Analytical studies of transformers operating modes in supply and distribution electric network of a field substation

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Abstract. We obtained new analytical dependencies for investigation of operating modes of power transformers, supply and distribution electric network of a field substation in order to take into account losses of power and electrical energy in all network elements. We substantiated the relevance of this article and the considered tasks, which depend on the object of study. It has been established that one auxiliary transformer and from eight to ten outgoing lines are connected to one bus section of a power transformer of a field substation. We developed mathematical models of electrical complexes of a field substation with individual transformers of outgoing power lines, as well as with individual, node and centralized compensating units. We obtained new analytical dependencies, taking into account total losses of power and electrical energy in power transformers of field substation and distribution electrical network as a function of supply voltage. The well-known method for calculating the energy parameters of electrical units of field substation and auxiliary equipment has been improved by adding new analytical dependencies of total power losses in power transformers of field substation and distribution network as a function of 35 kV supply voltage. The scientific novelty of this work is obtaining new analytical relationships between total power loss in power transformers of the field substation and distribution network as a function of supply voltage, which take into account external and internal disturbances in the network. This allowed us to improve the well-known method for calculation the energy parameters of electrical installations of a field substation taking into account parameters of individual, nodal and centralized compensating installations.

1. Introduction

The aim of this article is analytical studies of the operating modes of transformers of supply and distribution electric network of a field substation, development of their mathematical models in order to obtain analytical dependencies that take into account electric power losses of power transformers as a function of supply voltage.

The object of the present research is a field substation of an oil and gas producing enterprise (Figure 1).

Figure 1 shows a diagram of electrical connections of a field substation with supply and distribution electric networks. Electrical systems of various hierarchical levels of ESS are also shown:
- Level 1 is electrical complexes of production well (ECPW) and auxiliary equipment (ECAE), which include booster and cluster pumping stations (BPS and CPS) and drilling rigs (DR);
- Level 2 is electrical complex of outgoing line (ECOL);
- Level 3 is electrical complexes of the enterprise (ECE) and field substation (ECFS);
Level 4 is electrical complex of nodal substation (ECNS).

During the system analysis of electrical connection circuit of the field substation, it was found that the following equipment is connected to one section of distribution buses: a power transformer; an auxiliary transformer; and eight to ten outgoing power lines connected to eight to ten individual transformers of production wells. At the same time, one third of the wells have two individual transformers for powering electric drives of electric centrifugal pump units (ECPU) and screw pumping units (SPU). Thus, about 130 transformers are connected to one input of the field substation, and in general the substation supplies about 262 individual transformers. A large number of transformers in electrical networks of an oil and gas producing enterprise implies a large component of electricity loss directly into them. Optimization of total power losses in transformers of the field network of an oil and gas production enterprise will reduce overall energy losses, improve the energy efficiency of field equipment and reduce the cost of oil produced.

Decomposition of power supply system of the field substation (Figure 1) according to hierarchical levels makes it possible to form the totality and interconnection of local mathematical models of electrical complexes of the object under study [1,2,4,7]. The structures of these models possess the properties of functional modules, i.e. if necessary, they can be independently refined, simplified, replaced, while maintaining the integrity of review of the entire system [1]. Decomposition of the object under study allows performing structural and parametric synthesis of the designated electrical complexes for the purpose of multi-level optimization of power losses.

The electrical complex of the field substation consists of a set of electrical complexes of an enterprise: outgoing lines, including electrical complexes of production wells and auxiliary equipment. When analyzing the operating modes of ECPW, ECAE and ECOL with compensating installations, it was established the following:

- Individual compensating units [3] are not installed on all ECPW electric motors, their parameters are not consistent with the operating parameters of electric drives;
- Individual compensating installations are not actively used in electrical complexes of auxiliary equipment, since these complexes use thyristor voltage frequency converters. In this case, when electric drive is connected to the network directly or when individual transformers operate at wells, reactive power compensation is not performed;
- There are no nodal compensating unit in electrical complexes of the outgoing lines.
Figure 1. Diagram of electrical connections of electrical systems of various hierarchical levels of ESS.
According to results of the conducted system analysis of ECPW, ECAE and ECOL operation modes (Figure 2), taking into account [1, 5-8, 10-15], it is recommended to use individual and node compensating installations, as well as to develop mathematical and simulation models of these complexes taking into account compensating installations.

Figure 2 shows electrical complex of a production well with an ECPU or SPU with a submersible electric motor (SEM), a nodal compensating unit UPEC3, a KTP step-down transformer, and sucker rod pumping unit with a chain drive (SRPU with CPU). From a special step-up power transformer of the TMPN-0.4kV type, which has a non-standard voltage of 1400 V on the secondary side, it receives power to SEM with a submersible individual compensating unit, which run into the well to a depth of 1.5 km [3]. Individual submersible compensating installation allows one to compensate the reactive component of linear motor current in cable line and in the TMPN transformer and reduce the active power loss by approximately 6% [5].

The total power loss in power transformers depends on two main parameters: steel core type and voltage level of the supply line.

To reduce these losses in transformers, it is important to solve two problems. The first task requires technical re-equipment of power transformers with replacement of existing electrical steel cores with amorphous steel cores, or the complete replacement of transformers. When analyzing a number of field substations, it was determined that the average number of individual transformers connected to one substation is 170. This situation requires a lot of money and time when replacing the transformer system, which makes solving this task difficult and time consuming.

The second task is to determine relationship between total power loss in power transformers and voltage level of supply and distribution electric network of the field substation and automatically control the voltage level in the power center while simultaneously compensating of reactive power (CRP) in order to optimize power losses.

The basis of automatic regulation of voltage level in the power center is based on the event of a multi-level optimization of voltage mode and power consumption of technological process of extracting and transporting oil flows. It is important to divide the distribution network of a field substation into levels as independent electrical systems according to load type and structure of the enterprise power supply system, while taking into account preservation of functional properties and connections with the main object of study, i.e. with power center (bus section of the field substation).
Reactive power is one of the main components of total power consumed from the network, the value of which significantly depends on the level of supply voltage. Therefore, when developing the concept of multi-level automatic voltage regulation, the voltage level in the center of the power supply on the higher voltage side is the main parameter for all levels of electrical network. According to the law of energy conservation, the balance of the consumed total power is compiled for one input of the field substation:

\[ S_{35} = S_6 + \Delta S_{Tr,35} + S_{b,a.t.} + \Delta S_{a.t.} = \]
\[ = \sqrt{3} \cdot U_{35} \cdot I_{35} = \sqrt{3} \cdot U_6 \cdot I_6 + \Delta S_{Tr,35} + \sqrt{3} \cdot U_6 \cdot I_{6a.t.} + \Delta S_{a.t.}. \]

It can be seen from this relationship that all elements are a function of supply voltage network, taking into account the transformation ratio of the power transformer.

The expression (1) includes the following elements:

a) \( S_{35} = \sqrt{3} \cdot U_{35} \cdot I_{35} \) is total power consumed by the field substation from energy system. This is power at the input of power transformer of the field substation;

b) \( \sqrt{3} \cdot U_6 \cdot I_6 = \sqrt{3} \cdot U_{35} \cdot I_{35} \) is load of power transformer on the secondary winding, where

\[ K_U = \frac{U_{35}}{U_6} \] is transformation ratio of the power transformer;

c) \( \Delta P_{r,t} + \beta_{l,35}^2 \Delta P_{k,r} \) is power loss in power transformer in a function of load factor of transformer;

d) \( \beta_{l,35}^2 = \left( \frac{\sqrt{3} \cdot U_6 \cdot I_6 + \sqrt{3} \cdot U_6 \cdot I_{6a.t.}}{S_{l,35}} \right)^2 = \left( \frac{\sqrt{3} \cdot U_{35} \cdot I_6 + \sqrt{3} \cdot U_{35} \cdot I_{6a.t.}}{K_U \cdot S_{l,35}} \right)^2 \)

\( \beta_{l,35} \) and \( S_{l,35} \) is load factor and total rated power of a power transformer of a field substation;

e) \( \sqrt{3} \cdot U_6 \cdot I_{6a.t.} = \sqrt{3} \cdot \frac{U_{35}}{K_U} \cdot I_{6a.t.} \) is total load (total capacity) of power auxiliary transformer;

f) \( \Delta P_{r,d,n} + \beta_{l,d,n}^2 \Delta P_{k,d,n} \) is active power losses in power transformers of a distribution electrical network in a function of supply voltage;

\[ \beta_{l,d,n}^2 = \left( \frac{\sqrt{3} \cdot U_{0.4} \cdot I_{0.4}}{S_{l,d,n}} \right)^2 = \left( \frac{\sqrt{3} \cdot U_6 \cdot I_6}{K_U \cdot S_{l,d,n}} \right)^2, \]

where \( \beta_{l,d,n} \) and \( S_{l,d,n} \) is load factor and total rated power of power transformers of a distribution electric network.

If active power losses of transformer at idle run are presented as a function of 35 V voltage of supply line:

\[ \Delta P_{r,35} = R_1 \cdot \left( \frac{i_{r,35} \cdot I_{35}}{100} \right)^2 = R_1 \cdot \left( \frac{i_{r,35} \cdot S_{l,35}}{100 \sqrt{3} U_{l,35}} \right)^2 = R_1 \cdot \left( \frac{i_{r,35} \cdot S_{l,35} U_{l,35}}{100 \sqrt{3} U_{l,35}} \right)^2 \]

then full power losses in power transformer and in auxiliary transformer in the function of supply voltage will be written in the following form:
Total power losses in individual power transformers of a 6 kV distribution electric network as a function of supply voltage is:

\[
\Delta S_{Tr,35} = \sqrt{R_c \left( \frac{i_{r,z} S_{Tr,35} U_{Tr,35}}{100 \sqrt{3} U_{Tr,35}} \right)^2 + \beta_{Tr,35}^2 \Delta P_{k,z}} + (\Delta Q_{r,z})^2
\]  

(2)

\[
\Delta S_{u.t.} = \sqrt{R_{c,u} \left( \frac{i_{r,u} S_{Tr,35} U_{Tr,35}}{100 \sqrt{3} U_{Tr,35}} \right)^2 + \beta_{Tr,35}^2 \Delta P_{k,u}} + (\Delta Q_{r,u})^2
\]  

(3)

where \( \beta \) is the number of individual power transformers in distribution electrical network connected to one bus section.

The total losses of total power of individual power transformers of a 6 kV distribution electric network are included into the first term (power balance) (6).

Taking into account the above, the power balance of the field substation is written:

\[
\Delta S_{Tr,6} = \frac{i_{r,z} S_{Tr,6} U_{Tr,6}}{100 \sqrt{3} U_{Tr,6}} + \beta_{Tr,6}^2 \Delta P_{k,6} + (\Delta Q_{r,6})^2
\]  

(4)

\[
\sum_{j=0}^{n} \Delta S_{Tr,j} = \Delta S_{Tr,6/1} + \Delta S_{Tr,6/2} + \ldots + \Delta S_{Tr,6/n}
\]  

(5)

where \( n \) is the number of individual power transformers in distribution electrical network connected to one bus section.

From formula (5) it can be seen that all the components of power balance, as well as consumption of total power in the distribution electric network, directly depend on supply line voltage (35 kV), i.e. loss of full power in power transformer and auxiliary transformer \([1,7,15]\).

At individual and nodal reactive power compensation in the nodes of a distribution electric network, the voltage level rises, which affects the increase in active and reactive power consumption. In this connection, to obtain a comprehensive analysis it is important to take into account the operating mode of the distribution electrical network when compensating of reactive power, and at the same time to correct the methods for calculating the energy parameters of all electrical systems using individual, nodal and centralized compensating installations using which the system analysis must be preliminary performed.

## 2. Conclusions

The scientific novelty of this work is the analytical dependences of total power losses in power transformers of the field substation and distribution electric network in the function of supply voltage, obtained by the authors, which take into account disturbances of external and internal network parameters. The other achievement is an improved method for calculating the energy parameters of a
field substation operating modes, which takes into account total power losses in power transformers and in distribution network as a function of 35 kV supply voltage, as well as parameters of individual, node and centralized compensation units.

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