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Increasing of the accuracy of estimating the coefficient of voltage harmonics of electrical supply systems

***Abstract**. In electrical networks that supply power electrical equipment with non-linear volt-ampere characteristics, harmonics, interharmonics and other harmful forms of powerful voltage signals significantly distort the shape of the sinusoidal voltage. Processing of the registered instantaneous value of the voltage of the distribution and supply electric network at the point of connection of the electric arc welding unit showed that the quantitative value of the distortion coefficient differs from the value obtained by the recommended analytical expressions given in the state norms and standards. This shows that the task of improving the methodology and technical control systems requires a solution. The authors proposed the structure of a potential technical system and showed on a real example the method of estimating the distortion coefficient of the voltage shape.*

Streszczenie.** W sieciach elektrycznych zasilających urządzenia elektryczne o nieliniowej charakterystyce woltoamperowej, harmoniczne, interharmoniczne i inne szkodliwe formy silnych sygnałów napięciowych znacznie zniekształcają kształt napięcia sinusoidalnego. Przetwarzanie zarejestrowanej wartości chwilowej napięcia sieci dystrybucyjnej i zasilającej w punkcie podłączenia urządzenia do spawania łukiem elektrycznym wykazało, że wartość ilościowa współczynnika zniekształceń różni się od wartości uzyskanej za pomocą zalecanych wyrażeń analitycznych podanych w normach i standardach państwowych. Pokazuje to, że zadanie poprawy metodologii i technicznych systemów kontroli wymaga rozwiązania. Autorzy zaproponowali strukturę potencjalnego systemu technicznego i pokazali na rzeczywistym przykładzie metodę szacowania współczynnika zniekształcenia kształtu napięcia. (**Zwiększenie dokładności szacowania współczynnika harmonicznych napięcia w systemach zasilania elektrycznego).

Keywords: distortion factor, harmonics, interharmonics, electric arc equipment.
Słowa kluczowe: współczynnik zniekształceń, harmoniczne, interharmoniczne, urządzenia łuku elektrycznego.

Introduction

Electric energy is one of the most used products not only by household, but also by industrial consumers of the world, so its parameters must meet the requirements of state norms and standards, since the deviation of these parameters from nominal values significantly affects the efficiency of electrical equipment or electrical receivers. Among the main normalized indicators of the quality of electricity, an important place belongs to the coefficient of distortion of the sinusoidal voltage form, which is defined as the ratio of the effective value of the higher harmonics to the effective value of the first harmonic [1 - 4]. The widespread use of electric arc units and the increase in the number of various devices in which semiconductor elements are used for industry and everyday life are increasingly deepening the problem of their generation of harmonics and interharmonics in power supply systems. Such a state significantly aggravates the problem of distortion of the sinusoidal form of the voltage at the connection nodes of the mentioned devices. Accordingly, this leads not only to an increase in the loss of electrical energy in the elements of the power supply system, but also to the deterioration of the operating modes and conditions of the electrical equipment.

The existing technical means of controlling the distortion coefficient of the sinusoidal voltage do not fully allow to determine its real value, because they are based on the use of the theory of harmonic analysis, and therefore do not allow to detect interharmonics, sub-frequencies and super-frequencies and, especially, non-harmonic components in the supply voltage. In this regard, there is an important technical task to more accurately estimate the distortion coefficient of the sinusoidal voltage form not only by harmonics, but also by other components, such as subharmonics and superharmonics, as well as exponentially changing components of currents and voltages.

The purpose of the work is to propose a method for determining the effective value of the entire set of component and non-industrial frequencies that distort the sinusoidal form of the main voltage harmonic in electrical networks and, thus, more accurately determine the coefficient of distortion of the voltage form and obtain information for effective management by technical means of ensuring the sinusoidal form of voltage in electrical networks.

Solving the problem

In the general case, the instantaneous value of the voltage distorted by non-linear consumers of electrical energy can be approximately written in the form:

$$(1)\quad u(t)=\sum_{k=0}^{\infty}\sum_{n=0}^{f-1}U_{m,k-n}e^{j((k+\frac{n}{f})\omega t+\psi_{k-n})}+\sum_{i}^{\infty}U_{m\,i}e^{-\gamma_i\cdot t}$$

where $f=50\ Гц$ – the frequency of the fundamental voltage harmonic, $\gamma_i=-\alpha_i\pm j\beta_i$ – indicator of the exponential components of the distorted voltage.

According to [1-4], the coefficient of voltage harmonics was defined as the ratio of the effective value of the higher harmonics to the effective value of the first harmonic of the controlled voltage. During calculations, harmonics from the second to the fiftieth inclusive are taken into account. This means that from the full spectrum of voltage frequencies, frequencies that are not multiples of the fundamental (interharmonics) and aperiodic components are not taken into account.

According to another method, the coefficient of voltage harmonics can be determined as the ratio of the effective value of higher harmonics to the effective value of the controlled voltage, which contains higher harmonics [4-5].

With the help of the Fourier transformation, the harmonic coefficient is accurately determined under the condition of a voltage that corresponds to the conditions of periodicity at a given time interval, which in real conditions is not always possible to ensure [6]. Taking into account the fact that the instantaneous value of the voltage in modern power networks contains not only harmonics, but also interharmonics, and the spectrum of harmonics is taken from the second to the fiftieth, the value of the harmonic coefficient is not accurate.

For frequency analysis of non-periodic voltages, a short-wave transformation is used, which makes it possible to distinguish a wide range of frequencies, both multiples and non-multiples of the fundamental (harmonics and interharmonics) [1, 7-9]. The result of the frequency analysis depends on the discretization step, the duration of the process, that is, the parameter of the signal window, and the selected set and type of approximating functions. Even the use of the best variant of short-wave transformations does not give an exact value of the voltage distortion coefficient, because in this way it is difficult to obtain the amplitudes of the entire frequency spectrum that the voltage contains at a given time interval [10-13]. In addition, switching processes that continuously take place in power supply systems lead to the appearance of aperiodic components of voltages, which also distort the sinusoidal form of voltage [14-19].

Objective information about the real content of harmonics, interharmonics and other signals in the supply voltage of electricity consumers makes it possible to take optimal decisions regarding the choice of means, their parameters and modes to limit the negative impact of components that distort the form of the supply voltage of electricity consumers.

The authors of the study propose an improved method of determining the exact distortion coefficient of the controlled voltage, which consists in subtracting the nominal voltage of an ideal sinusoidal form from the measured voltage. The resulting difference contains the entire frequency spectrum up to infinity, as well as exponential components and the first harmonic, if there is a deviation of the voltage from the nominal value, or fluctuations of the controlled voltage with a certain low frequency [20]. If the difference contains the first harmonic, it means that there is a deviation of the voltage from the nominal value by the value of the effective value of the first harmonic. To do this, it is necessary to isolate the first harmonic from the difference and, through further processing, determine its effect on the deviation of the controlled voltage from the nominal value. Thus, we subtract from expression (1) the nominal instantaneous voltage value of the first harmonic, the phase of which is consistent with the controlled voltage, and obtain the first difference in the form of:

$$\Delta u(t) = u(t) - U_{1m\,n}\sin(\omega t \pm \psi_u) = = \sum_{k=0}^{\infty}\sum_{n=0}^{f-1} U_{m,k-n} e^{j((k+\frac{n}{f})\omega t + \psi_{k-n})} + \sum_{i}^{\infty} U_{m\,i} e^{-\gamma_i \cdot t} - U_{1m\,n}\sin(\omega t \pm \psi_u) \tag{2}$$

where $U_{1m\,n}$ - nominal amplitude value of the first harmonic of voltage.

The specified voltage difference may contain the first harmonic, the value of which depends on its deviation from the nominal value. The amplitude of the difference of the first harmonic was determined using spectral analysis, and its initial phase was taken as the same as the nominal. After subtracting the indicated difference of the first harmonic from the first difference of the Δu(t) controlled voltage, we get the instantaneous value of the second voltage difference almost without the first harmonic. After subtracting the selected difference of the $u_{1i} = U_{1m\,i}\sin(\omega t \pm \psi_u)$ first harmonic from the nominal value of the $\Delta u_1 = U_{1m\,n}\sin(\omega t \pm \psi_u)$ voltage of the first harmonic, we get the real value of the first harmonic in the controlled voltage, the effective value of which is used to calculate the distortion coefficient according to the formula:

$$K_C = \frac{\Delta U}{U_1}100\% \tag{3}$$

where ΔU – effective value of the second difference of the controlled voltage.

To calculate the voltage deviation coefficient from the nominal value according to the known expression, we use the instantaneous value of the voltage difference of the first harmonic, having previously calculated its effective value, in particular

$$K_B = \frac{\Delta U_1}{U_1}100\% \tag{4}$$

where ΔU_1 – effective value of the difference of the first harmonic of the controlled voltage.

The possibility of implementing the described method of determining the distortion coefficient of the voltage shape has been confirmed experimentally. To do this, we recorded the voltage of the real electrical power supply network of the repair and technical building, which houses various consumers, including electric arc welding units.

The one-line scheme of the external and internal power supply system (PSS) under study is shown in Fig. 1, where the 15 kV distribution substation buses are fed from the buses of the external power supply system through a power transformer with a voltage of 30/15 kV, to which, in addition to other consumers, a step-down transformer of 15/0.4 kV is connected. From the secondary winding of this transformer with a voltage of 0.4 kV, the power is transmitted through the power line to the 0.4 kV switchboard, from which, in addition to other consumers, the Deca PARVA 175 C electric arc welding machine is powered. The short-circuit current at the point of connection of the welding unit is almost 1000 A, while the total active short-circuit resistance of the power supply system is 9.230 Ohms, the active resistance is 0.226 Ohms, and the reactive resistance is 0.043 Ohms.

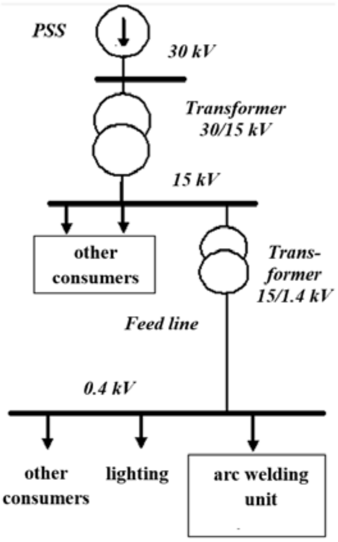

Figure 1. The facility's power supply system with an arc welding unit

The power of the electric arc welding unit can be changed in the range from 2 kW to 5 kW, and the value of the welding current - from 40 A to 160 A, while the nominal value of the input voltage is 230 V, and the output voltage is 48 V.

The instantaneous value of the voltages was recorded using a digital oscilloscope ATTEN FDS1022CL+, equipped with a CIECA60 attachment, a NANTEK T3100 voltage divider and a SONEL MPI-520 multifunctional measuring device. During the research, voltages were measured at the connection point of the electric arc welding unit in different modes: both nominal and maximum load.

With the help of the described equipment, the instantaneous voltage of the electrical network with a value of up to 1000 V was recorded at the connection point of the arc electric welding unit. The graphic image of the instantaneous value of the controlled voltage is shown in Fig. 2. A fragment of the instantaneous quasi-steady value of the voltage distorted by higher harmonics and interharmonics, generated by arcs of the welding unit and lamps, was registered at an interval of 0.45 s at the input of the welding unit in the maximum load mode.

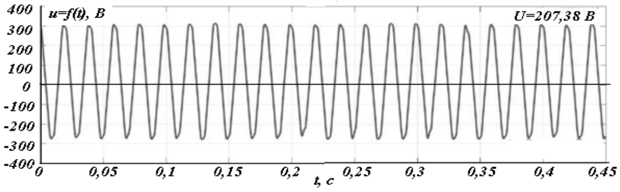

Figure 2. The instantaneous value of the controlled voltage

The nominal effective value of the phase voltage in Polish electrical networks is 230 V, while the amplitude value of the registered voltage is about 300 V. During the experiment, the effective value of the input voltage of the arc electric welding unit in the nominal load mode was 207.36 V, which corresponds to the amplitude value of the voltage of the first harmonic at 290.5 V. Such a decrease in the effective voltage value occurs due to voltage losses in the electrical power supply network.

As a result of the unequal electronic emission of the electrodes and the welded metal, a constant component with a positive sign appears in the arc voltage, which is transformed into a power supply network. The nominal amplitude value of the voltage of the first harmonic is equal to 324.2 V. From the difference obtained by subtracting the nominal instantaneous voltage from the instantaneous voltage measured in the load mode, shown in Fig. 3, it can be seen that it contains a sufficiently large first harmonic due to its deviation from the nominal value. The effective value of the difference between the instantaneous values of the measured and nominal voltages, which is shown in Fig. 3, is equal to 28.999 V, and the constant component in this difference is equal to 0.518 V.

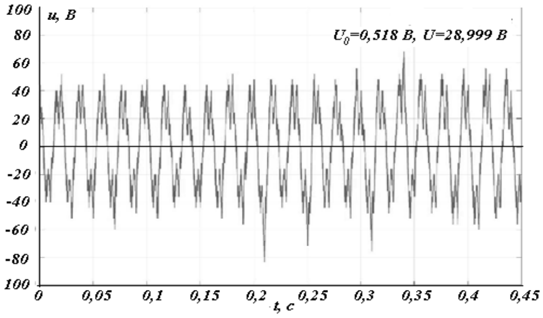

Figure 3. The instantaneous value of the difference between the controlled and nominal voltage

Fig. 4 shows the spectrogram of the amplitudes of the instantaneous value of the voltage difference. From the graphic dependence, it can be seen that due to the deviation of the voltage from the nominal value, the amplitude of the first harmonic reaches 35.4 V, and the value of the third, fifth and seventh harmonics are approximately 9 V, 7 V and 4 V, respectively, and their effective value is 7,2 V. Taking into account only the third, fifth and seventh harmonics of the measured voltage, the harmonic coefficient of this voltage is equal to 3.4%, which is lower than the real one. The calculated effective value of the difference using the data of the analyzed spectrogram (Fig. 4), in which only the value of voltage harmonics of 0.5 V and more is taken into account, is 26.5 V, which is 2.5 V less than what was registered by the measuring device.

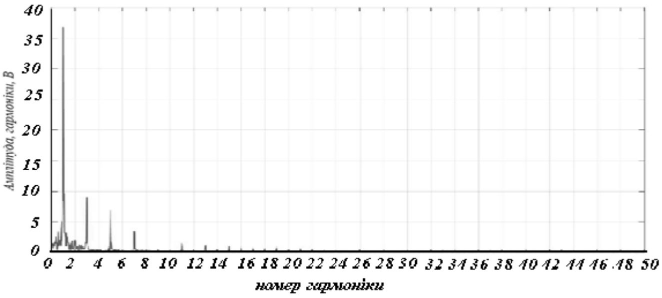

Figure 4. Histogram of the frequency spectrum of the supply voltage of the welding unit

The spectrogram also shows that there are multiple frequencies in the voltage difference between the first and eighth harmonics, especially in the interval from 50 Hz to 150 Hz. As mentioned above, in the load mode, the effective value of the voltage at the input of the welding unit is 207.36 V, and amplitude - 290.5 V. This confirms that failure to take into account the full spectrum of frequencies leads to the appearance of a significant error in the process determining the harmonic coefficient and, accordingly, the distortion coefficient.

The research results indicate that disregarding the full spectrum of frequencies different from the main and other components does not ensure a sufficient quantitative assessment of the level of voltage distortion in power supply networks. Accordingly, it does not make it possible to fully connect the distortion of the voltage form in electrical networks with negative effects and the conditions and terms of operation of power electrical equipment, as well as power losses.

The proposed method of determining the distortion coefficient of the voltage form is that the appropriate mathematical operations and the processing of the received information provide higher accuracy of the distortion coefficient and asymmetry of the supply voltage. The essence of this method is that we register the instantaneous value of the voltage in the electrical network, from which, at a given time interval after synchronization, we subtract the instantaneous nominal value and obtain the first voltage difference. As a result of subtracting the instantaneous values of the registered and nominal voltage, two options are possible.

The first of which is the equality of voltages of the fundamental frequency, that is, the first harmonic. In this case, the first harmonic is absent in the first voltage difference, which indicates the absence of voltage deviation from the nominal value, so the effective value of the voltage of the first harmonic and the effective value of the first voltage difference were determined. After dividing the effective value of the voltage of the first difference by the effective value of the nominal voltage, we obtain the coefficient of distortion of the voltage form.

The second option is that the first difference between the registered voltage and the nominal one contains the first harmonic due to the effect of the deviation of the first harmonic of the registered voltage from the nominal value.

On the way of the distortion factor calculation, we determined the effective value of the first harmonic of the registered voltage, which differs from the nominal value. Next, from the first difference of the instantaneous voltage, we determine the value and initial phase of the first harmonic of the voltage and subtracted it from the first difference; accordingly, we obtained the instantaneous voltage deviation from the nominal value. As a result of this operation, we obtain the second difference of instantaneous voltage values, which does not contain the voltage of the first harmonic (deflection voltage), but only harmonics, interharmonics, and constant and exponential components. To obtain the distortion factor, we determined the effective value of the second difference of voltage and divided it by the effective value of the voltage of the first harmonic. After determining the effective value of the deviation voltage and dividing by the effective value of the first harmonic of the registered voltage, we obtain the coefficient of deviation of the controlled voltage from the nominal value.

In fig. 5, one of the versions of the proposed method implementation is given in the form of a structural and logical scheme, which can be used as a basis for building a measuring system of both the distortion coefficient and the coefficient of deviation of the controlled voltage in electrical networks.

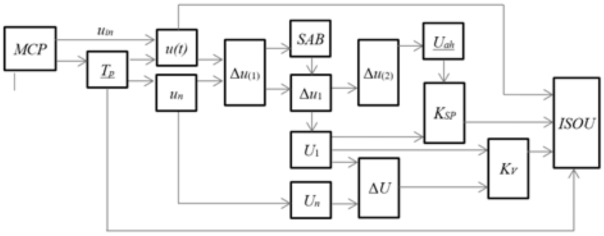

Figure 5. Structural and logical scheme of implementation of the proposed method

Through the mode control panel (MCP), the uin input voltage is supplied to the input of the unit for storing the u(t) instantaneous voltage value at the time interval of registration set by the Tp block, which is also set with the MCP. This time interval can be changed depending on the form and periodicity of the monitored instantaneous voltage. In the block of Δu(1), the ui nominal sinusoidal voltage is subtracted from the registered u, and the difference is transferred to the spectrum analysis block (SAB) in order to detect the presence of the first harmonic in the Δu(1) first voltage difference.

If the first harmonic of the controlled voltage is equal to the nominal or differs from the nominal by the amount of the measurement error, then the value of the voltage deviation coefficient is assumed to be zero, and the process of its determination is not performed. If there is a residue of the first harmonic in the first difference, the instantaneous value of this residue is formed in the Δu1 block, which is subtracted in the Δu(2) block from the first difference of Δu(1). The result is the second difference Δu(2), which contains the full spectrum of frequencies, including a constant component.

In the ΔU block, the difference between the effective value of the first harmonic of the U1 measured voltage and the Ui effective value of the nominal voltage is determined, and in the Uah block, the effective value of all components of the controlled voltage except for the first harmonic is determined. In the KSP block, the distortion coefficient of the voltage form is determined by expression (3), and in the KV block, the deviation coefficient of the effective value of the first harmonic of the controlled voltage from the nominal value is determined by expression (4). Repeated spectral analysis of the second voltage difference provides information about the voltage frequency with the largest amplitude, which must be reduced by using certain technical means and mode solutions. The information about the distortion and asymmetry coefficients, as well as the prevailing non-industrial frequency of the voltage, is sent to the information storage and output unit (ISOU) for the purpose of displaying information on the screen, printing or in another form for operational personnel who use this information accordingly.

The considered method of controlling the specified indicators of the quality of electricity is quite promising, taking into account the pace of introduction of powerful nonlinear dynamic receivers of electrical energy, which significantly distort the form of voltage in electrical networks. Taking into account the level of development of microprocessor technology, information technology and software products, the implementation of this method is not difficult.

Conclusions

The existing technical means of controlling the distortion coefficient of the sinusoidal voltage do not fully allow to determine its real value, because they are based on the use of the theory of harmonic analysis, and therefore do not allow to detect interharmonics, sub-frequencies and super-frequencies and, especially, non-harmonic components in the supply voltage. In this regard, there is an important technical task to more accurately estimate the distortion coefficient of the sinusoidal voltage form. The authors of the study propose an improved method of determining the exact distortion coefficient of the controlled voltage, which consists in subtracting the nominal voltage of an ideal sinusoidal form from the measured voltage. The method proposed by the authors for determining the distortion coefficients and voltage deviation in the connection nodes of electrical energy receivers allows taking into account the influence of the full spectrum of non-industrial frequencies, including constant and exponential components, which provides significantly higher accuracy compared to existing methods. The implementation of the specified method will make it possible to control the distortion coefficients and voltage deviations in electric networks, as well as to adjust the requirements for the electromagnetic compatibility of electric energy receivers with power supply systems.

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