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Issues on optimization of operating modes of power transformers

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Abstract. The article presents measure to optimize the operating modes of power transformers in order to minimize losses of electrical energy. The influence of actual voltage and service life of power transformers on electric power losses is shown. It was proposed to determine the economic capacity of power transformers taking into account the indicated factors, as well as taking into account the time of transformer switching on into the electric network and the form of the load schedule.

1 Introduction

The task of optimizing the management of power supply systems has received close attention, starting with appearance of the first computer-aided design systems and computer-based automated control systems. The existing software systems allow one to check the reality and optimality of design solutions for individual energy facilities, as well as the reliability of functioning of the operating power system as a whole by solving specific technological problems. The software is also used for comparative analysis of various strategies for design, installation, optimization and operation when making decisions based on the state and parameters of the electrical network mode.

The main elements of electrical network are power transformers of substations and power lines. In any analytical or synthetic software product these elements are represented by their mathematical models. In general case, two main types can be chosen from the entire set of models, which are used to solve the posed problems:

1) The generally accepted graphical model of electrical circuit of a power system (including power transformers and power lines);

2) Specialized models of design schemes describing the scheme of electrical network of a power system at the level of the requirements of the applied mathematical methods and specific technological problems.

The tasks of improving the energy efficiency of power supply systems of various objects require the implementation of measures, often associated with engineering calculations. Engineering calculations in the field of energy saving are a time consuming process. Taking into account the complexity and high cost of such work, the need and usefulness of energy saving measures are not always obvious to the management of enterprises, organizations and institutions.

Most decisions are strictly regulated by laws, guidelines and other regulatory documents. This makes it possible to automate the solution of many private and complex tasks, including tasks to improve the energy efficiency of operating power transformers.

2 Materials and methods

As a rule, two power transformers are installed at transformer substations. Depending on the total load of substation during unloaded hours, it is advantageous to disconnect one transformer. This mode of operation should be considered as an energy saving measure, since the efficiency of the transformer remaining in operation approaches the maximum value.

The optimal load of transformer SOPT, corresponding to the highest possible efficiency, can be found using the formula [1]:

$$S_{OPT} = S_B \left(\frac{\Delta P_{NL}}{\Delta P_{SL}} \right)^{1/2} \qquad (1)$$

where S_B is rated power of transformer, kV·A; ΔP_{NL} is idle-running losses, kW; ΔP_{SL} is short circuit losses, kW.

The ratio of the optimal load of transformer and its rated power is the optimum load factor of transformer k_L:

$$k_L = \frac{S_{OPT}}{S_B} \qquad (2)$$

When using the expressions (1) and (2), the load factor of transformers is quite low (in the range 0.45–0.55), since the transformers are produced with a ratio of losses at idle running and short circuits in the range of 3.3–5.0. Usually in design practice, the maximum loads

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are used, by which the loading of transformers is determined. The load factor is significantly lower than the optimal value, therefore, currently operating power transformers have a low load and many of them operate in a non-optimal mode.

Power loss in a power transformer is determined by the formula [1]:

$$P = \Delta P_{NL}\left(\frac{U}{U_B}\right)^2 + \Delta P_{SL} k_L^2, \quad (3)$$

where U is actual voltage at the terminals of the transformer high voltage winding, kV; U_B is rated voltage of the high voltage winding, kV.

Electricity losses in a power transformer depend on the on-time of the transformer, the shape of the electrical load schedule and are determined by the formula

$$W = \Delta P_{NL}\left(\frac{U}{U_B}\right)^2 T_Y + \Delta P_{SL} k_L^2 \tau, \quad (4)$$

where T_Y is transformer operation hours per year, *h*; τ is time of the highest losses, determined by the actual load schedule or using the reference value of the number of hours of the maximum load use, *h*.

The minimum energy losses in the transformer during the year will be obtained at equal energy losses at idle running and short circuit. The transformer load, which takes into account the indicators of the electrical load schedule T_Y, τ and corresponds to the minimum electric power losses can be found taking into account (4) at $U = U_B$

$$S_{OPT} = S_B\left(\frac{\Delta P_{NL} T_Y}{\Delta P_{SL}\tau}\right)^{1/2} \quad (5)$$

We carried out comparative calculations using formulas (1) and (5), taking into account the average values of maximum load duration in industry [2]. The calculations have shown that step-down transformers require a higher load than they have in practice.

In some cases, it may be appropriate to disconnect part of transformers operating for total load *SL*. We define the cost-effective load $S_{EC,\Delta P}$ during operation, within which the most advantageous loading of transformers is achieved. When the load changes from zero to $S_{EC,\Delta P}$, the operation of one transformer is expedient; with a load above $S_{EC,\Delta P}$, the operation of two transformers is economically advantageous. The load $S_{EC,\Delta P}$, at which it is advisable to disconnect one of the transformers governed by equality of power losses during operation of one and two transformers is determined by the formula:

$$S_{EC,\Delta P} = S_B\left(\frac{2\Delta P_{NL}}{\Delta P_{SL}}\right)^{1/2} \quad (6)$$

We suppose to determine the load $S_{EC,\Delta W}$, governed by equality of electricity losses during operation of one and two transformers, by analogy with (6), taking into account the transformer turn-on time and the electrical load schedule according to the expression:

$$S_{EC,\Delta W} = S_B\left(\frac{2\Delta P_{NL} T_Y}{\Delta P_{SL}\tau}\right)^{1/2} \quad (7)$$

3 Results and discussions

The figure 1 presents relationships between power and electricity losses in power transformers of a two-transformer substation and the load power on low-voltage buses S_L, obtained from equations (3) and (4).

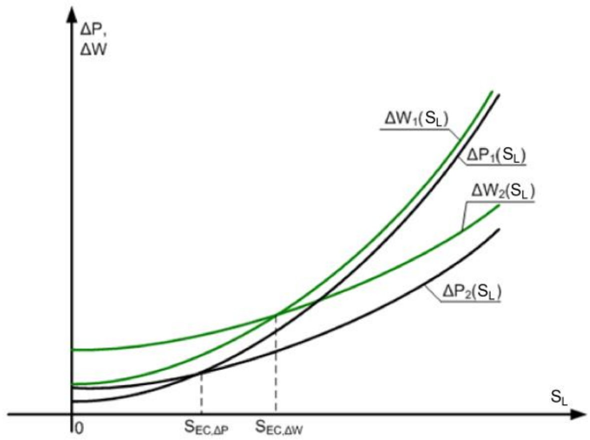

Fig. 1. Determination of economic power of transformers according to the criteria of minimum power and electricity losses: ΔP_1, ΔW_1 are power and energy losses during operation of one transformer; ΔP_2, ΔW_2 are power and energy losses during operation of two transformers.

Analysis of dependences $\Delta P(S_L)$ and $\Delta W(S_L)$ shows the shift of economic power in the direction of its increase when taking into account the time of switching on the transformer and the actual electrical load schedule. When calculating $S_{EC,\Delta W}$ using (7) the interval of economic power increases. In this case, the operation time of a substation with a single transformer with uneven load schedule increases. Savings are achieved due to the absence of idle losses of the disconnected transformer.

The influence of actual voltage *U* of the transformer terminals on power and energy losses is shown in formulas (3) and (4). In order to reduce losses, it is advisable to establish such a transformer mode for which the voltage of the higher voltage windings does not exceed the nominal value. A significant reduction in voltage is also unacceptable, since it may not meet the GOST requirements for voltage deviation at the consumer. Reducing voltage at substations also leads to an increase in power losses in power lines.

It should be noted that within the life cycle of a power transformer, we observe changes in magnetic properties of electrical steel and an increase in idle losses ΔP_{NL}. When calculating electric power losses in power transformers, it is recommended to use the actual values of idle losses obtained by measuring under operating conditions. This is primarily attributed to groups of power transformers that are in long-term operation. Recent studies show that for power transformers with a service life of more than twenty years, the passport idle losses ΔP_{NLP} in calculations should be increased by 1.75% for each year of operation over 20 years [4, 5]:

$$\Delta P_{NL,LT} = \Delta P_{NL}\left[1+0.0175\left(T_{LT}-20\right)\right], \quad (8)$$

where T_{LT} is transformer service life, years.

Then, taking into account (2), (4), (5) and (8), the optimal long-term load factor of a power transformer that has been in operation for more than 20 years should be determined using the formula:

$$k_{OPT,LT} = \frac{U}{U_B}\left(\frac{\Delta P_{NL,LT}}{\Delta P_{SL}\tau}\right)^{1/2} \quad (9)$$

Obviously, disconnecting part of transformers for economic reasons should not affect the reliability of power supply to consumers. For this purpose, transformers taken out of operation should be accompanied by automatic input reserve devices. It is advisable to automate the operations of transformers switching off and on. To reduce the number of operational switching, the frequency of transformers output in the reserve should not exceed 2-3 times per day. In addition, the loading of transformers, determined by the formulas (7) and (9) should not exceed the permissible values [3]. Based on the ratio of profitability and reliability indicators, the approaches considered in this article are highly relevant for substations that have seasonal load variations.

4 Conclusions

The provisions on optimizing the operating modes of transformers given in this article are implemented in the form of software [6]. The “Online Electric” web service allows managers of enterprises and institutions to fairly quickly evaluate the technical and economic indicators of measures to improve the energy efficiency of transformer equipment and determine their feasibility, and energy auditors to complement and justify energy certificates of buildings and structures in a shorter period of time.

The implementation of energy-saving measures on transformer equipment through using the “Online Electric” service has a number of advantages compared with the classical solution of such tasks “manually” or using software installed at personal computers, namely:

1) You do not need to purchase and install application programs on your computer;

2) It is possible to connect to the system from anywhere in the world;

3) The user does not need to monitor and constantly update software versions;

4) Reports providing the used formulas make it possible to verify the accuracy of calculations.

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