On the efficiency of power transformers with «star-zig-zag with zero» winding connection scheme in rural electricity networks supplying household consumers

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Abstract: The dependencies of the loss coefficient on the value of reverse- and zero-sequence current unbalance coefficients are obtained, allowing estimating the energy efficiency of power transformers operation at different unbalance characteristics. The electricity losses were calculated from these dependencies and from data obtained from instrumental measurements at rural substations supplying household consumers. It was obtained that the power transformer with «the star-zigzag with zero» scheme is 6 times more energy efficient than the power transformer with «the star–star with zero» scheme. However, with small values of the currents asymmetry (for five cases studied), the power transformer with «the star-zigzag with zero» scheme has overestimated power losses.

1. Introduction
The condition of rural electricity networks supplying household consumers up to 1000 V is currently at a difficult stage of development. On the one hand, there is an increase in the power equipment of everyday life, the development of consumer electronics and household appliances, the active introduction of digital technologies and microprocessor control systems [1], on the other hand, in electrical networks of rural regions prevails morally and physically obsolete equipment, networks have low carrying capacity, non-energy efficient power transformers and uninsulated wires are used [2].

The application of power transformers with «the star-star with zero» winding connections scheme at 6-10 / 0.4 kV substations, which have the highest zero-sequence resistance in comparison with other types of transformers, negatively affects the operation efficiency in an asymmetric mode. Such a transformer will have increased electricity losses, the symmetry of the output voltage will be significantly distorted, and the influence of harmonic components of the current on the electrical network will increase [3-5].

The established situation in rural electrical networks, as well as the emerging trend of their development, sets the tasks of decisions developing to increase the energy efficiency of the electric networks data [6].

2. Materials and methods
Transformers with «the star-star with zero» winding connections scheme have simplicity of design, are reliable in operation, relatively simple and economical in operation, and also have a low cost. Such qualities are beneficial to them from other transformers and determined their widespread use.
A significant disadvantage is the high value of the zero sequence resistance. The ratio of the total resistance of the zero sequence to the full resistance of the direct sequence is an average of 11, the active resistance of the zero sequence is average in 12.5 times more than the resistance of the direct sequence, and the reactive - in 10.9 times more [7]. The ratio of zero sequence impedance to positive sequence impedance averages 11, while the positive sequence impedance averages 12.5 times the positive sequence impedance and the reactive impedance 10.9 times the positive sequence impedance.

The power transformer with «the star-zigzag with zero» winding scheme have a more complex design, which obviously affects both the reliability of work and operating costs and the cost of production.

The windings connection in zigzag is obtained by separating the secondary winding into two semi-windings. The ends of the first semi-winding are connected in series with the ends of the second semi-winding of the adjacent phase, thus the oncoming switching on the two phases is obtained. The beginning of the first semi-winding is derived to the load, and the beginning of the second semi-winding is connected to a common point forming a neutral.

That is, when connecting secondary windings into the zigzag scheme, the secondary voltage decreases in comparison with the "star" scheme in 0.866 times. In order for a power transformer with a "star - zigzag with zero" circuit to receive the same secondary voltage as a transformer with a "star - star with zero" circuit, 15.5% more turns are required. Copper amount increasing also increases the active resistance of the windings, resulting in higher short-circuit losses.

The ratio of the total resistance of the zero sequence to the full resistance of the direct sequence is on average 0.252, i.e. in 1 / 0.252 = 4 times less, the active resistance of the zero sequence is on average 2.24 times less than the resistance of the direct sequence, and the reactive is 7.70 times less.

In order to estimate the degree of reduction in the energy efficiency of the power transformer, we denote the loss coefficient of the ratio of electricity loss in the power transformer in the asymmetric mode $\Delta P_{zm}$ to the loss of electricity in the power transformer in symmetric mode $\Delta P_{m1}$ (while taking into account that the resistance of the direct and reverse sequence is equal) [7]:

$$ K_p = \frac{\Delta P_{zm}}{\Delta P_{m1}} = 1 + \left( K_{z1}^{100} \right)^2 + \left( K_{z0}^{100} \right)^2 \cdot \frac{R_{m1}}{R_{m0}} \quad (1) $$

where $K_{z1}$, $K_{z0}$ are the coefficients of currents asymmetry on the reverse and zero sequence,%; $R_{m1}$, $R_{m0}$ are the active resistance of the power transformer to the direct and zero sequence currents, Ohm.

The loss coefficient indicates how many times the electricity losses in the power transformer will increase in the current asymmetry presence in the electrical network. The value of this coefficient does not depend on the load of the power transformer, but only on the value of currents asymmetry and the ratio of power transformer active resistances.

During the study, the values of the currents asymmetry coefficients will be changed from 0 to 100%. At the same time, the mode in which the currents asymmetry coefficients over the reverse and zero sequence are 100% is a single-phase load mode.

In order to determine the following options use effectiveness in real electrical networks, we will compare the electricity losses reduction in the power transformer according to measurements obtained in real electrical networks.

Using the data obtained during the measurement of current asymmetry indicators in real electrical networks for 24 transformer substations 10 / 0.4 kV with a capacity of 40 to 250 kVA feeding consumers, we will calculate the loss of electricity for the studied types of power transformers.

The power losses are defined as

$$ \Delta W = K_3^2 \cdot \Delta P_k \cdot K_p \cdot \tau, \quad (2) $$

where $\tau$ is the time of maximum electricity loss for household consumers without electric stakes accept $\tau = 1600$ hours per year; $K_3$ is the loading coefficient of the power transformer; $\Delta P_k$ is the loss of short circuit of the power transformer, W.

We also define the difference in annual losses of electricity for power transformers with the Y/Yz and Y/Yz/2 schemes.
3. Results and discussion

Figure 1 demonstrates the loss coefficient dependence from the currents asymmetry values over the reverse and zero sequence for transformers with a Y/Yz scheme and the 250 kVA capacity.

![Figure 1. Dependence of the loss coefficient on the asymmetry coefficients for the Y/Yz transformer with a 250 kVA capacity](image)

These dependences obtained from the calculation results show clearly the predominance of the effect on the power loss value and the zero sequence currents power in comparison with the reverse sequence currents. So in the most adverse conditions, when connecting a powerful single-phase load, power loss can be 15 times more than losses in symmetric mode.

With a current asymmetry coefficient in zero sequence of 4%, we have a loss coefficient of the order of 1.2, i.e. the power loss in this case will increase by 20%. With a current asymmetry coefficient of 8 %, it is 1.8, i.e. in this case the losses will increase by 80 %. It should also be noted here that since the loss coefficient does not depend on the transformer loading magnitude and the current asymmetry coefficients at which the voltage factor violation occurs increase with decreasing load, it can be concluded that in case of voltage asymmetry at an under-loaded power transformer, the efficiency of such a transformer is further impaired.

Figure 2 demonstrate the dependence of the loss coefficient on the current asymmetry coefficient in the reverse and zero sequence for transformers with a Y/Zz scheme and 250 kVA capacities.

The dependences obtained from the calculation results demonstrate the predominance of the reverse sequence currents influence on the amount of power and electricity losses in comparison with the zero sequence currents, i.e. the situation is opposite to that obtained for a power transformer with a Y/Yz scheme. This is due to the fact that for a power transformer with a Y / Zz scheme, the zero sequence resistance is several times less than the reverse sequence resistance.
Analyzing the results obtained, it can be noted that the loss coefficient for the power transformer with the Y/Zz scheme is several times less than for a power transformer with the Y/Yz scheme. So in the most adverse conditions, when connecting a powerful single-phase load, power loss will be no more than 2.5 times more losses in symmetric mode. This means that in the same operating mode of the power transformer, the power losses due to asymmetry in a Y/Zz power transformer will be 6 times less than in a Y/Yz power transformer.

Figure 3 shows the calculation results of electricity losses in power transformers with the Y/Yz and Y/Zz schemes according to the instrumental measurements on the rural substation, feeding household consumers.
Figure 3. Results of electricity losses calculating in power transformers with Y/Yz and Y/Zz schemes for 24 substations studied.
According to the calculations results, it can be noted that the use of power transformers with the $Y / Z_z$ scheme instead of $Y / Y_z$ scheme will allow in the amount to reduce electricity losses at 17758.78 kWh per year, which is 16.05% of the initial value of electricity losses in the power transformer with $Y / Y_z$ scheme.

Despite the fact that the use of power transformers with the $Y/Z_z$ scheme gives a greater total reduction in electricity losses, this effect is not true for all substations, so for five of the 24 substations studied electricity losses increased in comparison with the power transformer with the $Y/Y_z$ scheme.

4. Conclusion

When an unbalanced load is connected, the power loss in the power transformer with the «star-star with zero» scheme can increase by up to 15 times and in the power transformer with «star-zigzag with zero» scheme by up to 2.5 times under the same conditions.

The power transformer with «star-zigzag with zero» scheme is 6 times more energy efficient than the power transformer with «star-star with zero» scheme. However, with small values of the currents asymmetry (for five cases studied), the power transformer with the «star-zigzag with zero» scheme has overestimated power losses.

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