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INTERHARMONICS IN POWER SUPPLY SYSTEMS

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ІНТЕРГАРМОНІКИ В СИСТЕМАХ ЕЛЕКТРОПОСТАЧАННЯ

Purpose. To investigate the understudied aspects of voltage quality and electromagnetic compatibility and provide mathematical description for the analysis of voltage interharmonic components in mixed spectrum.

Methodology. Methods of research are based on the theory of spectral analysis and general electrical engineering.

Findings. The stress is made on the necessity to take into account the impact of interharmonics while analysing the quality of voltage in industrial power supply systems. The process of interharmonics occurrence in power supply systems is explained in terms of physics, the sources generating this kind of interference are described. Mathematical dependences that allow identifying interharmonics in the general energy of distorted spectrum are provided. The focus is placed on the feasibility of using spectral analysis in computations. We have analysed the values of error in calculations of electric power quality indexes (EPQI) and the following reasons for its occurrence: error in setting the parameters of electric equipment, their reduction, etc. It has been established that the expected error is within the range of 3–13 %.

Originality. The Fourier integral application for the analysis of interharmonics has been theoretically substantiated. Dependences between the commutating angles of the inverter rectifiers and the level of interharmonics in the converter line current have been established. The appropriateness of preparing instructions for the application of estimating calculation methods, which are similar to those used in power engineering and other industries, has been emphasized.

Practical value. Analysis of the obtained solutions allows making a quantitative estimation of levels of interharmonics and higher harmonics as the markers of the voltage quality. The approximate formula for assessing interharmonics levels while applying a linear law of invertor control has been inferred. Certain parameters used in estimating calculations are provided. It is shown that the calculated values of estimated losses in power engineering of Ukraine coincide with the results of more specific research based on factual data.

Keywords: *voltage quality, interharmonics, spectral analysis, estimating method, error*

Introduction. The issue of power quality (PQ) is still one of the critical components of a more general problem of energy efficiency which significantly defines the present state of power engineering. The importance of PQ problem is determined by its nonsinusoidality, i.e. higher harmonics (HH) of currents and voltages. Despite a lot of theoretical research and achievements in solving applied tasks [1, 2], the significance of PQ becomes even more notable. This is explained by not always timely solutions aimed at correction of nonsinusoidality values. Thus, for instance, the content of HHs in Swiss low voltage distributed networks has risen by 30 % over recent years. This figure can reach 8–10 % for electromagnetic loss at the expense of nonsinusoidality. Here the difference is made by various frequency convertors (FC) which have been actively introduced recently. It has been reported that sometimes the cost of implementing FC-based advanced technologies turns bigger than the losses associated with HHs.

The recent decades have been characterised not only by the classic ideas about HH composition, with prevailing integer values, but also by the awareness of the role and significance of intermediate harmonics or interharmonics (IH).

The IH sources are consumers working constantly or temporarily in the transient mode [3]. This mode is conditioned either by the load change associated with the technological processes mode, or by peculiarities of the electromagnetic processes, accompanying operation of electrical appliances, e.g. half-duplex operation of FC rectifiers. In the first case, the processes of current (voltage) change are characterized by randomness or nonperiodicity. In the second case, if the effect of different random interferences is neglected, the processes of current (voltage) change of IH sources can be treated as periodical. This approach can be applied to both analysis and computation of IHs generated by different sources.

IHs occur as a result of the main frequency and HH modulation by other frequency components and are observed during the operation of static FCs, particularly cycloconvertors, induction motors (IM), asynchronous converting cascades, arc furnaces, welding machines, etc.

On the whole, the impacts of IHs and HHs on electrical equipment, communication and telemechanical systems are alike, but in certain cases the IH effect can be greater than that of HH, partially from the viewpoint of the necessary level of interference immunity. That is why the research into their generation, propagation and aggregation is important for ensuring quality and reliability of power supply.

Defining IH from the graph of stochastic processes. In order to define the amplitudes and frequencies of IHs, it is possible to apply Fourier transform directly to the graphs of stochastic processes describing the actual envelope currents $I(t)$ and volumes $U(t)$. Decomposition is done to a concrete realization on the idle interval. Harmonic analysis can be easily conducted by means of fast Fourier transform (FFT). IH energy according to the graph $I(t)$ is taken as a sum of real values squares A^2. Energy values are defined by the area under the curve $I(t)$ and are equal numerically to the process dispersion. To obtain the spectral composition of the periodic components, it is possible to apply FFT to the "tail" of correlation function (CF); thus yielding the spectrum of IH squares (A^2).

Discrete spectrum allows estimating the relationship between IH energy and the general value of the process energy $I(t)$. The research has proved that the share of IH discrete spectrum energy in electric networks with electrotechnological units is 10–25 % of the total energy of the process mixed spectrum.

Defining IH on the basis of Fourier integral. Analytical studies of nonperiodic processes in many cases are done on the basis of direct Fourier transform (or Fourier integral); when decomposition into Fourier series, i.e. inverse Fourier transform, is not possible.

In the spectral theory of stochastic processes, the relationship between the processes in time and frequency domains of the $\xi(t)$ takes the form

$$S(\omega) = \int^{\infty} \Sigma(t) e^{-j\omega t} dt,$$

where $S(\omega)$ is spectral density of the process or the complex spectrum of nonperiodic process $\xi(t)$. Module $|S(\omega)|$ is sometimes called *spectrum* for simplicity. Process $\xi(t)$ can be presented as a sum of infinitely great number of infinitely small oscillations that are infinitely similar in frequency, reflecting the so called continuous spectrum. The spectrum of the process square Σ^2 represents the process energy W_T, emitted during the time T

$$W_T = \int_0^T \Sigma^2 dt = \frac{1}{\pi}\int_0^{\infty} \left|S(\omega)\right|^2 d\omega. \quad (1)$$

Mean process power is

$$\frac{W_T}{2} = \frac{1}{\pi}\int_0^{\infty} \left|S(\omega)\right|^2 d\omega = G(\omega), \quad (2)$$

where $G(\omega)$ is energy spectrum, i.e. power per frequency unit or spectral power density.

Formula (2) stands for the so called Rayleigh theorem.

Spectral densities $S(\omega)$ and $G(\omega)$ and correlation coefficient (CC) are the main elements of the spectral-correlation theory of stochastic processes.

Stochastic processes in electrotechnological units are narrow band for these progresses

$$G(\omega) = \frac{D}{2\pi} \cdot \frac{\alpha}{\alpha^2 + (\omega_1 - \omega)^2},$$

where D is process dispersion; ω_1 and α is the coefficient of fading and CC own frequency.

Energy spectrum $G(\omega)$ consists of continuous G_N and discrete G_D components.

$$G = G_N + G_D.$$

Distribution of the continuous IH spectrum is characterized by G_N component. The formula for current $I(\omega)$ is derived on the basis of Rayleigh formula considering the ratio (Kharkevich A. K.)

$$I(\omega) = \frac{2}{T} G(\omega).$$

The values of $G(\omega)$ can be practically found from the equation of energy spectrum and correlation function (CF), while CF values can be established either by measurements or analysis.

The proposed technique of computing amplitude spectrum of IHs allows extending the method of calculating HHs of currents and voltages in the nodes of industrial mains onto IHs calculation by means of nodal voltages method. If there are several IHs sources connected to the mains nodes, the stochastic process of current change of this nodal nonlinear load is a sum of stochastic processes of load currents from each separate source. Loads which are the sources of IHs can be treated as independent. Then the spectral nodal current density of the mains with several IHs sources is a sum of spectral current densities of the corresponding nonlinear loads. To define the IHs spectrum of voltage, we set a system of nodal equations, which has the following matrix form

$$Y_y(\omega)U(\omega) = I(\omega), \qquad (3)$$

where $Y_y(\omega)$ is the matrix of mains nodal conductances; $U(\omega)$ is the matrix of IH voltage spectra modules in mains nodes; $I(\omega)$ is the matrix of IHs current spectra modules in mains nodes (matrix of master currents IHs modules).

Matrix nodal equation (3) is solved via the matrix of nodal voltages spectra

$$U(\omega) = Z_y(\omega)I(\omega),$$

where $Z_y(\omega)$ is the matrix of mains nodal resistances

$$Z_y(\omega) = Y_y(\omega).$$

Computation of frequency converter IHs. Industrial power supply systems are actively implementing FCs with the direct current element (DCFC), in addition to direct FCs that are no longer manufactured. They generate IHs which are commensurable to the amplitudes of conventional HHs, and, as a rule, significantly exceed them. Spectral composition of the input DCFC current is determined by the output frequency f_2, the type of modelling function, depth of modulation and coefficient of the load reactive power tgφ. In practice, we use linear, sinusoidal, triangular and rectangular laws of control. Determination of the spectral composition of the input DCFC currents is a very complex and sophisticated task which cannot be approached without computational technology. It is only for certain occurrences that approximate equations have been found for frequencies and amplitudes, particularly for the linear law of control. In such a case, relative IH frequencies are defined by

$$n_1 = \left|6p + 1 \pm 6p\chi\right|;$$

$$n_2 = \left|6p + 1 \pm \left(6p + 2\right)\chi\right|,$$

where p is the pulse convertor; $\chi = {}^{t_{out}}\!/_{t_{in}}$.

IH amplitudes $I_{x12}(p)$ with the error up to 10 % approximately equal

$$I_{x12}(p) = \frac{1}{6p \pm 1}.$$

As an example below, we provide the values of n_1, n_2 and $I_{x12}(p)$ for the input current of low frequency three-phase bridge 6-pulse convertor for the linear control law at $\chi = 0.2$ and $\mathrm{tg}\,\varphi_H = 0.2$.

For other control laws, as of today, there are no relatively simple approximate formulas for IH frequencies and amplitudes because of extreme complexity of their original expressions. Solution of this problem is very important for theoretical and practical development of FCs implementation. Computation of IH input current given in [1] is not presented here. It should be noted that the total IH values in such a case are smaller than those for DFCs.

In the practice of designing and operating power networks and electric systems, we face, as a rule, the necessity to estimate mode parameters, electric equipment cost, to compute the accounts between the energy suppliers and consumers, etc. Such an approach is acceptable for making a project decision on the estimation of capital construction expenditures and other costly solutions, facilities reconstruction, variant calculations, etc. In such a case, consolidated indices are used, which, of course, allow obtaining only an approximate, i.e. estimated value. In operational conditions, making such decisions is only possible in emergency situations: urgent replacement of the working electrical equipment, estimation of economic loss, etc., if it is impossible to use the expert evaluation method.

Estimating methods, as a rule, are based on analogies, replicas of physical processes, known peculiarities of mutual influence of certain kinds of electric equipment or precedents. Generally, these methods are combined with simplified approaches: hence, a group of different kinds of electric equipment (motors, generators, transformers, etc.) is treated as a single physical body with parameters which are in fact a sum of different equipment unit parameters. Changes in the quantity of this or that kind of equipment are represented as the corresponding change in power consumption. Consolidated indices are used for the known kinds of equipment [4].

Under such an approach, it may be difficult in some cases to average out the cost of different types of a single equipment set and the cost of 1 kWh of power, because this value may be different for different regions, industries, etc. In such cases, it is reasonable while averaging out to consider several groups of the country industrial complex, taking into account the ratio between the ter-

Table

Calculation of interharmonics

p	n_1	n_2	$I_{x12}(p)$
-4	27.32	26.09	0.043
-3	20.24	19.88	0.059
-2	13.16	12.8	0.091
-1	6.08	5.72	0.2
0	1	1	1
1	8.08	8.44	0.54
2	15.16	15.38	0.143
3	22.24	22.6	0.077
4	29.32	29.68	0.053

ritory and population [4], the value of the annual power production, etc.

The accuracy of PQ values estimation depends on the error set for the nominal parameters of electric equipment and power networks, and on incompleteness or incorrectness in analysing the composition and modes of electric equipment.

The errors of resistance reduction do not usually exceed 5–10 %, but, if there are non-linear appliances present, the errors can be sufficiently bigger. The same refers to the resistances of the direct and reverse sequences. The errors of calculating resistances on the harmonics frequencies can be bigger, as the values of inductive resistances rise proportionally to the numbers of higher harmonics (HH).

The reverse sequence resistance of the feeding network is assumed to be equal to the short circuit resistance in the considered nod; the calculation error for this resistance is within 3–13 %. Its frequency characteristic is substantially non-linear.

The values of calculation error are significantly affected by incomplete and incorrect information contained, for example in the tasks related to power supply engineering: in fact, about 30–50 % of the necessary data are not known. The following information is also usually missing: mode characteristics of electric networks, prospective growth of capacities and changes in configuration of the supplying power system. The values of HH and interharmonics (IH) currents, as well as negative sequence currents I_2, necessary for calculating non-sinusoidal and asymmetric modes, are also set with substantial error. For example, mathematical expectation $M[I_2]$ and dispersion $D[I_2]$ of the relative calculation error for the negative sequence current at chosen substations turn to be within the range $M[I_2] = 0.04 \div 0.10$, $D[I_2] = 0.14 \div 0.18$. For HH, the corresponding values are even bigger.

The error in calculating PQ in industrial networks and power systems can reach 10–15 %. As evident from practice, a similar accuracy can be reached in singular cases with the help of the so called estimating calculations, when there is no necessity to take into account the maximum number of affecting factors. In some cases, it means that application of complex programs considering a lot of effecting factors or physical models in calculating PQ in power networks is unfeasible [1].

In estimating calculations, we take into account certain average values of the following parameters [2]:

- cost indices (currencies rate ratio) are assumed to be: $ 1 equals UAH 26; the cost of 1 MVA of transformer capacity is assumed to be equal to 1 mln roubles or 250 thousand UAH or 3000 dollars;
- decrease in the life time of the transformer and electric motor insulation caused by low quality power (unacceptable values of asymmetry, non-sinusoidality, voltage deviation) is taken to be 20 %;
- total capacity of transformers exceeds the total installed capacity of the power plant generators by 4–5 times;
- probability of supply disconnection or limitation at substations is taken to be 5 %;
- electric drive consumes 70 % of all generated power.

Estimation of economic losses in Ukraine related to low quality power. The total transformer capacity W_Σ is 5 times higher than the total capacity of the power plant generators W_E. In Ukraine, W_E = 50.000 MVA. Thus, $W_\Sigma = 50 \cdot 5 = 250$ GW.

According to the averaged estimation of Energoset-projekt institute [4], annual failure of transformers ΔW_T resulting from additional wear of insulation because of low quality power is 20 %, if more than 75 % of transformers are working at a capacity of over 50 %. Hence, GW.

$$\Delta W_T = 0.2 \cdot 0.75 \cdot W_\Sigma = 0.15 \cdot 250 = 37.5.$$

Expenditures related to transformers replacement: 37500·0.25 = 9375 mln UAH/year or 9375/8 = 1.17 bln dollars/year.

Electric motors (electric drives) consume about 70 % of all generated power S_E. In 2012, this value was $S_E \approx 200$ bln kWh. $S_M = 0.7 \cdot S_E = 0.7 \cdot 200 = 140$ bln kWh.

Values of losses ΔS_M, related to the effect of low quality power on electric motors damage is $\Delta S_M = 0.2 \cdot S_E =$ $= 140 \cdot 0.2 = 28$ bln kWh.

The cost of additionally consumed power (0.5 UAH/kWh): $S_M'' = 28 \cdot 0.5 = 14$ bln UAH/year = 1.75 bln dollars/year.

The cost of annual losses in electric networks (12 % according to 2012 data): $200 \cdot 0.12 \cdot 0.5 = 12$ bln UAH/year =1.5 bln dollars/year.

The cost of total electromagnetic power losses: $S_\Sigma = 1.17 + 1.75 + 1.5 = 4.42$ bln dollars.

Thus, the estimated value of electromagnetic losses in electric networks of Ukraine can be taken as 4.4 bln dollars/year.

Let us determine the technological component of the prospective loss related to overheating or supply limitation with probability $q = 0.05$ [2], considering the values of systemic failure flow $\lambda_s = 0.1$/year [2]. The probable value of the technological component of loss ΔS_{prob} will be: $\Delta S_{prob} = 0.05 \cdot 0.1 \cdot 200 = 1$ bln kWh/year.

Considering the value of specific loss Y_0 for industry and housing and utilities sector $Y_0 = 0.3$ dollars/kWh, the probable value of the technological component of the prospective loss will be $S_{prob} = 1 \cdot 0.3 = 0.3$ bln dollars/year.

The estimated value of the total loss is $S_\Sigma + S_{prob} = 4.42 +$ $+ 0.3 = 4.72$ bln dollars/year.

Or, by rounding, we obtain $S_\Sigma + S_{prob} \approx 5$ bln dollars/year.

Sometimes, in estimating calculations, when electric systems and economic activities have a similar structure, we can consider estimated values for population, power generation, territory, etc. for instance, the ration of power generation in Russia and Ukraine is (according to 2012 data) $\frac{1000}{200} = 5$, which allows estimating the annual losses due to low PQ in Russia at 25 bln dollars/year.

This result corresponds to the figure in [4] based on much more accurate calculation taking into account the real data about losses.

Peculiarities of determining losses for the case with capacitor banks. When capacitor banks (CB) are installed for increasing the power factor in industrial electric networks of 0.4, 6 or 10 kW with non-sinusoidal voltages, it is possible that currents resonance will appear in the capacitor bank circuit – external network at HH frequencies. In this case, capacitors are subjected to current and power overload, which can lead to their failure. As a result, it is impossible for CB to operate in a regular mode without special measures aimed at failure prevention. With non-sinusoidal voltages, capacitors should be either protected by reactors against HH penetration or included into the circuits of HH filters otherwise they should be shut down. In this case, the loss is determined by the annual expenditures on installation and operation of protective reactors or filter reactors (UAH/year) [3]

$$Y_n^{(p)} = E^{(p)} K^{(p)},$$

where $E^{(p)}$ is the norm coefficient of capital investment efficiency $K^{(p)}$ and coefficients of allowances for depreciation, current repairs, and maintenance.

When CBs are shut down, the losses are defined by the cost of additional power and capacity losses during the operation of electric network with a low power factor. i.e.

$$Y_n^{(k)} = \delta\left(\alpha k_M + \beta\tau\right)\cdot\left(\Delta P_M - \Delta P_M^{(k)}\right),$$

where ΔP_M and $\Delta P_M^{(k)}$ are maximum losses of active power for shut down and working capacitors correspondingly, kW; α stands for specific costs determined by the increased power of the system plants in order to compensate losses of active power, UAH/kW; β stands for specific costs on power generation and expansion of fuel base, UAH/kW; $k_м$ is the ratio of active power losses at the moment of energy system peak load to the maximum losses of its active power; τ is the number of maximum losses hours; δ is the coefficient, incorporating expenditures on the electric networks area expansion resulting from the power transfer to compensate the active power losses.

Conclusions.

1. Interharmonics are the most serious kind of electromagnetic interferences in systems of power supply. As of today, there is no serious research into the physical processes linked to generation and distribution of these interferences in power supply systems. Besides, there are no official documents regulating their assessment and standardization in electrical networks of Ukraine.

2. It is feasible to compute IHs in industrial power supply systems on the basis of the spectral theory of stochastic processes using fast Fourier transform.

3. Computing IHs of DFC input currents is only possible on the basis of state-of-the-art software, taking into account the laws of inverter control. It is important here to develop reasonably correct approximate formulas.

4. The suggested approaches to estimating losses and other parameters of PQ in electric networks of industrial enterprises and energy systems can be used for calculating their approximate (also variant) values while solving the problems of engineering and operation.

5. In order to develop estimating calculation methods, it is necessary to conduct further research related to specific objects, with statistical processing and analysis of the results.

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Мета. Розглянути маловивчену частину питання якості напруги та електромагнітної сумісності й дати математичний опис для аналізу інтергармонічних складових напруги у змішаному спектрі.

Методика. Методика досліджень заснована на теорії спектрального аналізу й загальної теорії електротехніки.

Результати. Наголошено на необхідності врахування інтергармонік при аналізі якості напруги в системах електропостачання підприємств. Пояснюється фізика процесу появи інтергармонік у системах електропостачання, описуються джерела, що генерують даний вид перешкод. Представлені математичні залежності, що дозволяють ідентифікувати інтергармоніки в загальній енергії спотвореного спектра. Підкреслено доцільність використання в розрахунках методів спектрального аналізу. Проаналізовано значення похибок розрахунків показників якості електроенергії (ПКЕ) і причини, що їх зумовлюють: похибки завдання параметрів електрообладнання, їх еквівалентування й т.і. Встановлено, що математичне очікування похибок знаходиться в межах 3–13 %.

Наукова новизна. Дано теоретичне обґрунтування доцільності використання методу Інтеграла Фур'є для аналізу інтергармонік. Встановлені залежності між кутами комутації вентилів інвертора й рівнем інтергармонік у мережевому струмі перетворювача. Показана доцільність підготовки керівних вказівок по оціночним методам розрахунку, аналогічних відомим в енергетиці та інших галузях господарства.

Практична значимість. Аналіз отриманих рішень дозволив кількісно оцінити рівні інтергармонік і вищих гармонік як показників якості напруги. Представлена наближена формула для оцінки рівнів інтергармонік при лінійному законі управління інвертором. Розкрита відповідність розрахункового значення оціночних втрат в електроенергетиці України результатам, отриманим дослідниками при більш докладних дослідженнях, заснованих на фактичних даних.

Ключові слова: *якість напруги, інтергармоніки, спектральний аналіз, оціночний метод, похибки*

Цель. Рассмотреть малоизученную часть вопроса качества напряжения и электромагнитной совместимости и дать математическое описание для анализа интергармонических составляющих напряжения в смешанном спектре.

Методика. Методика исследований основана на теории спектрального анализа и общей теории электротехники.

Результаты. Подчеркнута необходимость учета интергармоник при анализе качества напряжения в системах электроснабжения предприятий. Объясняется физика процесса появления интергармоник в системах электроснабжения, описываются источники, генерирующие данный вид помех. Представлены математические зависимости, которые позволяют идентифицировать интергармоники в общей энергии искаженного спектра. Подчеркнута целесообразность использования в расчетах методов спектрального анализа. Проанализированы значения погрешностей расчетов показателей качества электроэнергии (ПКЭ) и причины, их обусловливающие: погрешности задания параметров электрооборудования, их эквивалентирование и др. Установлено, что математическое ожидание погрешностей находится в пределах 3–13 %.

Научная новизна. Дано теоретическое обоснование целесообразности использования метода Интеграла Фурье для анализа интергармоник. Установлены зависимости между углами коммутации вентилей инвертора и уровнем интергармоник в сетевом токе преобразователя. Показана целесообразность подготовки руководящих указаний по оценочным методам расчета, аналогичных известным в энергетике и других отраслях хозяйства.

Практическая значимость. Анализ полученных решений позволил количественно оценить уровни интергармоник и высших гармоник как показателей качества напряжения. Представлена приближенная формула для оценки уровней интергармоник при линейном законе управления инвертором. Раскрыто соответствие расчетного значения оценочных потерь в электроэнергетике Украины результатам, полученным исследователями при более подробных исследованиях, основанных на фактических данных.

Ключевые слова: *качество напряжения, интергармоники, спектральный анализ, оценочный метод, погрешности*

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