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The Influence of a Transformer with "Double Zigzag with Zero Output" Windings on the Level of Asymmetry and Nonsinusoidal Currents in a 0.38-kV Network

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Abstract—The results of laboratory studies of the transverse inclusion of a transformer with a circuit for connecting "double zigzag with zero output" windings to a 0.38-kV network model in order to increase the capacity of the electrical network by reducing the operating current in the zero working conductor of a three-phase four-wire electrical network are presented. The analysis of currents creating a load of the zero working wire of the network with a voltage of 0.38 kV is performed. For the load side of the power transformer, the equations of the instantaneous values of the most significant harmonic components of the currents are presented, which are obtained from experimental studies with different load coefficients of the power transformer. The shunting effect of a transformer with a "double zigzag with zero output" winding connection scheme on the asymmetry coefficients of currents and voltages of the reverse and zero sequence, as well as on the distortion coefficients of the sinusoidal curves of currents and voltages and the coefficients of the third harmonic component of current and voltage, is estimated. The revealed patterns of changes in the current load of the zero working wire make it possible to improve the efficiency of electricity transmission in the electrical network, extend the service life of cable lines, and reduce the fire hazard of electrical installations.

Keywords: transformer with a "double zigzag with zero output" circuit for connecting windings, zero wire of the network, zero sequence current of the fundamental frequency, third harmonic current

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There have been significant changes in the structure of rural electricity supply in recent years: an increase in electricity consumption by household loads against the backdrop of a decline in electricity consumption by industrial loads. An increase in the share of single-phase nonlinear electrical receivers in load nodes leads to an increase in currents in the neutral working wires of four-wire electrical networks with a voltage of 0.38 kV and power transformers of 6–10/0.4 kV. Asymmetry and nonsinusoidality of currents are the main factors causing an increase in currents in the neutral working wire of the network.

Harmonic components of currents that are multiples of 3 are close to being in phase and, when summed in the neutral working wire, can form a current exceeding phase currents at a frequency of 150 Hz.

Most of the cable lines in networks with a voltage of 0.38 kV are made of four wires; the neutral conductor of such a cable may be of a smaller or the same cross section as the phase conductors. According to the heating conditions, a four-core cable with a neutral core of a smaller cross section is in worse conditions. In power transformers, current harmonics divisible by a three- and zero-sequence current of the fundamental frequency lead to an increase in additional power losses and a decrease in insulation service life [1].

The described situation is typical for rural and municipal electrical networks with a voltage of 0.38 kV. Therefore, the task of reducing zero-sequence currents of the fundamental frequency and currents with harmonics that are multiples of 3 in a four-wire network is of scientific and practical interest.

The use of transformers in electrical networks with windings connected in "zigzag" and "double zigzag with zero output" circuits [2] has shown their promise in limiting currents in the neutral wire. The purpose of the article is to study the possibility of increasing the capacity of the electrical network by reducing the effective current in the zero working conductor of a three-phase four-wire electrical network.

For research, a transformer was manufactured with the windings connected in a "double zigzag with zero output" (2Zn) circuit; the ratio of the number of turns on each rod constituted 1 : 0.5 : 0.5 [3]. The cross-sectional areas of each of the rods, on which the windings are placed, are identical. Transformer T2 with wind-

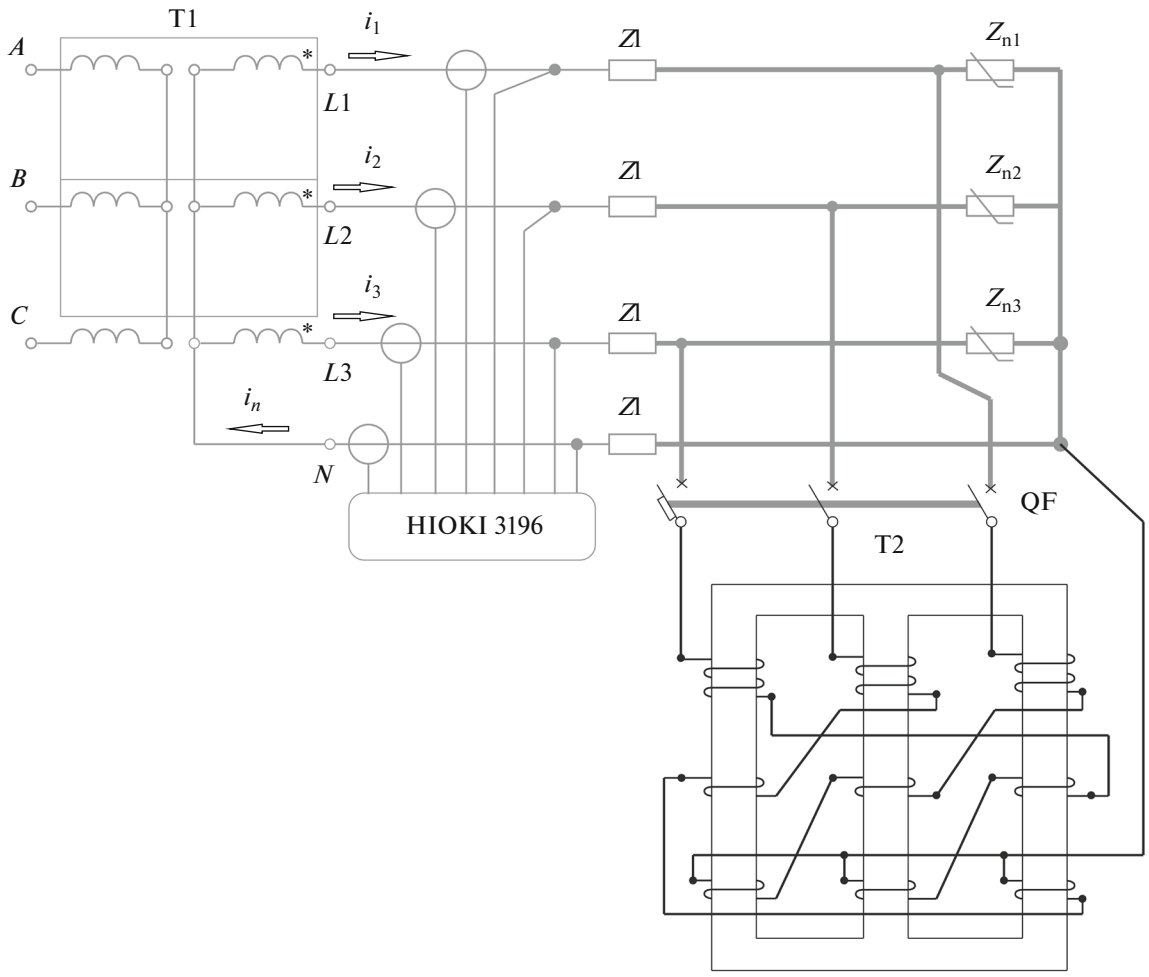


Fig. 1. Laboratory setup diagram.

ings 2Zn was connected by a QF circuit breaker to a model of a three-phase four-wire network between the power source and the load Z_{n1}–Z_{n3} (Fig. 1).

The network model was powered by power transformer T1 of type TS-1.5 with a star/star winding connection circuit with a neutral wire (Y/Yn). The active-inductive load Z_{n1}–Z_{n3} was simulated for various power combinations of switched DRL gas-discharge lamps; electrical quantities were recorded with a HIOKI 3196 device certified in Russia. During measurements, the current clamps of the HIOKI 3196 device covered the linear and neutral working conductors of the network model. Phase voltages were measured at the terminals of power transformer T1 on the load side.

The studies were carried out in various load modes: in a mode with a symmetrical phase load and in modes with an asymmetrical load, created by changing the power of DRL lamps. In each mode, two experiments were carried out: with transformer T2 disconnected and connected (via the QF switch), which led to a change in the load factor of transformer T1; the main results of the experiments are presented in Table 1.

Indicators of asymmetry and nonsinusoidality of currents obtained in experiments after connecting transformer T2 are presented in Table 2.

As follows from the data in Table 1, the voltage and current asymmetry indicators in the experiments varied within the following limits (Table 1): voltage asymmetry coefficient for the zero sequence K_{0U} from 0.31 to 0.38%, current asymmetry coefficient for the zero sequence K_{0I} from 12.99 to 26.74%, negative sequence voltage asymmetry coefficient K_{2U} from 2.62 to 4.88%, and negative sequence current asymmetry coefficient K_{2I} from 13.76 to 30.67%.

Sinusoidal distortion coefficients of voltages K_U and currents K_I changed accordingly: K_U from 1.28 to 2.32% and K_I from 3.14 to 9.64%.

As the most significant harmonics of voltages and currents, the first and third harmonics were analyzed, including the distortion coefficient of the sinusoidality of the current curve in the neutral wire of the K_{In} net-

Table 1. Coefficients of asymmetry and nonsinusoidality depending on the operating mode of the network model

Indicator	Load factor β of transformer T1, switch position QF					
	β = 0.81 QF off	β = 0.93 QF on	β = 1.29 QF off	β = 1.44 QF on	β = 1.31 QF off	β = 1.55 QF on
	Characteristics of asymmetry					
K_{0U},%	0.31	0.31	0.35	0.33	0.38	0.34
K_{0I},%	12.99	3.47	22.34	1.01	26.74	2.89
K_{2U},%	2.62	3.31	4.20	4.66	4.88	4.91
K_{2I},%	19.62	3.38	13.76	20.84	30.67	33.60
	Nonsinusoidal characteristics					
$K_{U(3)}$,%	0.27–0.73	0.26–0.68	0.34–0.92	0.16–0.86	0.52–0.76	0.49–0.84
$K_{I(3)}$,%	2.62–9.22	3.24–6.24	3.21–7.60	3.04–8.67	6.0–8.03	2.93–9.53
K_U,%	1.28–2.09	1.34–2.42	2.16–2.32	2.47–2.60	1.42–1.85	1.80–2.02
K_I,%	3.14–9.64	6.76–7.85	4.02–8.04	4.72–9.03	6.72–8.45	5.02–9.93
$K_{In(3)}$,%	30.7	140.2	25.12	343.9	26.87	98.71

Table 2. Harmonic components of current in the neutral wire of the network under various operating modes

Mode	Effective values of the harmonic components of the network neutral wire current			
	$I_{n(1)}$	$I_{n(3)}$	$I_{0(1)}$	I_n
β = 0.81, QF off	0.295	0.420	0.098	0.521
β = 0.93, QF on	0.226	0.322	0.075	0.400
β = 1.29, QF off	1.911	0.480	0.637	1.972
β = 1.44, QF on	0.107	0.336	0.036	0.391
β = 1.31, QF off	2.938	0.531	0.979	2.987
β = 1.55, QF on	0.391	0.290	0.130	0.493

work model. The coefficients of third harmonic voltage component $K_{U(3)}$ ranged from 0.27 to 0.92%, and coefficients of the third harmonic component of the current $K_{I(3)}$ ranged from 2.62 to 9.22%.

Before connecting transformer T2 to the network model (first experiment) with load factor β = 0.81, K_{0U} = 0.31%, K_{2U} = 2.62%, K_{0I} = 12.99%, K_{2I} = 19.62%, and $K_{In(3)}$ = 30.7% instantaneous voltages and currents of the most significant harmonics in the network section with resistance Z_l from supply transformer T1 to the connection point of transformer T2:

$$u_1 = 302.29\sin(\omega t) + 0.92\sin(3\omega t + 102°)\,\text{B};$$

$$u_2 = 302.84\sin(\omega t - 123°) + 0.85\sin(3\omega t - 96°)\,\text{B};$$

$$u_3 = 285.88\sin(\omega t + 118°) + 2.01\sin(3\omega t - 73°)\,\text{B}.$$

$$i_1 = 2.46\sin(\omega t - 50°) + 0.24\sin(3\omega t - 20°)\,\text{A};$$

$$i_2 = 2.97\sin(\omega t - 177°) + 0.18\sin(3\omega t - 39°)\,\text{A};$$

$$i_3 = 2.65\sin(\omega t + 65°) + 0.20\sin(3\omega t - 40°)\,\text{A};$$

$$i_n = 0.42\sin(\omega t - 56°) + 0.59\sin(3\omega t + 149°)\text{A}.$$

After turning on the QF circuit breaker (second experiment), the load factor increased to β = 0.93 due to the additional connection of transformer T2. Changes in other coefficients in this operating mode are presented in the third column of Table 1.

Connecting transformer T2 with the same phase load of the network model led to a change in the currents in the linear and neutral wires:

$$u_1 = 302.13\sin(\omega t) + 1.90\sin(3\omega t + 131°)\,\text{B};$$

$$u_2 = 306.06\sin(\omega t - 124°) + 0.33\sin(3\omega t - 40°)\,\text{B};$$

$$u_3 = 284.92\sin(\omega t + 117°) + 1.77\sin(3\omega t - 50°)\,\text{B}.$$

$$i_1 = 3.20\sin(\omega t - 62°) + 0.17\sin(3\omega t + 44°)\,\text{A};$$

$$i_2 = 3.44\sin(\omega t + 179°) + 0.23\sin(3\omega t + 104°)\,\text{A};$$

$$i_3 = 3.10\sin(\omega t + 59°) + 0.13\sin(3\omega t + 102°)\,\text{A};$$

$$i_n = 0.33\sin(\omega t + 15°) + 0.45\sin(3\omega t - 97°)\,\text{A}.$$

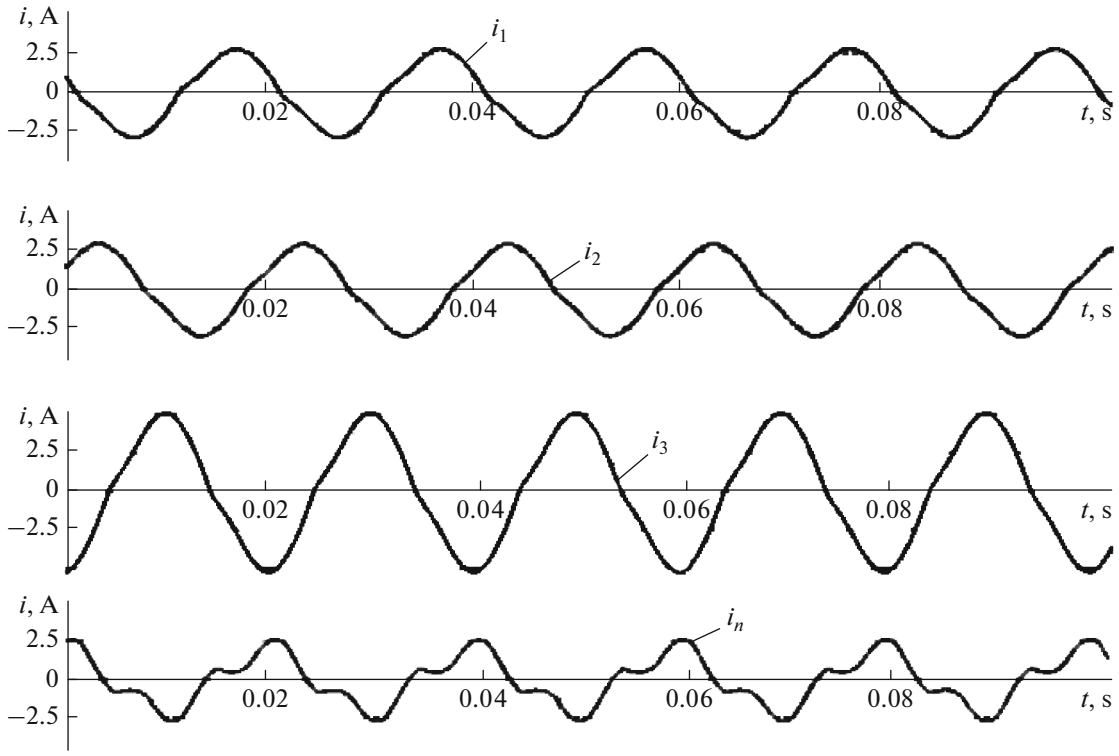


Fig. 2. Oscillograms of currents during initial network loading with β = 1.29 before turning on transformer T2.

After connecting transformer T2 to the network model, the currents of the first and third harmonics in the neutral wire decreased by 1.3 times. At the same time, the initial phases of the third harmonic currents changed in both linear and neutral wires. The effective value of the current in the neutral wire at the input of transformer T1 decreased from 0.521 to 0.400 A (Table 2).

The phase voltages remained virtually unchanged. So, in the future, attention will be paid to changes in the currents of the most significant harmonics.

At the next load with β = 1.29 (third experiment) and transformer T2 turned off, the current equations in the network model for the most significant harmonics were described by the expressions

$$i_1 = 3.05\sin(\omega t - 54°) + 0.23\sin(3\omega t - 35°)\text{ A};$$

$$i_2 = 3.82\sin(\omega t + 177°) + 0.12\sin(3\omega t - 31°)\text{ A};$$

$$i_3 = 5.57\sin(\omega t + 64°) + 0.35\sin(3\omega t - 30°)\text{ A};$$

$$i_n = 2.70\sin(\omega t - 98°) + 0.68\sin(3\omega t + 151°)\text{ A}.$$

Oscillograms of these currents are shown in Fig. 2, while the coefficients characterizing the asymmetry and nonsinusoidality of the considered network operating mode were K_{0U} = 0.35%, K_{2U} = 4.2%, K_{0I} = 22.34%, K_{2I} = 13.76%, and $K_{In(3)}$ = 25.12%.

Connecting transformer T2 (fourth experiment) led to an increase in load to β = 1.44 (Table 1) and the following equations for currents:

$$i_1 = 4.4\sin(\omega t - 72°) + 0.14\sin(3\omega t + 64°)\text{ A};$$

$$i_2 = 4.03\sin(\omega t - 169°) + 0.35\sin(3\omega t + 117°)\text{ A};$$

$$i_3 = 5.58\sin(\omega t + 61°) + 0.17\sin(3\omega t + 27°)\text{ A};$$

$$i_n = 0.15\sin(\omega t + 172°) + 0.52\sin(3\omega t - 97°)\text{ A}.$$

Analysis of the data in Table 2 shows that the main harmonic current in the neutral wire, due to the inclusion of transformer T2, decreased by 1.911/0.107 = 17.86 times; the third harmonic current in the neutral wire, by 1.43 times; and the zero-sequence current at the fundamental frequency, by 17.69 times.

As follows from the oscillograms in Fig. 3, in the neutral wire the third harmonic of the current prevails, which accounts for almost 86% of the effective value of current I_n.

The effective value of the current in the neutral wire at the input of transformer T1 decreased from 1.972 to 0.391 A (Table 2), that is, by five times.

The most significant was the decrease in coefficient K_{0I}: from 22.34 to 1.01%, that is, by 22.1 times. The shapes of the phase current and voltage curves deteriorated slightly; however, the third harmonic component in the phase voltage curves decreased.

With a further increase in the asymmetrical and nonsinusoidal load (β = 1.31, fifth experiment) before connecting transformer T2, the following currents were obtained:

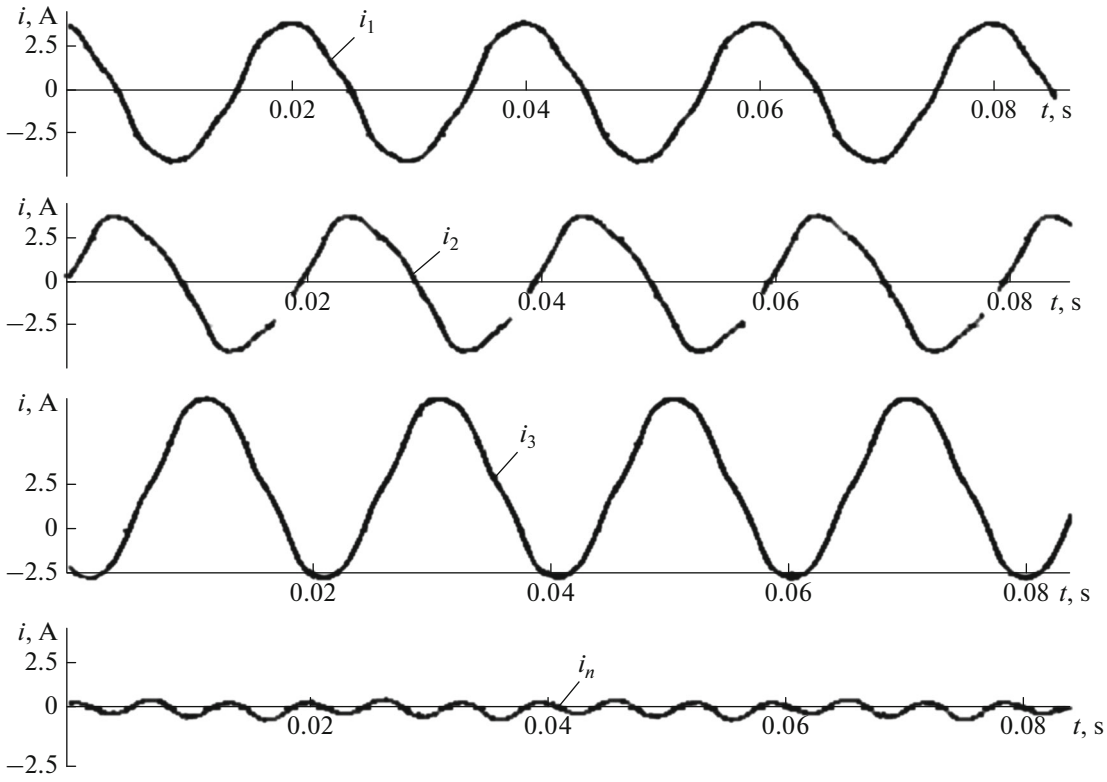


Fig. 3. Oscillograms of currents in a network with connected transformer T2 at β = 1.44.

$$i_1 = 2.71\sin(\omega t - 57°) + 0.19\sin(3\omega t - 48°)\text{ A};$$

$$i_2 = 2.92\sin(\omega t - 164°) + 0.24\sin(3\omega t + 7°)\text{ A};$$

$$i_3 = 7.50\sin(\omega t + 63°) + 0.38\sin(3\omega t - 17°)\text{ A};$$

$$i_n = 4.16\sin(\omega t - 120°) + 0.75\sin(3\omega t + 163°)\text{ A}.$$

The main contribution to the current load of the neutral wire of the network at β = 1.31, $K_{0U} = 0.38\%$, $K_{2U} = 4.88\%$, $K_{0I} = 26.74\%$, $K_{2I} = 30.67\%$, and $K_{In(3)} = 26.87\%$ remains with fundamental frequency current.

After connecting transformer T2 to the network model at the same load (sixth experiment), the following values changed: β = 1.55, $K_{0U} = 0.34\%$, $K_{2U} = 4.91\%$, $K_{0I} = 2.89\%$, $K_{2I} = 33.60\%$, and $K_{In(3)} = 98.71\%$. The most noticeable downward change, from 26.74 to 2.89% (that is, by 9.25 times), was found in the zero-sequence current asymmetry coefficient. Phase currents i_1 and i_2 increased slightly due to an increase in the fundamental harmonic current component:

$$i_1 = 4.51\sin(\omega t - 82°) + 0.20\sin(3\omega t + 117°)\text{ A};$$

$$i_2 = 4.53\sin(\omega t - 149°) + 0.38\sin(3\omega t + 114°)\text{ A};$$

$$i_3 = 7.73\sin(\omega t + 60°) + 0.28\sin(3\omega t - 25°)\text{ A};$$

$$i_n = 0.55\sin(\omega t + 171°) + 0.41\sin(3\omega t - 91°)\text{ A}.$$

In the neutral wire, the effective value of current i_n decreased by six times, while the fundamental harmonic current decreased from 2.938 to 0.391 A (by 7.5 times) and the third harmonic current from 0.531 to 0.29 A (by 1.8 times). As follows from the above equations for the operating mode under consideration, after connecting transformer T2, the components of the main and third harmonics of the current in the neutral working wire became comparable due to the reduction of the zero-sequence current by the basis of the harmonic (Table 2).

CONCLUSIONS

(1) Transverse connection of a transformer with a "double zigzag with zero output" winding connection diagram to a three-phase four-wire network with an asymmetrical nonlinear load reduces the current load in the neutral wire in the network section from the point of connection of the transformer to the power source. Moreover, with an increase in the asymmetrical nonlinear load on the line, the effect of reducing the current in the neutral working wire manifests itself to a greater extent due to a decrease in the currents of the fundamental and third harmonics.

(2) Connecting a transformer with a "double zigzag with zero output" winding connection diagram leads to a decrease in the zero sequence of the fundamental

harmonic on the current line, with the degree of reduction depending on the nature of the load.

(3) Connecting a transformer with a "double zigzag with zero output" winding connection diagram leads to a decrease in the third harmonic in the neutral wire of the current line. The degree of reduction also depends on the nature of the load.

(4) The results obtained on the physical model can be recommended for use in 380-V electrical networks with an asymmetrical nonlinear load.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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