countries are presented in Table 6.3.

Transformers with split windings, having split factor in bounds of (0 ... 4), are often used for 12-pulse valve inverters. If low voltage windings are mixed, then $k_{sf} = 0$; if magnetic coupling is not available or there are two transformers with different connections, then $k_{sf} = 4$. Equivalent circuits, values of k_{sf} and $x_{tr,n}$ for different cases are given in Table 6.4.

Table 6.4

Equivalent circuits of transformers and their parameters

| Converter circuit | Equivalent circuit | k_{sf} | $x_{tr,n}$ |
|---|---|----------|--|
|  |  | 0 | $\frac{u_{sc} \% S_{conv}}{100 S_{tr}}$ |
|  |  | 0.4 | $\frac{u_{sc} \%}{100} (1 + k_{sf}) \frac{S_{conv}}{S_{tr}}$ |
|  |  | 4 | $\frac{2u_{sc} \% S_{conv}}{100 S_{tr}}$ |

Calculation of voltage and current harmonics in complicated branching power

supply systems of enterprise with different levels of rated voltage, or in a case when the systems of several enterprises with own heat and power plants form a stand-alone electric power system, is performed with the help of nodal voltage or mesh-current method. It is expedient to apply PC for this purpose.

Nonlinear loads in equivalent circuits are presented as sources of harmonic currents either individual or equivalent for the bus section (system). Validity of such approach is confirmed by the fact that harmonics driving currents remain practically non-changed when the network operating condition varies up to resonance arising at frequency of any harmonic.

Consider determination of harmonic currents for the individual loads and groups of loads.

Nonlinear loads working under surgeless conditions

To such loads belong valve inverters of continuous rolling mill drives working with practically invariable rectified current, converters of electrolysis baths, chloral stations of pulp and paper plants, gaseous-discharge lamps etc. Equivalent current harmonics values of section (bus system) of valve inverter equal

$$\underline{I}_{n\Sigma} = \sum_{p=1}^m \underline{I}_{np}$$

where \underline{I}_{np} is complex of n th current harmonic of p th source taking into account its rms value I_{np} and initial phase φ_{np} ; m is loads number.

If the valve inverter overlap angles are neglected, have:

$$I_{n\Sigma} = \frac{S_{\Sigma} k_{n\Sigma}}{\sqrt{3} U_r n}$$

where S_{Σ} is valve inverters design rated power; $k_{n\Sigma}$ is a factor which takes into account availability of phase displacement between current harmonics of discrete converters; in complex form it is

$$\underline{k}_{n\Sigma} = \sum_{p=1}^m \underline{k}_{np}$$

where $\underline{k}_{np} = \frac{S_p}{S_{\Sigma}} e^{j\varphi_{np}}$, S_p is p th nonlinear load apparent power.

For approximate calculations of networks containing valve invertors it may be accepted that $k_{n\Sigma} = 0.9$ at $n = 5$ and 7 , and $k_{n\Sigma} = 0.75$ at $n = 11$ and 13 ; for arc-discharge lamps and also for fluorescent lamps $k_{n\Sigma} = 1$ at any value of n .

Sharply variable nonlinear load

Calculations of current harmonics, caused by reversible inverters of roll mills, electric arc furnaces while melting process, electric arc welding plants and other similar by time behavior loads, are based on the probabilistic concept.

In the case of such loads simultaneous operation ($m \geq 4$), the values of $I_{n\Sigma}$ are normally distributed (see Chapter 7). At this, the mean-squared departure value $\sigma(I_{n\Sigma})$ may be found by three-sigma rule as 1/3 of the mathematical expectation. In return, it equals 0.5 of the maximally possible value. So, we have:

$$M[I_{n\Sigma}] = \frac{\sum_{p=1}^m k_{lp} S_p}{2\sqrt{3}U_r n}$$

Where S_p and k_{lp} are apparent power of p th nonlinear load and the factor taking into account loading by apparent power. With probability of 95 %, it may be found:

$$I_{n\Sigma}^{(95\%)} = 0.83 M[I_{n\Sigma}].$$

At calculation of valve inverters load for rolling mills and similar installations operating on specified cycles, the mean-squared values of apparent power and currents, corresponding with the current harmonics mean-squared values are determined:

$$S_{m-sq\Sigma} = \sqrt{\sum_{p=1}^m S_{m-sq p}^2}; \quad I_{m-sq n} = \frac{S_{m-sq\Sigma}}{\sqrt{3}U_r n}.$$

When 6-pulse and 12- pulse valve inverters are the nonlinear loads, which the mean-squared values of apparent power are equal to $S_{m-sq\Sigma}^{(6pls)}$ and $S_{m-sq\Sigma}^{(12pls)}$ respectively, equivalent current harmonics are determined by the expression:

$$I_{m-sq n\Sigma} = \frac{S_{m-sq}^{(6pls)}}{\sqrt{3}U_r n} \quad \text{for } n = 5, 7, 11, 13, \dots;$$

When both types 6- pulse and 12- pulse inverters are available:

$$I_{m-sq n\Sigma} = \frac{\sqrt{[S_{m-sq}^{(6pls)}]^2 + [S_{m-sq}^{(12pls)}]^2}}{\sqrt{3}U_r n}.$$

It is obvious that

$$I_{m-sq n\Sigma} = \sqrt{M^2[I_{n\Sigma}] + \sigma^2[I_{n\Sigma}]}.$$

In shops of machine-building, metallurgical and other enterprises, welding plants and small power electric drives (exciters and other relatively small loads) have total installed power which is equal to or even exceeds the installed power of large nonlinear loads. For this case, it is acceptable to determine mean-squared value of nonlinear loads apparent power on calculated active power P_{calc} and weight average value of the power factor $\cos \varphi_{wa}$

$$S_{m-sq\Sigma} = \frac{P_{calc}}{\cos \varphi_{wa}}$$

For a group of welders (spot, press, butt and butt-seam welding machines) current of n th harmonic of so called the averaged welding machine $I_{av n}^{(ph)}$ is determined as:

$$I_{av n}^{(ph)} = \frac{K_{I(n)} \sum_{i=1}^{m_{ph}} S_{ri} k_{li}}{n^2 m_{ph} U_r}$$

where m_{ph} is the number of machines connected to the considered phase.

The mathematical expectation of total current I_{nA} in phase A caused by operation of all machines:

$$M[I_{nA}] = I_{tot n}^{(ph)} m_{ph} t_{ph av}$$

where $t_{ph av}$ is average cyclic duration defined by the expression:

$$t_{ph av} = \frac{\sum_{i=1}^{m_{ph}} t_{ph i}}{m_{ph}}$$

The n th current harmonic calculated value for phase A (B , C) is determined as

$$I_{np}^{(A)} = M[I_{nA}] + \beta \sigma(I_{nA}).$$

Based on of 5% level of the results significance the statistic factor β is assumed to be equal 1.73.

Under the single phase-to-ground fault in resonant earthed system, current of n th harmonic in the point of metallic short circuit to ground is equal to triple value of zero sequence current:

$$I_{sc n} = \frac{3I_{\Sigma n} x_{\Sigma n}}{2x_{\Sigma n} + 3(x_{rr n} - x_{c0n})}$$

where $I_{\Sigma n}$ is equivalent current of n th harmonic, $x_{\Sigma n} = x_{1\Sigma n} = x_{2\Sigma n}$ is equivalent reactance assumed equal to network reactance for positive and negative sequences; x_{rrn} is

reactance of the faulted phase reactor; x_{c0n} is capacitive reactance for zero sequence:

$$x_{c0n} = \frac{3U_{ph}}{I_c n}$$

where U_{ph} and I_c are phase voltage and capacitive current of the network at fundamental frequency.

Under stable connection through the transient contact resistance r , the current of n th harmonic in place of short-circuit is

$$I_{sc n}^{(r)} = I_{sc 0} \beta_r$$

where $\beta_r = \frac{1}{\sqrt{1+k_r^2 k_n^2}}$, $k_r = \frac{r}{x_{c0}}$, $k_n = n - \frac{1}{n}$.

In practice of calculations it is accepted that frequency response of the network elements resistance $R(n)$ is selected taking into account strong skin-effect influence: $R(n) = R \sqrt{n}$. With it, as experience shows, voltages and currents of the harmonics can be rather accurately determined for 6-10kV networks and not always sufficiently for networks with voltage below 1kV.

However, estimation of the parameters in resonant conditions, the losses as well as other quantities characterizing the harmonics influence on electric equipment needs rather accurate values of the resistances. They should be determined taking into account not only skin effect but also proximity effect, effect of eddy currents, parameters distribution and other circumstances.

Equivalent value of the resistance in the network node point may be found on equivalent circuit including only resistances without taking reactance into account. Calculation error for frequencies up to 650 Hz is not more than 7 %.

If extended overhead lines and/or cable lines are available in the system, two problems arise: for what line length distribution of its parameters should be taken into account, and how many Π - or T- shaped links must be accepted.

To calculate non-sinusoidal conditions, approximate approach can be used that permits to obtain rather accurate results for frequencies up to 2,5kHz. For simulation electromagnetic processes in the line which possesses distributed with the help of circuit consisting of N links, of its impedance Z_c to the line characteristic impedance Z_{ch} must be provided.

If the impedances are not equal, the error Δ appears:

$$\frac{Z_c}{Z_{ch}} = 1 - \Delta. \quad (6.4)$$

For a link of Π -shaped equivalent circuit it is

$$Z_c = 2 \sqrt{\frac{Z}{Y} \frac{1}{4 + ZY}} \quad (6.5)$$

where Z and Y are series impedance and shunt admittance of the link.

After transformation:

$$\frac{Z_c}{Z_{ch}} = \frac{1}{\sqrt{1 + \left(\frac{\gamma l}{2N}\right)^2}} \quad (6.6)$$

Here $\gamma = \alpha + j\beta$ is the propagation coefficient; α and β are the attenuation and phase-change coefficients; l is the line length.

Substituting (6.4), solve equation (6.6) in respect to N . The result is:

$$N \cong \frac{\gamma l}{2.82\sqrt{\Delta}} \quad (6.7)$$

As $\alpha \ll \beta$ and difference between them increases at growth of n , it may be accepted that $\gamma \cong \beta_n$. Taking into account that $\beta_n = \frac{2\pi n}{6000} = \frac{n}{955}$, it is obtained finally:

$$N = \frac{nl}{270\sqrt{\Delta\%}} \quad (6.8)$$

The obtained approximate expression makes possible to come to important practical conclusions. So, if $\Delta = 1\%$, one-link circuit may represent lines of the following length:

| | | | | | |
|---------------|----|----|----|----|----|
| n | 5 | 7 | 11 | 13 | 25 |
| l , km..... | 54 | 39 | 25 | 21 | 11 |

For longer lines greater number of links should be accepted. Thus, to simulate processes in 100-km line at frequency of the 25th harmonic, it is necessary to connect 9-10 Π - or T-shaped links in series.

When the number of links increases the model becomes complicated taking into account that N is selected based on the highest value of n . That is why use of physical models for investigation of non-sinusoidal conditions in electric networks is restricted.

The obtained results bring to conclusion concerning critical length of the line at which taking the parameters distribution into account is necessary:

$$l_{cr} = \frac{270\sqrt{\Delta\%}}{n}$$

Specifying $\Delta = 1\%$, we find that $l_{cr} = 270/n$

Sometimes the expression corresponding with 2% error is used:

$$l_{cr} = 360/n.$$

Calculation of interharmonics produced by direct-type frequency converter

Frequency contents of the direct-type frequency converter input current is determined with the help of output frequency f_2 , type of simulating function and the depth of modulation. It also depends on the load power factor.

Under linear control law, relative frequencies of harmonics of three-single-phase 6-pulse bridge direct frequency converter input current are determined by means of the expressions:

$$n_1 = |6l + 1 \pm 6l\chi| \quad (6.9)$$

$$n_2 = |6l + 1 \pm (6l + 2)\chi| \quad (6.10)$$

where $-\infty < l < \infty$; $\chi = f_2/f_1$ is relative value of the output frequency of the converter.

The interharmonic amplitudes in the range of output frequency from 0 to $0,3\chi$ may be determined by the approximate equation with an error not more than 10 %:

$$I_{*n}(l) = \frac{1}{|6l \pm 1|}. \quad (6.11)$$

Under sine control law, relative frequencies of input current harmonics of 6-pulse three-single phase bridge direct frequency converter are determined by means of the expression

$$n = |6l + 1 \pm m\chi|$$

where $-\infty < l < \infty$; $m = 0, 1, 2, \dots$

For the case of direct-type frequency converter with three-phase output, have

$$n = |6s + k \pm 3m\chi|$$

where $-\infty < s < \infty$; $k = 1, 3, 5, \dots$

Thus, amplitude spectrum of three-phase and single-phase input current of 6-pulse direct-type bridge frequency converter under sine control law are represented with both left and right adjacent frequencies of the fundamental and higher harmonics typical for 6-pulse rectifiers and being away from them at a quantity multiple of the

relative output frequency χ . In the case of direct-type frequency converter with three-phase output, all odd harmonics are available in the input spectrum, and both left and right side components lag by the angles multiple of 3χ .

At sine control law of the direct-type frequency converter, unlike the linear law, analytic expressions for calculation of interharmonics of the input current are difficult to obtain due to the complicated structure of its frequency content. This is manifested in much greater number of harmonic and their superposition. In this connection, calculation of the input current interharmonics of three phase-single phase and three phase-three phase direct-type 6-pulse bridge frequency converters under sine control law may be performed on the basis of numerical calculation technique.

In the general case calculation of direct-type frequency converter interharmonics is rather cumbersome and is practically impossible without use of computing facilities.

Example

Calculate relative values of interharmonics of the three phase-single phase 6-pulse direct-type bridge frequency converter input current with linear control law supplying the induction motor.

Table 6.5

Results of interharmonic amplitudes calculations

| l | Interharmonics relative frequencies | | Interharmonics relative amplitudes |
|-----|-------------------------------------|-------|------------------------------------|
| | n_1 | n_2 | |
| -4 | 27.8 | 27.4 | 0.043 |
| -3 | 20.6 | 20.2 | 0.059 |
| -2 | 13.4 | 13.0 | 0.091 |
| -1 | 6.2 | 5.8 | 0.2 |
| 0 | 1.0 | 1.4 | 1 |
| 1 | 8.2 | 8.6 | 0.143 |
| 2 | 15.4 | 15.8 | 0.077 |
| 3 | 22.6 | 23.0 | 0.053 |
| 4 | 29.8 | 30.2 | 0.04 |

Initial data: output frequency of the converter $f_2 = 10$ Hz, the network frequency $f_1 = 50$ Hz.

Solution

Calculations of relative frequencies are performed by the expressions:

$$n_1 = \left\lfloor 6l + 1 + 6l \frac{f_2}{f_1} \right\rfloor, \quad n_2 = \left\lfloor 6l + 1 + (6l + 2) \frac{f_2}{f_1} \right\rfloor$$

Relative amplitudes of interharmonics are calculated according to (6.11). Calculation results are given in Table 6.5. Fig. 6.6 shows spectrum of the interharmonics

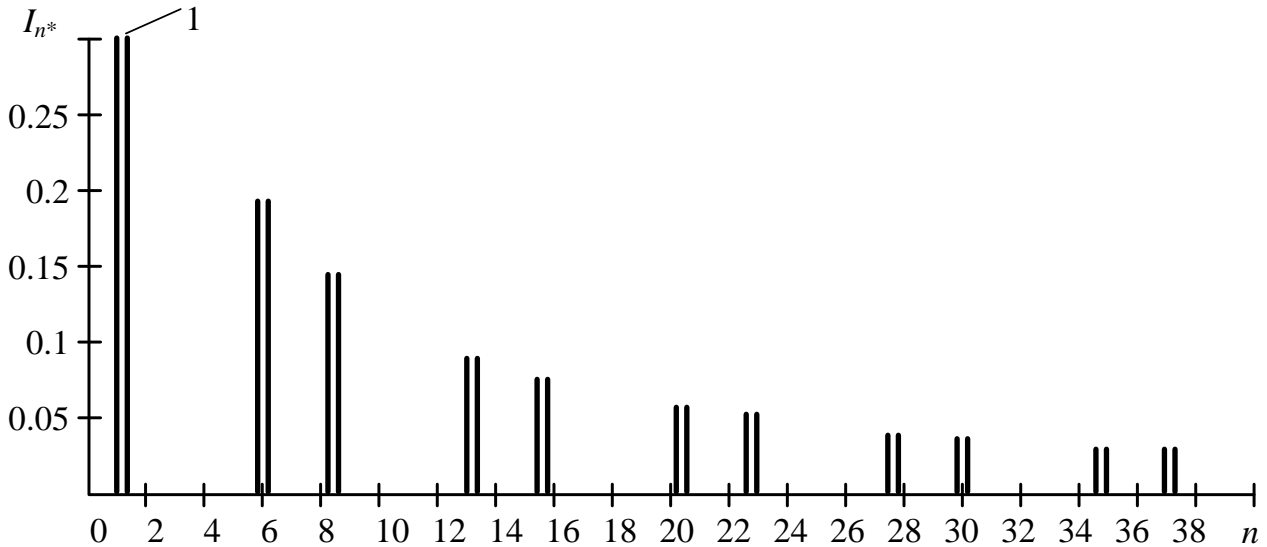


Figure 6.6 Spectrum of interharmonics

6.5. Calculations of voltage fluctuations

To determine values of flicker dose, two approaches may be used:

- Use of flicker-meter for direct determination of the fluctuation intensity
- Use of calculation methods.

The second approach may be used not only in designing but also under conditions of a power supply system operation.

In the case of voltage periodic fluctuation having sine and triangular shape in some frequency ranges it is possible to use the curve of permissible values of the voltage fluctuation amplitude, depending on frequency and factors F_e providing reference the fluctuations shape to equivalent rectangular waveform for which permissible-value curve has been build. For example, for approximate determination of rectangular voltage fluctuation equivalent to fluctuation of sine shape the factor 1.27 is used.

The method of flicker dose determination with the help of permissible-value curve and Fourier analysis is also used to study other periodic fluctuations. Intensity of flicker may be rather simply determined for some specific type of isolated or repeating voltage fluctuations.

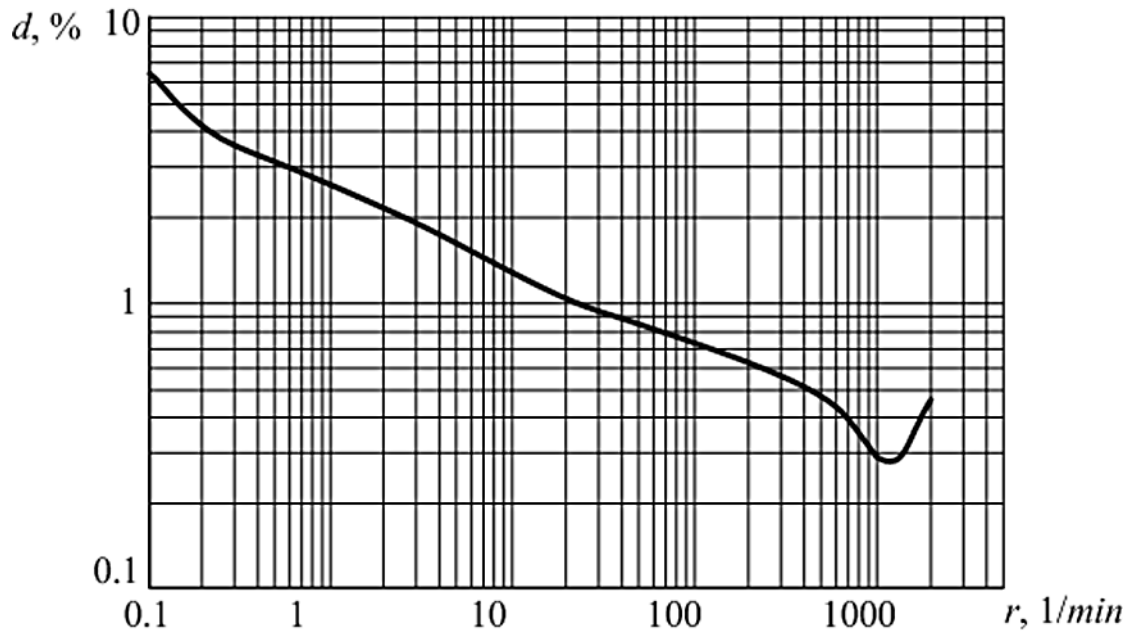


Figure 6.7 Curve of admissible voltage fluctuations

General approach to calculations of the voltage fluctuation is determination of short-time flicker dose P_{St} , caused by the voltage fluctuations of different shape. The resulting flicker dose for time T is determined and calculated as a result of fluctuations having stepped shape P_{Sts} with the help of the factor F_e called the equivalence factor:

$$P_{St} = F_e P_{Sts}.$$

In practice, one of the two methods described below is used.

1. Method of flicker dose determination on permissible-value curve

According to this method, the flicker intensity is determined with the help of curve (Fig. 6.7). If repeated stepped variations d_0 occur with frequency r_0 , the flicker dose P_{St0} will be the value which corresponds to ordinate of curve of flicker intensity. If under the same repetition rate of the stepped voltage variation is equal to d_1 , the flicker dose relevant value P_{St1} will be determined as

$$P_{St1} = \frac{d_1}{d_0} P_{St0}.$$

2. Analytical method is applied if repeating disturbances are available. In such cases the following relation is used:

$$P_{St} = 0.365 d F_e r^{0.31} R$$

where d is relative value of the voltage variation in %; r is voltage variation frequency in 1/min; R is a factor depending on the repetition rate (Fig. 6.8).

For example, if using equipment produces $\Delta U = 1\%$ ($d = 1$), the stepped voltage variation with $r = 3$ 1/min is determined with the help of flicker dose curve determine. The stepped voltage variation in this case equals $d_0 = 1.95\%$. Under disturbance $d = 1\%$. The flicker dose value is

$$P_{St1} = \frac{1}{1.95} \cdot 1 = 0.51.$$

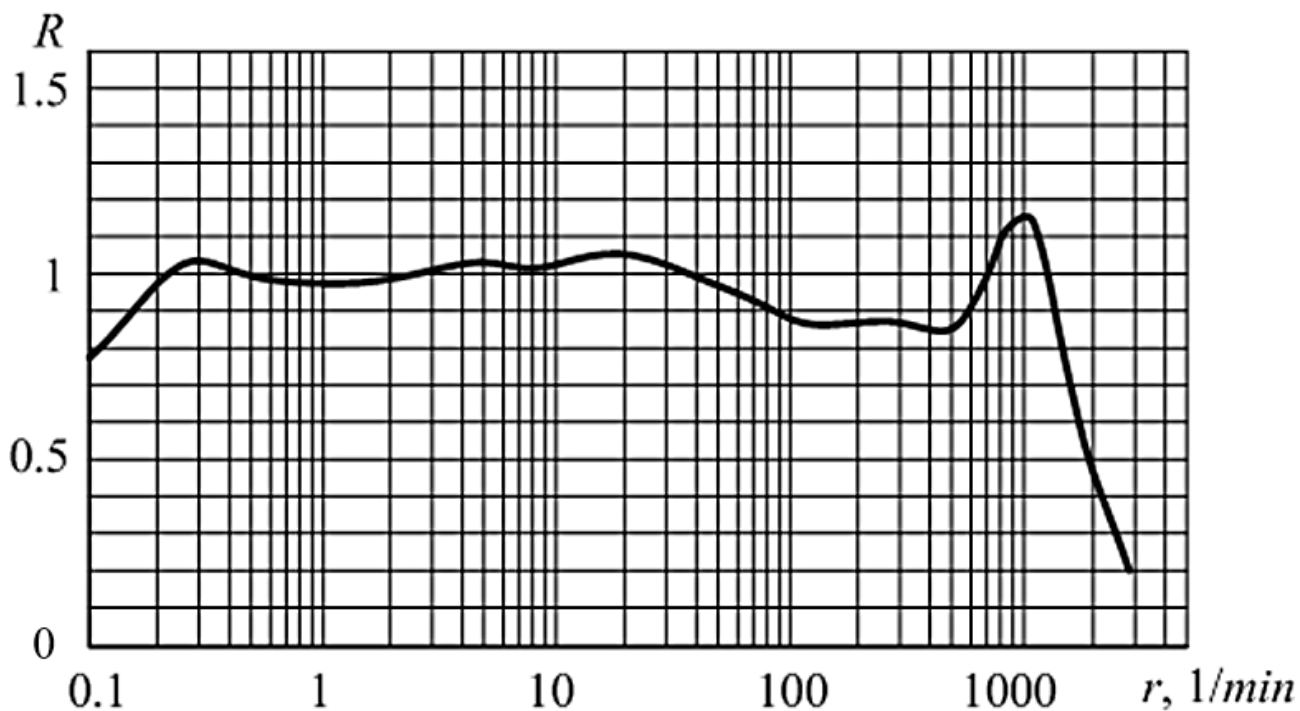


Figure 6.8 Dependence of factor R on voltage repetition rate

In analytical method the equalities $F_e = 1$ and $R \approx 1$ take place. Therefore,

$$P_{St1} = 0.365 \cdot 1 \cdot 1 \cdot 3^{0.31} = 0.51.$$

Annex to the standard ГOCT 13104-97 includes curves for determination of value F_e for different types of voltage fluctuations shape.

Calculations of voltage fluctuations in systems of electric power supply of rolling mills may be performed by a simplified method according to the following procedure:

1. The range of rectangular shape voltage fluctuations are calculated as

$$d_i = \delta U_i.$$

2. The equivalent frequency of fluctuation is determined using the interval duration T (min):

$$r = \frac{1}{T}, \text{ min}^{-1}.$$

3. Based on Fig. 6.9, permissible range of voltage fluctuations is determined by value of r :

$$d_0 = f(r).$$

4. Dose of short-term flicker is expressed as

$$P_{St} = \frac{\sqrt[3]{\sum_{i=1}^n d_i^3}}{d_0} = \frac{\sqrt[3]{\sum_{i=1}^n \delta U_i^3}}{d_0}.$$

Calculation error of calculation is not more than 1.5 %.

Under operating conditions permissibility of the voltage fluctuations may be determined with the help of the formula

$$\sum_{i=1}^n \Delta t_{gi} \leq T$$

where n is number of the excursions per time interval $T = 10$ min time; Δt_{gi} is minimal acceptable period between excursions with magnitude δU_i determined by the scale in Fig. 2.2.

In networks of industrial enterprises voltage fluctuations having either rectangular (Fig. 6.9) or sloping (Fig. 6.10) shape taking place at cyclic loads, electric motors, rolling mills etc. may be calculated on the following method.

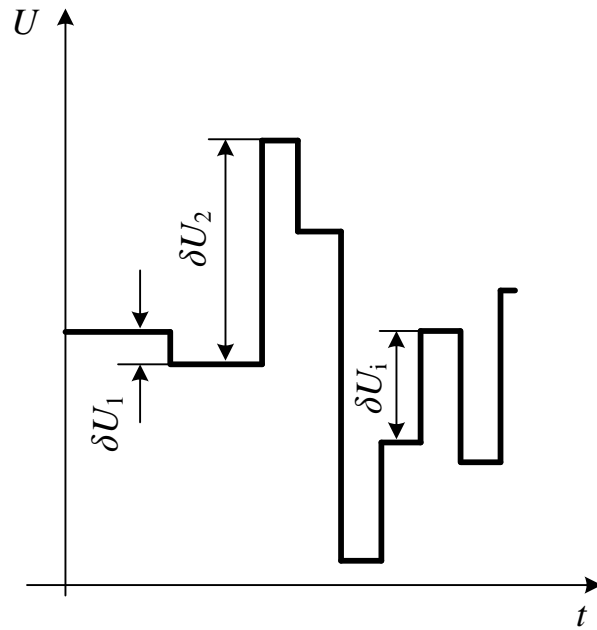


Figure 6.9 Rectangular shape fluctuations

In the case of rectangular shape fluctuations, time of flicker perception t_{fi} for i th fluctuation may be found by the expression:

$$t_{fi} = 2.3(\delta U_i)^{3.2}.$$

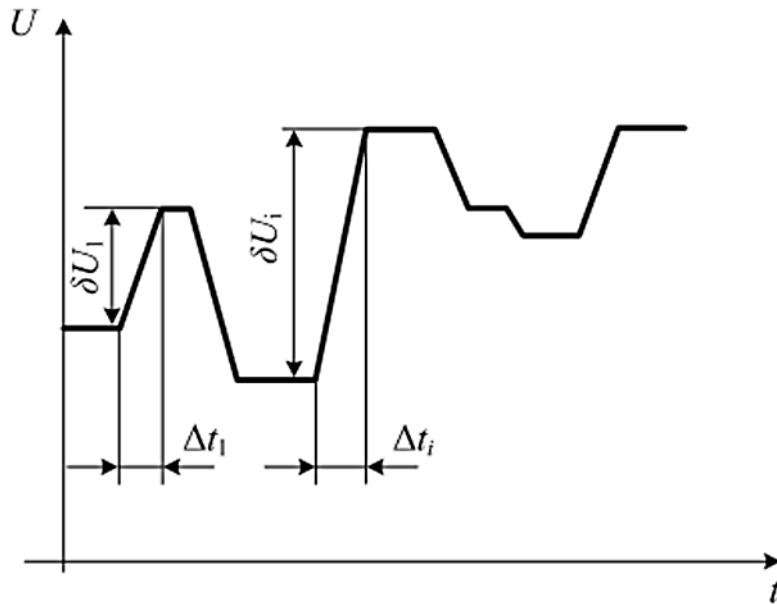


Figure 6.10 Sloping fluctuations

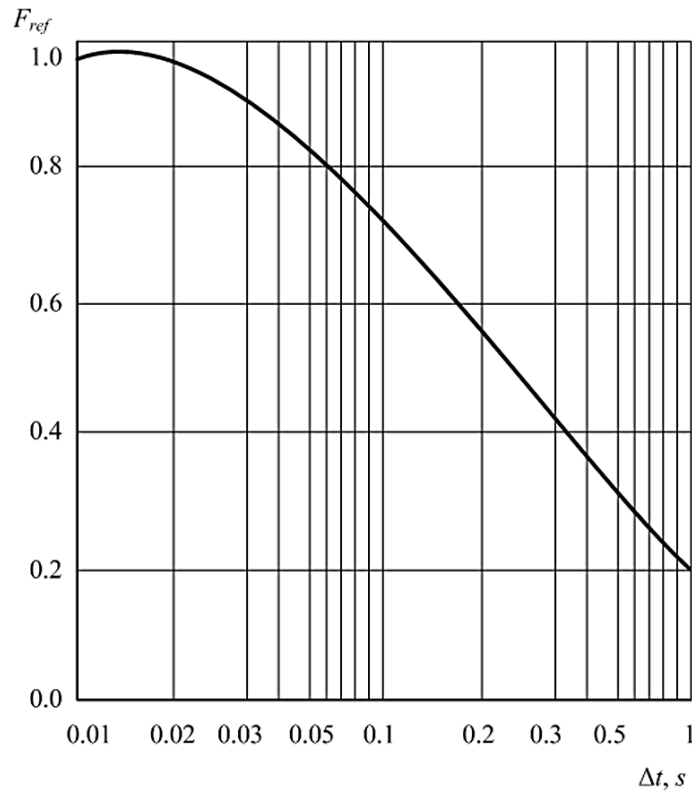


Figure 6.11 Reference factor F_{ref} for fluctuations of sloping shape

Knowing the time of the perception of flicker at every short interval T_{sk} equal 10 min, we find that short-term dose of flicker:

$$P_{St k} = \left(\frac{1}{T_{sk}} \sum_{i=1}^m t_{fi} \right)^{\frac{1}{3.2}}.$$

Long-term dose of flicker P_{Lt} is determined by means of the root-mean-cube value of the short-term flicker doses within interval T_L which duration is two hours:

$$P_{Lt i} = \sqrt[3]{\frac{1}{12} \sum_{k=1}^{12} P_{St k}^3}.$$

In the case of sloping shape fluctuations it is necessary to determine the referred range of the voltage fluctuations using the expression:

$$\delta U_{ref i} = F_{ref i} \delta U_{t i}$$

where $F_{ref i}$ is reference factor given in Fig. 6.11.

Dependence of reference factor F_{ref} on the sloping fluctuation curve segment duration may be approximated with the help of the expression:

$$F_{ref} = \frac{1}{6.646 - 5.725e^{-\Delta t}}$$

In general case, when both rectangular and sloping types of fluctuation are present, the engineering method of voltage fluctuation indicators may be used. This method may be used for determination of short-term and long-term flicker dose as for as periodical as non-periodical voltage fluctuations. The calculations are performed in the following order:

1. Within time interval of measurement (not less than 24 hours), long-term observation intervals of $T_L=2$ hours corresponding to periods of greatest voltage fluctuations in their range and number of changes are assigned.

2. The long-term observation intervals T_L are divided into 12 short-term intervals of $T_{st}=10$ min each.

3. The range of fluctuations δU_i and their duration t_i are determined within each short-term interval T_{st} .

4. All ranges of fluctuation are referred to the oscillations of meander shape according to the expression

$$\delta U_{ref i} = F_{ref i} \delta U_i$$

where the reference factor $F_{ref i}$ corresponds to a curve given in Fig. 6.10.

5. Time of flicker perception is determined for each the voltage fluctuation:

$$t_{f i} = 2.3(\delta U_{ref i})^{3.2} = \left(\frac{\delta U_i}{6.646 - 5.725e^{-\Delta t_i}} \right)^{3.2}$$

6. Short-term dose of flicker is determined for each the short-term period $T_{st k}$:

$$P_{st k} = \sqrt[3.2]{\frac{2.3}{T_{st k}} \sum_{i=1}^m \left(\frac{\delta U_i}{6.646 - 5.725e^{-\Delta t_i}} \right)^{3.2}}$$

where m is the number of fluctuations within interval $T_{st k}$.

7. The long-term dose of flicker is calculated within each long-term interval T_{Lt} :

$$P_{Lt} = \sqrt[3]{\frac{1}{12} \sum_{k=1}^{12} P_{st k}^3}$$

where $P_{st k}$ is short-term dose of flicker within k th interval $T_{st k}$ inside the long-term interval T_L .

8. Both short-term P_{St} and long-term P_{Lt} doses of flicker are compared with corresponding standardized values.

As components of the electric power supply systems are mainly of inductive character, the flicker dose may be rather easily estimated for the network nodes connected by means of transformers, overhead lines or cables containing a source of voltage fluctuations. Under such an assumption shape of the voltage fluctuations in different nodes corresponds to the shape of the source voltage fluctuation. This is manifested in reduction of the voltage fluctuations amplitude in the network nodes directly proportionally to the voltage transmission factor $k_u^{(n)}$ or to the factor of voltage distribution between the node of fluctuations source and the m th network node.

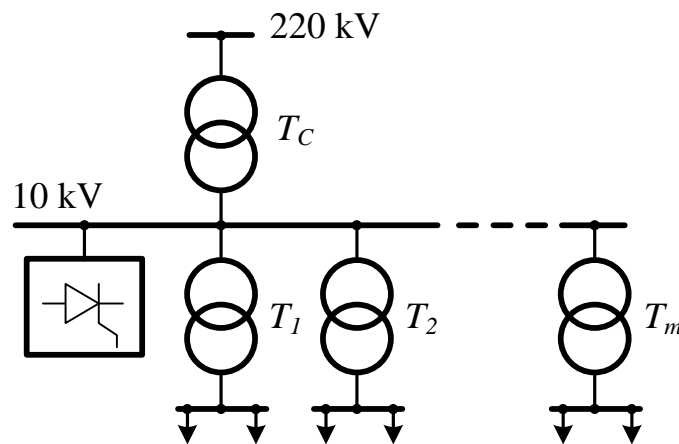


Figure 6.12 Simplified electric power circuit of mill

In this case, dose of flicker in the network nodes is determined by the expression:

$$P_{St}^{(m)} = P_{St}^{(m)} k_u^{(m)}$$

where $P_{St}^{(m)}$ is intensity of flicker in node of the voltage fluctuations source.

Factor $k_u^{(m)}$ is in fact the flicker dose distribution factor $k_{fd}^{(m)}$.

Fig. 6.12 shows a simplified electric circuit of a rolling mill supply system. The mill valve inverter being an sharply varying load is the source of the voltage fluctuations. The used symbols are: T_s is the transformer connecting the supply system with the power system; $T_1 \dots T_m$ are transformers supplying energy to other consumers of the substation.

The flicker dose distribution factor k_{fd} on the side of 220 kV of this circuit is determined according to the expression:

$$k_{fd} = \frac{x_{sc}}{x_{sc} + x_{T_s}}$$

where x_{sc} is the supplying system short-circuit reactance.

Availability of separate capacitor banks or harmonic filters can reduce accuracy of k_{fd} estimation. In such a case, the value of k_{fd} should be decreased by 5-10 %.

Example

Determine admissibility of fluctuations in electric network of 10kV of a slab mill. Graph of reactive load $Q(t)$ behavior is given in Fig. 6.13. The short circuit power is 300 MVA.

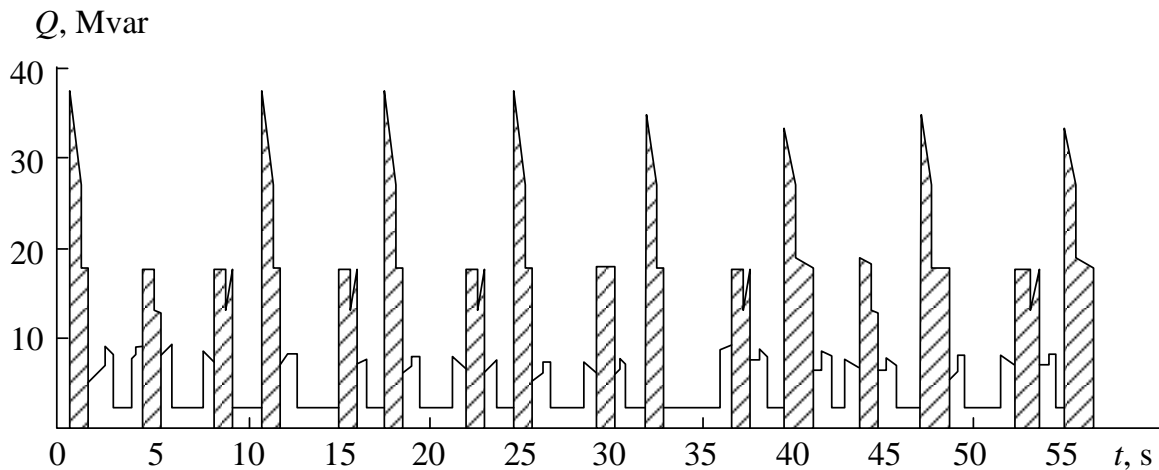


Figure 6.13 Graph of load reactive power

Solution

Here we apply a method used for rectangular voltage fluctuations.

1. With the graph $Q(t)$ we define the range of voltage deviation at all the sections

$$\delta U_t = \frac{\delta Q}{S_k}, \%; \quad \delta U_{t \max} = 39 \%$$

2. Determine the sum $\sum_{i=1}^k \delta U_{ti}^3$ taking into account only vertical portions of the reactive power graph; the total number of the portions equals k .

In our case $\sum_{i=1}^k \delta U_{ti}^3 = 21760$.

3. Equivalent frequency of fluctuations is $r = \frac{1}{T} = \frac{1}{1} = 1$ 1/min.

In compliance with the curve in Fig. 6.7 the admissible range of fluctuations is $d_0 = 3$.

The short-term flicker dose is defined as

$$P_{St} = \frac{\sqrt[3]{21760}}{3} = 9.3 > 1.$$

So the value of the fluctuations range is significantly higher than standardized value.

Estimation of electromagnetic compatibility of arc steel furnaces in electric power supply systems of industrial enterprises

Fluctuations as a result of electric arc furnaces operation are the main type of electromagnetic disturbance in industrial electric networks. Current fluctuations are mostly intensive in the period of melting, their range with probability of 95 % does not exceed the current rated value I_r . Appearance of fluctuations with range up to $(2\div 4)I_r$ is possible. But probability of such fluctuations is in bounds of 5 % that corresponds with significance level that is generally accepted in the electrical engineering. Thus, maximum possible range of the current fluctuations is $0 \div I_r$. Distribution law of the fluctuations range is close to the normal law of distribution.

As the results of numerous investigations standard the dispersion of the current fluctuations of electric arc furnaces ДСП-100 and ДСП-200 is $D_I = 0,06 \dots 0,1$ (in per units) and mean-square deviation $\sigma_I = \sqrt{D_I}$ is within $0,25 \dots 0,35$.

As it is known, relation between dispersions of voltage D_U and current D_I is similar to expression for Ohm's law: $D_U = 3Z_{ps}^2 D_I$ and $\sigma_U = \sqrt{3}Z_{ps}\sigma_I$. Here Z_{ps} is impedance of the power system in the considered point.

For fluctuations estimation based upon extreme event when the range of current fluctuations is $\delta_I = I_r$ we find: $\delta I_t = \frac{S_{tr}}{\sqrt{3}U_r}$ where S_{tr} is rated load of the furnace transformer.

Expression for estimation of the voltage fluctuations has the appearance:

$$\delta U_t = \sqrt{3}\delta I_t Z_{ps}$$

or, after transformations :

$$\delta U_t = \frac{S_{tr}}{S_{sc}} 100 \%$$

Here S_{sc} is the short-circuit power in the point of connection.

The practice shows that if $\frac{S_{tr}}{S_{sc}} 100 \% < 1 \%$, flickering of lamps is not available.

In industry-specific regulatory documents of a number of power supply companies of Western Europe and the USA it is accepted to determine electric arc furnace connection permissibility with the relationship:

$$\frac{S_{tr}}{S_{sc}} 100\% < \vartheta_t \text{ at } \vartheta_t = 0.5 \dots 1.5 \%$$

Recent studies made possible to correlate values of $\frac{S_{tr}}{S_{sc}}$ with the flicker dose value: for a short-term flicker dose $P_{St} = 60 \frac{S_{tr}}{S_{sc}}$ and for a long-term dose $P_{Lt} = 40 \frac{S_{tr}}{S_{sc}}$. If several electric arc furnaces operate simultaneously under melting conditions, different factors which permit to estimate equivalent power of the transformers are introduced.

6.6. Calculations of voltage dips

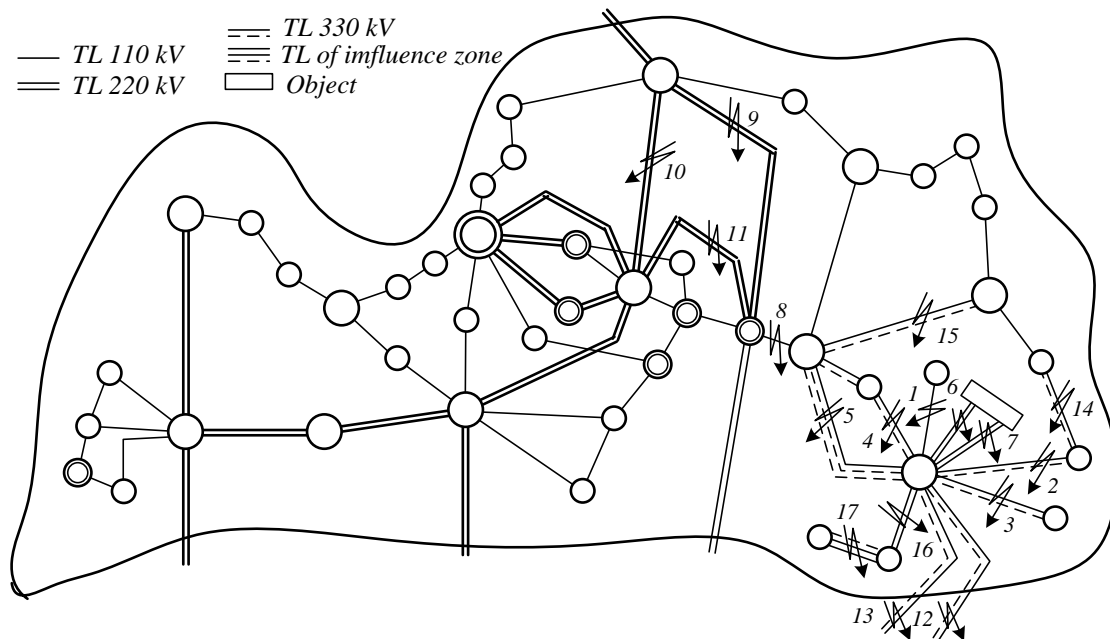


Figure 6.14 Zone of influence of disturbances, generated by power system

Most of industrial enterprises are supplied from power systems by means of overhead lines which voltage is 110kV and more. Up to 4 failures a year is typical for them. About 80 % of failures are voltage dips.

Table 6.6

Voltage dips on busses of main step-down substation arising at single-phase short circuit in the points of zone of disturbance influence

| Obtained by | δU_d % in the point number | | | | | | | | | | | | | | | | |
|-------------|------------------------------------|----|----|----|-----|-----|----|----|----|----|----|----|----|----|----|----|----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| calculation | 18 | 21 | 28 | 84 | 100 | 100 | 75 | 30 | 24 | 44 | 21 | 30 | 7 | 6 | 88 | 38 | 18 |
| measurement | 20 | 18 | 25 | 86 | 100 | 100 | 75 | 25 | 22 | 41 | 19 | 35 | 6 | 5 | 85 | 35 | 15 |

Not all electromagnetic disturbances arising in power networks have influence on

disturbance sensitive elements of electric consumers. On this reason zones of electromagnetic disturbance influence for the investigated sensitive elements are determined. Determination of an influence zone that is specific sections of the power networks, which failures result in fault of the studied electric equipment makes possible to forecast the equipment failures as well as losses caused by them. Fig. 6.14 shows zones of influence of electromagnetic disturbances, produced by the network, on sensitive to interference elements equipment for a chemical fiber factory. In Table 6.6 values of voltage dips are determined from calculations and measurements are presented. Disagreement of calculation and measurement results is comparatively small. Failures of electric consumers and the loss resulting from them at faults in power supply systems do not exceed 15 % and are not group failures. Increase in power and number of overhead lines enabling simple electromechanical consumers reliability increase causes decrease of complicated electronic systems reliability.

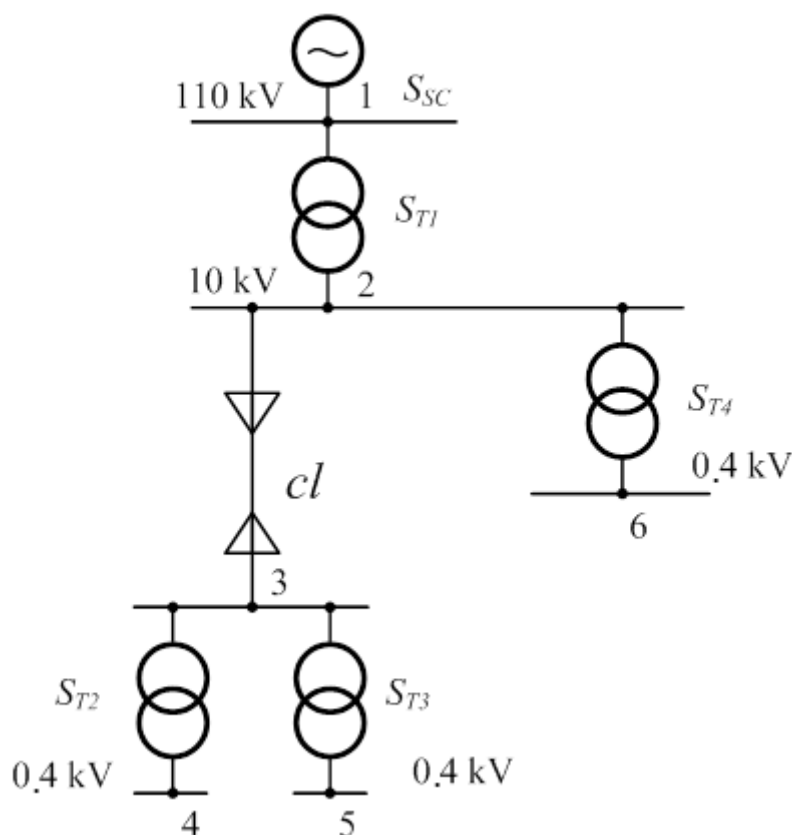


Figure 6.15 Original electric power supply system

Available extensive experience confirms that more than half of electric equipment stops are caused by rather short-term voltage dips. Response of major part of sensitive to disturbances electronic components is in the bands of 10^{-6} - 10^{-5} s that is practically immediate. Therefore, influence of voltage dips duration is negligible. The same applies to the parameters of a power system r , x , z variation which may be considered as constant during the dips as also for duration of other types of electromagnetic disturbances.

This fact makes possible to recommend method of resistive equivalent to calculate

voltage dip depth representing impedance of the network elements $z = \sqrt{r^2 + x^2}$ as resistance. Voltage dips in points (nodes) of a network having sensitive to disturbances electronic components are calculated using such a circuit. The dip is considered as a voltage source. Flicker doses for the nodes may be calculated in the same way. In all cases, the error does not exceed 10% in the direction of overestimation.

It is evidently, that there are cases when application of this method can bring incorrect results.

Failure of automated control system (failure of sensitive to disturbance element) depends on a number of factors: availability of non-sinusoidal current and voltage in electric power supply system, structure of the load, the valve inverter control depth, the node to which a sensitive to disturbance element is connected, the network phase, or the dip depth as well as shape of electromagnetic disturbance.

Example 1

Determine value of the voltage dip in nodes of the network shown in Fig. 6.15 if the voltage dip in point 4 equals $\delta U_d = 80\%$. Parameters of the circuit are: $S_{SC} = 2500 \text{ MV}\cdot\text{A}$, $S_{T1} = 16 \text{ MV}\cdot\text{A}$, $u_{SC1} = 10.5\%$, $S_{T2} = S_{T3} = S_{T4} = 1000 \text{ kV}\cdot\text{A}$, $u_{SC2} = u_{SC3} = u_{SC4} = 10.5\%$, $l_{cl} = 800 \text{ m}$, $X_0 = 0,08 \text{ Ohm/km}$.

In this case the impedance is practically equal to the reactance, that is $z \cong x$.

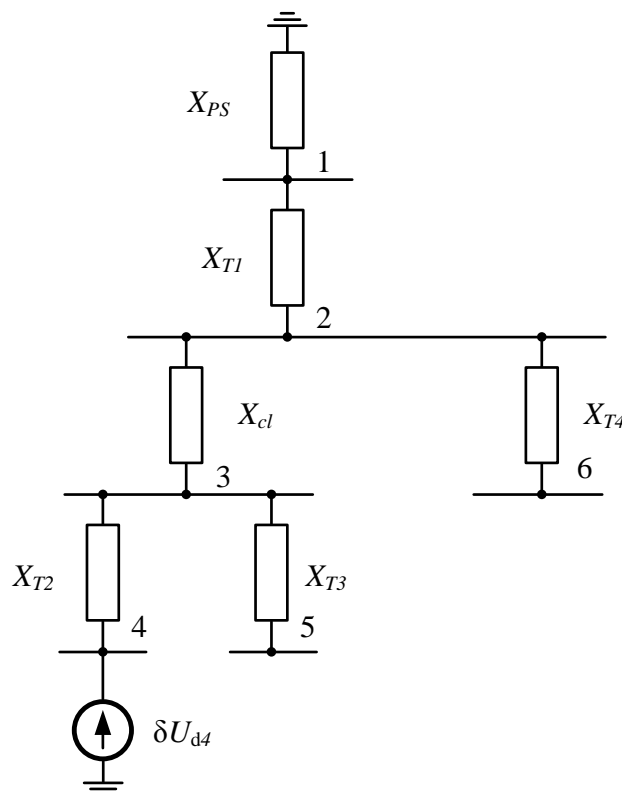


Figure 6.16 Equivalent circuit

Solution

Appearance of the voltage dip in point 4 is equivalent to adding of voltage equal to δU_{d4} . Therefore, to determine values of the voltage dips in all the nodes (Figure 6.15), apply voltage δU_{d4} to point 4 under condition that the value of the source voltage is equal to zero (Fig. 6.16).

The voltage dip in node 1 is

$$\delta U_{d1} = \frac{\delta U_{d4} x_{ps}}{x_{ps} + x_{T1} + x_{cl} + x_{T2}} = \frac{80 \% \cdot 0.064}{0.064 + 1.05 + 0.093 + 16.8} = 0.3 \%$$

Calculations are performed in relative units determined at $S_b = 160 \text{ MV}\cdot\text{A}$.

The power system reactance equals

$$x_{ps} = \frac{S_b}{S_{SC}} = \frac{160}{2500} = 0.064.$$

The transformers reactance:

$$X_{T1} = \frac{u_{sc1} S_b}{100 S_{T1}} = \frac{10.5 \cdot 160}{100 \cdot 16} = 1.05$$

$$X_{T2} = X_{T3} = X_{T4} = \frac{u_{sc2} S_b}{100 S_{T2}} = \frac{10.5 \cdot 160}{100 \cdot 1.0} = 16.8.$$

The cable line reactance is

$$x_{cl} = l_{cl} x_0 \frac{S_b}{U_r^2} = 0.8 \cdot 0.08 \cdot \frac{160}{10.5^2} = 0.093.$$

As the current in reactance x_{T3} and x_{T4} is equal to zero the following equalities for the voltage dips take place: $\delta U_{d3} = \delta U_{d5}$, $\delta U_{d2} = \delta U_{d6}$.

The depth of the voltage dip in nodes 3 and 5 is

$$\delta U_{d3} = \delta U_{d5} = \frac{\delta U_{d4} (x_{ps} + x_{T1} + x_{cl})}{x_{ps} + x_{T1} + x_{cl} + x_{T2}} = \frac{80 \% (0.064 + 1.05 + 0.093)}{0.064 + 1.05 + 0.093 + 16.8} = 5.4 \%$$

Depth of the voltage dip in nodes 2 and 6 is

$$\delta U_{d2} = \delta U_{d6} = \frac{\delta U_{d4} (x_{ps} + x_{T1})}{x_{ps} + x_{T1} + x_{cl} + x_{T2}} = \frac{80 \% (0.064 + 1.05)}{0.064 + 1.05 + 0.093 + 16.8} = 4.9 \%$$

If the source of oscillations is connected to a transformer with split winding or through coupled reactor, it is necessary to estimate fluctuation level in different network nodes (Fig. 6.17). The source of oscillations may be electric arc furnace or rolling mill. In such a case the source is represented or by the fluctuations δU_t or by the flicker dose. Valve inverters are represented as sources of harmonics.

To simplify calculations, specific tables were developed. In them, values of the transfer ratio between a source and a network node for which fluctuations level K_{s-n} in relative units is estimated. Thus

$$\delta U_{ti} = K_{s-n} \delta U_{tn}.$$

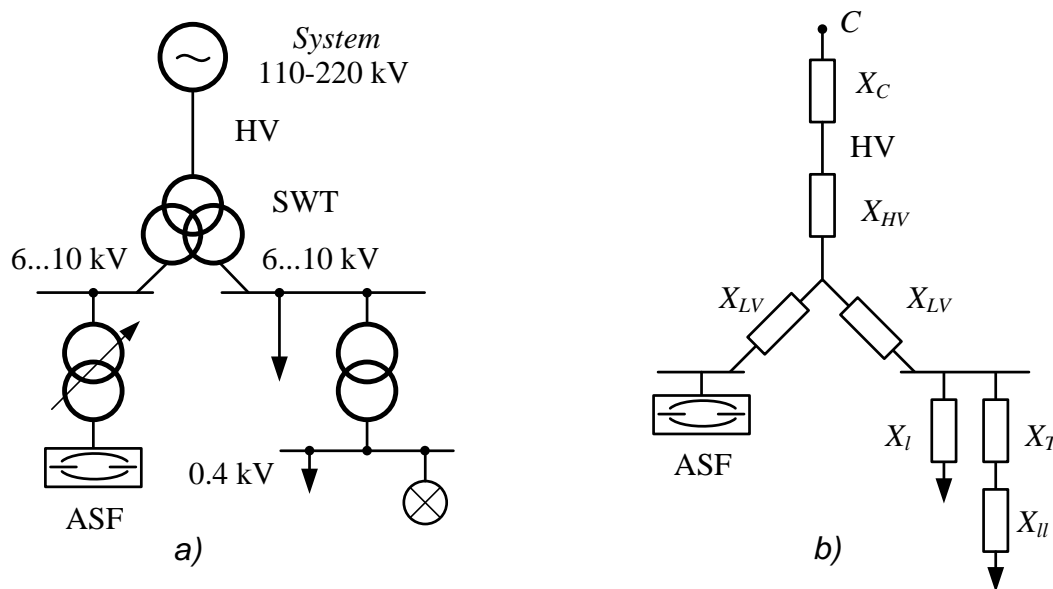


Figure 6.17 System of power supply of electric arc furnace: from transformer with split windings (a); equivalent circuit of power supply for calculations of voltage tions δU_t and distortion factor K_U (b)

The transfer ratio is $K_{s-n} = K_{s-mp} K_{mp-lb}$, where K_{s-mp} and K_{mp-lb} are transfer ratios between the source and the transformer midpoint, the midpoint and the load buses.

Table 6.7 gives the voltage fluctuations transfer, the voltage dips and distortion factors at use of transformers with split windings for arc furnaces supply under rated voltage of $U_r=110$ kV.

Table 6.7

| Calculated values of voltage fluctuations transfer ratio | | | |
|--|----------|----------------|-------------|
| S_T | S_{sc} | Transfer ratio | |
| MVA | MVA | K_{s-n} | K_{mp-lb} |

| | | | |
|----|------|-------|-------|
| 25 | 2000 | 0.122 | 0.488 |
| | 3000 | 0.104 | 0.386 |
| | 4000 | 0.095 | 0.323 |
| 32 | 2000 | 0.137 | 0.549 |
| | 3000 | 0.114 | 0.446 |
| | 4000 | 0.103 | 0.379 |
| 40 | 2000 | 0.153 | 0.604 |
| | 3000 | 0.125 | 0.502 |
| | 4000 | 0.112 | 0.433 |

Example 2

The voltage dip with depth $\delta U_d = 0.85$ appears in the circuit of transformer with split windings, having power $S_T = 25$ MVA and voltage 11/10 kV and loaded by power of $S_l = 4$ MVA, on buses 10 kV of electric arc furnace. Determine the voltage dip depth on 10 kV load buses if short-circuit power of the system is $S_{SC} = 2000$ MVA.

Solution

1. Select $K_{s-mp} = 0.122$ from Table 6.7 at $S_T = 25$ MVA and $S_{SC} = 2000$ MVA.

2. Value of K_{mp-lb} assume equal the unit as the transformer winding impedance is much less compare to load resistance.

Graduate students are recommended to make certain of that with by means of calculation.

3. Find value of the transfer ratio between source of the dip and load buses

$$K_{s-n} = K_{s-mp} K_{mp-lb} = 0.122 \cdot 1 = 0.122.$$

4. The sought-for dip depth on load buses is

$$\delta U_{d(lb)} = 0.85 \cdot 0.122 \cong 0.10 \text{ or } 10 \%$$

Test questions

1. How are electromagnetic disturbances represented in calculation equivalent circuits?

2. How are nonlinearities of power system elements taken into account at electromagnetic interference calculations?

3. Show graphs of frequency characteristics of power supply system elements used at calculations of electromagnetic interferences.
4. Give the equivalent circuit used for calculation of current harmonics at single-phase short circuit to ground.
5. What are the values of negative sequence impedance of valve inverters?
6. What elements of electric power supply system are represented as reactance at electromagnetic interferences calculation?
7. Specify known to you methods of the voltage fluctuations calculation and the scope of their application.
8. Is there difference in calculations of harmonics and interharmonics arising in industrial enterprises electric power supply systems?
9. How is electromagnetic compatibility of an electric arc furnace and an enterprise power supply system estimated?
10. What is the method of ohmic equivalent used at calculation of the voltage dips?

Topics for essay

1. Impact of power networks frequency characteristics on higher harmonics level?
2. Features of harmonics and interharmonics calculation.
3. Methods of voltage dip arising in the nodes of power networks calculation.
4. Frequency characteristics enterprises electric equipment.
5. Frequency characteristics of power networks nodes.

7.1. Reduction of voltage unbalance

The voltage unbalance as a result of using unbalanced power consumers can be reduced to $K_{2U} \leq 0.02$ values with the help of circuit designs or specific balancing sets.

If a relation of short circuit power in the network node S_{SC} and single-phase load S_{sph} is $S_{SC} \geq 50S_{sph}$, the voltage unbalance factors of negative sequence do not exceed the standardized by ДСТ13109-97 value. Power consumers causing unbalance are connected with the help of the network nodes which short-circuit power satisfies the above expression.

Balancing by means of balancing sets consists in compensation of equivalent negative-sequence current of the unbalanced load and the voltage caused by it. Individual, group, centralized and combined types of balancing are distinguished. Individual balancing sets are placed directly in unbalanced power consumers. In the case of group balancing several balancing units are placed in different network points. Each of the units provides balancing definite section of the network with connected to it group of unbalanced consumers. At centralized balancing one balancer unit is placed in the power distribution network. The combined method consists in combination of two or three balancing units.

Individual method of balancing provides unbalance removal directly at the consumer. But in this case the balancing devices elements installed power is used irrationally. Centralized method requires less total installed power of balancer elements but current unbalance remains in the network with unbalanced load. Group method of balancing combines advantages and disadvantages of both individual and centralized methods. Selection of a balancing method is mainly defined by the network parameters and the load conditions.

Balancing units are produced both as controlled and uncontrolled devices depending on the load diagram singularities. There is great number of balancing devices circuits having electrical or magnetic coupling between their elements. Consider some of known balancing units.

Available balancing units can be divided into two large groups - with electric and electromagnetic coupling. In the balancing devices with electric coupling the balancing elements and loads are connected either in delta or in three-rayed star. In construction the balancing devices are divided in types having single-element, two-element and three-element circuits.

Fig. 7.1 shows a circuit of single-element balancing unit with inductive L_{AB} or capacitive C_{AB} , depending on load conditions, balancing element and compensating capacity C_c . In the case of a balanced network having great power factor, such a unit has low efficiency and is of little use for balancing.

Of two-element balancing units, Steinmetz circuit shown in Fig. 7.2 is of most

use.

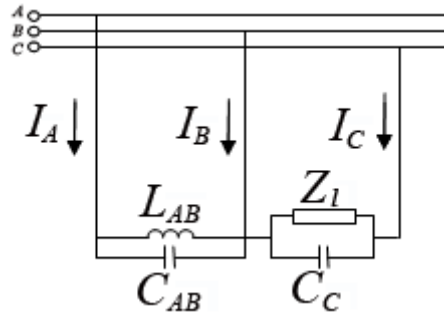


Figure 7.1 Single-element balancing circuit

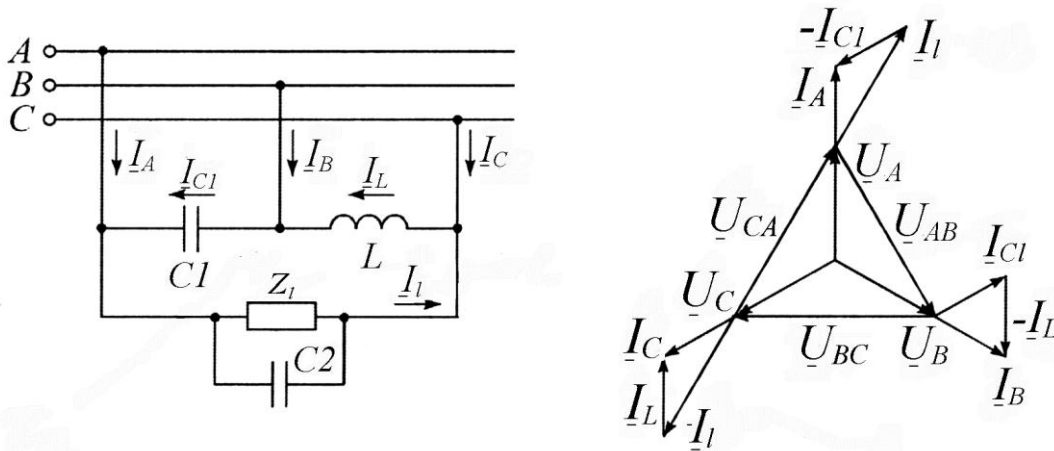


Figure 7.2 Steinmetz circuit and its vector diagram

A vector diagram explaining the principle of the device is shown in the same figure. Steinmetz balancing circuit is mostly efficient at the load power factor equal to one. Therefore at combined active and inductive load the capacitor bank C2 is connected in parallel to it.

Steinmetz balancing unit also provides balancing of combined active and inductive load without use of capacitor banks C2. But in this case, the power factor decreases significantly to values less than the load power factor.

Balancing at invariable parameters of balancing elements is provided for only one value of the load power. For substantiation of uncontrolled balancing units application at networks with changing load, statistical study of unbalance parameters should be executed. The controlled balancing devices may use as continuous (analogous), as stepped (discrete) control method. Capacitor banks of discrete balancing units consist of several groups, one of which is connected constantly and others - alternately. Commutation is performed with thyristor switches. Nowadays smooth control of capacitor elements by means of parallel connection of reactors controlled by thyristors is applied.

Three-element balancing units are the most universal and flexible ones. Low duty factor is among their disadvantages (Fig. 7.3)

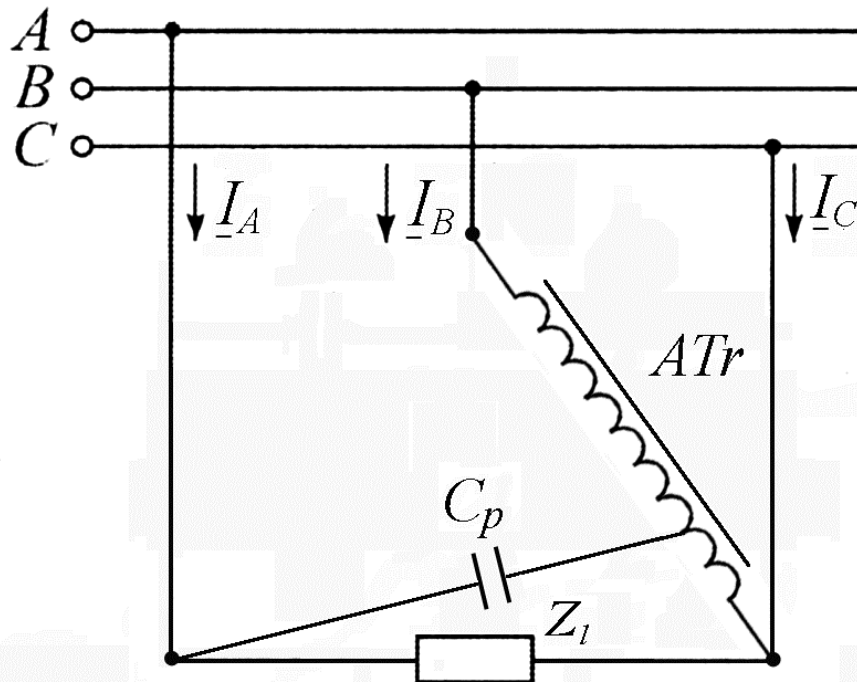


Figure 7.3 Three-element balancing unit

For balancing a system of line-to-line voltages under single-phase, two-phase and three-phase unbalanced loads capacitor banks with unequal phase powers, which are applied for network reactive power compensation, are widely used (Fig. 7.4).

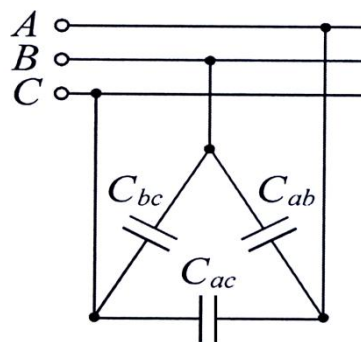


Figure 7.4 Balancing circuit with capacitor banks

Balancing units with electromagnetic coupling may be divided into two groups: with voltage dividers (autotransformers) and with transformers. As a rule, in the units with voltage dividers the balancing unit power is accepted equal to the load power. By means of autotransformer tap changing, it is possible to balance nonlinear load with having variable power factor. A circuit with one adjustable element C_p is presented in Fig. 7.5. Such a circuit has the power factor $\cos\varphi \leq 0,7$.

Balancing units of transformer type are various. As an example, Fig. 7.6 shows supplying circuit for balancing of two-phase load by means of Scott transformer, and vector diagrams of the currents and voltages. Ratios of the

transformer turns are chosen in such a way that their secondary voltages are equal to one another. The transformer type balancing units are individual and uncontrolled.

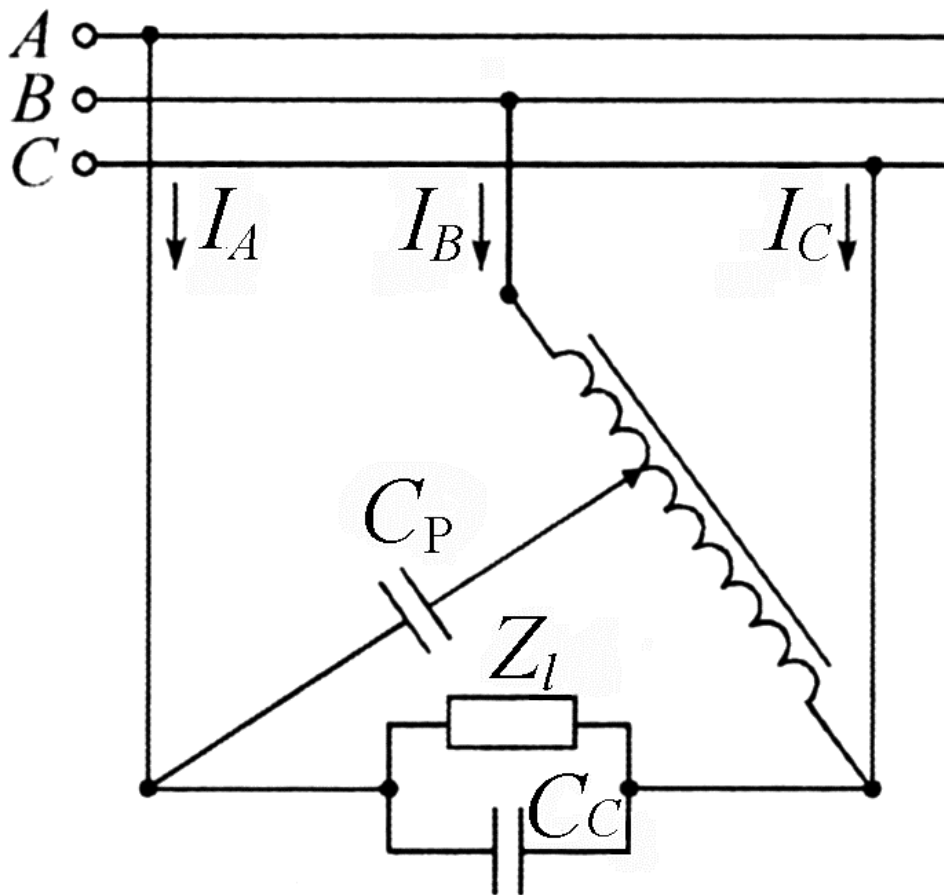


Figure 7.5 Autotransformer with adjustable element C_p

Balancing of voltage system can also be performed by means of the introduction of extra voltage sources. Such sources forming a negative-sequence system, are connected into line conductors break between the source and the consumer. As a result of the main and extra sources voltage summation their symmetrical components of negative sequence are compensated and consumer voltage becomes balanced. A synchronous generator, series adjusting transformers and transformer with individual phase ratio regulation can be used as a source of extra voltage system. Other balancing circuits that are rarely used in practice are also known.

Besides, nonsymmetrical filtering and compensating devices find application as balancing sets which are harmonic filters assembled on the basis of capacitor banks (Fig. 7.7).

Selecting of the line-to-line voltages to which circuits of filtering and compensating unit are connected, as well as relation of power of capacitor banks in the filter phases, are performed by condition of balancing. But for provision of the filtering and compensating device capacitor bank normal operation and effective decrease harmonics in the network definite specific requirements should be carried out.

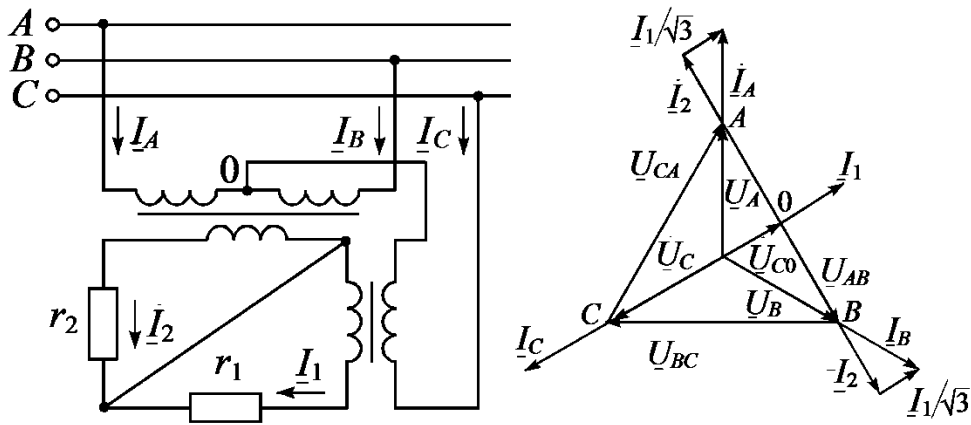


Figure 7.6 Circuit for balancing of two-phase load by means of Scott transformer and its vector diagram

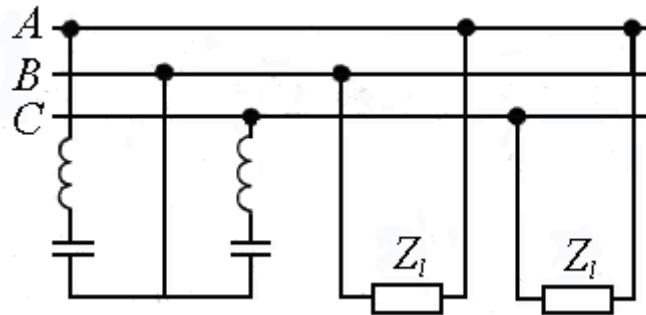


Figure 7.7 Nonsymmetrical filter

Functional polyvalence is an important property of capacitive balancing devices that are sources of reactive power.

In practice, complete balancing providing $K_{2U} = 0$ turns out to be technically and economically inadvisable. Partial balance is used at which value $K_{2U} \leq 0.02$ is provided by means of either non-direct compensation or balancing units application. Condition of partial balancing may be expressed as

$$K_{2U} = \frac{I_{2res} Z_2}{U_r} \leq K_{2adm} = 0.02$$

where I_{2res} is the residual current of negative sequence obtained a result of joint action of the unbalanced load and the balancing device.

The total power of the capacitive balancing device is determined by the condition of reactive power compensation. It is redistributed among the balancing device phases in such a way that the negative-sequence current of nonsymmetrical capacitor bank would compensate the negative-sequence current of the non-balanced load.

Determination of the capacitive balancing device capacitor bank parameters is carried out as follows. The capacitor bank power and the capacitors connection to the phase circuits are determined depending on the argument $\varphi_{2\Sigma}$ of the equivalent negative sequence current vector $I_{2\Sigma}$ in the I, II or III area (Fig. 7.8).

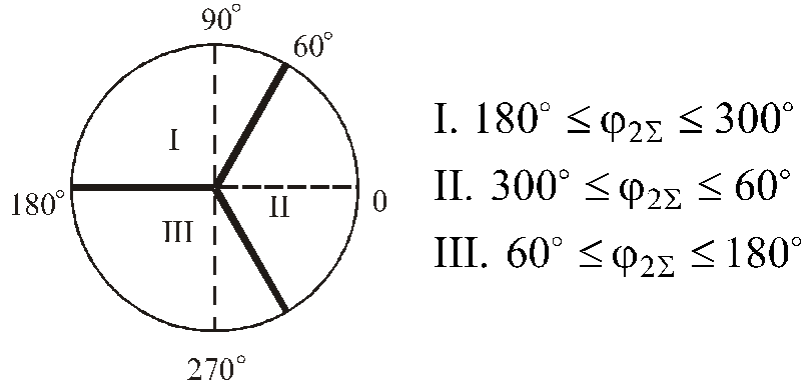


Figure 7.8 Distribution of negative-sequence current argument $\varphi_{2\Sigma}$

The total reactive power of the capacitor bank under complete balance (on the assumption that it operates under rated voltage) is determined on the expressions:

I area $Q_\Sigma = \sqrt{3}U_r I_{2\Sigma} (\sqrt{3} \sin \varphi_{2\Sigma} + \cos \varphi_{2\Sigma})$

II area $Q_\Sigma = 2\sqrt{3}U_r I_{2\Sigma} \cos \varphi_{2\Sigma}$

III area $Q_\Sigma = \sqrt{3}U_r I_{2\Sigma} (\sqrt{3} \sin \varphi_{2\Sigma} - \cos \varphi_{2\Sigma})$

The power ratios Q_{AB}/Q_Σ , Q_{AC}/Q_Σ , Q_{CA}/Q_Σ at the capacitors connection to the voltage in the areas I, II and III are defined by the expressions:

I area $\frac{Q_{AB}}{Q_\Sigma} = \frac{2}{3 + \sqrt{3} \cot \varphi_{2\Sigma}}; \frac{Q_{CA}}{Q_\Sigma} = 1 - \frac{Q_{AB}}{Q_\Sigma}$

II area $\frac{Q_{AB}}{Q_\Sigma} = 0.5 - \frac{1}{2\sqrt{3}} \tan \varphi_{2\Sigma}; \frac{Q_{BC}}{Q_\Sigma} = 1 - \frac{Q_{AB}}{Q_\Sigma}$

III area $\frac{Q_{AB}}{Q_\Sigma} = \frac{2}{3 - \sqrt{3} \cot \varphi_{2\Sigma}}; \frac{Q_{CA}}{Q_\Sigma} = 1 - \frac{Q_{BC}}{Q_\Sigma}$

The reactive power calculation is one of the most important questions at selection of the multifunctional compensating device parameters.

7.2. Estimation of reactive power

Estimation of reactive power in the presence of electromagnetic interference has some peculiarities. In steady state of linear three-phase network with balanced sinus-

oidal source voltage, the reactive power Q is determined by the apparent power S and the active power P :

$$Q = \sqrt{S^2 - P^2}.$$

In unbalanced conditions at unbalanced load and/or line-to-line voltages, Q is determined by the phase reactive powers summation:

$$Q = Q_A + Q_B + Q_C.$$

In the presence of unbalance and harmonics, $Q_{A(B,C)}$ values are determined using methods described below.

According to Budeanu approach based on frequency representation, in the presence of harmonics, we have:

$$Q_B = \sum_{n=1}^{\infty} U_n I_n \cos \varphi_n = \sum_{n=1}^{\infty} Q_n.$$

In this case, the apparent power is

$$S_B = \sqrt{P^2 + Q_B^2 + D^2}$$

where D is the distortion power.

Approach suggested by Budeanu does not meet the essence of the processes occurring in the circuit at non-sinusoidal modes. Values of Q_B are not suitable for assessment of reactive power balance. In practice, power Q_B is used to estimate maximum permissible values of the power for the capacitor banks of filtering and compensating devices. Nevertheless, this approach is accepted in the IEC Standard.

Integral method based on the Vries theory considers the load current $i(t)$ decomposition into two components: active i_{act} and reactive i_{react} :

$$i(t) = i_{act}(t) + i_{react}(t)$$

where

$$i_{act}(t) = \frac{P}{U^2} u(t); \quad i_{react}(t) = i(t) - i_{act}(t).$$

Correspondingly to that

$$P = UI_{act}; \quad Q_F = UI_{react}; \quad Q_F = \sqrt{S^2 - P^2}.$$

Vries theory has several shortcomings. Thus, knowledge of Q_F value does not permit to assess active losses in the network arising in presence of harmonics. It is also impossible to draw up a balance of the reactive power.

Despite of the disadvantages, this theory has spread, in particular, in development of active filters control systems.

In practice, at wave form distortion less than 15 %, the method of equivalent sine waves is applied.

Equivalent sinusoidal waves of the voltage and current have rms values equal to

$$U_e = \sqrt{\sum_{n=1}^{\infty} U_n^2}, \quad I_e = \sqrt{\sum_{n=1}^{\infty} I_n^2};$$

the apparent, active and reactive power

$$S_e = U_e I_e, \quad P = \sum_{n=1}^{\infty} U_n I_n \cos \varphi_n, \quad Q_e = \sqrt{S_e^2 - P^2}.$$

The power factor is

$$\lambda = \frac{P}{S_e}.$$

For valve inverters λ is found as

$$\lambda = \gamma_u \cos \varphi_1$$

where

$$\cos \varphi_1 = \frac{P}{S_1}.$$

S_1 is the apparent power of valve inverter determined by the main voltage and current harmonics values.

As it is known, $\cos \varphi_1$ is determined by known rectified voltage U_d , corresponding to the delay angle $\alpha \neq 0$, and the value U_{d0} at $\alpha = 0$ as

$$\cos \varphi_1 = \frac{U_d}{U_{d0}}.$$

Network current distortion factor γ_u is determined by ratio of the current fundamental and the net current :

$$\gamma_u = \frac{I_1}{I_e},$$

The active and reactive power are found as

$$P = S\gamma_u \cos \varphi_1, \quad Q = Q_e.$$

In calculation of the voltage deviation the reactive power value determined by the voltage and current fundamentals may be used. But the calculation error increases with increase of the appropriate curves distortion.

The reactive power as a quantity characterizing the electromagnetic energy exchange rate between the generator and the consumer may also be used for calculation and correction of the voltage fluctuations.

So, at short circuit on electric arc furnace electrodes and smooth or stepped variation of valve inverter delay angles it is possibly to talk about corresponding variation (or surge) of the reactive power. Its calculations techniques do not contradict the physics of the processes taking place in electric power supply systems of industrial enterprises.

7.3. Means of reactive power compensation

Installations of direct reactive power compensation

Direct compensation provides generation of the reactive power with a static compensator. Stepped and smooth reactive power control is distinguished. In the first case different numbers of capacitor bank sections are connected with the help of thyristor keys. In the second case frequency converters with forced commutation of thyristors are applied.

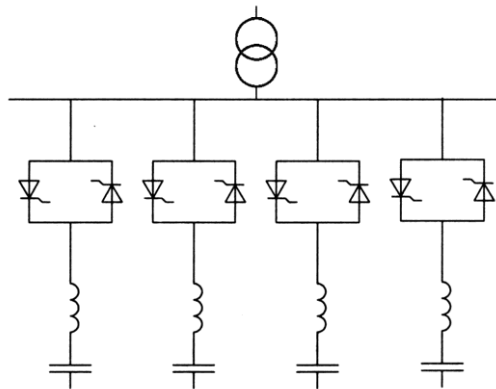


Figure 7.9 Direct compensation of reactive power with stepped control

In the case of stepped control the needed number of capacitors banks is switched on by means of thyristor keys as the reactive power increases (Fig. 7.9). Increase of the capacitor banks steps number the reactive power control becomes smoother.

To reduce the transient current arising at switching on the next step of the compensator its connection is carried out under equality of the voltage on the capacitor bank and the network. At the time of a bank section switching the network voltage has its maximum value that corresponds to the capacitor bank current passing the zero.

As switching on the capacitor bank is made in strictly defined time instants, operating speed of the compensator is small. Maximum possible delay at frequency of 50 Hz is 10 ms.

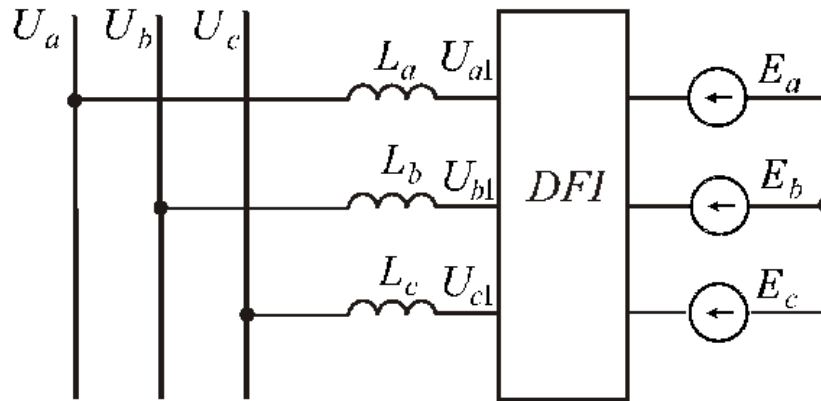


Figure 7.10 Direct compensation of reactive power with direct frequency converter

Direct frequency converters are applied for smooth control of the reactive power. Such a compensator is non-controlled high-frequency generator that is connected through direct frequency converters (Fig. 7.10).

Depending on relation of voltages u_a, u_b, u_c and the direct frequency converter output voltages u_{a1}, u_{b1}, u_{c1} the compensator can either generate or consume reactive power. At this, the reactive power is consumed from high-frequency generator. Therefore, a static device containing LC circuit can be used as the generator (Fig. 7.11). As capacitors in the considered compensators operate at high frequency, it has certain advantage by its dimensions and cost in comparison with other types of compensators.

Compensators with forced commutation of thyristors are also used as reactive power sources for direct compensation. Such a compensator consists of two three-phase converters connected in parallel. Change of the thyristors delay angle is provided by forced current commutation in valve circuits by means of the voltages of the commutating capacitors but not by the network voltage.

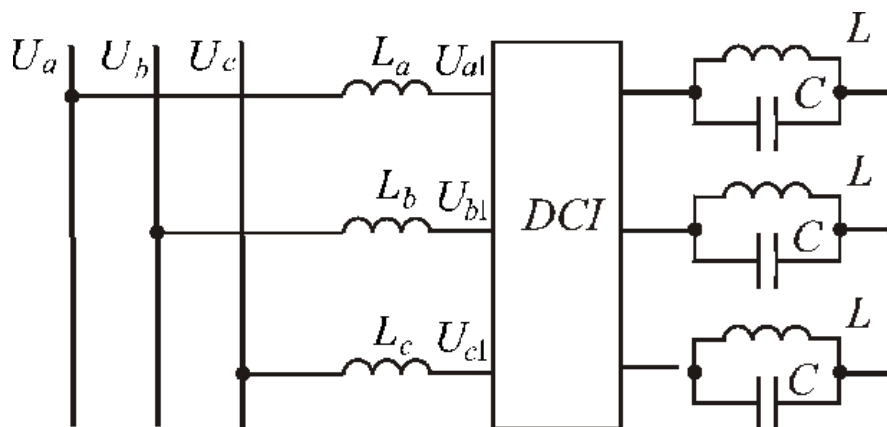


Figure 7.11 Direct compensation of reactive power with direct frequency converter and LC-circuits

7.4. Filtering and compensating devices

Resonant filters (filtering and compensating devices for energy purposes)

Reduction of harmonic levels in power networks is a part of general task of non-linear load influence on the power network reduction and electric power quality in the enterprise power supply system improvement. Complex solution of the problem based on application of multifunction devices is more economically expedient than usage of methods providing improvement of the converter network current curve shape. The example of such multifunction devices is the resonant filters that are called the filtering and compensating devices. They, along with reduction in harmonics level, generate reactive power and give it to the power grid.

At parallel connection of LC -circuits tuned for frequencies of the definite harmonics, the chain filtering and compensating device is realized. In this case, reactive power shortage on the buses of a substation may be completely covered with the help of capacitor bank of the filtering and compensating devices. At this the installed power of the capacitors is used by 80–90 %. Thus, filtering and compensating devices are the simplest and economical filters that stipulate their wide application.

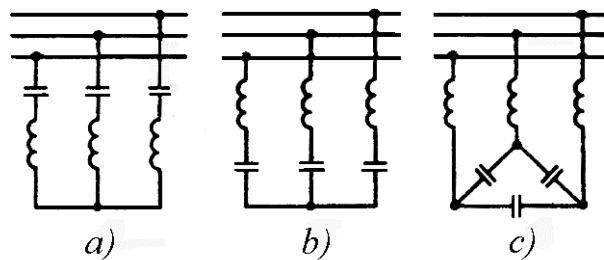


Figure 7.12 Circuits of simplified filtering and compensating devices

Simplified filtering and compensating devices circuits are shown in Fig. 7.12. In the circuit in Fig. 7.12, a insulation of capacitors to ground is under voltage not exceeding the network phase voltage. This improves reliability of the battery. Circuit shown in Fig. 7.12, b has the widest application because ease of the equipment mounting and it high reliability.

Specifications for the capacitor banks operation include limitation of the voltage and current excess over the rated values by definite values c_u and c_i (expressed as fractions of the rated values). Depending of the capacitors type $c_u=1$ or 1,1; $c_i=1,3$ or 1,5. In the case of the capacitors operation in presence of harmonics the additional requirement limiting the capacitor bank power under rated conditions is sometimes established.

Determine an expression for power of the capacitor bank of a filtering and compensating device of n th harmonic assuming that in its circuit only current of the fundamental and n_p th harmonics are flowing. Voltage across the capacitor bank is not more than permitted (rated) value if

$$K_Q a_p k_u \leq c_u \quad (7.1)$$

where

$$a_p = \frac{n_p^2}{n_p^2 - 1}; K_Q \cong 1 + Q_p/S_{SC}, \quad (7.2)$$

n_p is the harmonic number to which frequency the device having power Q_p is tuned;

$$k_u = U_m/U_{r,p}, \quad (7.3)$$

where U_m is maximum possible value of line-to-line voltage on the substation buses during operation; $U_{r,p}$ is rated line-to-line voltage.

After the filtering and compensating device connection, the net voltage increases proportionally to factor a_p .

Thus, maximum voltage across the capacitor bank terminals U_{CPmax} is expressed as

$$U_{CPmax} = U_{gr} k_u K_Q a_p$$

where U_{gr} is the network voltage.

Inadmissible overloading of the filtering and compensating device capacitors by current does not take place if

$$\sqrt{I_{1p}^2 + \sum I_{np}^2} \leq c_i I_{r,p} \quad (7.4)$$

where I_{1p} and I_{np} are currents of the fundamental and n_p th harmonics to which the filtering and compensating device is tuned; $I_{r,p}$ is rated current of the capacitor bank.

If there are several filtering and compensating devices in a circuit, it is possible to assume that through each the device passes currents of the fundamental and the harmonic to which frequency the device is tuned. In this case, the expression of the capacitor bank of the n th harmonic filter power may be represented in a form

$$Q_p \geq \frac{\sqrt{3} U_{r,p} I_{n\Sigma}}{\sqrt{c_i^2 - a_p^2 k_u^2}} \quad (7.5)$$

Simplified expression for Q_p , convenient for practical application, is

$$Q_p \geq 1.2 k_c U_{r,p} I_{n\Sigma} \quad (7.6)$$

where $k_c = 3$ at wye and $k_c = \sqrt{3}$ at delta connection.

The current $I_{n\Sigma}$ is determined by the formula (if m harmonics are taken into consideration):

$$I_{n\Sigma} = \sqrt{\sum_{n=2}^m (I_{nq} \sigma_{nq})^2} \quad (7.7)$$

where I_{nq} is the current of n_p th harmonic; σ_{nq} is a portion of the n_p th harmonic current passing through filtering and compensating device of this harmonic. The coefficient σ_{nq} is determined by the expression:

$$\sigma_{nq} = \frac{1}{\frac{1}{k_p n_p^2} (1 - n_{q*}^2) + 1} \quad (7.8)$$

where $n_{q*} = n_p / n_q$.

To take into consideration the limitations of the capacitor bank power, the following condition should be also met:

$$Q_p \geq Q_{1p} + Q_{np} \quad (7.9)$$

where Q_{1p} and Q_{np} are reactive powers of the capacitor bank under frequencies of the fundamental and the n_p th harmonic.

This condition is satisfied if

$$\alpha_p^2 k_u^2 + \sum_{p=2}^m \left(\frac{I_{np}}{I_{rp}} \right)^2 \frac{1}{n_p^2} \leq 1. \quad (7.10)$$

Under stable voltage unbalance, filtering and compensating devices can be simultaneously used as balancing sets as at low mains frequency the reactors inductive reactance is small compared to the capacitor banks reactance.

Example

It is necessary to determine parameters of a filtering and compensating device for a substation supplying an electrolysis shop. Initial data: the short circuit power is $S_{SC} = 195$ MVA; the 12-pulse converter power is $S_{vc} = 12$ MVA; the rated voltage is $U_r = 10.5$ kV; optimum value of the reactive power is $Q_0 = 2800$ kvar; $U_{11*} = 5.1$ %; $U_{13*} = 3.9$ %; $K_U = 6.8$ %. The capacitors rated voltage is 6.6 kV.

Solution

1. Determine the converters harmonic currents:

$$I_n = \frac{S_{vc}}{\sqrt{3} U_r n}, \quad I_{11} = \frac{12000}{\sqrt{3} \cdot 10.5 \cdot 11} = 60 \text{ A}, \quad I_{13} = \frac{12000}{\sqrt{3} \cdot 10.5 \cdot 13} = 51 \text{ A}.$$

2. Decide to install a single filtering and compensating device tuned to frequency of the 11th harmonic. Assume the capacitor bank power equal to the reactive power optimum value:

$$Q_0 = 2800 \text{ kvar}, \quad k_p = \frac{Q_0}{Q_{SC}} = \frac{2800}{195 \cdot 10^3} = 1.44 \cdot 10^{-2}.$$

3. Find the portion of the 13th harmonic current passing through the filtering compensating device using formula (7.8):

$$\sigma_{n11} = \frac{1}{\frac{1}{1.44 \cdot 10^{-2} \cdot 11^2} \left[1 - \left(\frac{11}{13} \right)^2 \right] + 1} = 0.86.$$

The harmonics current in the capacitor bank circuit is

$$I_{n\Sigma} = \sqrt{60^2 + (51 \cdot 0.86)^2} = 80 \text{ A}.$$

The capacitor bank minimum power for three phases equals

$$Q_p = 3 \cdot 1.2 \cdot 80 \cdot 6.6 = 1900 \text{ kvar} < 2800 \text{ kvar}$$

that confirms admissibility of the capacitor bank installed power.

4. After the selected filtering and compensating device installation, the residual voltage of harmonics and the wave distortion factor will be equal to:

$$\Delta U_{11*} = 0, \quad \Delta U_{13*} = 3.9 \cdot (1 - 0.86) = 0.55 \text{ \%}.$$

Damping Filters

In the case of dense interharmonic spectrum, which arises for example at a direct frequency converter with sine control law, use of the damping filters (the second order filters) turns out to be expedient. Damping filter consists of a capacitor and a reactor to which a resistor is connected in parallel (Fig. 7.13).

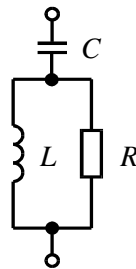


Figure 7.13 Circuit of damping filter

The filter impedance is determined by the expression:

$$Z(jn) = \frac{Rn^2\omega^2L^2}{R^2 + n^2\omega^2L^2} + j \left(\frac{R^2n\omega L}{R^2 + n^2\omega^2L^2} - \frac{1}{n\omega C} \right)$$

where n is the number of a harmonic or interharmonic.

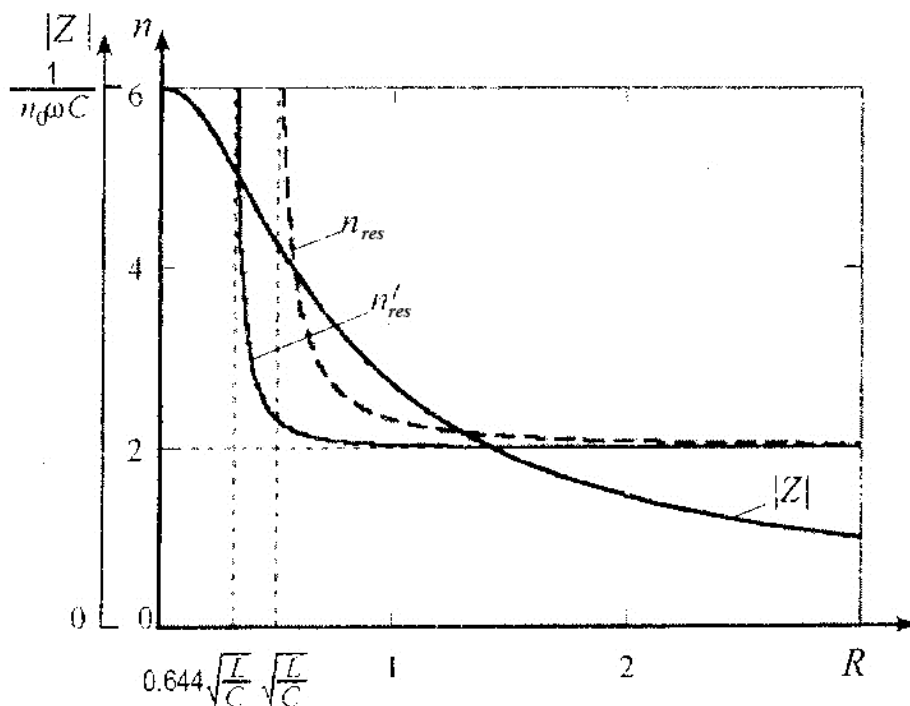


Figure 7.14 Dependences $n_{res} = f(R)$, $n'_{res} = f(R)$ and $|Z| = f(R)$

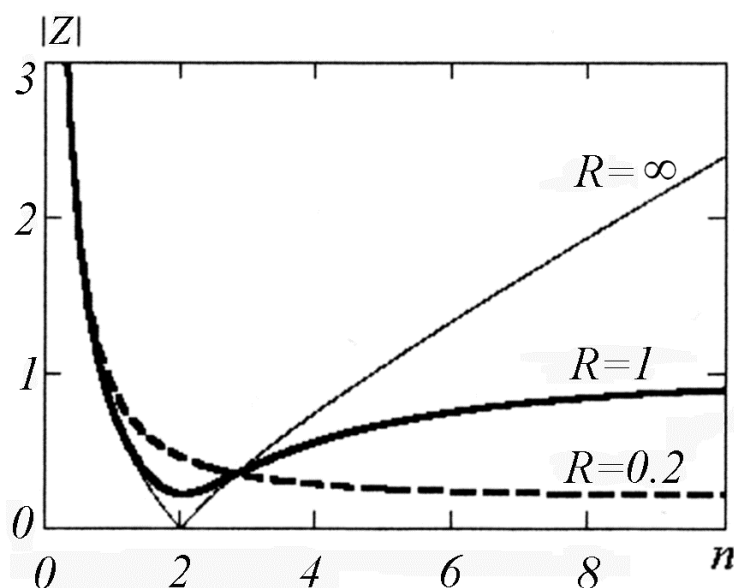


Figure 7.15 Frequency characteristics of impedance for damped filter

In terms of the circuit theory the resonant filter frequency n_{res} is determined proceeding from the condition of equality to zero the imaginary part of the above expression. So we have:

$$n_{res} = \frac{R}{\omega \sqrt{LCR^2 - L^2}}$$

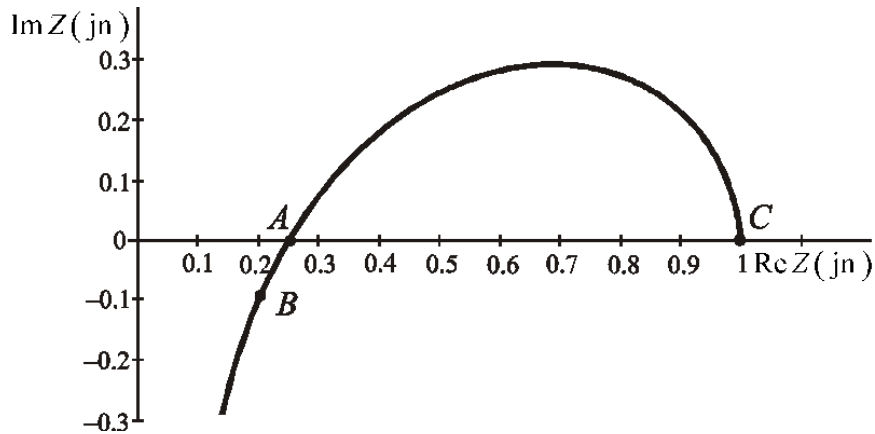


Figure 7.16 Impedance locus of damped filter at $R=1$

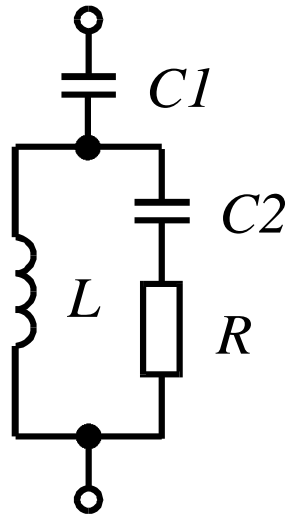


Figure 7.17 Circuit of total filter

Nevertheless, frequency n'_{res} at which the filter impedance magnitude has minimum value is more important for minimization of higher harmonics and interharmonics. Frequency n'_{res} is the filter tuning frequency. Determining the first-order derivative of the of the filter impedance magnitude and equating it to zero, find the expression for n'_{res} at which the condition $|Z(jn'_{res})| = \min$ is met (as the second derivative is $|Z(jn'_{res})|'' > 0$):

$$n'_{res} = \frac{R}{\omega L} \sqrt{\frac{L^2 + RL\sqrt{R^2 C^2 + 2LC}}{R^4 C^2 + 2LR^2 C - L^2}}$$

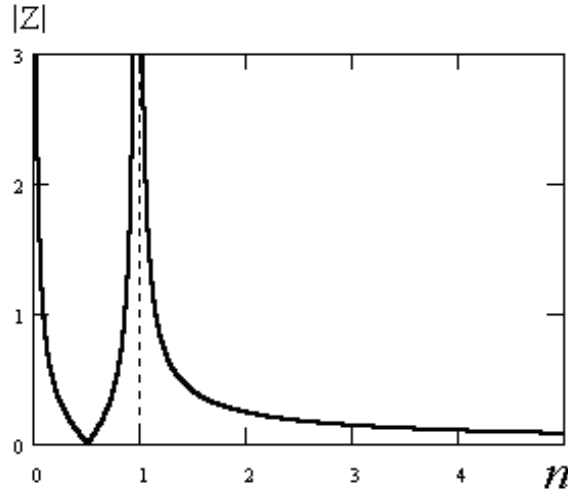


Figure 7.18 Frequency characteristic of impedance for total filter

In this formula the condition $R^4 C^2 + 2LR^2 C \geq L^2$ for the radicand in the denominator must be satisfied. Hence, resistance of the damping filter should meet the inequality:

$$R \geq \sqrt{\frac{L}{C}(\sqrt{2} - 1)} \cong 0.644 \sqrt{\frac{L}{C}}.$$

In Fig. 7.14 the dependencies of n_{res} and n'_{res} against resistance R at the resonant frequency $n_0 = 1/(\omega\sqrt{LC}) = 2$ are presented. Here L and C are minimum values of the reactor inductance and capacity of the filter capacitor bank.

Resonant and filter tuning frequencies always meet inequality $n_{res} > n'_{res} > n_0$. If the resistance $R \rightarrow \infty$, we have $n_{res} = n'_{res} = n_0$ and $|Z(jn'_{res})| \rightarrow 0$. When the resistance decreases, the magnitude of impedance at the tuning frequency will increase. At frequencies $n > n'_{res}$ it decreases.

Besides, the less resistance R , the higher filter adjustment frequency n'_{res} compared to n_0 . At $R < 0.644\sqrt{L/C}$ the damping filter does not have a specific tuning frequency and is a high-pass filter. Fig. 7.15 shows frequency characteristics of a damping filter impedance under different values of R and $n_0 = 2$. Fig. 7.16 shows the filter impedance locus curve at $R = 1$. Point A corresponds to the filter resonant frequency n_{res} , and point B – to the tuning frequency n'_{res} in which the filter impedance has the least value. Point C corresponds to the filter impedance equal to R at $n \rightarrow \infty$.

If it is required to minimize higher harmonics and interharmonics it is also expedient to use total filters (third order filters). Fig. 7.17 shows circuit with such a filter.

Filter impedance is determined by means of the expression:

$$Z(jn) = \frac{n^2 \omega^2 L^2 R}{R^2 + \left(n\omega L - \frac{1}{n\omega C_2}\right)^2} + j \left[\frac{n\omega LR^2 + \frac{L}{n\omega C_2^2}}{R^2 + \left(n\omega L - \frac{1}{n\omega C_2}\right)^2} - \frac{1}{n\omega C_1} \right]$$

Filter has two resonant frequencies. One of them corresponds to series resonance, another - to inverse resonance. Fig. 7.18 shows frequency characteristic of the total filter impedance with parameters: $R = 0.01 \Omega$; $L = 0.94 \text{ mH}$; $C_1 = 30 \text{ mF}$; $C_2 = 11 \text{ mF}$. The filter impedance locus is represented in Fig. 7.19. Point A corresponds to series resonance frequency and point B - to inverse resonance frequency; point C corresponds to the filter impedance equal to R under $n \rightarrow \infty$. Possibility of the described filter minimization at frequencies beneath 50 Hz is its advantage.

7.5. Active filters

Different methods and multifunctional techniques are used to improve power quality indices. Filtering and compensating devices on the basis of simple resonant filters or total combined ones perform filtration of the higher harmonics and interharmonics as well as reactive power compensation. Active filters, as well as hybrid filters, used to reduce level of interharmonics, provide more wide opportunities.

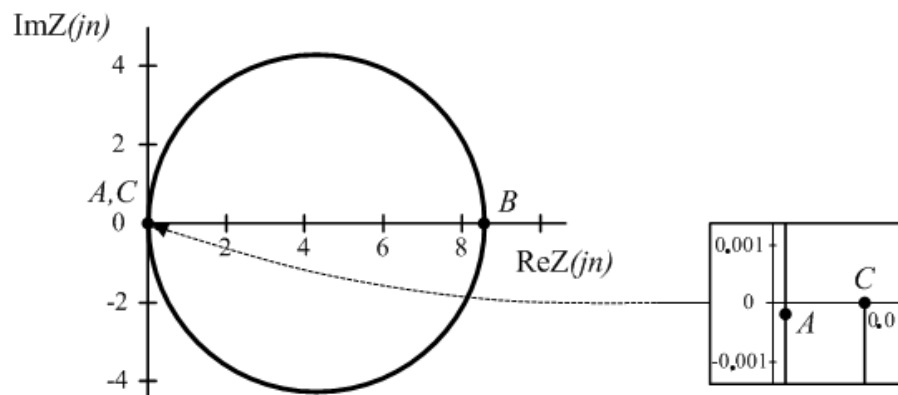


Figure 7.19 Impedance locus of total filter

Active filters are rather promising multifunctional devices which, depending on their structure, assure harmonics and interharmonics filtration, compensation of reactive power, decrease in depth and duration of the voltage dips and consumer voltage control.

In general case, active filters are a source of load reactive current of fundamental frequency and frequency of harmonics and intended to their compensation. As active filters, thyristor or transistor voltage inverters are used. An active filter is connected either in parallel to the load (Fig. 7.20) or in series into the line break (Fig. 7.22). The control unit forms control signals according to algorithm which provides generation by the filter the compensating reactive current i_{hi} consisting of the nonlinear load

current i_l harmonic and interharmonic components. The source current $i_s = i_{hl} + i_l$ is theoretically purely active and has practically sinusoidal shape (Fig. 7.21).

In the case of series (longitudinal) connection, the active filter is independent source of alternating voltage entered between the power source and the load. The amplitude and phase of the independent voltage source are varied

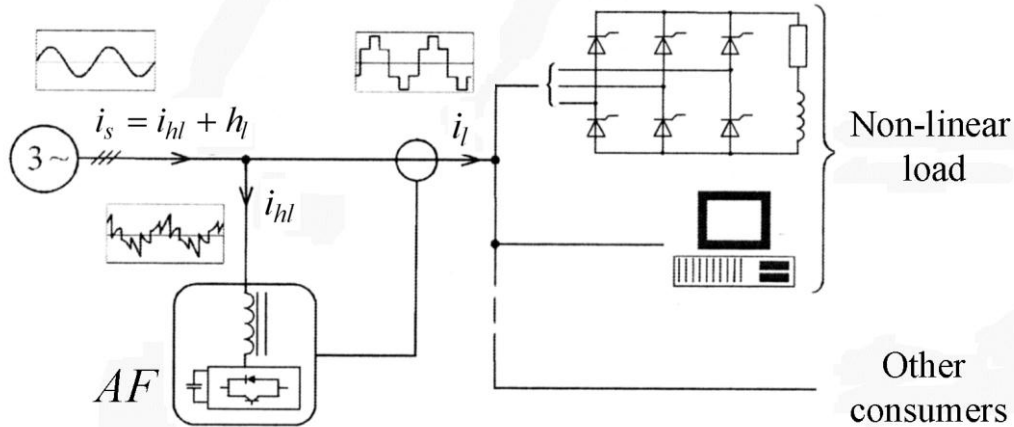


Figure 7.20 Structure of active filters

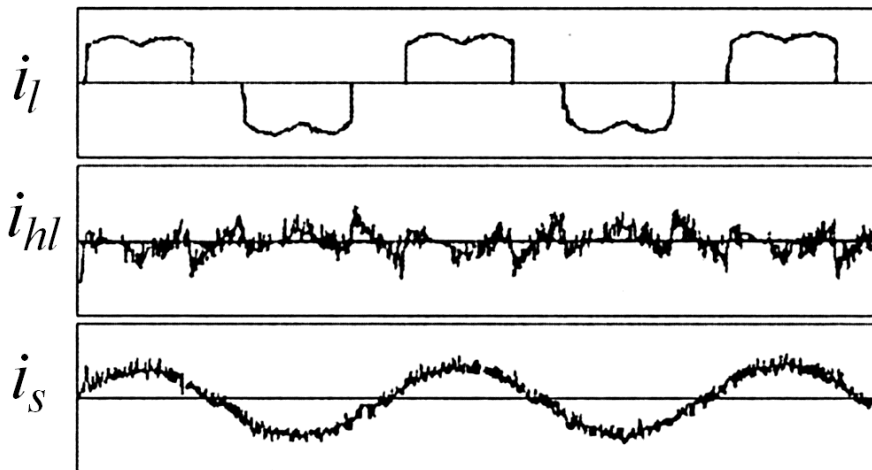


Figure 7.21 Oscillogram of currents demonstrating effectiveness of parallel active filter

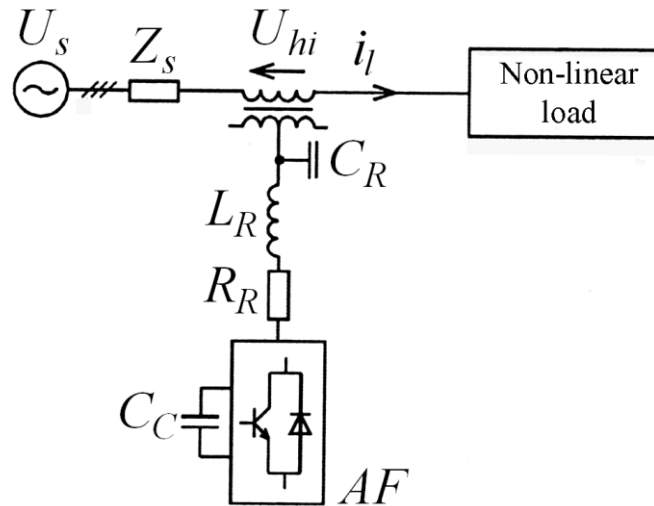


Figure 7.22 Longitudinal system of compensation and filtration using active filter

according to a preset law providing the required output voltage U_{hi} . Such connection permits not just to minimize harmonics and interharmonics but also to provide the consumer voltage control.

Hybrid Filters. Alternative solution reducing costs for power quality improvement by means of the active filtration is application of hybrid filters in which active filters are connected in parallel or in series to filtering and compensating device.

Herewith, a filtering and compensating device is tuned to frequencies of the most expressed harmonics, and an active filter provides additional harmonics reduction. In this case much less active filter installed power is required. A hybrid filter, in which active filters connected in series and in parallel are used, is called the power quality conditioner. Table 7.1 shows performance of active and hybrid filters.

Table 7.1

General characteristics of filters application

| Active filter connection | Observed effect | |
|--------------------------|---|------------------------------|
| | Influence of load on network | Influence of network on load |
| In parallel | Filtration of current harmonics, reactive power compensation, current unbalance, voltage fluctuations | |

| | | |
|---------------------------|--|--|
| In series | Current harmonic filtering, Reactive power compensation, current unbalance, voltage fluctuations, voltage unbalance | Voltage dips/ voltage surges, voltage distortions, power supply interruptions, voltage unbalance |
| In parallel and in series | Filtration of current harmonics, reactive power compensation, current unbalance, voltage fluctuations, voltage unbalance | Voltage dips/ voltage surges, voltage unbalance, voltage distortions, power supply interruptions, voltage fluctuations |

Balancing and compensating devices provide reduction of harmonics and interharmonics, balancing of the line-to-line voltage system, reactive power compensation and, in some degree, decrease of voltage deviations. Under the ratio of the unbalanced load power S_l and short circuit power S_{SC} in the connection node of $S_{SC}/S_l \geq 50$ no additional arrangements are required.

7.6. Reduction of electromagnetic interference at traction substations

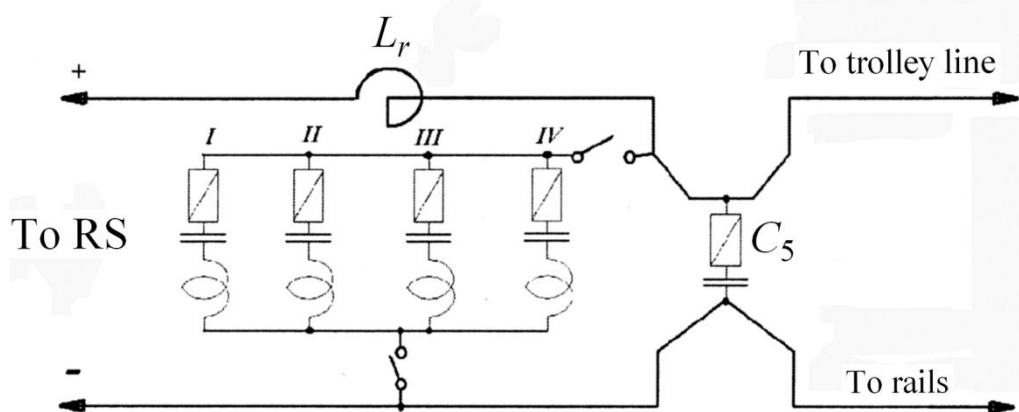


Figure 7.23 Reduction of electromagnetic interference at railway traction substations

The circuit shown in Fig. 7.23 is used to decrease level of electromagnetic interference at railway traction substations. The device consists of reactor L_r , resonant circuits and separately located capacitor C_5 . Each of the four resonant circuits is tuned to

resonance at one of the main harmonics of the fluctuating voltage that have frequencies of 300, 600, 900 and 1200 Hz. Thus, the circuits provide short-circuit conditions for these harmonics current.

Large capacitance C_5 (the fifth parallel path) is intended to reduce the interference intensity at high frequencies. Reactor L_r has great resistance for high-frequency currents ($L_r \approx 4,5-6,5$ mH), and it also reduces level of electromagnetic disturbances.

At traction substation of underground electric transport, the circuit for suppressing of electromagnetic disturbances shown in Fig.7.24 is applied. The interference level reduction is performed with the help of capacitive blocking of the traction substation collecting busses by means of capacitor C_b and connection of capacitors C_f between each rectifier valve anode and its common cathode. Such a circuit is intended to decrease interference mainly in the high-frequency range (> 30 kHz).

An interference-protective filter is placed directly on the rectifier unit frame to shorten length of the connecting conductors. Such a filter installation reduces interference intensity by 2-4 times.

The most efficiently and cost effectively the electromagnetic interference, caused by a traction substation, is reduced at installation only blocking capacitors C_b having a capacity of $10 \mu\text{F}$ connected in parallel to each the rectifier unit.

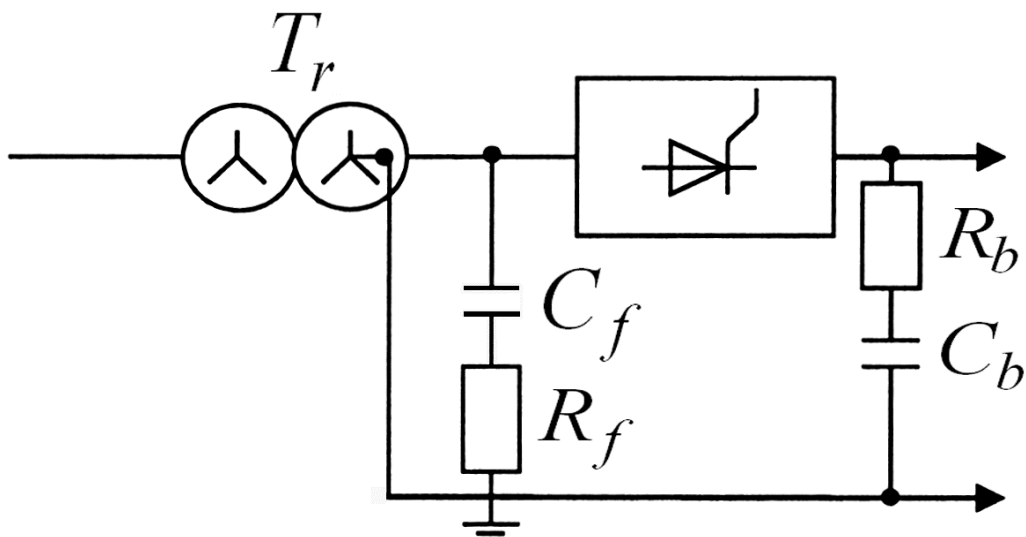


Figure 7.24 Circuit for suppressing of electromagnetic disturbances

To decrease high-frequency electromagnetic interferences in power supply systems of industrial enterprises, special treatment all devices being sources of electromagnetic interference is required. Treatment of electric welding sets using DC and AC consists in installation of capacitive or $L-C$ filters on their input terminals. Shielding of equipment is used too. Filters are also installed on electric machines enclosure.

7.7. Compensation of voltage fluctuations

Reduction of voltage fluctuation level maybe provided with use of two methods: by means of rational network structure use, and application of special techniques for voltage fluctuations reduction.

The first method consists in such a circuit design at which it short-circuit power is greater as possible, and selection such sensible to voltage fluctuation loads and fluctuation sources separation that electrical connection between them exists on as higher as possible voltage level. Disadvantage of the system short-circuit power is need of switching equipment power increase. Short-circuit power is limited by the system (or network) power in the point to which the network is connected (or has been connected). Application only the circuit design method for voltage fluctuations reduction does not give positive effect in many cases. It is confirmed by the fact that during last 10-15 years voltage fluctuations in networks of 110-220kV increased. Apparently, further increase in power unit number and of voltage fluctuation sources complicates the problem. In this connection application of special technical means providing the voltage fluctuations compensation is required. To these technique dual and controlled reactors, longitudinal compensating installations, static sources of reactive power and synchronous compensators belong.

Dual reactors are the simplest means to reduce the voltage fluctuations. Quiet and sharply variable loads are connected to different sections (coils) of the reactor. Dual reactors are similar by their construction to common smoothing concrete reactors. Two sections (coils) having common axis and the same direction of coils winding are placed one above another that provides their subtractive polarity. Usually the both coils are designed for equal inductance. The center-tapped lead is designed to double current.

As mutual induction between sections is $M \neq 0$ the voltage drop on each of them at load currents I_1 and I_2 can be found as:

$$\underline{\Delta U} = jx_L(\underline{I}_1 - k_M \underline{I}_2) = jx_L(\underline{I}_2 - k_M \underline{I}_1)$$

where x_L is inductance of the reactor section; $k_M = L/M$ is a factor of the mutual inductive coupling. Its value $k_M = 0.5 \dots 0.6$.

Ideally, when $\underline{I}_1 = \underline{I}_2$ the voltage drop equals $\Delta U = I_{1(2)} x_L (1 - k_M)$. This means that the voltage drop caused by the inductive coupling decreases by 50—60%. And when $\underline{I}_1 = \underline{I}_2$, a value of ΔU will be perhaps even less.

Transformers with split windings are also used for sharply variable and quiet loads. If the quiet load is connected to one of low-voltage windings and the sharply variable load - to another one, interrelation between values of the voltage fluctuations ΔU_2 and ΔU_3 at the buses may be presented as

$$\Delta U_2 = \frac{4 - k_s}{4 + k_s} \Delta U_3$$

where k_s is the split factor. In average it is assumed $k_s = 3.5$.

Absence of electrical and weak magnetic coupling between the split windings lead to much less voltage fluctuation in the network with quiet load in comparison with the network loaded by sharply variable load.

Controlled longitudinal compensating installations

Series connection of capacitors in a line break contributes to reducing the network resulting reactance and to decrease of the voltage fluctuations level.

The longitudinal compensation has several disadvantages which cause limited application of this method for voltage fluctuations and deviations reduction. These disadvantages are increase of a network short-circuit current, appearance of overvoltage on the capacitors at short-circuits behind them and also arising subharmonic oscillations.

Subharmonic oscillations, that are oscillations with frequency less than the source frequency, arise in a circuit with series connection of inductance a capacity in the case when the capacitive reactance at this frequency significantly exceeds the inductive reactance. The oscillations are excited under and often repeated of load surges.

Static sources of reactive power

Use of static source of reactive power for compensation of voltage fluctuations is recognized as the most promising method. Their advantages are high operating speed, simplicity in exploitation and possibility of phase-by-phase control, which permits to compensate the circuit unbalance simultaneously with the fluctuations.

Static sources of reactive power can be divided into static reactive power sources with smooth and stepped reactive power variation. Smoothly controlled static reactive power sources are divided into sources with current control of capacitor banks and of reactors.

At stepped control total power capacity of installed capacitor banks is selected by the condition of greatest fluctuations compensation at connection of all the capacitor banks. The number of steps is chosen by the condition of the mostly common voltage fluctuation levels compensation. In this case fluctuations at each the step connection should not exceed the values standardized by ДСТ 13109—97 .

A circuit of static reactive power source with smooth reactive power control is represented in Fig 7.25. In this case the capacitor bank power capacity remains invariable, but generated by the source total reactive power is determined by the thyristor keys 3, regulating the reactor current, commutation delay angle.

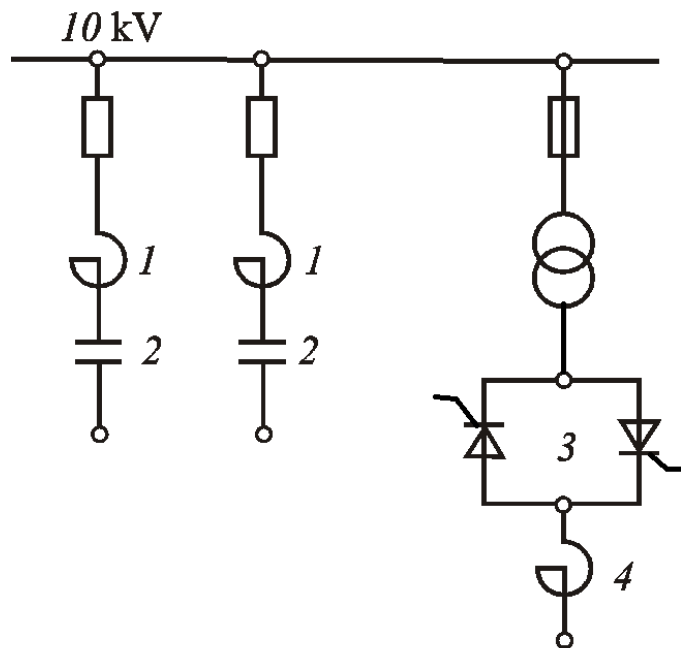


Figure 7.25 Static source of reactive power with smooth reactive power control

Varying the delay angle between the limits of $\pi/2$ and π it is possible to vary reactive power of the source from maximum value to zero. Disadvantage of the described reactive power source is high magnitude of harmonics generated to the supply network. For their suppression, harmonics filters are applied, such as capacitor banks 2 with reactors 1 (Fig. 2.25) tuned for harmonics of some certain order. The same filters may serve to reduce levels of harmonics generated into network by other harmonics sources. The considered static reactive power source disadvantage is also great losses being 25% more compared to previously described circuit of static reactive power source. Advantages of this circuit of a reactive power source are its higher operating speed and possibility of smooth control. Besides, the controlled reactor does not require compliance of voltage polarity at its switching on. In some countries, biased reactors are applied as controlled reactors in the considered circuit of reactive power source.

Compensation of voltage fluctuations in circuits of rolling mills is performed by means of reactive power surges compensation. Maximum effect of compensation may be achieved only in the case when delay in reactive power generation by the compensator is minimal. It is important to prevent the voltage fluctuation growth. So, for example, at compensation of reactive power of rectangular shape (Fig. 7.26) with some delay Δt , two surges of reactive power instead of one will take place (Fig. 7.27) that results in increase of voltage fluctuations level.

Maximum compensating ability of compensator is determined by maximum peak-to-peak voltage fluctuation value $\Delta U_{fl,max}$ to be compensated:

$$Q_{c,max} = \frac{\delta U_{fl,max}}{100\%} S_c = \frac{d_{fl,max}}{100\%} S_c.$$

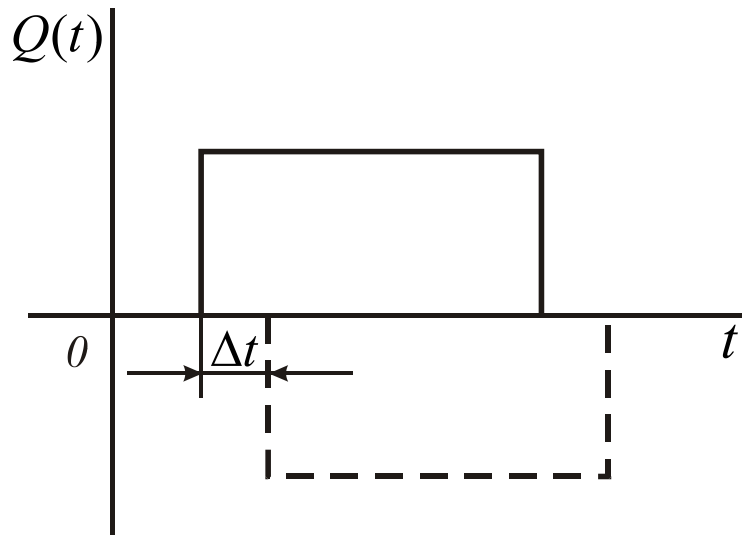


Figure 7.26 Graphs of load (solid line) and of compensator (dashed line) reactive power

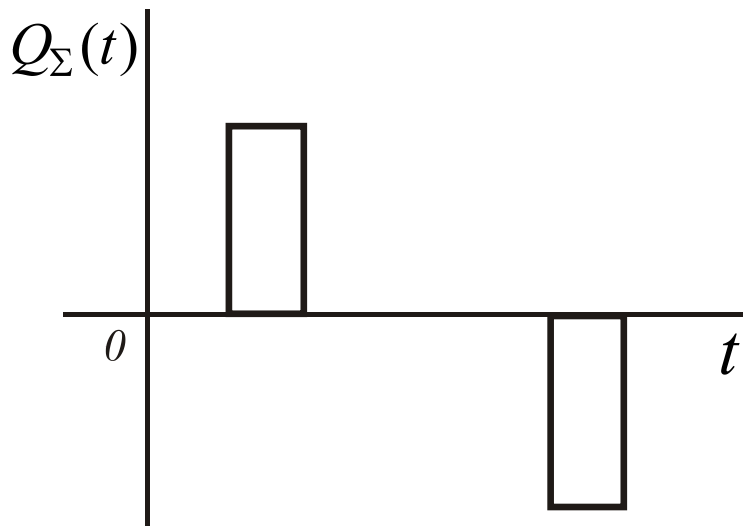


Figure 7.27 Surges at compensation of reactive power of rectangular shape (Fig. 7.26) with some delay Δt

Evidently, the voltage fluctuations on the level $d_i < d_{fl,max}$ will be completely compensated, and at $d_i > d_{fl,max}$ they will be compensated till the value of $d_i - d_{fl,max}$. The flicker dose after compensation is

$$P_{St} = \sqrt[3]{\sum_{i=1}^m \left(\frac{F_{ref,i} \Delta d_i}{d_0} \right)^3}$$

where

$$\Delta d_i = \begin{cases} d_i - d_{fl,max} & \text{at } d_i > d_{fl,max} \\ 0 & \text{at } d_i < d_{fl,max} \end{cases}$$

The value of $d_{fl,max}$ as well as maximum power of compensator is determined by the acceptable voltage fluctuation level ($P_{Stfl} = 1$). Analytical solution of the above equation is difficult. Therefore, the following method may be recommended.

Equivalent number of voltage fluctuations r_{eqv} , determined under condition that all the fluctuations have maximum swing d_{max} , is found from the equality:

$$\frac{F_{ref} d_{max}}{d_0(r_{eqv})} = P_{St}$$

where F_{ref} is the reference coefficient (Fig. 6.11)

On the other hand, when the voltage fluctuations have been compensated up to acceptable level ($P_{St} = 1$) we can obtain the expression:

$$\frac{F_{ref}(d_{max} - d_{fl,max})}{d_0(r_{eqv})} = 1.$$

Using the two latter expressions, find:

$$d_{fl,max} = d_{max} \left(1 - \frac{1}{P_{St}}\right) \text{ or } Q_{fl,max} = Q_{max} \left(1 - \frac{1}{P_{St}}\right).$$

Calculations by this expression returns some overestimated value (error is in the range of 5-10 % depending on the voltage excursions magnitude).

Example

Find the power capacity $Q_{fl,max}$ of a static source of reactive power for reduction of fluctuations to allowable value using data of the example given in div. 6.5.

Solution

Maximum compensating capacity of a compensating device is defined by the reactive power value:

$$Q_{fl,max} = Q_{max} \left(1 - \frac{1}{P_{St}}\right) = 39 \left(1 - \frac{1}{9.3}\right) = 35 \text{ Mvar.}$$

Dose of flicker after compensation is

$$P_{St} = 9.3 \frac{39-35}{39} = 0.93 < 1.$$

Synchronous compensators

Nowadays, synchronous compensators are the most common means of reducing

the voltage fluctuations. Reactive power supplied by asynchronous compensator under maximum disturbance

$$Q_{max} = kQ_r k_{if}$$

where Q_r is the rated reactive power of the synchronous compensator; k is the factor taking into account influence of the synchronous compensator magnetic circuit saturation.

Factor k_{if} characterizes overloading capacity of a machine for the point of the reactive power generation. For serial synchronous compensators $k_{if} = 2 \dots 2.6$.

Synchronous compensators have natural property regulation which appears in reducing the voltage fluctuations at peak loads.

At large voltage fluctuations level they can't be compensated by using common standard type synchronous compensators. It is mainly explained by their non-sufficient overloading capacity in regard to the field current. As a rule, the largest voltage of the field winding is 200—300 V. Proceeding from insulation service conditions its value is assumed not greater than 500 V. Besides the required excitation forcing ratio must be not less than 10. Synchronous machine should also have fast system of excitation control providing continuous following fluctuations of reactive power and voltage. The latter is possible if the control loop, including circuits of the machine stator and rotor, has fast response. On this reason special types of synchronous compensators have small rated field voltage (20—50 V) and reduced in comparison with common compensators time constant and stator reactance.

7.8. Load separation

One of the ways to provide electromagnetic compatibility of sensitive to interference consumers is separation of loads, being sources of electromagnetic interference (electric arc furnaces, rolling mills, welding installations etc.), and other, so called quiet loads (lighting, electric motors, home appliances etc.), so that the required level electromagnetic compatibility is achieved. This is illustrated by Fig. 7.28 and 7.29: at power supply of the electric arc furnaces and the linear load the dose of flicker on their common buses is $P_{St} = 3.78$; when the linear load is supplied through a transformer directly from the power system, dose of flicker became equal $P_{St} = 0.47$ that is acceptable.

The most common technique used for loads separation are dual reactors, split winding and three-winding transformers.

In a circuit with dual reactor, due to mutual inductive coupling, level of harmonics (if capacitors are not available) the dose of flicker decreases by 50 to 60% in comparison with their values on buses of electromagnetic interference source. In some cases, this circuit application for connection of electric arc furnaces, powerful

electric drives of the rolling mills, electric motors etc. permits in some cases to provide allowable level of electromagnetic compatibility on the buses of sensitive to interference quiet linear load.

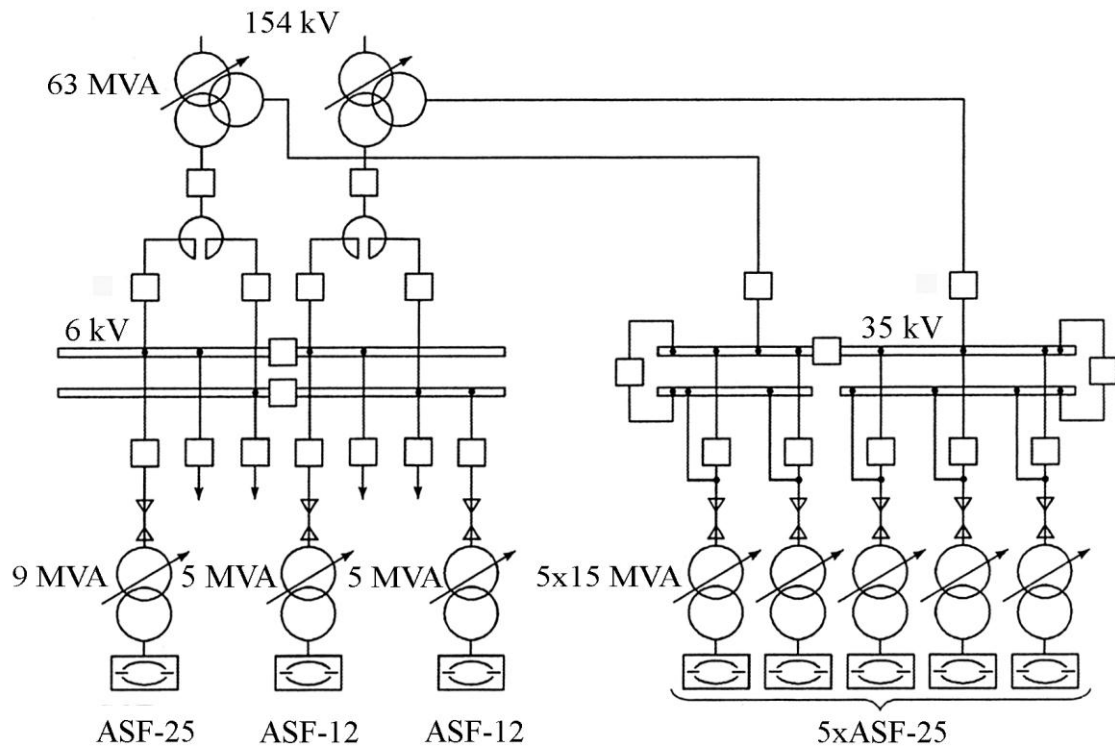


Figure 7.28 Diagram of enterprise power supply (before reconstruction)

A competitive solution is application of split windings transformers. When they are used in networks with sharply varying load, such as electric arc furnaces or rolling mills, the voltage excursions δU_{tq} on buses of a quiet load compared to their levels on buses of the fluctuation source δU_{tfl} equals

$$\delta U_{tq} = \delta U_{tfl} \frac{4 - k_s}{4 + k_s}$$

where k_s is the split factor, in average $k_s = 3.5$.

Application of split transformers in networks of 6–10 kV makes possible to ensure voltage fluctuations in allowable limits.

At connection of a sharply variable load to a node of network of 110–220 kV in the cases when short-circuit power is 2–4 thousand MVA (a node of network of 110 kV) or 4–6 thousand MVA (a node of network of 220 kV) values of P_{St} and P_{Lt} are in allowable limits.

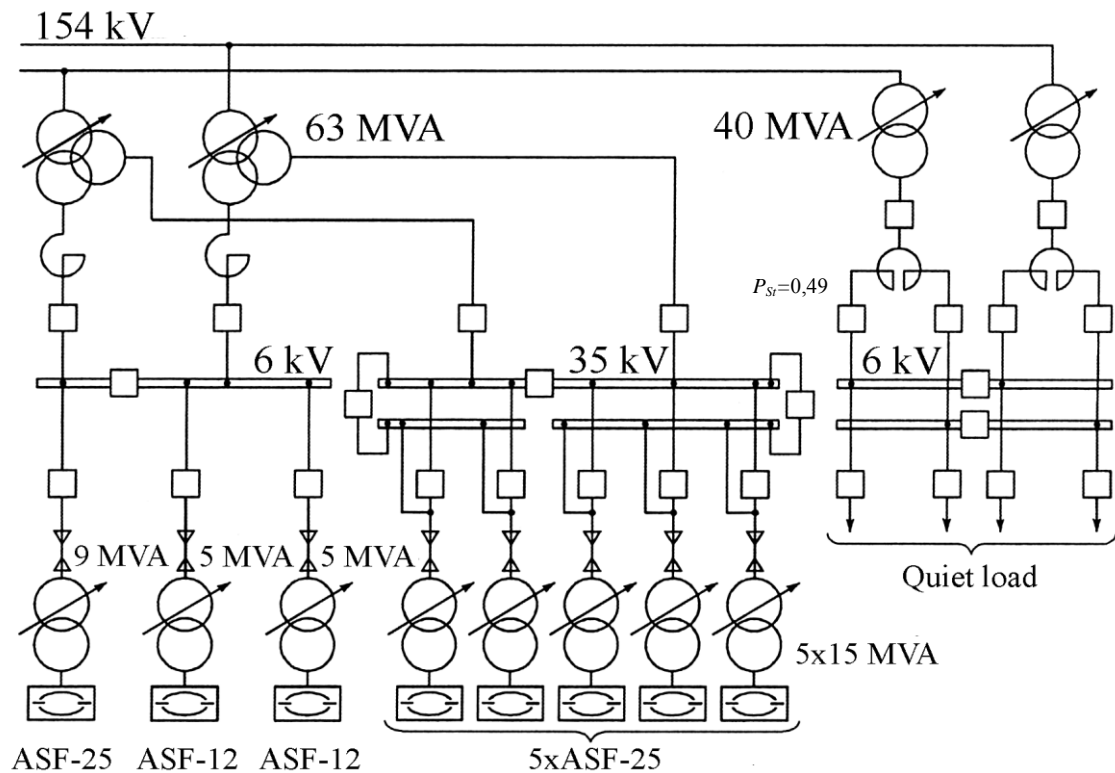


Figure 7.29 Diagram of enterprise power supply (after reconstruction)

Test questions

1. What are the main methods of ensuring electromagnetic compatibility of sensitive to interference electric power consumers?
2. What is effectiveness of the method of loads separation in electric power supply systems of enterprises?
3. What technical means are used for separation of loads in electric power supply systems of industrial enterprises?
4. Explain the principle of the indirect static reactive power compensator.
5. Why are the resonant filters referred to filtering and compensating devices?
6. Compare the frequency response characteristics of filters of the 2nd and 3rd order.
7. Explain the principle of an active filter.
8. What is the electric power quality conditioner?
9. Explain peculiarities of the synchronous compensators as means of fluctuations reduction.
10. Why does effectiveness of the static thyristor compensators depend on their operating speed?

Topics for essay

1. Filtering and compensating devices and active filters.
2. Damping filters of different order.
3. Methods and means of voltage fluctuation compensation.
4. Analysis of higher order filters impedance locus diagrams.
5. Impact of filtering and compensating devices parameters deflection on their performance effectiveness.

PART 2

FIELD INTERFERENCE

CHAPTER 8 LIGHTNING OVERVOLTAGE

8.1. Lightning

Lightning is a variety of spark discharge in the air when one of electrodes is a thunder cloud and another one is the earth. Strong ascending airflows provide vertical growth of the thunder cloud and promote electric charges separation in the air. Charges separation has complicated stochastic nature. But normally negatively charged water drops are gathered in the bottom of the cloud while positively charged ones are in the upper part of it (Fig. 8.1).

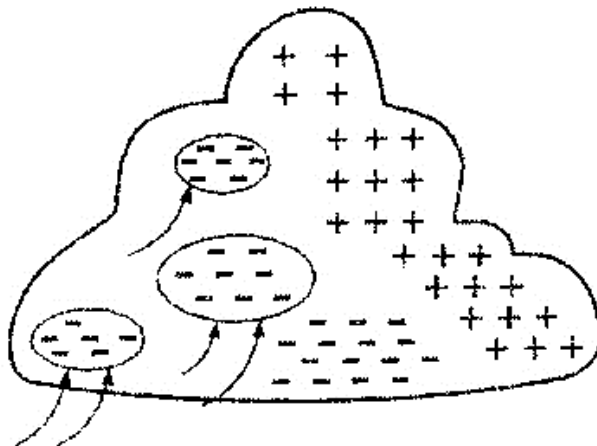


Figure 8.1 Charges disposition in a thunder cloud and ascending airflows direction

Negative charges can form volumes separated from each other. It is possible formation of similar concentrated positive charges at the bottom of the cloud that most frequently initiates the lightning striking onto the earth. At this, in 80-90% of cases a lightning strike has negative polarity, but sometimes positive polarity is possible as well.

Lightning consists of several separate strikes, each the lightning starts with the leading discharge and completes with inverse main discharge which speed can reach 0.5 of the light speed. Under influence of negative electric field of developing lightning leader, positive charges are accumulated on earth directly beneath the leader channel. Lightning strike into the earth happens at the place of the highest these charges concentration. As a rule, the lightning strikes land plots possessing increased

conductivity, for example, owing to availability of ground waters and also lakes, seas, rivers.

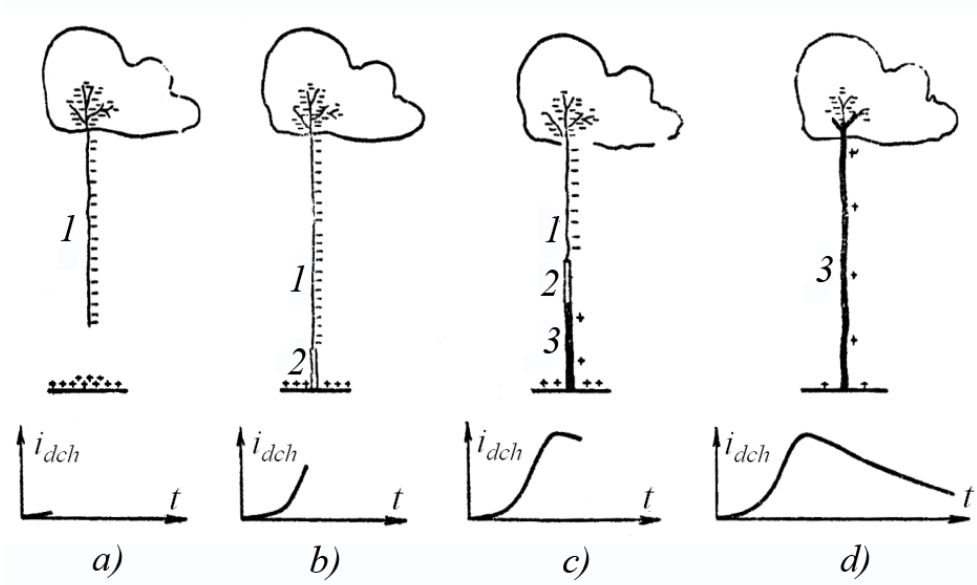


Figure 8.2 Separate stages of inverse discharge development and the lightning current variation in time:

- a* – the last stage of leader discharge;
- b* – formation of intense ionization zone nearby the ground surface;
- c* – intermediate phase of inverse discharge development;
- d* – final stage of the inverse discharge development;
- 1* – leader channel; *2* – zone of the channel rearrangement; *3* – inverse discharge channel

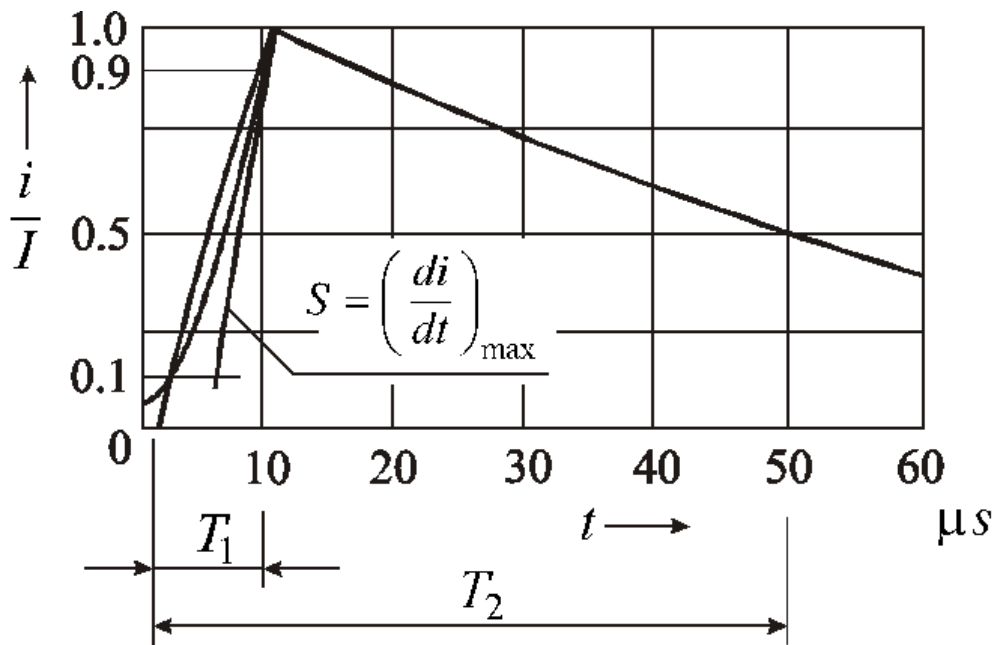


Figure 8.3 Idealized form of lightning current

After discharging, the leader (direct) channel obtains the ground potential and the movement of the inverse (main) channel, in which the lightning current amplitude can reach 200 kA, begins. Stages of the inverse discharge strike development and variation of the lightning current in time are shown in Fig. 8.2.

The ideal form of lightning current impulse is used in calculations of electromagnetic situation stipulated by the lightning (Fig. 8.3). The main parameters are the amplitude of inverse lightning current I , maximum current growth rate (or maximum steepness $S = (di/dt)_{max}$; impulse charge $Q = \int idt$; impulse of squared current on resistance of 1 Ohm (or specific energy), impulse front duration T_1 and impulse duration T_2 passing until the current value reduces to $I/2$. The parameter values are of stochastic nature and are approximately subject to a logarithmic normal law. Roughly, maximum values of the parameters are: $I = 200 \text{ kA}$, $S = 300 \frac{\text{A}}{\mu\text{s}}$, $Q = 100 \text{ C}$, $W = 10 \frac{\text{MJ}}{\Omega}$, $T_1 = 10 \mu\text{s}$, $T_2 = 55 \mu\text{s}$.

While the inverse current, the current of cloud-to-cloud discharge flowing and the leader development (direct current) the electromagnetic fields in the bands of high and ultrahigh frequencies are generated, which are serious source of radiated disturbances. These electromagnetic disturbances are not considered at the analysis of electromagnetic compatibility in power supply systems. The main type of electromagnetic interference is overvoltage.

8.2. Initiation and development of lightning overvoltage

In the analysis of lightning overvoltage the events of lightning strike near a line or to one of its element are considered. In the first case, induced overvoltage generated, which rarely exceed 200 kV. In the second case, direct overvoltage takes place, which is much larger than the induced ones. Direct overvoltage depends on a line structure and on the element being hit.

As a rule the following four cases are considered (Fig.8.4):

1. Lightning strike to operating wire having wave impedance Z (Fig. 8.4, *a*). Lightning current I_{lgh} is divided into two equal parts to which the voltage $U'_1 = 0.5ZI_{lgh}$ is related. At wave impedance $z = 500 \text{ Ohm}$ and mean value $I_{lgh} = 25 \text{ kA}$ the voltage $U'_1 = 6.25 \text{ MV}$. High voltage line insulation cannot withstand such a voltage.

2. Lightning strike to the lightning arrester with wave impedance Z_1 at some distance from a transmission tower (Fig. 8.4, *b*). The voltage on a hit wire equals $U'_2 = kU'_1$ where k is the coefficient of inductive coupling between the wires. Voltage across the line insulation can be found as their difference as $U_{12} = (1 - k)U'_1$. If U_{12} is higher than the insulation with stand voltage, the voltage surge from the grounded part to the insulated one occurs. This surge is often called the inverse surge.

3. Lightning strike to the vertex of the line support not having a lightning arrester (Fig. 8.4, c). The problem reduces to calculation of the voltage on the upper part of the support with the use either the method of multiple wave reflection on its edges or to use of the simplified dependence $U_W = R_S I_{lgh} + L_S \left(\frac{di_{lgh}}{dt} \right)_{max}$, where R_S and L_S are resistance and inductive reactance of the support grounding, I_{lgh} is rms value of the lightning current i_{lgh} . Under this voltage influence the inverse voltage surge on the insulated line can occur if insulation withstand voltage U_i is not exceeded. From comparison U_W and U_i the greatest value of grounding resistance R_S , at which occurrence of inverse surge is excluded, is determined.

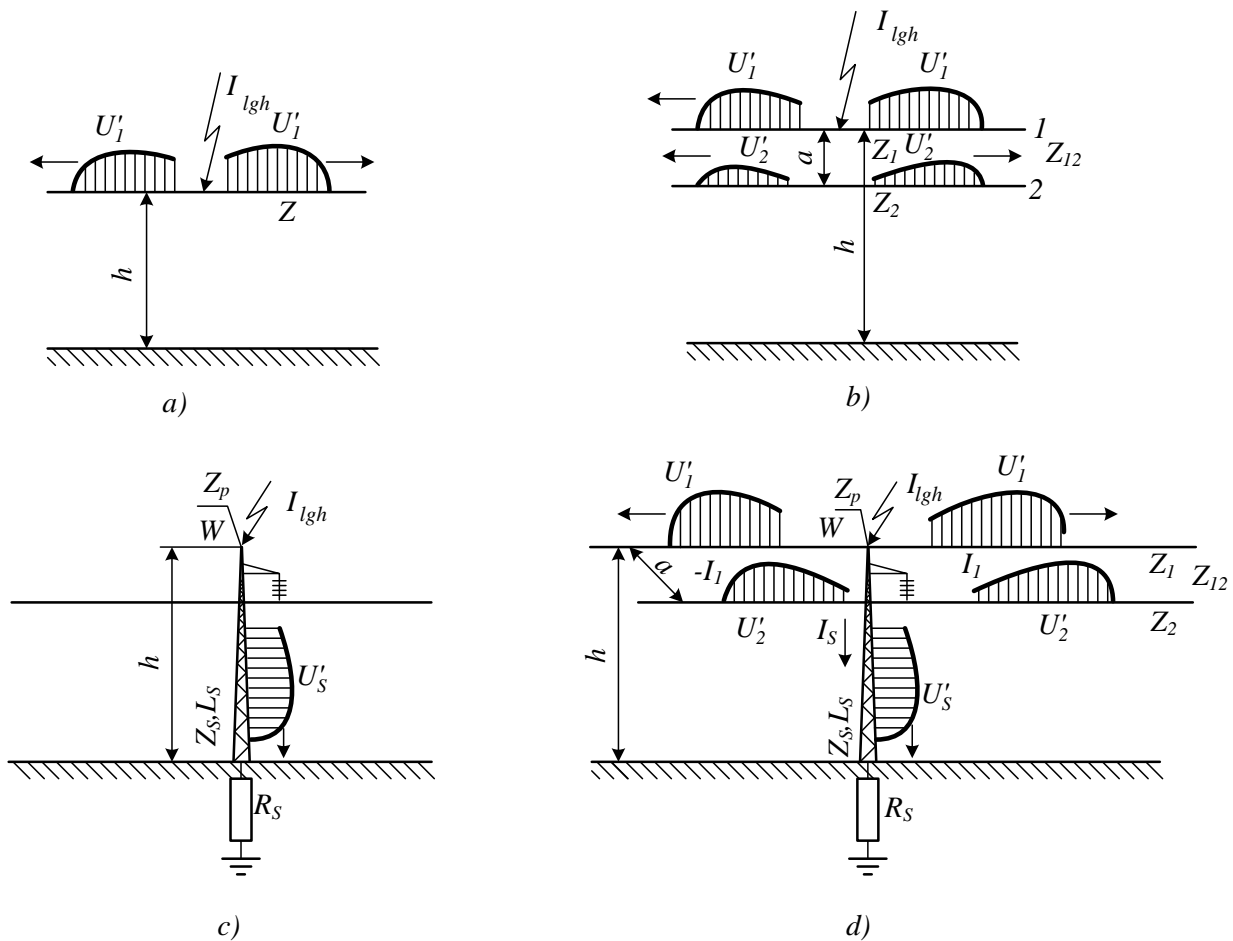


Figure 8.4 Formation of overvoltage at the lightning stroke to overhead line conductor (a), to wire of lightning protection (b); to tower without protection wire (c); to tower with protection wire (d)

4. Lightning strike to the vertex of the line support having a lightning arrester (Fig. 8.4, d). The line current is divided in two parts -the current in the arrester $I_1 = \frac{Z_s}{Z_1 + 2Z_s} I_{lgh}$ (in practice $I_1 \cong 0.2 I_{lgh}$) and the current in the support $I_s = \frac{Z_1}{Z_1 + 2Z_s} I_{lgh}$ (usually $I_s \cong 0.6 I_{lgh}$). For calculation of the voltage on the support top, the method of multiple wave reflection as in the previous case can be used. But in

practice the method of the pole wave impedance Z_S and/or the lightning arrester impedance $Z_1/2$ exclusion in accordance with design diagrams is applied.

Taking into account that $L_S = l_S \frac{Z_S}{v}$, where l_S is the support height and v is the speed of current i_{lgh} wave, the voltage across line insulation at rms current I_{lgh} may be represented with the following simplified dependence:

$$U_{12} = (1 - k) \left[R_S I_S + L_S \left(\frac{di_S}{dt} \right)_{max} \right].$$

At a known line insulation strength this dependence allows to find maximum resistance R_S , which further increase can cause a voltage surge on the line insulation and, possibly, the line turn-off.

Occurrence and influence of geomagnetic phenomena in north areas located near the magnetic pole of the Earth have specific features.

Geomagnetic storms in the northern hemisphere in the region of the magnetic north pole occur during periods of solar activity. During the storms electric field is formed on the ground surface which with the gradient reaches 2 V/m and current frequency from 0.001 to 0.1 Hz. Amplitude of geomagnetic currents can reach several hundred amperes. Essentially geomagnetic current is quasi-permanent or permanent. Flow of such a current in windings of transformers or autotransformers with dead-grounded neutral leads to significant increase of the magnetizing current and harmonics magnitude, the third harmonic magnitude first of all. As a consequence, the overloading of power equipment elements occurs, false operations of relay protection and control systems can take place. On actuation of blocking against hunting the lines turn-off can occur. Increase of the leakage flux and additional losses in a transformer results in its windings and constructional elements overheating, and insulation degradation. At this, the transformer service life period is reduced.

8.3. Means of overvoltage protection

Levels of insulation in networks of 3-35 kV provide enough reliability under influence of internal overvoltage. Therefore, the main problem to be solved is lightning protection. The main measure for improvement of power supply system lightning protection is application of ungrounded or compensated neutral system and also use of auto-reclosing. The latter promotes elimination of interphase and several phase flashover consequences.

According to Electrical Code internal overvoltage protection is not required in networks of 110-220 kV as well. Main lightning protection means are lightning rods, conductors with power transmission poles grounding, discharge arresters and overvoltage suppressors.

Main element of the discharge arrester is the protective spark gap that separates the current-carrying elements of an electric installation from the ground loop. At

overvoltage the breakdown of protective spark gap occurs and the overvoltage wave tail takes the form shown in Fig. 8.5. Limitation the overvoltage first takes place to the voltage level of protective spark gap breakdown U_z and then to the voltage level U_0 stipulated by the voltage drop on the arrester path impedance Z .

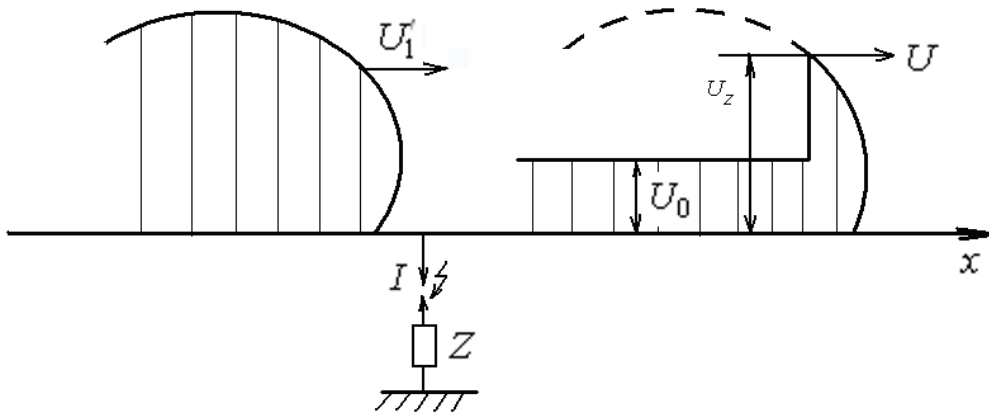


Figure 8.5 Impact of spark gap operation on voltage level change

For safe overvoltage reduction the discharge voltage-time curve of the protective spark gap (e.g. dependence of breakdown time on the voltage applied) should not be higher than the voltage-time curve of the protected insulation (Fig. 8.6). However, at short prestrike time ($t_1 \leq 2\mu s$), the insulation can become non-protected. The insulation turns to be unprotected. At the spark gap break down, short-circuit current flows through the arc. In major cases, it cannot die out spontaneously. At this, undesirable dynamic impacts affect the electric equipment.

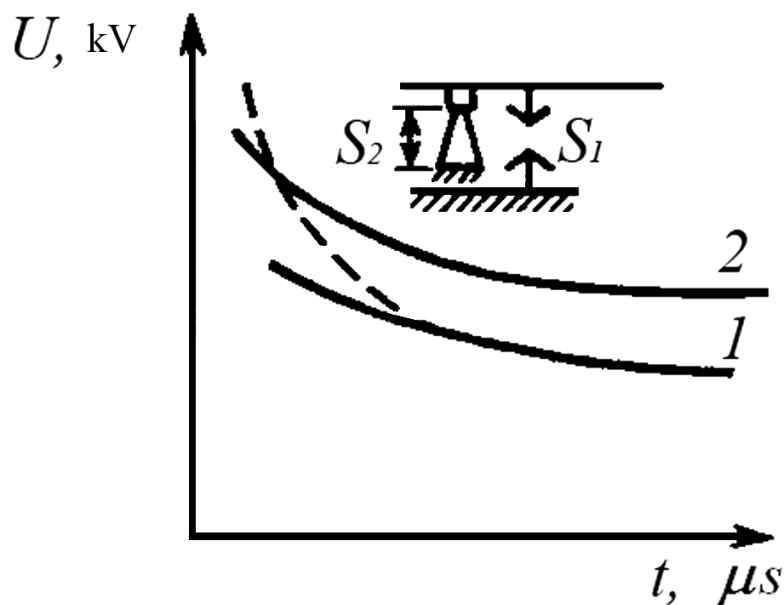


Figure 8.6 Voltage-time curve of arrester and protected insulation:
 1—arrester impulse response; 2- insulation impulse response

This effect is eliminated at the arc forced quenching, for what the protective gap is placed into the tube I made of gas-generating material such as ebonite, fiber etc. (Fig. 8.7). Such an arrester is called the expulsion-type surge arrester. The expulsion-type surge arrester has external S_1 and internal S_2 spark gaps. The gap S_2 , located between the rod electrode 2 and the ring electrode 3, provides the arc quenching, and the gap S_1 serves to separate the tube from the network.

After the gaps S_1 and S_2 breakdown, the lightning impulse current and short circuit current of base frequency flow through them. At the first passing of the current through zero value the ark dies. Non-stability of the voltage-time curves and rapid wear of gas-generating materials, stipulating high maintenance expenses, are the significant disadvantages of an expulsion-type surge arrester.

Valve arresters are widespread in high-voltage power networks. They consist of spark gaps and non-linear resistances connected in series (Fig. 8.8). In many cases shunting resistors or capacitors are connected in-parallel to spark gaps, that allows to control the voltage distribution between great number of spark gaps connected in series.

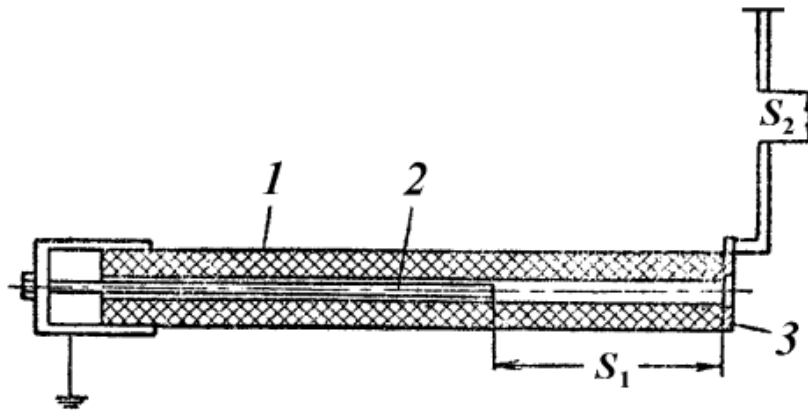


Figure 8.7 Expulsion-type surge arrester design: I – gas-generating tube; 2 – stick electrode; 3 – ring electrode; S_1 – internal spark gap; S_2 – external spark gap

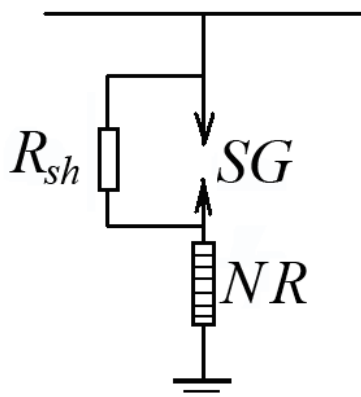


Figure 8.8 Schematic circuit of valve arrester: SG – spark gap; NR – non-linear resistance; R_{sh} – shunting resistance

In the circuits of valve arresters are used spark gaps with the fixed arc of concomitant current (short circuit current of the basic frequency), spark gaps with the arc rotating under the influence of the magnetic field and spark gaps with stretching out arc. In this case the protective factor of a discharger is $k_p = 2 \dots 3$.

Here

$$k_p = U_{res}/(2U_d)$$

where U_{res} is amplitude of the voltage remaining on a discharger when impulse current flows through it; U_d is rms value of the blanking voltage of the discharger concomitant current.

Valve discharger resistance should have nonlinear characteristic and able to pass impulse and concomitant currents repeatedly. At impulse current, its resistance should be minimal and vice a versa it should be maximal at arc extinction voltage with the purpose of concomitant current restriction. These requirements are met with nonlinear resistances made of materials based on carborundum SiC (binding materials are vilite or tervite). Volt-ampere curve of such an arrester is characterized by the static dependence having the form of:

$$U = CI^\alpha$$

Where C is the constant, dependent on material properties and nonlinear resistance dimensions; α is the nonlinearity factor.

In the area of high (impulse) currents $\alpha = 0.1-0.25$, in the area of the concomitant currents of lightning discharges and most currents of switching overvoltage $\alpha = 0.28-0.38$. Widely used valve arresters with nonlinear resistance on the base of silicone carbide do not allow limit overvoltage level to $2U_{ph}$ as a consequence of insufficient nonlinearity of material.

Further improvement of the protective characteristics of dischargers is attained with the giving-up of spark gaps use and transition to nonlinear resistances with more strongly expressed volt-ampere characteristic nonlinearity ($\alpha \leq 0.1$). These requirements are met with resistors from semiconducting material based on zinc oxide – varistors. Protective devices made of such resistors are called the nonlinear overvoltage suppressors.

8.4. Overvoltage protection of electric installations

Overvoltage protection of electric installation is based on rational use of the described technical means of lightning protection and their appropriate disposal in power supply system taking into account the required distance between them and protected elements of power equipment according to directive documents (operational code for electrical installations and others).

Requirements of these documents are somewhat different in different countries relative arrester types application and admissible distances, what is reasonably

explained in view of diverse intensity of thunderstorm activity in different latitudes. But general principles of thunderstorm protection system structure are basically identical. From these considerations, problems of overhead lines and electrical substations protection against lightning overvoltage are discussed below.

In the networks with voltage to 1000 V valve dischargers are main and often the only means of overvoltage protection. They are used on transformer substations and in the all overhead lines connected to this substation with interval to 500m. On overhead lines dischargers are installed at the following points:

- of great number of using equipment with great total capacity;
- of long dead-ended lines or overhead lines connected with the help of cable lines;
- beside objects, containing inflammable or explosive materials;
- at location of equipment controlling street lighting.

On the approach to a transformer substation, the dischargers should be located as close as possible to a transformer or to a grounded support. Discharger ground resistance should be at most 100 Ω .

In the networks of medium voltage (to 110 kV), where the current of one-phase ground fault exceeds the current admissible according to the Operational Code for Electrical Installations, one of the main overvoltage protective means is neutral grounding with ground-fault neutralizer or resistance. To protect electric networks expulsion-type surge arresters are used in the cases of:

- transformers feeding exceptionally using equipment of low-voltage networks;
- overhead lines on approach to transformer substations ;
- connections of overhead lines on conductive (metallic) supports with overhead lines on nonconductive supports, and at connection of overhead lines with cable lines of voltage of 10 kV and higher;
- spans of transmission lines with increased support height.

Distance from a transformer to the discharger and to connection to grounding conductor should be as short as possible; the grounding resistance should be at most 15 Ω .

Valve arresters are also used (Fig. 8.9), in particular in the cases of:

- high-voltage feeding transformers with $U_r > 110$ kV;
- switching devices with the voltage $U_r < 110$ kV at substations with $U_r > 110$ kV;
- connections of HV lines with cable lines with $U_r < 10$ kV;
- external installation of oil tanks and other containers, when solid grounding of the transformer neutral is not applied;
- transformers under no-load conditions or not connected to buses and cables longer than 100 m if other windings are protected with valve arresters.

At protection of substation equipment and in particular transformer windings the shortest distance from the arrester to appropriate devices is provided. Otherwise significant overvoltage on protected equipment in comparison with the voltage across arrester can occur. The arresters grounding resistance should not exceed 10 Ohm.

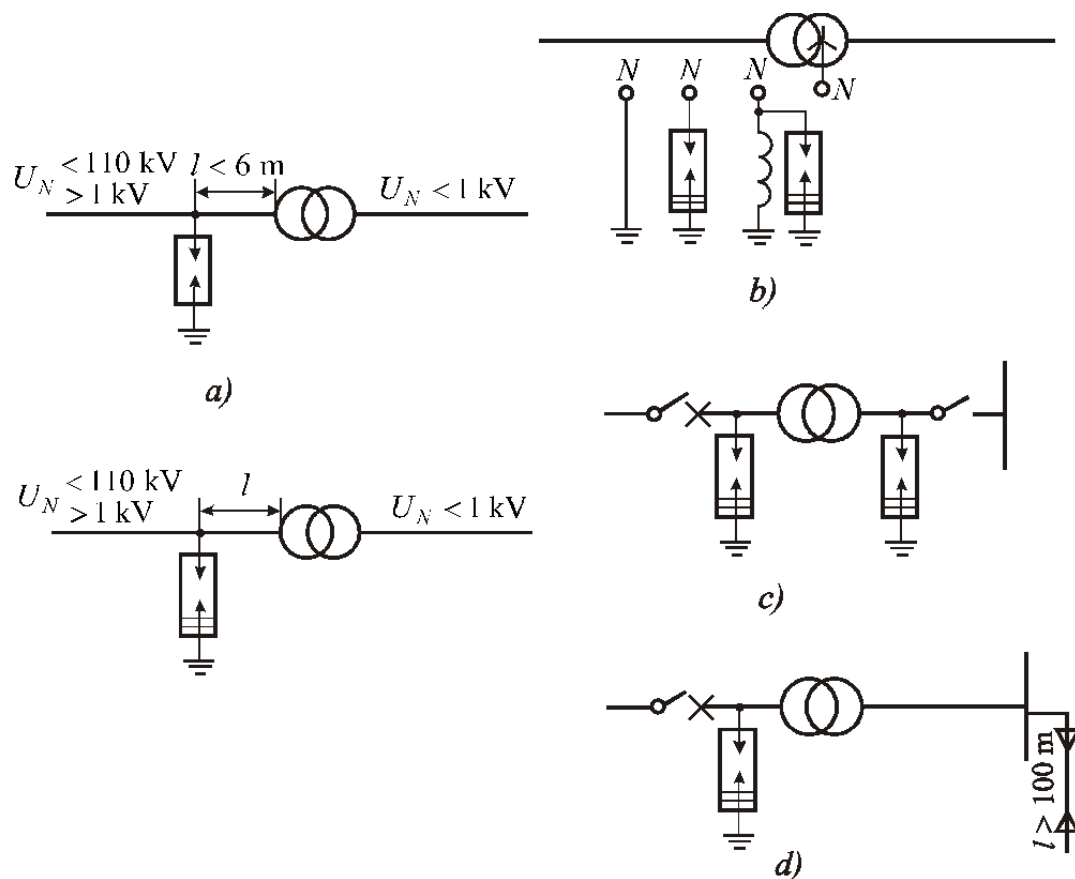


Figure 8.9 Examples of dischargers use for transformer protection: with expulsion-type surge arrester or valve arrester(a); in resonant earthed system with containers (tanks) installed outside (b); winding of the transformer under no-load condition (c); connected from outside with the help of bus-bars and cables longer than 100 m (d)

Direct lightning stroke protection of medium voltage overhead lines by means of lightning wires is not in use. Quite good solution is zone protection of substations at transformer capacity more than 1.6 MVA.

Oil tanks and other containers can be installed on substations constructions except the transformer portals, from which they should be moved aside for not less than 3 m and must be grounded.

In the networks with voltage of 110 kV and higher efficient neutral grounding is used. Overhead lines are protected from lightning strokes with the help of one or two lightning protective wires along the entire length; the wires should be grounded on each the line tower.

For limiting overvoltage, the resistances of towers grounding should be within 10-20 Ohm depending on resistance of soil $\rho \geq 1000$ Ohm.

In the networks with voltage higher than 110 kV valve dischargers are used for protection of:

- transformer windings at the distance l according to Operational Code for Electrical Installations ;

- capacitors of outside installation in the networks where the neutral dead grounding is not provided;
 - overhead lines connection with cable lines;
 - switchgears with voltage $U_r \geq 400$ kV around the perimeter, regardless availability of dischargers protecting transformers.
- Grounding resistance of valve arresters must not exceed 10 Ohm.

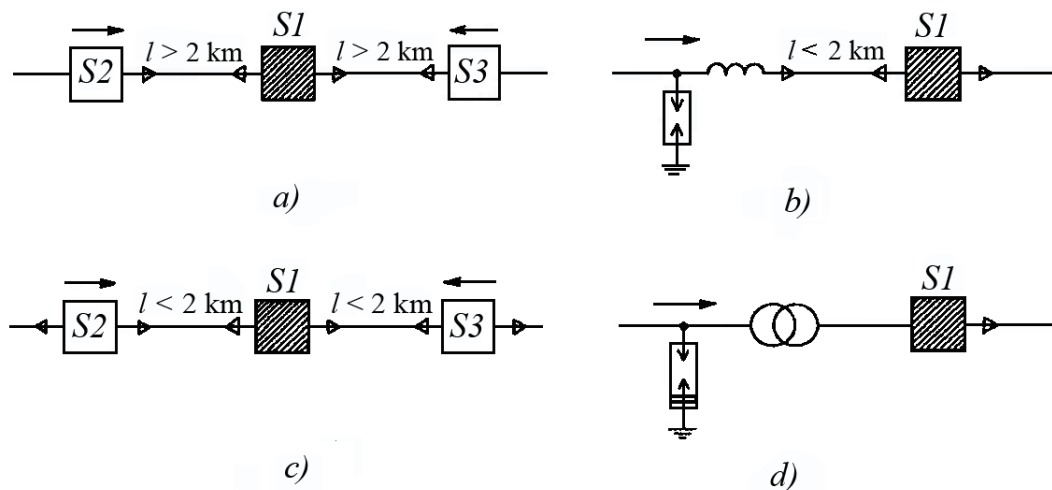


Figure 8.10 Cases when substation S_1 protection against waves arriving from overhead lines is not required: overhead lines come to substations S_2 and S_3 (a); cable lines come to S_2 and S_3 (b); cable is protected with reactance coil (c); substation S_1 is connected with overhead line by protected transformer (d)

Expulsion-type surge arresters or spark gaps dischargers are used to protect longitudinal line segments, which have not reinforced insulation, or old overhead lines without protective wires. Spark gap dischargers are also intended for protection of switchgears of 110 kV against overvoltage, coming from overhead lines directly or through a protected approach. Fig. 8.10 presents the cases when there is no need in overvoltage protection on the substation S_1 .

Test questions

1. What is the lightning?
2. Specify the stages of inverse striking development.
3. What are lightning current parameters used in the calculations of the electromagnetic situation?
4. Explain the overvoltage occurrence in the case of lightning strike.
5. How is the occurrence and effect of geomagnetic actions defined?
6. Name the means of overvoltage protection.

7. Draw the voltage-time curve of a discharger.
8. What is construction of expulsion-type surge arrester?
9. Describe use of arresters (dischargers) for transformer protection.
10. When is substation protection against arriving waves not required?

Topics for essay

1. Appearance and development of lightning discharges.
2. Modern devices for overvoltage protection.
3. Methods and means of overvoltage protection.
4. Idealized form and parameters of lightning impulse.
5. Substations protection from arriving overvoltage waves.

9.1. Electromagnetic situation at sites of power supply systems

Under current conditions powerful non-linear electrical and electronic devices are used at industrial enterprises, transport and in household. They significantly distort electromagnetic situation. At this, values of electric E and magnetic H field strength can essentially exceed values typical for natural conditions, being a factor of negative impact on human well-being and health. The problem of electromagnetic compatibility under the given conditions as ecological problem of electric, magnetic and electromagnetic fields influence on biological objects is investigated, and recommendations have been worked out by such organizations as World Health Organization (WHO), International Electrotechnical Commission, CENTLEC .etc.

Electromagnetic situation is characterized by the values of magnetic H and electric E field strength. Results of numerous studies of the fields influence on human being state show that current density in the human body is considered to be safe at value about 10 ma/m^2 with frequency 50 Hz that corresponds to external fields parameters $E = 20 \text{ kV/m}$ and $H = 4 \text{ kA/m}$. Athigh frequencies plane electromagnetic wave effect have to be considered.

Electromagnetic situation is divided into natural and artificial, stipulated by the operation of various technical means. The fields of natural and artificial origin overlap and effects of vectors \vec{E} and \vec{H} are totalized. Fig. 9.1 and Table 9.1 present typical strength values of electric and magnetic fields on sites of power supply systems. The field limiting values perceived by human and causing heart disorder are given in the table.

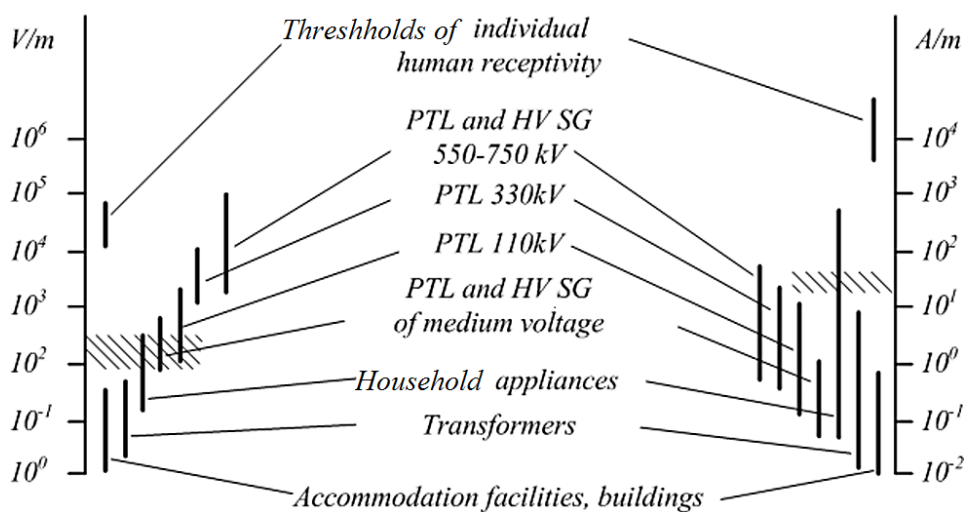


Figure 9.1 Typical strength values of electric and magnetic fields of commercial frequency

It follows from the data of Fig. 9.1 and Table 9.1 that at commercial frequency strong electric fields are caused by overhead lines, transformers, high voltage apparatuses and bus-bars of switchyards. At higher frequency electric fields have relatively low strength values.

Table 9.1

Electromagnetic situation on the objects of electrical energy industry

| Objects and parameters | Strength of electric field, V/m | Strength of magnetic field, A/m |
|---|---------------------------------|---------------------------------|
| HV switchgear 500, 750 kV | $10^3-5 \cdot 10^4$ | 10–100 |
| Overhead line 380 kV | 10^3-10^4 | 1–40 |
| Overhead line 330 kV | $10^3-5 \cdot 10^3$ | 10–100 |
| Overhead line 110 kV | $10^2-3 \cdot 10^3$ | 0.1–20 |
| Overhead line 6–35 kV | $10-5 \cdot 10^2$ | 0.1–2 |
| Bus-bar bridge 6 kV | 10^3 | 40–100 |
| Indoor switchgear 6 kV | – | 200 |
| Accommodation facilities, buildings | 1–100 | 0.01–0.5 |
| Electrical household appliances | 5–500 | 0.1–300 |
| Individual receptivity threshold | $10^4-2 \cdot 10^4$ | $3 \cdot 10^3-3 \cdot 10^4$ |
| Threshold of heart rhythm disturbances | $5 \cdot 10^7$ | 10^6 |
| Electric strength of air-gaps | $5 \cdot 10^5-3 \cdot 10^6$ | - |
| Design and experimental secure field strength on the condition of body cells stimulation | $2 \cdot 10^4$ | $4 \cdot 10^3$ |
| Normative field strength according to WHO and IRPA taking into account potential effect on organism | $5 \cdot 10^3$ | 80 |
| The same according to DIN VDE | $7 \cdot 10^3$ | 320 |

Near overhead lines 220kV and higher, value of electric field strength can reach human receptivity threshold (hair stirring sensation, tingling in the time of micro-discharges between body and clothes etc.). At frequency of 50 Hz the magnetic field strength can be rather high if overhead line, powerful transformers and other electrical devices are located close to the place.

Electromagnetic situation distortion caused by household appliances is as a rule insignificant.

At working places and power supply system objects values of electric and magnetic fields strength can exceed values of natural origin by dozens of times.

9.2. Features of electromagnetic interference influence on human body

Electromagnetic field influence on human being is stipulated by the currents induced in a body which bring not only the change of the potential difference between outer and inner surface of cell membrane but also the living tissues temperature rise.

Magnetic field influence depending on frequency is illustrated by Fig. 9.2. The threshold of magnetic field sensation is presented by curve 2. At field strength higher than 10^5 A/m sight abnormalities, disease state and cephalalgia occur (curve 3).

Nearly 5 % of people can perceive the presence of electric field of commercial frequency with intensity $E = 7$ kV/m while 60 % cannot feel influence of the field with the strength up to 20 kV/m, i.e. field perception is exclusively individual.

Temperature rise of tissues is stipulated by capacitive or induction currents flow in them. Temperature increase of 1 C° is considered to be safe, it corresponds to specific power equal to 4 Wper1 kg of body mass. Such power value can take place at the external electric field of strength $E = 4$ MV/m or at external magnetic field of strength $H = 50$ MA/mat frequency of 50 Hz. It is seen that at frequency of 50 Hz, the values of electromagnetic field strength, at which tissue temperature rises by 1°C , is by some orders higher than the threshold of human receptiveness. In the case of high frequencies the situation looks different as induced currents increase with increase of the frequency (curve 6).

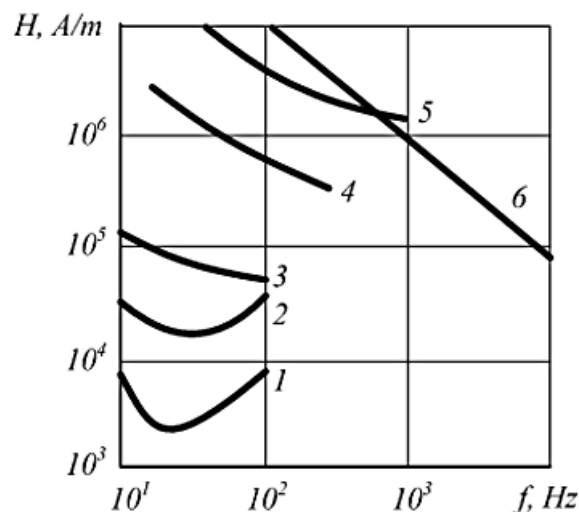


Figure 9.2 Effects on human of the magnetic field at different frequency: 1—twinkling on the peripheral area of visual field ; 2 – sensation of field presence; 3 — objectively registered sight abnormalities, ailment, cephalalgia; 4 — heart disorder; 5 - disorder of nervous system ; 6 - Joule heating of tissue at power 4 W/kg

Thus in low-frequency fields of high strength effect of the potential difference change on cell membrane prevails, at high-frequency in a field of high power the temperature rise influence prevails. Weak field influence on human body is being studied.

9.3. Regulation of safe values of electromagnetic field strength

The base of regulation of strength acceptable values is described above scientifically justified mechanisms of the fields influence on human. Basic quantity is safe current density in tissues: in the frequency band of 4–1000 Hz the acceptable value is 10 mA/m; at the frequency higher than 10 kHz the acceptable energy density is 4 W/kg. At commercial frequency this current density corresponds to external fields strength $E=20\text{kV/m}$ and $H=4\text{ kA/m}$. At regulation of acceptable strength values on working places and for population the safety factor is introduced.

Guidelines and standards, accepted in different countries are not consistent with each other and sometimes are considerably different. Nowadays the regulations ENV50166 by CENELEC are considered to be the most grounded and complete. In these regulations are, as the basic, accepted the following values of E at long-time exposure: for constant electric field - 42 kV/m, for alternating field with frequency of 0.1–4 Hz - 30kV/m, at frequency of 4–1000 Hz basic value of current density is taken equal 10 mA/m² that matches the strength values of 20kV/m and 4 kA/m.

The current in a human body, being in contact with subjects that are in electric field of commercial frequency, is also normalized: on working places it is accepted equal 3.5 mA, for population–1.5mA.

Requirements for limiting the values of E and H at 50 Hz on working places are subdivided into three categories: informing the staff concerning the field; measures on limitation for staying in the field; warning on dangerous working conditions.

Consider regulations of the field parameters at one of EU countries, for example, in Poland.

In Poland, “The Decree of Minister of Mines and Energy“ establishes acceptable strength of electric fields under overhead lines and within the territory of a substation. There are protective zones of the first level in which electric field strength exceeds 10 kV/m, and of the second level in which electric field strength is 1–10 kV/m. At substations, where movement of electrified equipment is possible, the electric field strength up to 15 kV/m is allowed, and up to 20 kV/m - in special cases. In Polish switchgears of 400 kV the electric field strength does not as a rule exceed 15 kV/m and only in exceptional cases it reaches 20 kV/m. Allowable time of person staying in the zones with different values of electric field strength at 50 Hz is:

At $E \leq 1\text{ kV/m}$ there is no time limitation (residence-permissible zone);

at $1\text{ kV/m} < E \leq 10\text{ kV/m}$ —up to 8 hours a day;

at $10\text{ kV/m} < E \leq 20\text{ kV/m}$ —up to 2 hours a day or use of screens or protective clothing.

Measurement of undistorted field strength (i.e. without man’s presence) is made at the height of 1.8 m above the ground surface. In the case of working at greater height the electric field strength should be measured in the most unfavorable space zone where people have to work.

Allowable norms of magnetic field influence on people are defined only on working places. Three protective zones are discerned:

– safe zone, where strength of permanent magnetic field is less than 8 kA/m, variable magnetic field strength at frequency of 50 Hz is less than 0.4 kA/m. In this zone

personnel's staying is permitted up to 8 hours per day;

–zone of potential hazard, where intensity of permanent magnetic field is $8 \text{ kA/m} \leq H \leq 80 \text{ kA/m}$ and variable magnetic field strength at frequency of 50 Hz is in the limits of $0.4 \text{ kA/m} \leq H \leq 4 \text{ kA/m}$. The personnel staying in this zone is limited to 8 hours;

– dangerous zone, where the strength of permanent magnetic field exceeds 80 kA/m, the strength of magnetic field at 50 Hz is 40 kA/m; staying in this zone is prohibited.

9.4. Shielding against magnetic fields

One of the ways of protection against electromagnetic field interference is the use of protective shields. There are following types of shields:

- 1) shield of two parallel plates;
- 2) cylindrical screen;
- 3) spherical screen.

Consider in more details problems of application and designing of electromagnetic shields.

Shield of two parallel plates

is shown in Fig. 9.3. The shielded space is the area between the two plates. Edges of shield plates are connected by transverse walls, so the current in these plates can flow around the shielded area.

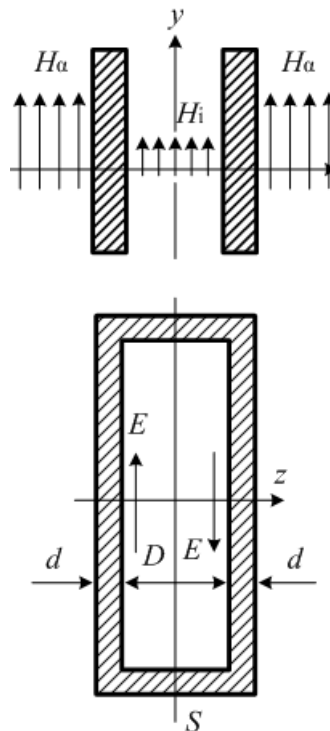


Figure 9.3 The shield of two parallel plates

At the shield inner space the field is uniform. The shield impact is characterized by the quantity S_H called the shielding factor:

$$S_H = 20 \lg \frac{H_a}{H_i} = 20 \lg \frac{1}{Q}$$

where H_a and H_i are the magnetic strength values out and inside the shield.

The shield attenuation is defined by the expression:

$$b_Q = \ln \left| \frac{H_a}{H_i} \right| = \ln \frac{1}{|Q|}$$

It may be determined for high and low frequency ranges:

$$b_Q = \ln \left| \frac{H_a}{H_i} \right| \approx \begin{cases} \frac{1}{2} \ln \left[1 + \left(\frac{\omega \mu_0 \sigma D d}{2m} \right)^2 \right] \text{ for } d < \delta \text{ (low frequency)} \\ \frac{d}{\delta} + \ln \frac{\mu_0}{\mu} \cdot \frac{D}{2\sqrt{2}m\sigma} \text{ for } d > \delta \text{ (high frequency)} \end{cases} \quad (9.1)$$

where σ is specific conductivity of the shield material; D is the distance between the plates; d is the plates thickness; δ is the equivalent penetration of electromagnetic wave; μ is the relative permeability; $\mu_0 = 4\pi 10^{-9} \text{H/cm}$ is the magnetic constant.

The given formulae show that in all cases the shield attenuation is greater at greater distance between the plates, that is, at greater values of D . Fig. 9.4 shows the shield attenuation as dependence of frequency. The graphs show that at $d > \delta$ the value of b_Q sharply increases.

In the expressions (9.1) the factor m takes into account the shield shape: for cylindrical screen dimension D should be replaced with diameter and accepted $m = 2$; for spherical screen $m = 3$; for plain screen $m = 1$.

In practical calculations the screen thickness according to (9.1) can be determined from the formula:

$$d = \begin{cases} \frac{\mu}{\mu_0} \frac{m\delta^2}{D} \sqrt{e^{2b_s} - 1} = \frac{2m\sqrt{e^{2b_s} - 1}}{\omega \mu_0 \sigma D} \text{ for } d \leq \delta \\ \delta \left[b_s - \ln \frac{1}{2\sqrt{2}} \frac{\mu_0}{\mu} \frac{D}{m\sigma} \right] \text{ for } d > \delta \end{cases}$$

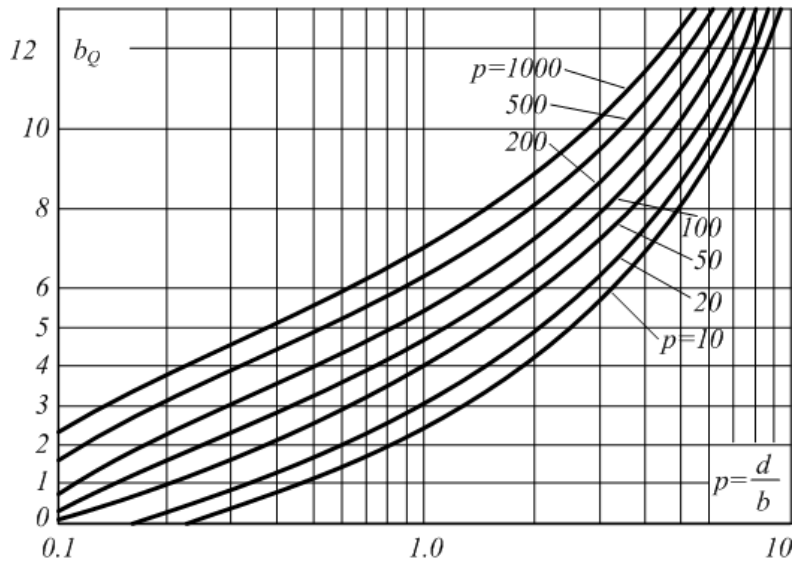


Figure 9.4 Shield attenuation for cylindrical and plain screens

In the case of great shield attenuation ($b_Q > 1$) the lower expression is always recommended, as it corresponds with phenomenon of skin effect.

Fig. 9.5 represents the graphs, by means of which the shield parameters can be obtained at given shield attenuation, taking for plain screen $m = 1$. D_S is the distance between plates or screen diameter respectively.

In consequence of the fact that field direction is parallel to the shield surface shielding factor is equal 1 at zero frequency. The same effect occurs for iron shield with high magnetic permeability ($\mu_0 \ll \mu$).

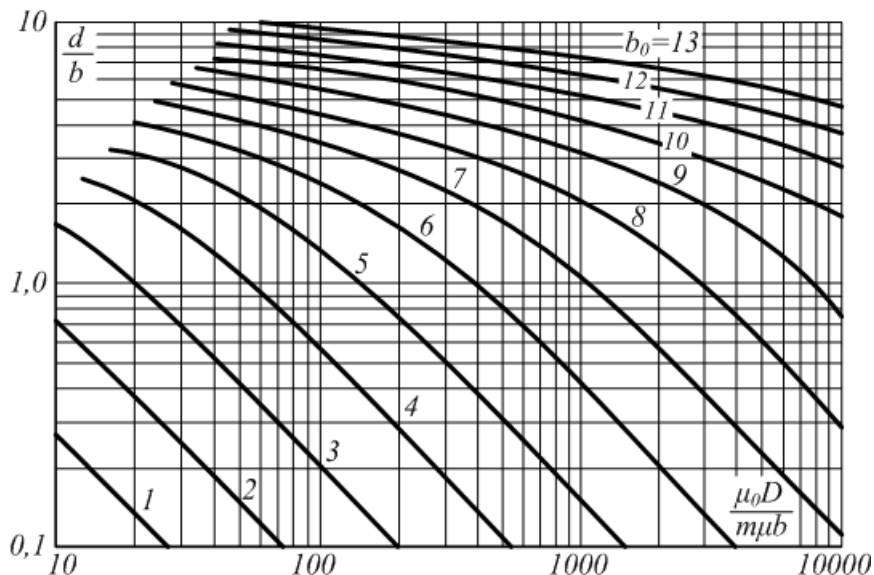


Figure 9.5 Determination of shield case thickness d for the given shield attenuation b_Q

Cylindrical screen (Fig. 9.6)

Electric field value E in the inner space of cylindrical screen, that is, in the longitudinal field

$$E = -j\omega\mu_0 H_i \frac{R}{2}$$

For the cylindrical screen the quantity $Q = H_i/H_a$ is three times greater and the shield attenuation is 0.7 times less than for the plain screen.

The thicker is shield and the greater is magnetic permeability μ , the less is H_i/H_a , and therefore shielding is more effective. With the frequency increase the iron shield would behave as an electromagnetic shield because at high frequency the effective section of the shield walls is insufficient due to skin effect.

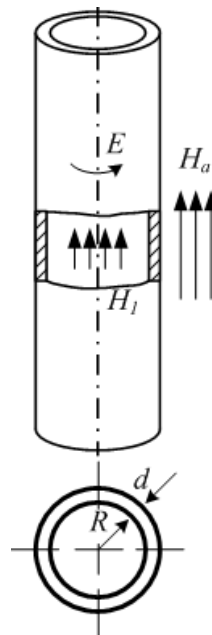


Figure 9.6 Cylindrical shield in axially directed field

Thin-shelled spherical shield

Spherical shell is the simplest screen type all three dimensions of which are finite. Most of closed shields of various shapes can be approximately replaced with spherical shield. Thus the cylindrical closed shield with the diameter of lateral section equal to the shield height can be approximately replaced with a spherical shield. Equivalent spherical shield should have walls of the same thickness and approximately equal volume.

In a spherical shield the field inside it is also uniform and for calculation it is enough to know the value of Q :

$$Q = \frac{1}{1 + \frac{2}{3} \frac{\mu}{\mu_0} \frac{d}{R}}$$

Value Q at the same wall thickness d and the same radius R appears to be rather less than of the cylindrical shield.

At frequency increase spherical shield behaves like a cylindrical one.

Values of Q for plain, cylindrical and spherical shields are in proportion of 1: 2: 3 in the case of their walls thicknesses and radiuses equalities.

Thus the shields of these types have different shielding effect. Shields of different types can be replaced with the most suitable equivalent shield of one of the three types with sufficient accuracy. At this, it is important that the shield wall thickness remained invariable as it is related to characteristics of shield action by exponential dependence.

Fig. 9.7 – 9.9 show the graphs of acceptable values of field strength, determined according to the regulations VDE 0848.

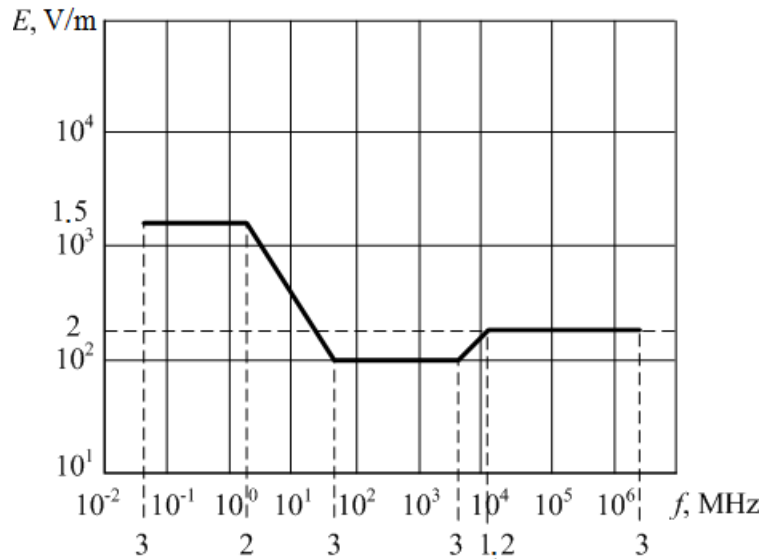


Figure 9.7 Limiting effective value of allowable strength of high frequency electric fields (VDE 0848)

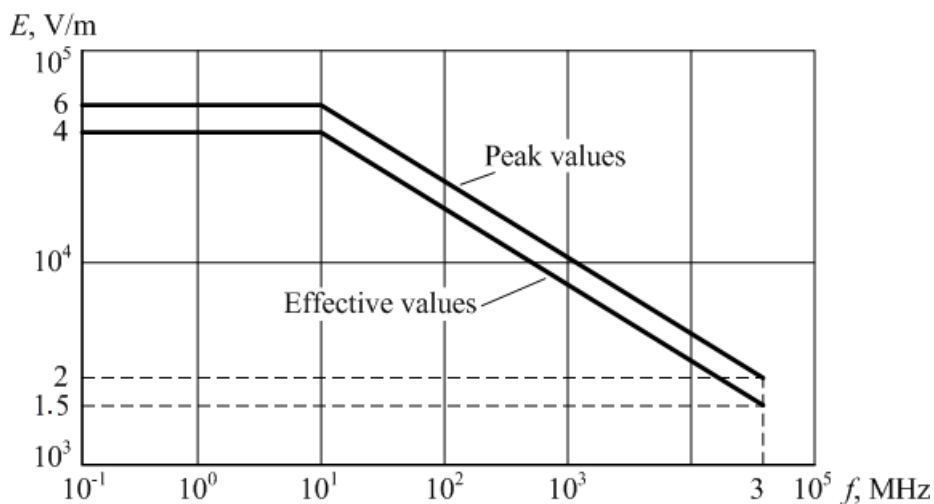


Figure 9.8 Allowable effective and peak values of low frequency electric fields strength at immediate impact

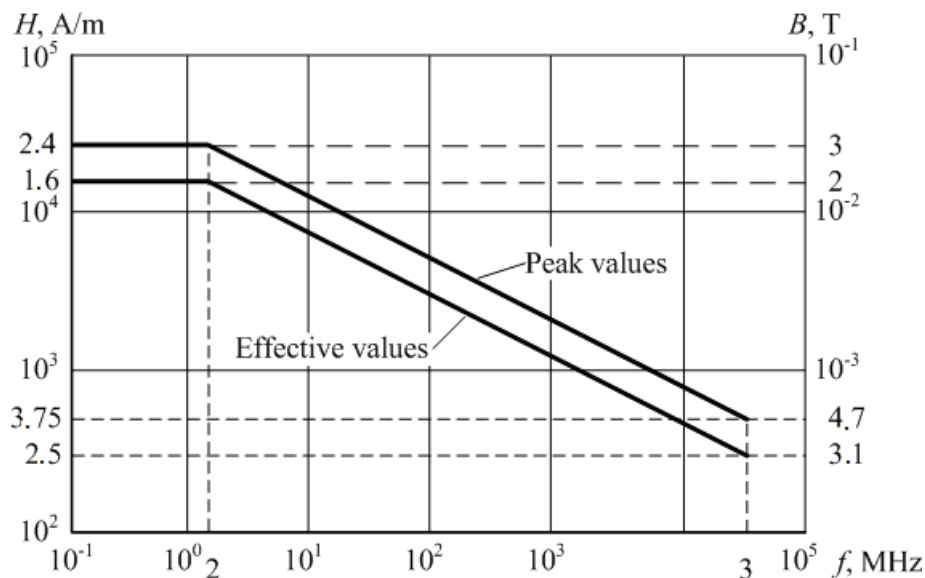


Figure 9.9 Allowable effective and peak values of low frequency magnetic fields strength

9.5. Grounding

Structure and types of grounding

Grounding is intended for maintaining of low (safe for people) potential (voltage) at some object.

In practice the following types of grounding, that is, intentional connection to the ground are used.

The working grounding is intended to insure normal operation of electrical installation or its components in selected for them operating conditions. To this type grounding of neutrals of power and instrument transformers are referred. In the case of the grounded neutral, insulation is selected by the phase voltage, in the case of insulated neutral it is selected by the line- to-line voltage. Due to this, safety of service and operation is increased as selectivity of relay protection operation is provided by means of grounding.

The protective grounding is grounding of all metal parts of an installation (enclosures, framings, driving gears, protection guarding, supporting and assembly structures), that normally are not alive but can turn to be alive in the case of insulation failure. Protective grounding is intended to increase of operating safety and reduce possibility of electric injury of humans and animals. Obviously operating safety is provided only in the case of properly designed and implemented constructions of protective grounding, use of personal protective means and fulfillment of the requirements of safety instructions.

The lightning protection grounding is grounding of lightning rods, lightning protective wires and discharge arresters intended to provide safe drainage of the lightning discharge current to the ground and minimization of the induced lightning overvoltage level. Grounding is carried out as concentrated one or with current spreading in several directions.

In all the cases implementation of above indicated measures is aimed to carrying out the requirement of reduction of voltage on the grounded electric equipment admissible values at previously envisaged adverse situations and also of properly selected grounding placement. Resistance between the ground conductor and the ground is the resistance of ground connection. Evidently, the resistance of ground connection R_g must obey the condition:

$$R_g \leq \frac{\delta U_g}{I_z} \Omega \cdot \text{m}$$

Where δU_g is the admissible steady-state value of the voltage on grounding conductor (commonly 65 V or 130 V); I_z is possible (by calculation) maximum steady-state value of current flowing through the ground electrode.

The grounding (the grounding system) consists of grounding conductors and strips, connecting contacts and the ground electrodes. Ground electrodes are in direct contact with the ground and are the main part of the grounding.

According to “Electric Installation Code”, the value of R_g must be:

- In systems with solidly grounded neutral

$$R_g \leq 0.5 \Omega$$

- In systems with isolated neutral

$$R_g \leq \frac{250}{I} \Omega$$

if the grounding is used only for high-voltage installations, and

$$R_g \leq \frac{125}{I} \Omega,$$

but its value must be accepted not less than 10 Ω .

The design current I in the installations without compensating devices is the output current of single- phase-to-ground fault:

$$I = 3U_{av}\omega C$$

where C is phase to ground capacitance, μF .

Fig. 9.10 presents the equivalent circuit of a ground electrode in the soil having resistivity $\rho \leq 5 \cdot 10^3 \Omega\text{m}$ for the case when in the capacity of the grounding electrodes both vertical rods and horizontal strips with inductivity L and conductivity g per unit length are used.

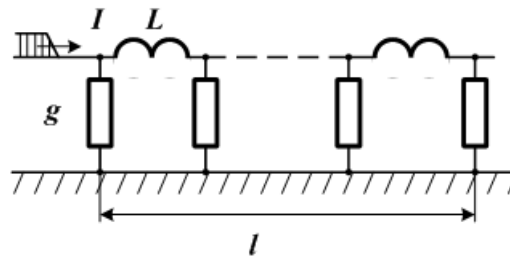


Figure 9.10 Equivalent circuit of grounding system

Conductivity g is associated with resistance R_g by simple relation:

$$g = \frac{1}{R_g l}$$

Transient period in the ground electrode is $T = gLl^2$. The static (for working and protective grounding) and impulse (for lightning protection grounding) ground electrodes resistance are distinguished. Ratio of impulse to static ground resistance is

$$\alpha_{imp} = Z_{imp}/R_g$$

where Z_{imp} is the impedance of the ground electrode at the instant of peak lightning current.

There are natural groundings (pipe lines, foundations, etc.), situated in the soil not with the aim of grounding, and artificial groundings (vertical or horizontal rods, or horizontal rods, tubes, plates and strips), placed into the soil especially for grounding.

Types of grounding conductors

Several types of grounding conductors are presented in Fig. 9.11. Simplified expressions of the ground connection resistance R_g can be obtained for these types of conductors.

For instance, in the case of conductor shown in Fig. 9.11, a, resistance of half-circular part of the soil of average radius x and thickness dx at the soil specific resistance ρ can be presented by the dependence:

$$dR_g = \frac{\rho}{2\pi x^2} dx.$$

Integrating in the limits of $x = r$ to $x = \infty$, we get:

$$R_g = \frac{\rho}{2\pi r}.$$

For other types of grounding conductors it is done in the same way, though calculations can be more complicated. Their simplified results are given in Table 9.2.

At n separate grounding conductors having resistance R_g their mutual influence takes place. In this case equivalent resistance of grounding conductors:

$$R_{g\Sigma} = R_g/\eta^n$$

where η is the grounding conductor utilization factor ($\eta < 1$).

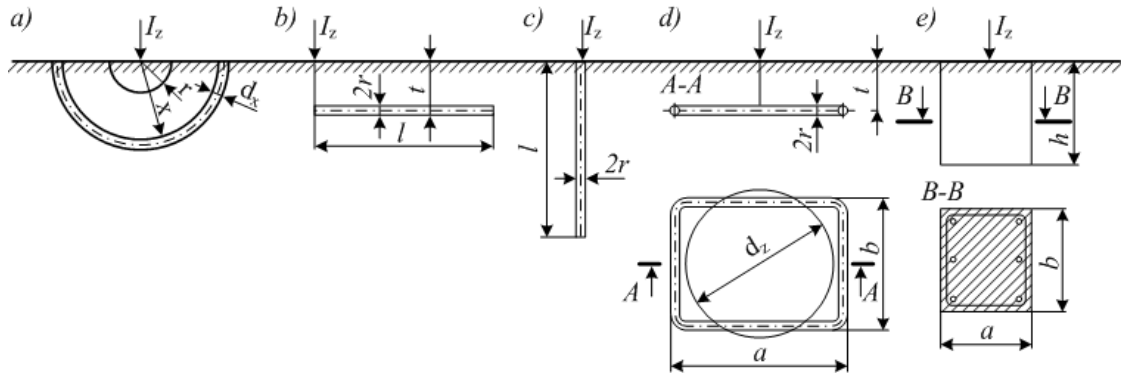


Figure 9.11 Different types of grounding conductors: half-circular (a); horizontal (b); vertical (c); circular (d); basement type (e).

This factor depends on distance between separate rods. Appropriate example is given in Fig. 9.12.

Table 9.2

Simplified expressions of grounding resistance for different conductors

| Types of grounding conductors | Expressions of R_g | Note |
|-------------------------------|---|--|
| Half-circular (Fig. 9.11, a) | $\frac{\rho}{2\pi r}$ | — |
| Horizontal (Fig. 9.11, b) | $\frac{\rho}{\pi l} \ln \frac{l}{r}; \frac{2\rho}{l}$ | For $l = 0.5 \div 1\text{m}$ |
| Vertical (Fig. 9.11, c) | $\frac{\rho}{2\pi l} \ln \frac{l}{r}; \frac{\rho}{l}$ | — |
| Circular (Fig. 9.11, d) | $\frac{\rho}{\pi^2 d_z} \ln \frac{d_z}{r}; \frac{2\rho}{d_z}$ | $d_z = \sqrt{\frac{4ab}{\pi}}$ For $l = 0.5 \div 1\text{m}$ |
| Basement (Fig. 9.11, e) | $\frac{\rho}{2\pi r}$ | $r = 0.8 \sqrt[3]{abh}$ |

Impulse (dynamic) resistance of grounding conductor R_{imp} depends on number of reasons but mainly on lightning current amplitude and soil resistivity:

$$R_{imp} = \alpha_{imp} R_g.$$

Ratio $\alpha_{imp} < 1$ can be found by the curves in Fig. 9.13.

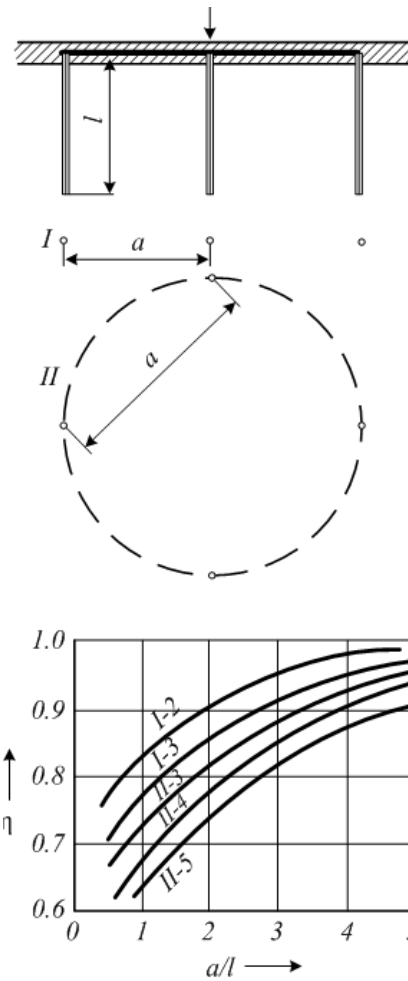


Figure 9.12 Chart for determination of η

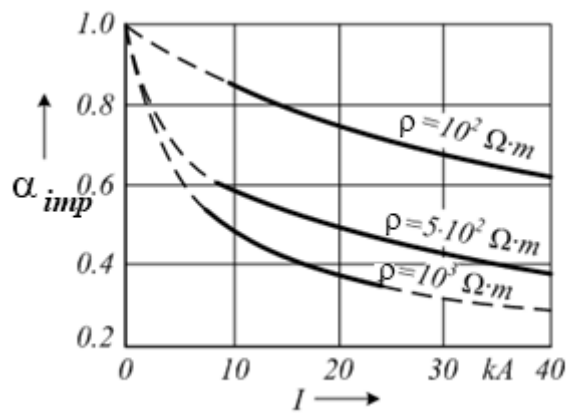


Figure 9.13 Chart for determination of α_{imp}

Contact voltage and step voltage

Current spreading around a grounding electrode causes the voltage drop in soil resistance.

Voltage between the grounding electrode and the point on the ground surface that is situated out of ground current effect is called the grounding voltage U_g (fig. 9.14). Value of U_g along the length of 1 m on the earth surface is called the step voltage (in CIS countries the step length is taken to be 0.8 m). If one of the ends this line segment touches a conducting device connected to the ground, the corresponding voltage drop is called the touch voltage U_d (Fig. 9.14). Voltage U_d between the touch point and the grounding electrode or the ground surface can include, along with component U_{dR} caused by resistance, the reactive (inductive) component U_{dL} . On the other hand voltage U_d equals the sum of voltage drops across the human body resistance U_{dr} and resistance of the ground U_{dp} . Similarly step voltage U_{st} is the total voltage drop on human body and the ground.

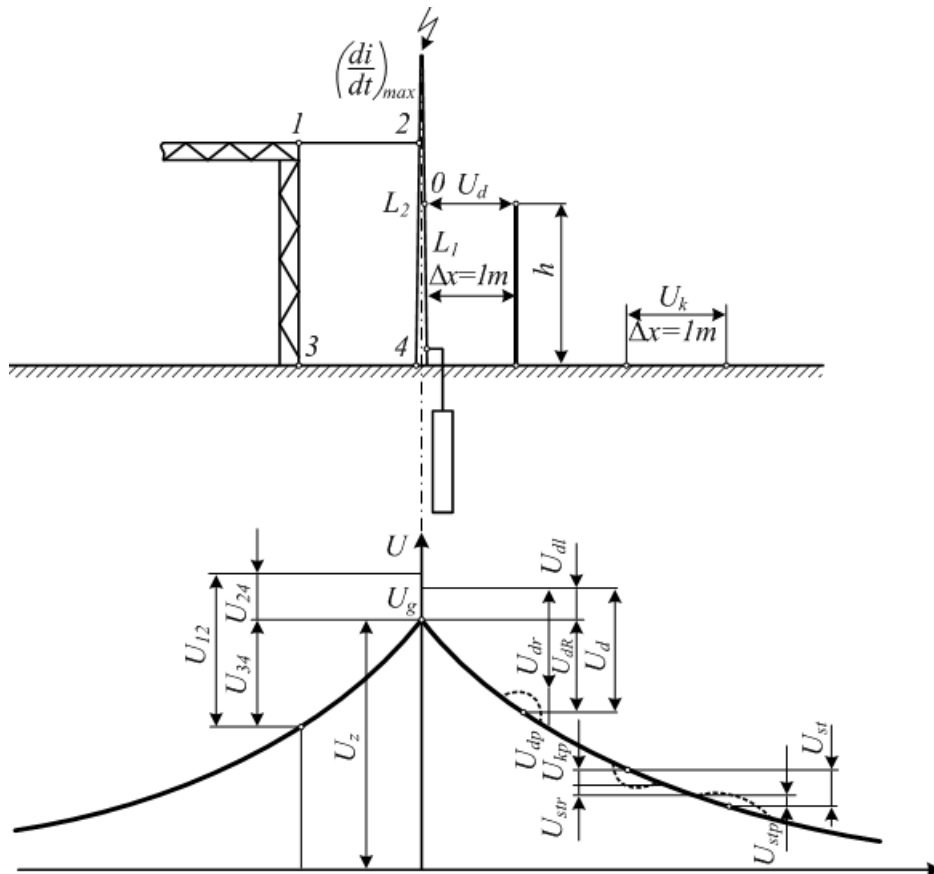


Figure 9.14 Determination of touch and step voltage

Assuming that maximum rate of the current flowing through the grounding conductor increase practically takes place simultaneously with variation of its rms value, the following expressions can be written:

$$U_d = U_{dr} + U_{dL} = U_{dr} + U_{dp};$$

$$U_{st} = U_{str} + U_{stp}; \quad U_{12} = U_{34} + U_{24}.$$

where

$$U_{dL} = L_1 \left(\frac{di}{dt} \right)_{max} ; \quad U_{24} = L_2 \left(\frac{di}{dt} \right)_{max} ; \quad U_{dr} = \alpha_d U_g = \alpha_d R_g I_g ;$$

$$U_{st} = \alpha_{st} U_g = \alpha_{st} R_g I_g ; \quad U_{34} = \alpha_{34} U_g = \alpha_{34} R_g I_g .$$

In the above expressions α_d, α_{st} are coefficients of touch and step resistance respectively; α_{34} is ratio of voltage drop U_{34} to U_g ; L_1 and L_2 are respectively inductance of sections 0 – 4 and 2 – 4 with current I_g .

The coefficient values are in the limits: $\alpha_d = 0.45 \dots 0.75$, $\alpha_{st} = 0.1 \dots 1.3$.

To calculate voltage drops U_{dp} and U_{stp} , it is usually accepted $R_{dp} = 1.5\rho_p$. where ρ_p is the ground surface resistance. Human body resistance is taken equal 500 ... 1000Ω.

Electric parameters of soil

Resistivity of soil is major parameter that is applied in calculation of grounding and its construction. Resistivity of soil ρ [Ohm·m or Ohm·cm] is resistance between Sides of the cube having the edge of 1 m (or 1 cm):

$$\rho = RF/l$$

where R is resistance of some volume of soil, Ohm; F is its cross-section area, m² or cm²; l is the length, m or cm.

At this, it is understood that the cube is located in the soil massif and ρ is not the resistance of sample cube cut out of soil.

The soil resistivity depends on composition, homogeneity and structure of soil and on climatic conditions (humidity, temperature, salt occurrence). It is determined by means of measurement. As it was indicated above, averaged values of resistivity are used for approximate calculations which are:

| <i>Soil</i> | ρ , Ohm·m |
|------------------|----------------|
| Sand..... | 400 and more |
| Loamy sand..... | 300 |
| Clay loam..... | 100 |
| Clay..... | 60 |
| Black earth..... | 50 |
| Peat..... | 20 |
| River water..... | 10–50 |

To calculate impulse resistivity of lightning protection ρ_{imp} it is necessary to know its pulse characteristics i.e. dependence on electric field strength E . Dependencies

$\rho_{imp}/\rho = f(E)$ are specified in form of curves. Note that always $\rho_{imp}/\rho < 1$. The grounding calculations are approximate and error estimation is rather problematic. Therefore, development of methods of probability calculations taking into account incompleteness and inaccuracy of background information remains an actual task.

9.6. Impact of electrostatic fields

Electro-static charges can occur in people's body as the result of contacts at movement, taking off clothing or carrying out domestic or professional activity, when charges are formed. Electrostatic electrization can also appear due to induction (Fig. 9.15). A human body can accumulate charges if it is insulated from ground, for example, by means of non-conducting footwear or a floor. Level of electrostatic charging of human body is defined as a rule by voltage to ground ratio: $v = Q/C$ where Q is electrostatic charge on human body, C is the body capacitance to ground. The capacitance depends on distance between human body and grounded objects or the floor. When thickness of footwear sole is 5–10 mm, the capacitance usually is from 70 to 250 pF. The capacitance of a sitting man is by 20–35 pF more than of standing man. For calculations average value of a human capacitance is accepted equal $C = 150$ pF.

Values of dielectric field strength which as a rule arise on human body are given in Fig. 9.16. The energy stored in the field of electrostatic charge is several tens of mJ. These figures considerably exceed the lowest energy of explosive mixture inflaming.

Static electricity impact on people and its negative consequences are considered in three aspects:

1) Biological impact of electric fields on human body. Being under the influence of electrostatic field a prolonged period has impact on peoples' health and well-being;

2) Objective and subjective impact of electrostatic charges that appear at approaching a grounded object. Besides unpleasant or unhealthy feeling these charges can be a reason of mechanical lesions caused by a man reaction, for instance by a hand abstraction etc. Lesions, caused by charges can manifest in the following ways: slightly tangible or intangible –at voltage up to 15 kV and the charge energy up to 2 mJ; medium tangible –at voltage up to 3 kV and energy of 10 mJ; strongly perceptible –at higher level of voltage and energy. Discharge of a human body or an object to grounded man with energy about 250 mJ can cause a severe shock;

3). Explosion hazard at the discharge from the man under the conditions of explosion or fire hazard. In explosion and fire hazardous zones and premises, where substances with minimal ignition energy (not exceeding 100 mJ) are utilized, the use of protective means against charge accumulation on body is required for people who permanently or temporarily stay at the named places. The main means of personnel protection is provision of people with corresponding working clothes and footwear with proper antistatic properties and personal equipment for workers such as gauntlets, helmets, and also furniture, the floor covering and other subjects contacted by personnel.

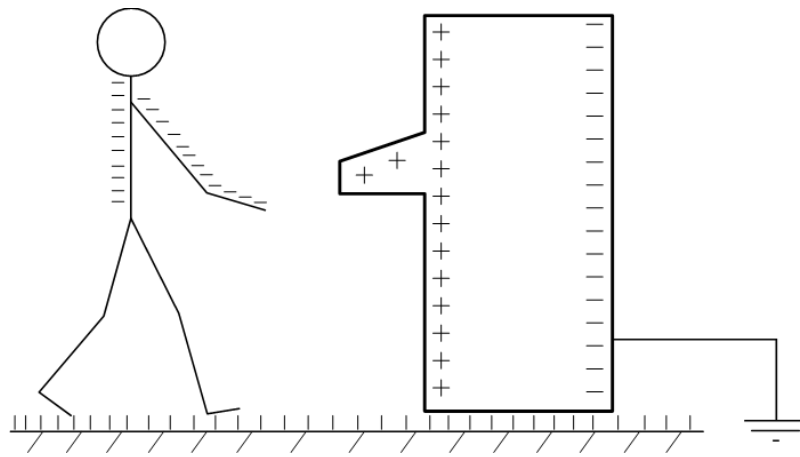


Figure 9.15 Human electrostatic electrization by induction

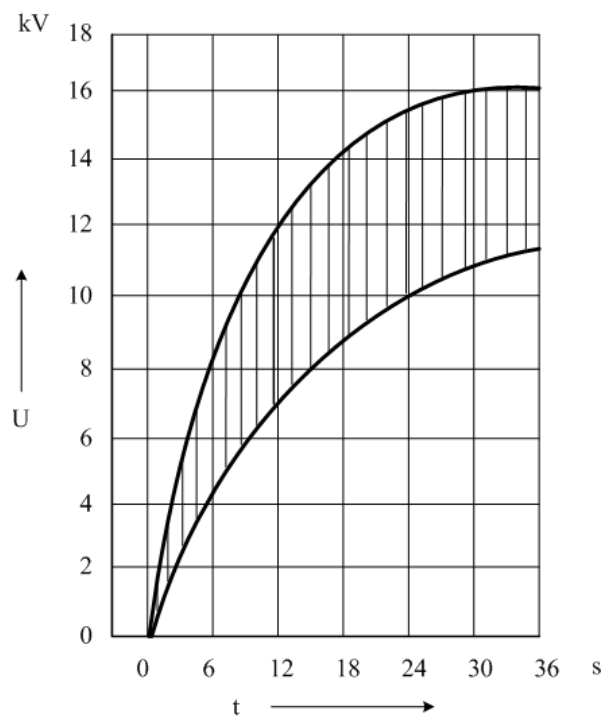


Figure 9.16 Voltage across human body in the case of broken floor insulation

Detailed instructions regarding worker's and objects protection from electrostatic phenomena should be determined by operating manuals.

Static electricity significantly influences on technological processes causing malfunction or defects in production. Such an effect is due to mutual attraction and repulsion of fibers, films, dust and so on and also due to occurrence of electrostatic microdischarges. Negative influence of electrostatic effects is of particular importance for electronic and computer industry as even small electrostatic charges can cause significant disturbances in production and equipment use. According to data of many companies producing electronic components and devices, from 25 to 50 % of spoilage of production is the result of electrostatic discharges. Electrostatic charges are generally brought by operating personnel.

9.7. Labor safety and environment protection

At electric power substations, people's health and life hazard arises first of all due to danger of electric injury, as a result of harmful influence of electric field, risk of burns from hot oil, poisoning with carbon monoxide liberating at electric cables or oil burning.

Personnel safety is ensured first of all by corresponding technical solutions with use of different devices and also by proper work organizing and strict working discipline.

Electric injury

Protection against electric injury is divided into principal (protection against direct contact) and supplemental protection.

Protection against direct contact is carried out first of all by ensuring so called safe distances from the devices that are alive as well as by use of protective means: casings, barriers etc. Supplemental contact protection in emergency situation of device operation is implemented by means of protective grounding and by additional means as well. Requirements regarding electrical injury protection are presented in documents of IEC.

The most common reason of electric injury is errors of operating personnel. Therefore not only readability and transparency of all indications but also use of identical notations of contact joining and devices, of informational and warning boards are of particular importance. With the purpose of wrong switching operations confinement, electric interlocking and mechanical locks of various types are used. But in operation it is impossible to rely only on blocking; and it is necessary to pay attention to correctness of switching carrying out.

9.8. Impact on the environment

Overhead lines significantly affect the environment and also impede the territory development. The impact on the environment increases with the rated voltage.

The lines occupy territory to place supports, limit the opportunity of using the part of the territory under conductors and near the line. These limitations touch also civil construction, placement and maintenance of agricultural machinery etc.

Location of transmission towers on agricultural land complicates the land machine processing. Passing overhead line through the territory planted with trees requires keeping branches on the definite distance from conductors.

Overhead lines have negative impact on the territory appearance and aesthetic design.

Impact of overhead lines can be reduced by:

- restriction to acceptable minimum number and extension of lines within cities territory;
- use of insulated conductors on overhead lines of medium and low voltage;
- use of arrow-supports for power lines;
- use of trees in forest as elements of support.

In many countries exists environmental legislation. Impact of electric substations on environment can be of electrical or non-electrical nature. Electrical influence is seen in extension electric charges beyond the substation and in impact of their electric field. Nonelectric impact involves territory development and negative landscape change, water pollution with oil and noise generation.

Protection against carry out electric potential consists in the use of grounding with maximally low resistance on the substation territory. Attention should be paid to prevention of carrying out potential by elements of other systems, for instance, water pipelines, armored cables, tv-cables, rails etc. Taking into account possibility of high potential carrying out, the ground loop of the network of 400/230 V is not made outside the substation.

Great threat off electric shock arises in the case of outside safety fence, especially, made of metal that is usually located outside grid grounding, in the area the sharp voltage drop. The distance from grid grounding circuit to outside fence should be not less than 3 m. The service personnel of substation should avoid moving inside this area.

With the purpose of protection people who are beyond the substation safety fence, apart from putting warning signs on this territory, separate grounding, located at the distance of 1 m from fence (from outer side) and depth 0,5 m is made. The grounding is connected with the fence. In turn, it should not be connected with the substation grounding or natural grounding, connected to grounding of the substation. Sometimes, instead of separate grounding, a stripe having the width not less than 1.25 m is made, the surface of which has great resistance. Such a stripe is made of gravel, crushed stone or asphalt.

To protect environment from misuse (territory occupation, appearance change) it's necessary to work out thoroughly the general plan of the substation in order to reduce the possible area of substation territory and also to exclude the substation placement on the land that is used in agriculture and in recreational areas and to use compact devices.

To protect waters from contamination by oil, drainage of sewage waters from the places of oil-containing devices location is made using oil separation. When the substation is situated nearby a river or lake, the complete protection of their water against oil penetration is necessary. Under the oil-containing devices consistent drip trays which must be able to accommodate all the oil available in the devices are placed.

Synthetic oils used in the capacitors of old type (i.e. chlorinated biphenyls with strong toxic properties) require particular measures against the soil contamination.

The noise source at electric substations is transformers constant noise) and air circuit-breakers (impulsive noise). Air compressors are also noise source. But they are usually installed inside the building and their noise is not highly perceptible for people around.

Allowable noise level on a substation territory is defined by special standard. Inside the building of indoor substation sound level should not exceed 65 dB, and in the control room – 55 dB. Allowable noise level outside the substation depending on kind of adjacent territory is given in Table 9.3.

Table 9.3

Allowable noise level

| Kind of territory | Equivalent sound level, dB | | Maximum short-time sound level, dB |
|--|----------------------------|-------|------------------------------------|
| | Day | Night | |
| Protective areas, heritage parks, ancient monuments | 40 | 30 | 65 |
| Suburban recreation zones | 45 | 35 | 70 |
| Residential areas, located near streets with light traffic | 50 | 40 | 75 |
| As above but with heavy traffic | 55 | 45 | 80 |
| Central parts of a city | 60 | 50 | 85 |

The cause of fire at substations is mostly electric arc burning in air or oil. Arc heat radiation and extremely high temperature of gases can cause heavy burns as well as hair or clothes inflammation. Substation personnel are recommended to wear woolen or cotton cloths (with low flammability) and headwear. Under the influence of high arc temperature insulating material can give off toxic gazes causing poisoning.

Consequences of arc burning in a barrel (container) with oil are highly dangerous. High pressure in the closed container can lead to its rupture, leaking out or spraying the burning oil, and also hydrogen leakage which reacting with air produces explosive mixture. The highest probability of arc ignition and transformer tank rupture takes place in time of storm. Therefore, service personnel should not stay at the substation territory during this time. Fire in closed building is additional reason of fast oxygen reduction and filling the rooms with non-transparent and poisoning gases. It threatens with loss of orientation, poisoning and human health deterioration. Cables with polyvinyl insulation are highly dangerous as regards to fire. During a fire polyvinyl emits great amount of non-transparent toxic and burning gas and also chlorine hydride that badly influences on concrete, building plaster and walls.

To limit oil burning at open substation, gravel bedding under oil-containing devices is made. Cable channels should be made at the distance not less than 1.5 m from the gravel edge. If it is impossible to provide this distance, channels should be filled with sand. In this way cable burning and burning oil spreading along cable channels is limited.

In the buildings of closed distribution stations where electric equipment containing more than 200 kg of oil, framing having the height that provides retention of all oil volume is arranged.

Test questions

1. What dangers can be faced at a substation?
2. By what protective zones of first and second level at substations are characterized?
3. How the distance between overhead line conductors and earth is selected?
4. Name methods of overhead line influence on biological organisms reduction.
5. Indicate types of protection against electric shock.
6. What is the danger of electric field impact on biological organisms?
7. What are standard requirements for protection against electric field?
8. What are standard requirements for protection against magnetic field?
9. What are the measures providing environment protection from electric and magnetic fields and the noise?
10. What is the danger of electrostatic fields (electrostatic electrization) impact for biological organisms?
11. What is the danger of electrostatic fields (electrostatic electrization) impact for electric equipment?

Topics for essay

1. Peculiarities of the electromagnetic fields influence on living bodies.
2. Shielding against electromagnetic fields.
3. Minimization of electromagnetic fields impact.
4. Shapes of electromagnetic shields and methods of their calculation.
5. Touch and step voltages.

PART 3

LEGAL AND ECONOMIC ISSUES OF ELECTROMAGNETIC COMPATIBILITY

CHAPTER 10 ECONOMIC ISSUES OF ELECTROMAGNETIC COMPATIBILITY

10.1. Losses resulting from inadequate electromagnetic compatibility

By estimations of experts, at the present stage of power industry development two main problems can be clearly marked out – power quality and power supply reliability that is essentially defined with the prescribed function of electric power supply systems, and consumers providing with electric power in required amount and of required quality. The rapidly changing of the structure of energy consumption, rapid development of business, science and technology, of high technologies and the society as a whole have led to the fact that the level of power supply quality that was considered to be acceptable for decades now causes essential losses. According to the research of EPRI – Electric Power Research Institute (USA), losses, caused by violation of the reliability of power supply, cost American economy \$104-164 billion annually. By other data “low” power supply reliability in the USA costs to consumers more than \$120 billion annually. Research of European specialists show that world-wide losses caused by disturbance of power supply reliability are estimated at €500 billion annually, i.e. make 50 % of turnover in electric power sector, and tend to increase. The growth of losses caused by disturbances of electric power supply system reliability is proved by researches carried out in many countries concerning damages caused by short supply of electric energy. As is known, the interrupted energy assessment rate (IEAR), or value of lost load (VOLL) y_i is normalized as follows: in the domestic practice its mean value for electric power system in the prices of 1985 year makes $y_1 = 0.6$ ruble/(kWh); in Great Britain in 1989 year the value $VOLL = £ 2/\text{kWh}$ was adopted (now it is about £ 2.5/kWh); in Australia the rated value is $IEAR = \$ 5/\text{kWh}$. However actual value of specific consumer loss caused by undersupply of one kWh of electric power exceeds the normalized values tenfold: in Great Britain the mean value is $VOLL = £ 11/\text{kWh}$; in Australia was got the value $IEAR = \$ 25/\text{kWh}$; for united power system “Interconnected Alberta System” (Canada) $IEAR = \$ 12/\text{kWh}$.

Annual losses caused by reduced power quality in some countries of the world are given below:

| <i>Country</i> | <i>Losses, Bln \$</i> |
|-------------------------|---------------------------|
| USA (1992) | 13.3 |
| USA (2001) | 15-24 |
| Europe (2000) | 15-20bln€ |
| USSR (1989) | 10 |
| Germany (2002) | 20-25 |
| France (2002) | 25 |
| Canada (2002 г.) | 1.2 |
| World-wide (2002) | about 100 |

According to different sources the figures are somewhat different; at a national scale the losses amount billion USD and tend to increase. For instance, according to the available data amount of annual losses of the USA caused by low power quality for 10 years increased twice. Meanwhile expenditures for means of power quality improvement are estimated in USA as \$2 bln annually, in Europe they estimated less than 5 % of losses from decline in power quality.

Losses from decline in power quality not always can be assessed in value terms. Along with direct losses (loss in productivity, damage of equipment, downtime of labor force, loss of data etc.) indirect loss also takes place: loss of customer confidence, loss of market share, delay of payment, a negative effect on cash flow, loss convenience and comfort etc. To significance of the problems of power quality and power supply reliability the results of consumers' survey indicate too. Thus according to one of them held in Europe 2500 consumers were enquired. It was found that 6 % of commercial consumers and 5 % of household consumers are not satisfied with the quality of power supply, more than 50 % of major consumers experienced problems with power quality. It is interesting to note that commercial consumers are now ready to pay 2 % more for electric power just to improve electric power quality.

Causes of losses from poor power supply

Among the main reasons are the following.

One of the reasons is rapid increase in the number of large computer systems that are used in business, commercial and financial structures, for managing, control and

Table 10.1

Losses from power supply interruption in IT area

| Business field | Losses, doll/min |
|-------------------------------------|------------------|
| Mobile communication service | 41000 |
| Telecommunication retailing | 72000 |
| Airplane tickets reservation system | 90000 |
| Bank card operations | 2580000 |
| Brokerage operations | 6480000 |

automation of technological processes that are rather sensitive to external disturbances. So called "digital business", i.e. firms involved in the activity connected

with acquisition, processing, transmission and use of information, is characterized by high sensitivity to electromagnetic interference (Table 10.1).

For example, according to the data of year 2001 in the USA digital business accounts for about 12 % of all consumed electric energy. Forecast for the period up to the year 2011 is growth of this amount to 16 %.

Complexity of modern technological processes and high requirements to their stability maintenance

Table 10.2 presents typical amounts of losses caused by power supply interruption in some industries.

Table 10.2

Losses from power supply interruption

| Industry (scope of activity) | Losses, euro/minute in power supply |
|---------------------------------|--|
| Semiconductors manufacturing | 3,800,000 |
| Computer center | 750,000 |
| Telecommunications | 30,000/min |
| Steel industry | 350,000 |
| Glass industry | 250,000 |

Complications of energy system structure and function, that leads to more severe aftereffects in the case of one component failure

Severe accidents that happened in the USA and Russia can be considered as examples.

Increase in installed capacity of nonlinear, unbalanced and sharply variable loads

For example, in Japan prior to 2000 year the voltage waveform distortion factor K_U reached 6–7 % for industrial sector and 4–5 % – for household consumers. In Switzerland K_U in distribution grids of 230/400 V increased from 3.6 to 4.7 % (by 30 %) over the period from 1979 to 1991. In the USA it increased on the average by 0.1 % annually over the last 10 years.

Depreciation of electric power enterprises capital assets

At the present time, failures caused by equipment aging and wear are a serious concern for most power systems, as many elements of the power systems reach limit state until the end of their operating life.

Deregulation, privatization and liberalization of the electricity sector in many countries of the world (Russia, USA, Great Britain, Spain, Germany etc.)

Transition to the new organizational structure of the industry and new sources of its financing, appearance of new owners and economic players of electric power market for whom commercial result tend to be main priority have negative effect on reliability and quality of consumers power supply.

The analysis of the results of research in different countries makes it possible to conclude that nation-wide losses from disturbances in electromagnetic compatibility amount to billions of dollars and tend to increase. The data given above show the

necessity of more detailed study concerning reliability of power quality and power systems.

10.2. Assessment of economic damages

Economic characteristics of electric equipment operation and, in some cases, output products quality and amount essentially depend on electromagnetic interferences occurrence and influence.

Calculation of economic loss caused by their affect might be necessary for proper selection of methods and means for electromagnetic interference protection at the stages of power systems design and operation. The need of the damage determination arises also at substantiation of electromagnetic interference acceptable level for correction of existing and development of new standards.

Economic damage caused by electromagnetic interference influence consists of two components -electromagnetic and technological ones. The electromagnetic component is mainly stipulated by active power loss variation and relevant change of electric equipment insulation durability. At this, the damage equals zero at sinusoidal form and balance of line-to-line voltage system, and absence of the grid voltage fluctuations. The damage is accepted equal to zero at the rated voltage. The technological component of the damage is caused by influence of interference on the equipment productivity and cost of production.

In general form, economic damage in the case of voltage fluctuation absence is continuous and differentiable function of corresponding electromagnetic interference indicators. If link between individual interference indicators does not take place, the loss caused by each of them separately may be presented by the power polynomial in concern of the appropriate indicator:

$$Y = \sum_{s=1}^m \left\{ \sum_{k=1}^3 [a_{s_k}^{(e)} + a_{s_k}^{(r)}] \delta U_y^k + \sum_{p=1}^2 [b_{s_p}^{(e)} + b_{s_p}^{(r)}] K_{2U}^p + \sum_{l=1}^2 \sum_{n=1}^n [c_{s_{nl}}^{(e)} + c_{s_{nl}}^{(r)}] K_{U(n)}^2 \right\}$$

where $a_{s_k}^{(e,r)}$, $b_{s_p}^{(e,r)}$, $c_{s_{nl}}^{(e,r)}$ are coefficients, stipulated by electromagnetic (e) and technological (t) parameters of electric equipment of s -type or process flow or production section; $\delta U_y, K_{2U}, K_{U(n)}$ are values of the voltage deviation, the negative sequence voltage distortion factor and then- th harmonic ratio, expressed in relative units.

Economic aspects of the electromagnetic compatibility problem

In many cases levels of electromagnetic interference exceed limits allowable according to international standards, national or industry standards. This circumstance has as a consequence the necessity of introduction of the technical solutions providing the specified levels of interference. Multi-version of possible solutions (centralized or decentralized correction of non-sinusoidal operating conditions by means of filtering and compensating device; installation of controlled filtering and compensating devices, active or hybrid filter; use of methods based on the circuit design; increase of pulses number of the converter and others) leads to the need for economic comparison of options providing satisfaction of technical requirements. It is evident, that options which do not provide fulfillment of the standard requirements are not considered. In view of stepwise character of sizes and parameters of the used electrical equipment, optimization of solutions is not always required.

Comparison of solutions destined for the electromagnetic interference levels minimization may be carried out on basis of different economic criteria. The most common is the method of reduced costs. The reduced cost (R) is the sum of annual costs A (including the deprecation for renovation) and the reduced capital costs $E \cdot C$ where E is the norm of capital costs effectiveness, C is the capital costs

$$R = EC + A$$

The norm of capital costs effectiveness is reciprocal to the payback period T_{pb}

$$E = 1/T_{pb}.$$

The above expression for costs is applicable in cases when capital expenditures are stable during one-two years and, practically, stable are annual costs. In practice, it is commonly used.

If capital investment and construction is carried out for several years and expenditures vary from year to year during design period, the following formula is used:

$$R = E \sum_{t=1}^{T_l} \frac{(C_t + A_t)}{(1 + E)^t} + Au$$

Where T_l is the last year of the calculated period; C_t and A_t are capital investment and annual expenditures of the current year; Au – permanent component of costs during operation period beginning from the year $t = T + 1$.

Under the condition of staged investment and construction activity

$$R = E \sum_{t=1}^{T_l} \frac{(EC_t + \Delta A_t)}{(1 + E)^t}$$

where ΔA_t – incremental costs during the current year in comparison with the previous one.

In some rather simple cases, only capital costs C are to be compared.

10.3. Calculation of electromagnetic contribution

Assessment of partial contribution of a consumer and power system to the values of power quality indicators in the point of common coupling (PCC) aimed to identification of a side, which contribution exceeds allowable by the standard (or contract for energy use), is made depending on a type of power quality indicators. In practice, the contributions are determined with the help of relevant measurements. As a rule, valid results can be obtained by measurements made before and after deviation of probable sources of electromagnetic interference. In conditions of exploitation the measurements can be made under operating deviations (on conditions of manufacturing process), and for the purposes of preventive inspection, repair etc.

In specific cases, disconnection of powerful non-linear consumer (arc steel-smelting furnace, rolling mill, electro-slag re-melting furnace, traction load, electrolysis plant etc.) permits to find out immediately the source of unallowable interference at the point of common coupling and also to estimate its contribution.

If sources of harmonics are available in both, consumer network and power system, determination of the reason of interference the method based on use of the network equivalent circuit (Fig. 10.1) is applied.

In the figure: $I_{net,n}$ and $I_{c,n}$ are currents of n th-harmonic of a network and consumer at the point of common coupling; $Z_{net,n}$ and $Z_{c,n}$ are equivalent impedances; $\underline{U}_{j,n}$ and $\underline{I}_{j,n}$ are voltage and current of n th-harmonic in the point of common coupling. Values $\underline{U}_{j,n}$ and $\underline{I}_{j,n}$ can be measured in amplitude and phase for every harmonic. Curves of the impedances frequency response can also be obtained by measurement.

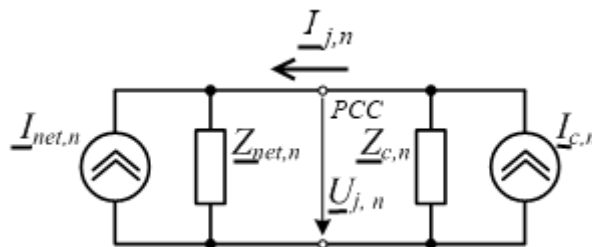


Figure 10.1 Equivalent circuit for estimation of partial contribution of consumer and power system into the level of non-sinusoidality in the point of common coupling

The expressions for the consumer and network contribution are:

$$\underline{U}_{c,n} = (\underline{U}_{j,n} + \underline{Z}_{c,n}\underline{I}_{j,n})\underline{Z}_{net,n}/(\underline{Z}_{net,n} + \underline{Z}_{c,n}) \quad (10.1)$$

$$\underline{U}_{net,n} = (\underline{U}_{j,n} - \underline{Z}_{net,n}\underline{I}_{j,n})\underline{Z}_{c,n}/(\underline{Z}_{net,n} + \underline{Z}_{c,n}) \quad (10.2)$$

The described method has not got tested enough.

It should be mentioned that even under normal operating conditions of an enterprise power supply system little background values of power quality indices always are present. So, there is a little unbalance of line voltages ($K_{2U} \neq 0$) stipulated by transformers magnetic circuits unbalance, difference of reactors and capacitors in the network phases reactance (in tolerance limits) and other reasons. Presence of nonlinearities stipulates background values of non-sinusoidality. Commutations in an electric equipment circuitry generate oscillation processes. The background values of power quality indices are negligibly small and they are not taken into consideration.

Partial contribution of the consumer (\underline{U}_{c2}) and of the network (\underline{U}_{net2}) into the level of voltage non-balance in the point of common coupling can be defined, similarly to the frequency interference, on basis of the equivalent circuit presented in Fig. 10.2:

$$\underline{U}_{c2} = (\underline{U}_{j2} + \underline{Z}_{c2}\underline{I}_{j2})\underline{Z}_{net2}/(\underline{Z}_{net2} + \underline{Z}_{c2})$$

$$\underline{U}_{net2} = (\underline{U}_{j2} - \underline{Z}_{net2}\underline{I}_{j2})\underline{Z}_{c2}/(\underline{Z}_{net2} + \underline{Z}_{c2})$$

where \underline{I}_{j2} and \underline{U}_{j2} are current and voltage negative sequence components in the point of common coupling; \underline{Z}_{c2} and \underline{Z}_{net2} are impedances of negative sequence of the consumer and system respectively.

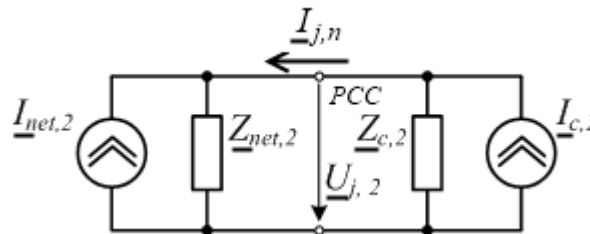


Figure 10.2 Equivalent circuit for estimation of partial contribution of consumer and power system into unbalance level in the point of common coupling

Test questions

1. How is economic damage from electromagnetic disturbance impact on electric equipment and automation systems estimated?
2. What is the economic aspect of the electromagnetic compatibility problem?
3. What are electromagnetic compatibility problem tasks of optimization?
4. Name the causes of economic damage due to low electric power quality.
5. Explain reasons causing increase of economic damage stipulated by low power quality.

Topics for essay

1. Economic damage caused unsatisfactory level of electromagnetic compatibility.
2. Methods of economic damage estimation.
3. Estimation of partial contribution at unsatisfactory state of electromagnetic compatibility.
4. Estimation of partial contribution of electromagnetic compatibility in the nodes of electric power network.
5. Documents regulating legal aspects of electromagnetic compatibility.

ANNEXES

Annex 1

Major publications in the field of EMC

Basic publications on general problems

| Reference | Publication status | Document subjects | Note |
|---------------------------|--|--|--|
| IEC GUIDE 107 ed3.0 | Mandatory document | Electromagnetic compatibility - Guide to the drafting of electromagnetic compatibility publications | |
| IEC 60050-161 ed1.0 | Horizontal standard in accordance with IEC Guide 108 | International Electrotechnical Vocabulary. Chapter 161: Electromagnetic compatibility | Terminology and symbols used in the field of EMC |
| IEC/TR 61000-1-1 ed1.0 | Technical Report | Electromagnetic compatibility (EMC) - Part 1: General - Section 1: Application and interpretation of fundamental definitions and terms | |
| IEC/TS 61000-1-2 ed2.0 | Standard | Electromagnetic compatibility (EMC) - Part 1-2: General - Methodology for the achievement of functional safety of electrical and electronic systems including equipment with regard to electromagnetic phenomena | |
| IEC 61000-1-3 | Technical Report | Electromagnetic compatibility (EMC) – Part 1-3: General – The effects of high-altitude EMP (HEMP) on civil equipment and systems | 77C - High power transient phenomena |

Basic publications concerning conditions of technical facilities

| Reference | Publication status | Document subjects | Note |
|---|--|--|------|
| <i>General provisions</i> | | | |
| IEC/TR 61000-2-5 ed2.0 | Technical Report with status of basic EMC publication in accordance with IEC Guide 107 | Guidance for considering and developing immunity requirements and the selection of immunity levels | |
| Low-frequency conducted disturbances | | | |
| IEC/TR 61000-2-1 ed1.0 | Technical Report | Information on the various types of disturbances that can be expected on public power supply systems | |
| IEC 61000-2-2 ed2.0 | Standard | Conducted disturbances in the frequency range from 0 kHz to 9 kHz, with an extension up to 148,5 kHz, specifically for mains signalling systems. Compatibility levels for public low voltage a.c. distribution systems having a nominal voltage up to 420 V, single-phase or 690 V, three-phase and a nominal frequency of 50 Hz or 60 Hz. | |
| IEC 61000-2-4 ed2.0 | Standard | Conducted disturbances in the frequency range from 0 kHz to 9 kHz. Gives numerical compatibility levels for industrial and non-public power distribution systems at nominal voltages up to 35 kV and a nominal frequency of 50 Hz or 60 Hz. | |

| | | | |
|--|------------------|---|---|
| IEC/TR 61000-2-6 ed1.0 | Technical Report | Assessment of the emission levels in the power supply of industrial plants as regards low-frequency conducted disturbances | |
| IEC/TR 61000-2-8 ed1.0 | Technical Report | Voltage dips and short interruptions on public electric power supply systems with statistical measurement results | 77A- EMC - Low frequency phenomena |
| IEC 50725 | Standard | Certificate impedors of low-voltage power supply networks | |
| Low-frequency radiated disturbances | | | |
| IEC/TR 61000-2-7 ed1.0 | Technical Report | Low frequency magnetic fields in various environments | |
| High-frequency conducted and radiated disturbances | | | |
| IEC/TR 61000-2-7 ed1.0 | Technical Report | Physiological effects on humans and animals and the deleterious effects on the performance of some electrical equipment, particularly video display units. Results are presented as reference values. | |

Mathematical apparatus of the theory of electromagnetic compatibility

A 2.1. Expansion of periodic functions in Fourier series

Solving various problems in the field of electromagnetic compatibility is based on spectral presentation of processes of currents and voltage changing with time. At this any periodic process is presented as amount of elementary harmonics.

Two types of spectra are distinguished – the amplitude spectrum and the phase spectrum.

The amplitude spectrum of a periodic process is dependence of amplitudes of separate harmonics on frequency. It is called the discrete line spectrum.

A phase spectrum is dependence of initial phases of harmonics on frequency.

As a rule, the amplitude spectrum is of main interest. In Fig. A 2.1 are shown a time plot and spectral (frequency) presentation of elementary sine wave (harmonic) having the form of

$$u_1(t) = U_{1m} \sin(\omega_1 t + \varphi_1)$$

where U_{1m} , φ_1 are the amplitude and initial phase of the harmonic respectively; $\omega_1 = 2\pi f_1$ is the harmonic angular frequency; f_1 is its frequency.

The angular frequency defines the period of oscillation $T = \frac{2\pi}{\omega_1} = 1/f_1$.

Most real processes of current and voltage change at power systems are not sinusoidal.

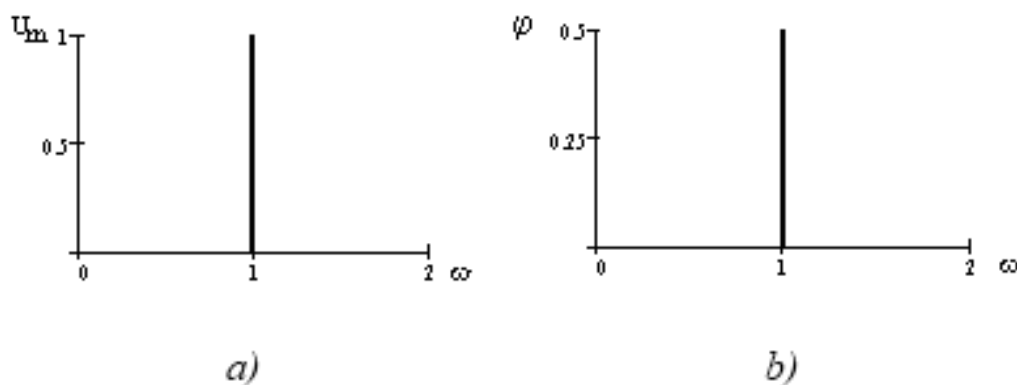


Fig. A 2.1 Presentation of harmonic oscillation as a time function (a) and corresponding amplitude and phase spectra (b)

A non-sinusoidal periodic function $u(t)$ with the period $T = \frac{2\pi}{\omega_1}$ may be presented as a sum of infinite number of harmonic components (harmonics), which is called the Fourier series.

There are several forms of the Fourier series.

The trigonometric form is

$$u(t) = \frac{U_0}{2} + \sum_{n=1}^{\infty} (A_n \cos n\omega_1 t + B_n \sin n\omega_1 t)$$

where

$$A_n = \frac{2}{T} \int_0^T u(t) \cos n\omega_1 t dt;$$

$$B_n = \frac{2}{T} \int_0^T u(t) \sin n\omega_1 t dt;$$

$$B_n = \frac{U_0}{2} \int_0^T u(t) dt.$$

A_n and B_n are Fourier trigonometric coefficients. Coefficient $U_0/2$ is equal to the mean value of function $u(t)$ a given time interval (constant component).

The amplitude-phase form is

$$u(t) = \frac{U_0}{2} + \sum_{n=1}^{\infty} U_n \cos(n\omega_1 t + \varphi_n)$$

where $U_n = \sqrt{A_n^2 + B_n^2}$, $\varphi_n = -\tan^{-1}(B_n/A_n)$.

Here U_n and φ_n are amplitude and phase of n th harmonic. The aggregate of amplitudes U_n and initial phases φ_n form the amplitude and phase spectra.

Complex form

$$u(t) = \frac{1}{2} \sum_{n=-\infty}^{\infty} \underline{U}_n e^{jn\omega_1 t}$$

where

$$\underline{U}_n = \frac{2}{T} \int_0^T u(t) e^{-jn\omega_1 t} dt.$$

Expansion of periodic functions in Fourier series is possible only for functions, satisfying to the Dirichlet conditions, i.e. having a finite number of a first type discontinuity and a finite number of extremes for a complete period.

Fourier expansion of even and uneven functions has a number of features. Remind that a function $f(t)$ is called even, if for all values of t $f(-t) = f(t)$; a function $f(t)$ is called uneven, if $f(-t) = -f(t)$. A chart of even function is symmetric in relation to a y-axis, and a chart of uneven function - in relation to the co-ordinates system origin.

Fourier series for an even function contains only terms with coefficients A_n :

$$u(t) = \frac{U_0}{2} + \sum_{n=1}^{\infty} A_n \cos n\omega_1 t$$

and for an uneven function – only members with the coefficients B_n :

$$u(t) = \frac{U_0}{2} + \sum_{n=1}^{\infty} B_n \sin n\omega_1 t.$$

In general case the Fourier series has infinite number of terms which in practice is limited to a finite number.

A 2.2. Expansion of non-periodic functions, Fourier integral

In the case of non-periodic functions Fourier series is not applicable due to the impossibility to determine of the repetition period T .

For non-periodic functions instead of Fourier series their presentation by means of the Fourier integral is used:

$$u(t) = \frac{1}{\pi} \int_0^{\infty} d\omega \int_{-\infty}^{\infty} u(\tau) \cos(\tau - t) d\tau. \quad (\text{A 2.1})$$

Here $u(t)$ is a non-periodic function, satisfying to the Dirichlet conditions. Besides, $u(t)$ must be absolutely integrable function on the interval $(-\infty, +\infty)$, i. e. the integral

$$\int_{-\infty}^{+\infty} |u(t)| dt$$

must converge

Formula (A 2.1) can also be presented in the form:

$$u(t) = \int_{-\infty}^{+\infty} [A(\omega) \cos \omega t + B(\omega) \sin \omega t] d\omega \quad (\text{A 2.2})$$

where

$$A(\omega) = \frac{1}{\pi} \int_{-\infty}^{+\infty} u(t) \cos \omega t dt, \quad B(\omega) = \frac{1}{\pi} \int_{-\infty}^{+\infty} u(t) \sin \omega t dt.$$

Formula (A 2.2) can be regarded as a limiting for expansion of non-periodic function $u(t)$ in the trigonometric series on the interval $(-T, T)$ at $T \rightarrow \infty$. Whereas the Fourier series gives presentation of periodic function (with the period T) as a sum of harmonic oscillations with frequencies $\omega_i = n\omega_1$ ($n = 1, 2, \dots$) and amplitudes U_{mn} , the Fourier integral presents the function $u(t)$ as a sum of infinite number of oscillations with continuously changing frequency ω .

By analogy with the Fourier series, the Fourier integral can be also written in a complex form

$$u(t) = \int_{-\infty}^{\infty} \underline{U}(\omega) e^{j\omega t} d\omega \quad (\text{A 2.3})$$

where

$$\underline{U}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} u(t) e^{-j\omega t} dt. \quad (\text{A 2.4})$$

Relationship (A 2.4) is called the direct Fourier transformation, which allows to find a spectral density (spectral function) $\underline{U}(\omega)$ for the prescribed function $u(t)$, and (A 2.3) is called the inverse Fourier transform which allows to calculate the instantaneous value of function of $u(t)$, if spectral density is specified.

If $u(t)$ is an even function, the direct and inverse Fourier transforms can be written as

$$U(\omega) = \frac{2}{\pi} \int_0^{\infty} u(t) \cos \omega t dt: \quad u(t) = \int U(\omega) \cos \omega t d\omega.$$

If $u(t)$ is uneven function, then

$$U(\omega) = \frac{2}{\pi} \int_0^{\infty} u(t) \sin \omega t dt: \quad u(t) = \int U(\omega) \sin \omega t d\omega.$$

The Fourier integral (A 2.3) presents the function of $u(t)$, defined on infinite time interval $(-\infty, +\infty)$, as the integral sum of functions $e^{j\omega t}$ with frequencies $(-\infty < \omega < +\infty)$, separated by infinitesimal amount $d\omega$ from each other. It means that non-periodic functions have continuous spectrum. It follows from expression (A 2.3) that amplitude of continuous spectrum constituents is infinitesimal at any frequency ω . Therefore, spectral density $\underline{U}(\omega)$ is used for description of frequency properties of a non-periodic function.

The spectral density $\underline{U}(\omega)$ possesses all basic properties of coefficients \underline{U}_{mn} of complex Fourier series.

A 2.3. Spectral presentation of stationary random processes

Expanding of random process realizations into the Fourier series is impossible due to non-periodic character of a random function. At the same time, integral Fourier transformation is also inapplicable to the stationary random process, because integrals being subject to calculation diverge due to non-fulfillment of Dirichlet condition.

The spectral analysis of stationary random processes is based on introduction of spectral density of the process, $S(\omega)$ being the Fourier transformation of the correlation function $K(\tau)$ of a random process $\xi(t)$:

$$S(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} K(\tau) e^{-j\omega\tau} d\tau. \quad (\text{A 2.5})$$

Based on the inverse Fourier transformation we obtain:

$$K(\tau) = \int_{-\infty}^{\infty} S(\omega) e^{j\omega\tau} d\omega \quad (\text{A 2.6})$$

Thus, formulas (A 2.5) and (A 2.6) are a pair of Fourier transformations, relating the spectral density and the correlation function of stationary random process, and are called the formulas of Wiener-Khintchine. There are other forms of Wiener-Khintchine formulas as well.

Physical significance of the spectral density $S(\omega)$ consists in the following. If a current or voltage is as a random process, then value $S(\omega)$ has dimension of energy. If it is accepted $\tau = 0$, we get based on formula (A 2.6):

$$D = K(0) = \int_{-\infty}^{\infty} S(\omega) d\omega \quad (\text{A 2.7})$$

where D is random-process dispersion $\xi(t)$.

Formula (A2.7) shows that the dispersion D ("energy") of random process is equal to the area under the curve of spectral density. The quantity $S(\omega)d\omega$ can be interpreted as the power of process $\xi(t)$ per frequency band $d\omega$. Based on this $S(\omega)$ is a spectral density of power, which is also called the power spectrum of random process.

The spectral density $S(\omega)$ is averaged characteristics of the random process and does not contain information about the phases of spectral constituents, and does not give the quantitative estimation of their amplitudes in explicit form as well.

Note the properties of the spectral density of stationary random process:

1. The spectral density can't have negative values, i.e. $S(\omega) \geq 0$ at any value of ω .
2. For real-valued random processes the spectral density is an even function, i.e. $S(\omega) = S(-\omega)$.

A 2.4. Method of symmetrical components

The electric networks of modern industrial enterprises are three-wire or four-wire three-phase systems. The three-wire system can be considered as a special case of the three-phase four-wire system (Fig. A 2.2).

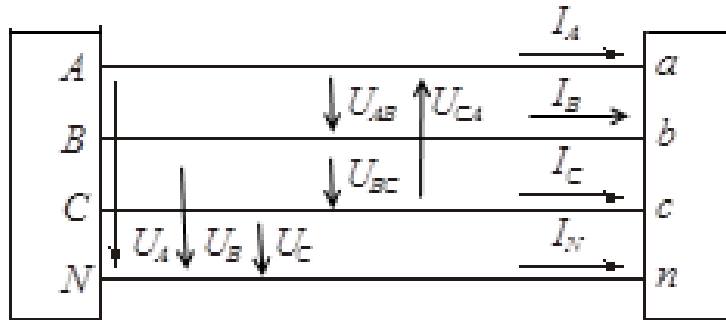


Figure A 2.2 Four-wire three- phase network

Line-to-line and phase voltage in the three-phase system are related as follows:

$$\underline{U}_{AB} = \underline{U}_A - \underline{U}_B; \quad \underline{U}_{BC} = \underline{U}_B - \underline{U}_C; \quad \underline{U}_{CA} = \underline{U}_C - \underline{U}_A.$$

In a four-wire system:

$$\underline{I}_A + \underline{I}_B + \underline{I}_C = \underline{I}_N.$$

In a three-wire system $\underline{I}_N = 0$ and

$$\underline{I}_A + \underline{I}_B + \underline{I}_C = 0.$$

The three-phase system can be both balanced and unbalanced. In the last case for simplification of calculations and analysis, the unbalanced system could be expressed as the sum of sets of symmetrical components. The system of symmetrical components includes the phasor sets of positive, negative and zero sequence. The phasor set of positive sequence $\underline{A}_1, \underline{B}_1, \underline{C}_1$, has the same phase sequence as the unbalanced phasor system $\underline{A}, \underline{B}, \underline{C}$. Phasors \underline{B}_1 and \underline{C}_1 , can be defined through the phasor \underline{A}_1 using the unit operator $a = e^{j2\pi/3}$ (fig. A 2.3, a) :

$$\underline{B}_1 = a^2 \underline{A}_1, \quad \underline{C}_1 = a \underline{A}_1.$$

The phasor set of negative sequence $\underline{A}_2, \underline{B}_2, \underline{C}_2$ has a reverse phase sequence (Fig. A 2.3, b), therefore

$$\underline{B}_2 = a\underline{A}_2, \quad \underline{C}_2 = a^2\underline{A}_2.$$

The phasor set of zero sequence $\underline{A}_0, \underline{B}_0, \underline{C}_0$ consists of vectors being in phase with each other (Fig. A 2.3, c)

$$\underline{A}_0 = \underline{B}_0 = \underline{C}_0.$$

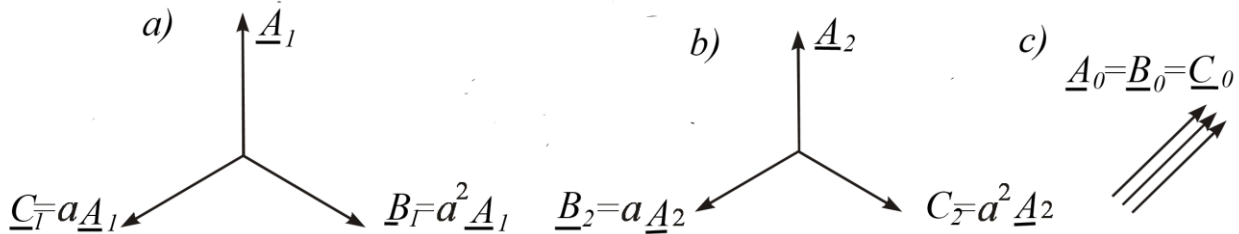


Fig. A 2.3 Phasor sets of positive, negative and zero sequence

Any unbalanced three-phase system can be presented as

$$\underline{A} = \underline{A}_0 + \underline{A}_1 + \underline{A}_2, \quad \underline{B} = \underline{B}_0 + \underline{B}_1 + \underline{B}_2, \quad \underline{C} = \underline{C}_0 + \underline{C}_1 + \underline{C}_2$$

from where we can get expressions for symmetrical components

$$\underline{A}_0 = \frac{1}{3}(\underline{A} + \underline{B} + \underline{C}),$$

$$\underline{A}_1 = \frac{1}{3}(\underline{A} + a\underline{B} + a^2\underline{C}), \quad (\text{A 2.8})$$

$$\underline{A}_2 = \frac{1}{3}(\underline{A} + a^2\underline{B} + a\underline{C}).$$

Instead of phasors $\underline{A}, \underline{B}$ and \underline{C} the corresponding phasors of voltage or current can be substantiated. Note that in a three-wire circuit the system the current zero sequence is equal to zero as

$$\underline{I}_0 = \frac{1}{3}(\underline{I}_A + \underline{I}_B + \underline{I}_C) = \frac{1}{3}\underline{I}_N.$$

The system of symmetric components can be used study processes, containing higher harmonics.

If the voltage curves of all three phases are distorted, but identically in all the phases, then harmonics in all three phases are equal by amplitude. The same is true for current harmonics. The angles between the voltage vectors of two phases in the symmetrical system are $2\pi/3$. For the symmetrical system harmonics of n th order

this angle equals $n2\pi/3$.

Thus we find, that in a symmetrical system phasors of harmonics which order n is multiple of three (including $n = 0$) are in phase with each other, i.e. constitute the system of zero sequence. In the system harmonics, which order n is by one greater than the order of zero system, positive phase sequence takes place, i.e. we have the system of positive-sequence. If the order n is by one less than the order of zero system, we get the system of negative sequence.

In general case the following relationships for determination of symmetrical components of an arbitrary order n are used:

$$\underline{U}_{0(n)} = \frac{1}{3}(1 + a^n + a^{2n})\underline{U}_0$$

$$\underline{U}_{1(n)} = \frac{1}{3}(1 + a^{2+n} + a^{1+2n})\underline{U}_1 \quad (\text{A 2.9})$$

$$\underline{U}_{2(n)} = \frac{1}{3}(1 + a^{1+n} + a^{2+2n})\underline{U}_0$$

where, \underline{U}_0 , \underline{U}_1 and \underline{U}_2 are the symmetrical components of zero, positive and negative sequence determined in accordance with (A 2.8).

Based on (A 2.9) find the systems for harmonics:

- the zero sequences at $n=3k$;
- the positive-sequences at $n=3k+1$;
- the negative sequences at $n=3k-1$
- where $k = 1, 2, 3, \dots$

Typical structure of damage from electromagnetic interference (EMI) and technological equipment failure for the two pulp-and-paper mills

| Damage component | Specific damage, % | |
|---|--------------------|------|
| Electromagnetic component of damage from electromagnetic interference including damage caused by: | 36.0 | 40.6 |
| non-sine distortion of voltage wave | 14.1 | 12.5 |
| reduction of power factor | 12.7 | 16.6 |
| energy losses for eliminating damage of product the same at production units restarting | 5.2 | 5.3 |
| excess of claimed power consumption in the peak hours | 3.0 | 3.6 |
| | 1.0 | 3.6 |
| Technological component of damage from electromagnetic interference including damage caused by: | 45.5 | 43.5 |
| direct damage from defect in workmanship | 9.7 | 13.1 |
| decline of production | 24.4 | 24.6 |
| increase in raw-materials and materials consumption | 7.2 | 5.8 |
| increase in number of single-phase faults turning into two-phase | 4.2 | 0 |
| Total damage from failures not related to EMI | 18.5 | 15.9 |
| TOTAL | 100 | |

Recommended topics of masters' works

1. Analysis of operation and principles of filtering and compensating device selection.
2. Methods of active filters simulation used in electric power supply systems with the nonlinear loading.
3. Problems of harmonics compensation in electric networks with the frequency converters.
4. Determination of current and voltage harmonics level in the networks of industrial enterprises taking into account resistance of network elements.
5. Research of additional power losses in electric network elements at decline in electric power quality.
6. Investigation of operating conditions of direct frequency converters.
7. Solving problems of voltage balancing in power supply systems of induction furnaces.
8. Overvoltage in networks of 6-10 kV of metallurgical plants caused by single-phase earth-faults.
9. Influence of frequency converters with the different control laws on the indices of electric power quality.
10. Extension of electrical equipment service life by means of electromagnetic compatibility by overvoltage provision.
11. Influence of voltage fluctuations on power supply system of steel-smelting plant
12. Study of problems related to electromagnetic compatibility of enterprises electrical equipment used in distributive networks of 6-10 kV.

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Step voltage - voltage between two points on the ground surface caused by current spreading when touched simultaneously by person's feet.

Transient [ДСТР 50397-92] – a process of changing a quantity which passes between two steady states.

Power quality index [ДСТ 23875-88] – a quantity which characterizes electric power quality by one or several its parameters.

Voltage dip in a power supply system [ДСТ 23875-88] - a sudden reduction of the voltage in a power supply system followed by its recovery.

Range of voltage deviation [ДСТ 23875-88] – a quantity which equals to difference between maximum and minimum values of voltage for specified time interval of steady state operation of a power source, electric energy converter or electric power supply system.

Zero sequence component of the voltage [ДСТ 23875-88] – symmetrical component of an unbalanced three-phase voltage system which phasors are in phase to one another.

Negative sequence component of the voltage [ДСТ 23875-88] - symmetrical component of an unbalanced three-phase voltage system which phasors phase sequence is reverse relatively to the sequence taken as basic at replacement the unbalanced system by the method of symmetrical components.

Positive sequence component of the voltage [ДСТ 23875-88] - symmetrical component of an unbalanced three-phase voltage system which phasors phase sequence is the same that the sequence taken as basic at replacement the unbalanced system by the method of symmetrical components.

Lightning current – the current arising at the time of lightning strike.

Lightning conductor – a part of external arrangement of the lightning protection system which discharges the lightning current to the grounding electrode.

Electrical device: – electrical, electronic or radio-electronic product (equipment, apparatus or system) containing electrical and/or electronic components (circuits);

- product, equipment, apparatus or its part which operation is based on laws of electrical engineering, radio engineering and/or also circuits that perform one or several of the functions: amplification, generation, transformation, connection and data storage [ДСТ Р 50397-92].

Immunity (to electromagnetic disturbance): – the ability of an electrical device, equipment or system to maintain the required quality of functioning in conditions of influence on it of external disturbances having specified values of parameters when additional means of protection from the disturbances, not belonging to the device, equipment or system operation principle or structure, are not available [ДСТ Р 50397-92];

- the ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance [IEC 62103, ed. 1.0 (2003-07), IEC 161-01-20].

Immunity level [IEC 60601-1-2, ed. 3.0 (2007-03), IEC 161-03-14] - the maximum level of a given electromagnetic disturbance incident on a particular device, equipment or system for which it remains capable of operating at a required degree of performance.

Level of electromagnetic disturbance [ДСТ P 50397-92] – the value of the disturbance measured in regulated conditions.

Flicker [IEC 60050-161:1990, 161-08-13] - impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Flickermeter [IEC 61000-3-3, ed. 2.0 (2008-06), IEC 161-08-14] - an instrument designed to measure any quantity representative of flicker.

Screen/shield (US) [IEC 61000-5-6, ed. 1.0 (2002-06)] - device intended to reduce the penetration of an electric, magnetic or electromagnetic field into a given region.

General-purpose electrical power network [ДСТ 13109-97] – the power network of supplying organization intended for transmission of electric power to different power consumers or to technical means.

Electromagnetic compatibility (EMC): - the ability of technical means to function with specified quality in its electromagnetic environment without introducing intolerable electromagnetic disturbances for other technical means [ДСТ P 50397-92];

- the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment [IEC 62003, ed. 1.0 (2009-03), IEC 161-01-07].

Electromagnetic environment: - the totality of electromagnetic phenomena and/or processes at a given spatial zone and/or at a given conducting environment in a frequency band and time range;

- the totality of electromagnetic phenomena, processes at a given spatial zone, frequency band and time range [ДСТ P 30372-92];

- the totality of electromagnetic phenomena existing at a given location [IEC 60601-1-2, ed. 3.0 (2007-03), IEC 161-01-01].

Electromagnetic disturbance: – electromagnetic phenomenon, process degrading quality of functioning of equipment [ДСТ P 50397-92];

- any electromagnetic phenomenon which may degrade the performance of a device, equipment or system, or adversely affect living or inert matter [IEC 60601-1-2, ed. 3.0 (2007-03), IEC 161-01-05].

Electromagnetic screen [IEV 161-03-26] - a screen of conductive material intended to reduce the penetration of a varying electromagnetic field into an assigned region.

Electromagnetic emission [ДСТ P 30372-92] - generation of electromagnetic energy by a disturbance source.

Electromagnetic impact – electromagnetic phenomenon that affects or can affect the equipment or living matter. To electromagnetic impacts belong electromagnetic, electrical and magnetic fields produced by equipment in the surrounding environment and/or currents and voltages produced by it in a given conductive medium.

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**ЕЛЕКТРОМАГНІТНА СУМІСНІСТЬ
У СИСТЕМАХ ЕЛЕКТРОПОСТАЧАННЯ**

Підручник
(англійською мовою)

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термінологія професора О.Б. Іванова

Друге видання

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