ISSN 1068-3712, Russian Electrical Engineering, 2023, Vol. 94, No. 2, pp. 111–115. © Allerton Press, Inc., 2023.
Russian Text © The Author(s), 2023, published in Elektrotekhnika, 2023, No. 2, pp. 45–49.

# On the Effectiveness of the Use of Transformers with a "Star/Double Zigzag with Zero Wire" Winding-Connection Scheme under Nonlinear Nonsinusoidal Load

**M. A. Yundin[a, *], K. M. Yundin[b], A. M. Isupova[c], V. V. Lukin[d], and L. V. Babina[b]**

[a] *Azov–Black Sea Engineering Institute of Don State Agrarian University, Zernograd, 347740 Russia*

[b] *Don State Technical University, Rostov-on-Don, 344002 Russia*

[c] *Federal State Budgetary Educational Institution of Higher Education "Stavropol State Agrarian University", Stavropol, 355017 Russia*

[d] *Yuzhny Kit LLC, Shakhty, 346523 Russia*

**e-mail: ukm_61@rambler.ru*

Received July 8, 2022; revised October 4, 2022; accepted October 8, 2022

**Abstract**—The results of experimental studies under the same loads of power transformers with "star/double zigzag with zero wire" and "star/star with zero wire" winding-connection schemes in laboratory conditions are presented. Both transformers were loaded with symmetrical and asymmetrical nonlinear loads at different load factors. The values of the distortion coefficients of the sinusoidal currents in the phases, K-factor, active power losses in power transformers, total gross power, total power factors, currents in the zero wire, load current unbalance coefficients in the zero sequence were controlled. The obtained results are compared, conclusions are drawn about the efficiency of using transformers with different winding-connection schemes.

**Keywords:** power transformers, "star/star with zero wire" and "star/double zigzag with zero wire" winding-connection schemes, asymmetry, nonsinusoidality, experiment

**DOI:** 10.3103/S1068371223020128

## INTRODUCTION

The load of most 6- to 10/0.4-kV power transformers is characterized by nonlinearity and nonsinusoidality caused by the specifics of power receivers in load nodes. Most electrical receivers are of nonlinear load, which creates distortion in the supply network. Agricultural and domestic electrical consumers largely do not have electromagnetic compatibility with other electrical receivers included in the common electrical grid and, as a rule, reduce the transmission efficiency and quality indicators of electrical energy.

Affordable price and maintainability of 6- to 10/0.4-kV power transformers with a star/star winding-connection scheme with a zero wire predetermined their overwhelming use in rural and urban electrical networks. However, in such transformers, uncompensated zero-sequence magnetic fluxes with a frequency of 50 Hz and magnetic fluxes from harmonic currents that are multiples of 3 cause an increase in zero-sequence resistance, which leads to an increase in power losses, both in the transformers themselves and in the load network connected to them. In addition, in an electrical network with such transformers, problems with the correct operation of current protection are likely.

In electrical networks of 0.38 kV, the sample average values of the current sinusoidality distortion factor vary in the range of 9.81– 17.48%, the voltage sinusoidal distortion factor in the range of 1.30–4.01%, and the zero sequence voltage unbalance factor in the range of 1.03–9.02% [1–4].

In [5], a power transformer with a "star–double zigzag with a zero wire" ($Y/2Z_H$) winding-connection scheme was proposed. It was originally designed to eliminate circulating currents when operating in parallel with the most common star/star zero wire ($Y/Y_H$) transformer; then, it began to be tested under laboratory conditions with nonlinear [6] and asymmetric [7] loads. However, these works do not indicate the values of the parameters of the investigated transformer itself with the "star–double zigzag with zero wire" winding-connection scheme (number of turns in the transformer windings, design format, etc.), as well as the parameters of the nonlinear load used, which is necessary for an objective assessment.

The purpose of the article is to investigate the operation of a power transformer with a $Y/2Z_H$ winding-connection scheme with a nonlinear nonsinusoidal load and compare the efficiency of transformers with

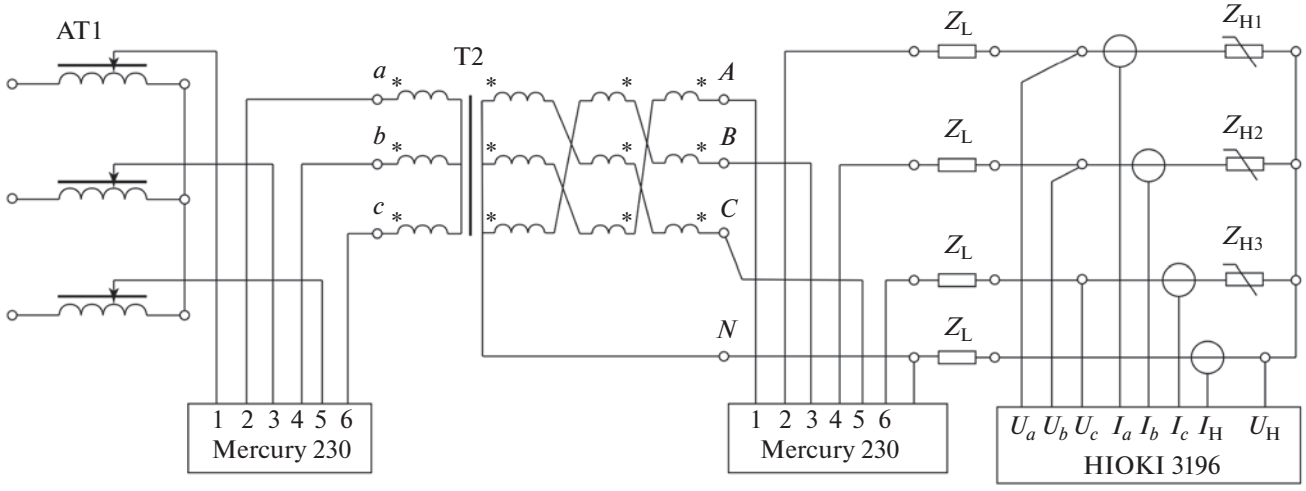



**Fig. 1.** Scheme of a laboratory setup when testing a power transformer with a $Y/2Z_H$ winding-connection scheme.

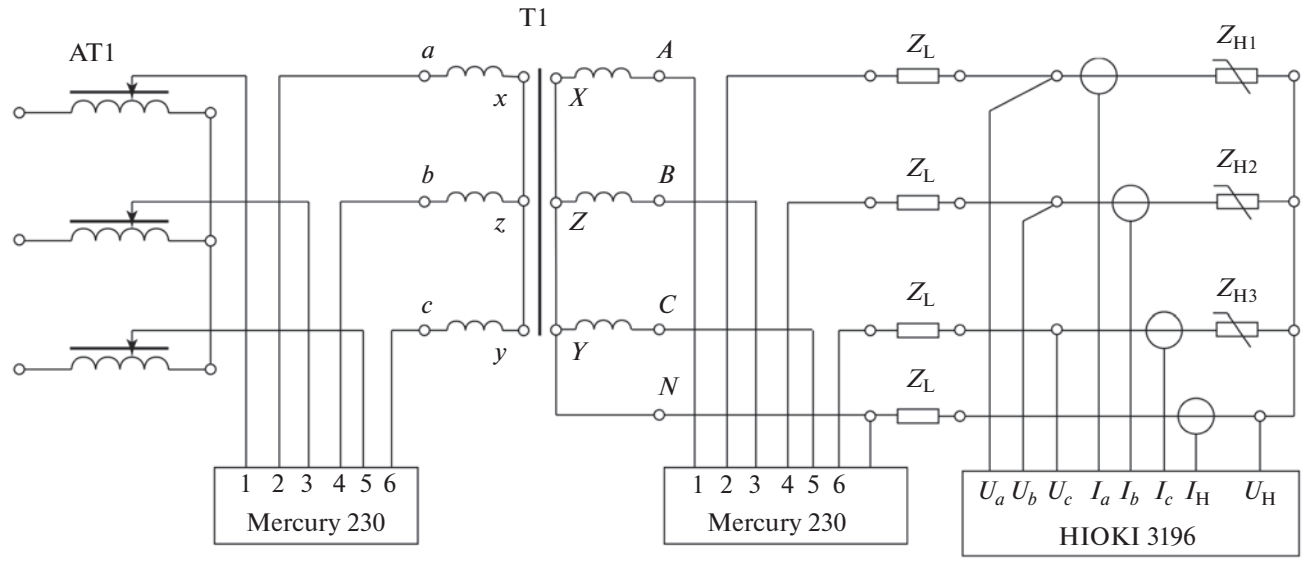



**Fig. 2.** Scheme of a laboratory setup when testing a power transformer with a $Y/Y_H$ winding-connection scheme.

$Y/2Z_H$ and $Y/Y_H$ connection schemes with the same nature of the load circuit.

## MAIN PART

Studies were carried out in laboratory conditions; two dry-type transformers of the same power (1.5 kVA) were used with $Y/2Z_H$ and $Y/Y_H$ winding-connection schemes. Transformer $Y/2Z_H$ had a ratio of the number of turns in the windings and half-windings of the load circuit on each of the magnetic core rods equal to 6.16 : 1 : 1.

The test circuit with a $Y/2Z_H$ transformer is shown in Fig. 1; that with a $Y/Y_H$ transformer, in Fig. 2.

As loads $Z_{H1}$–$Z_{H3}$ (Figs. 1, 2), DRL gas-discharge lamps with a power of 250 and 400 W were used. Electrical quantities were measured with a HIOKI 3196 device and Mercury 230 electricity meters installed on the primary and secondary sides of the transformers. Resistors $Z_L$ were used to simulate the parameters of the 0.38-kV load network. Autotransformers AT1 maintained the same voltage at the input of the load circuit.

By changing the number of DRL lamps in the load circuit $Z_{H1}$–$Z_{H3}$, the nature and level of load on both transformers varied. The tests were carried out at transformer load factors of 0.8, 1.0, and 1.3.

The obtained results are presented in the form of petal diagrams, which display the following main elec-

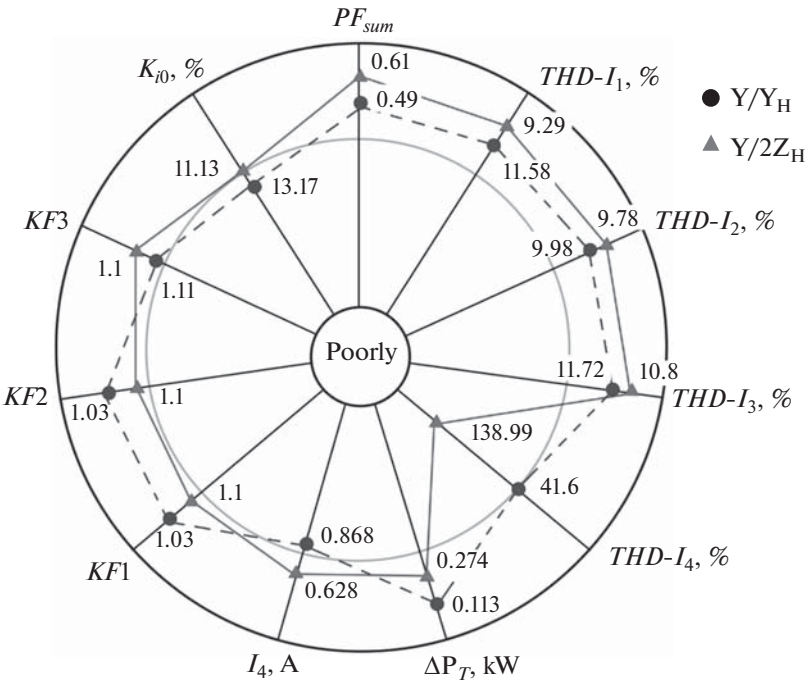



**Fig. 3.** Petal diagram of changes in the electrical values of the compared transformers with their load factor equal to 0.8.

trical quantities: $PF_{SUM}$ is the total power factor of loads including harmonics, $THD\text{-}I_1$–$THD\text{-}I_3$ are the distortion coefficients of the sinusoidal current curve in the line wires and $THD\text{-}I_4$ in the zero working wire, $\Delta P_T$ is the active power losses in the power transformer, $I_4$ is the current in the zero working wire, $KF_1$–$KF_3$ are the coefficients showing the increase in heat losses in the transformer phase windings due to nonlinearity of the load, and $K_{i0}$ is the zero-sequence current unbalance factor. When constructing petal diagrams, the worst result of the electrical quantity for the compared transformers was plotted along the beam closer to the center.

As follows from Fig. 3 with the same, phase-uniform total load of both transformers, active power loss $\Delta P_T$ of a transformer with a Y/2Z$_H$ circuit is greater than that of a transformer with a Y/Y$_H$ circuit. Sinusoidal current curve distortion factors in the linear wires turned out to be worse for the Y/Y$_H$ transformer with a load equal to 0.8. The worst results for this load at the transformer with the Y/Y$_H$ scheme turned out to be in terms of the current in the zero working wire ($I_4$) and in terms of coefficients $KF_3$, $K_{i0}$, and $PF_{SUM}$. Studies have shown that the current sinusoidal distortion factor in the zero wire when powered by a Y/2Z$_H$ transformer was almost three times higher than the same factor when the load was powered by a Y/Y$_H$ transformer. It should be noted that, at other load values, in terms of the current sinusoidal distortion factor in the zero wire, the transformer with the Y/2Z$_H$ winding-connection scheme was inferior to the Y/Y$_H$ transformer.

When the load of transformers is changed to the nominal value, the appearance of the petal diagram for the same indicators is shown in Fig. 4.

At the nominal load of the transformers (two 250-W DRL lamps were connected to each phase and one 400-W DRL lamp to the third phase), the load-current asymmetry has noticeably worsened and the shape of current curves in the load circuits fed from power transformers with the Y/2Z$_H$ and Y/Y$_H$ scheme has improved. Thus, for the Y/Y$_H$ transformer circuit, the zero-sequence current unbalance coefficient increased from 13.17 to 21.59%; for Y/2Z$_H$, from 11.13 to 26.84%. In addition to this indicator, the transformer with the Y/Y$_H$ scheme turned out to have the following indicators as the best ones: the total power factor of the loads, taking into account harmonics, $PF_{SUM}$ (0.63 vs. 0.62); sinusoidal current curve distortion factor in the zero wire $THD\text{-}I_4$ (34.33 vs. 36.06%); active power losses in the transformer $\Delta P_T$ (0.274 vs. 0.373 kW); and current in the zero working wire $I_4$ (1.619 vs. 1.979 A), as well as coefficients $KF1$ and $KF2$.

The petal diagram when loading transformers up to 1.3 rated power is shown in Fig. 5.

With a further increase in the asymmetric nonlinear load (three 250-W DRL lamps and one 400-W DRL lamp) in the compared transformers, the current asymmetry coefficient in the zero sequence of the

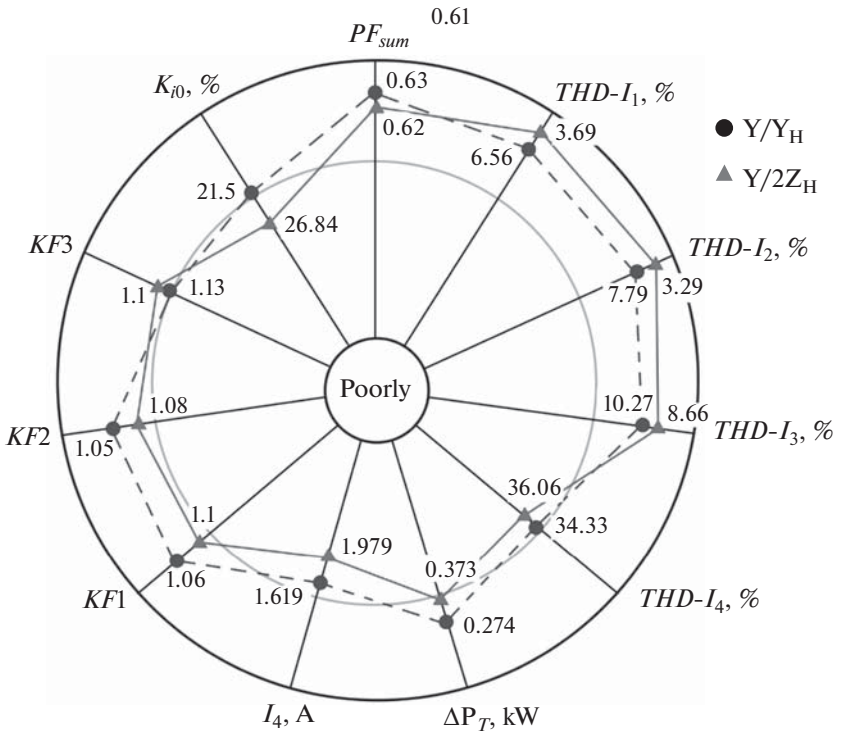



**Fig. 4.** Petal diagram of changes in the electrical values of the compared transformers at nominal load.

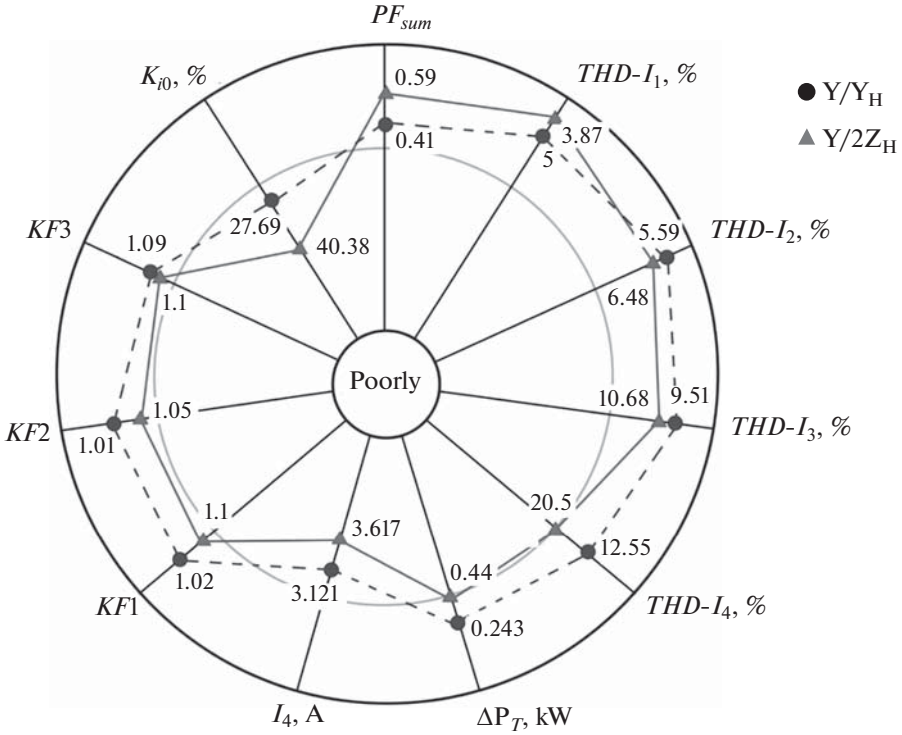



**Fig. 5.** Petal diagram of changes in the electrical values of the compared transformers with their load factor equal to 1.3.

transformer with the $Y/2Z_H$ circuit deteriorates markedly from 26.84 to 40.38%. The values of coefficients *KF*1, *KF*2, and *KF*3 also slightly decrease. The sinusoidal current curve distortion factor in the $THD\text{-}I_4$ zero wire of the $Y/2Z_H$ transformer turned out to be 7.95% higher than that of the $Y/Y_H$ transformer. Current in the zero working wire $I_4$ of the network when powered from the $Y/2Z_H$ transformer was 3.617 A, which is 0.486 A more than the same indicator when the network was powered from the $Y/Y_H$ transformer. Active power losses in the transformers themselves with such a load turned out to be greater for the $Y/2Z_H$ transformer at 0.197 kW. The only indicators in which the $Y/2Z_H$ transformer had advantages over the $Y/Y_H$ transformer turned out to be the power factors of the loads, taking into account harmonics $PF_{SUM}$ (0.59 vs. 0.41) and distortion coefficient of the sinusoidal current curve in one of the linear wires $THD\text{-}I_1$ (3.87 vs. 5%).

## CONCLUSIONS

1. Under simultaneous exposure to nonsinusoidal and asymmetric currents, the largest number of electrical values, according to which the power transformer with the $Y/2Z_H$ winding-connection scheme showed the best results (7 out of 11) relative to the $Y/Y_H$ transformer, turned out to be at rated load.

2. When loading power transformers with asymmetric and nonsinusoidal current in excess of the nominal value, the power transformer with the $Y/Y_H$ winding-connection scheme turned out to be the best (9 out of 11 indicators).

3. With a uniform nonnominal loading of transformers, the power transformer with the $Y/Y_H$ winding-connection scheme also turned out to be the best (7 out of 11 indicators).

4. A power transformer with a $Y/2Z_H$ winding connection does not have undeniable advantages over a transformer with a $Y/Y_H$ winding connection at different loads under conditions of multifactorial impact: the level of asymmetry and nonsinusoidality, the transformer's own power losses, the degree of current load of the zero working wire of the network of 0.38 kV, and the heating and power factor of the transformer.

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## REFERENCES

1. Rudi, D.Yu., Antonov, A.I., Vishnyagov, M.G., Gorelov, S.V., Zubanov, D.A., Ruppel, A.A., and Ruppel, E.Yu., Study of higher harmonics in low voltage electrical networks, *Omskii Nauchn. Vestn.*, 2018, no. 6, pp. 119–125. https://doi.org/10.25206/1813-8225-2018-162-119-125

2. Averbukh, M.A., Zhilin, E.V., and Sizganova, E.Yu., The statistical evaluation of coefficients characterizing nonsinusoidality and nonsymmetry of feed voltage in private housing projects' power supply systems, *Zh. Sib. Fed. Univ., Ser. Tekh. Tekhnol.*, 2017, vol. 10, no. 8, pp. 1079–1087. https://doi.org/10.17516/1999-494X-2017-10-8-1079-1087

3. Yundin, M.A., Gerasko, A.L., and Gondar, V.V., Modern statistical indicators of asymmetry and nonsinusoidal voltages in the network 0.38 kV, *Sovremennye nauchnye issledovaniya. Problemy i perspektivy. Materialy IV Mezhdunar. nauchno-praktich. konf.* (Modern Scientific Studies: Problems and Perspectives: Proc. 4th Int. Sci.-Pract. Conf.), Krylova, M.N., Ed., Moscow: Pero, 2019, pp. 248–253.

4. Lukina, G.V., Bondarenko, S.I., and Samarkina, E.V., The determination of power quality indicators in distribution networks of farmers' and suburban farms, *Vestn. Krasnoyarsk. Gos. Agrar. Univ.*, 2017, no. 3, pp. 86–91.

5. Zelen'kevich, A.I. and Zbrodyga, V.M., Three-phase symmetring transformer with even group of winding connection, Patent of the Republic of Belarus no. 16008, *Afitsyiny Byull.*, 2012, no. 3, pp. 180–181.

6. Prishchepov, M.A., Zbrodyga, V.M., and Zelen'kevich, A.I., Operation of a transformer with the star–double zigzag connection with zero wire under nonsymmetric loading, *Agropanorama*, 2018, no. 1, pp. 25–31.

7. Prishchepov, M.A., Zelen'kevich, A.I., and Zbrodyga, V.M., Experimental studies of the operation of a transformer with the star–double zigzag winding connection with zero wire under nonsymmetric loading, *Agropanorama*, 2019, no. 5, pp. 38–41.

*Translated by V. Selikhanovich*

SPELL: 1. OK