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Increasing reliability of power supply to electricity consumers

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Abstract. The article deals with the issues of increasing the reliability of power transformers used in power supply systems for agriculture and water management. Also, the degree of damage to power transformers was studied in terms of the physical and chemical composition of transformer oil, materials were given for assessing the state of insulation by the degree of damage to the insulation of individual units of the power transformer. By measuring the temperature of the most heated part and the chemical composition of the transformer oil, it is possible to determine the degree of wear of the insulation of the power transformer in the operating mode, which allows to increase their service life by 15% and prevent accidents in the networks.

1 Introduction

The power supply of agricultural and water management facilities is carried out by transformer substations and centers with a voltage of 110/35/10, 35/10, 35/6, 10(6)/0.4 kV. Electric energy from transformer substations to consumers is transmitted by overhead power lines with a voltage of 0.4; 6; 10; 35 kV. The power supply systems of agricultural enterprises throughout the year operate under uneven loads, for example, in pumping stations, transformers operate at full load only during irrigation periods, and the load factor during the year is in the order of $K_l = 0.4 \div 0.45$, in other agricultural enterprises this coefficient is in the range of 0.3-0.35. These facts show the insufficiency of economic indicators of the power supply system in agriculture and water management [1, 2].

In order to improve the efficiency and uninterrupted use of power transformers throughout the year, and to reduce the amount of power specific capacity per product, decrees and resolutions were adopted by the Cabinet of Ministers of the Republic of Uzbekistan [3]. The significance and content of the resolutions are that in the coming years, it is necessary to replace obsolete equipment with new and modern ones with higher energy performance, achieve significant savings in electrical energy, increase production

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efficiency, drastically reduce the number of unforeseen failures and downtime of electrical equipment, develop and implement in the production of more advanced designs of transformers and auxiliary equipment, so as to reduce the consumption of electrical energy by 10-15% [3- 5].

When performing research work, the authors were convinced that in order to achieve the efficiency of energy resources, reduce the accident rate of production, reduce the specific consumption of electrical energy per unit volume of output, increase production efficiency and productivity for electricity consumers, reduce the downtime of equipment, it is not enough to replace obsolete electrical equipment with a new, more advanced one. It is also necessary to adjust the technological equipment and units, control panels, electrical wiring, and other auxiliary equipment, to compensate for the reactive power of consumers with a low power factor. Problems of this kind are complex in nature and require a comprehensive solution. At the same time, the following tasks are solved: adjustment of electrical networks of both low and high voltage, and overhead and cable lines, repair and adjustment of power transformers and substation equipment; adjustment of power, control, protection, signaling and instrumentation circuits; replacement of inefficient electric motors; installation and adjustment of compensating devices to compensate for reactive power and increase the active power of operating units and machines; repair of facilities and structures. The object of research was the power transformers of the electric power system enterprises of the Gulistan district of the Syrdarya region with a voltage of 10 kV, which supply electricity to consumers.

There are 324 power transformers with a voltage of 10(6)/0.4 with a total capacity of 62150 kVA at the electric power system enterprises of the Uchtepa district of Tashkent city. Of these, 144 units, that is, 33% are working for more than 40 years, 114 units, that is, 25% - for more than 30 years, 6 units - for more than 20 years, 14 units - for more than 10 years. Only 116 units, that is, 26.85% have worked for less than 10 years [4]. These facts indicate the relevance of the gradual replacement and reconstruction of electrical equipment in electrical power systems.

During the operation of power transformers, their load current and oil temperature are monitored. Depending on the heating mode, the overload capacity of transformers is determined. The heating temperature of a power transformer depends on its loading and cooling conditions. Depending on the size of the transformer, different cooling systems are used. With an increase in size, the cooling system becomes more complex. The amount of power loss spent on heating the transformer depends on the change in the power of the transformer; it is determined from the following expression [6,7,8,9,10]:

$$\Delta P = c_1 S_{\text{т}}^{3/4} \tag{1}$$

here: c_1 - is a constant coefficient.

2 Statement of the problem and research methodology

The highest temperature of the transformer is reached in operating windings. The heat of the windings is transferred by oil contact and convection. The temperature difference between oil and transformer windings Δυ is within 20-30% of ΔT. Here, ΔT is the difference between the transformer winding temperature and the ambient temperature. The heat goes into the transformer housing, then into the ambient air. The temperature difference between the oil and the ambient is about 60-70% of the total temperature difference. The temperature of the upper oil layers of the transformer is higher than the temperature of the lower layers (Fig.1) [11-14].

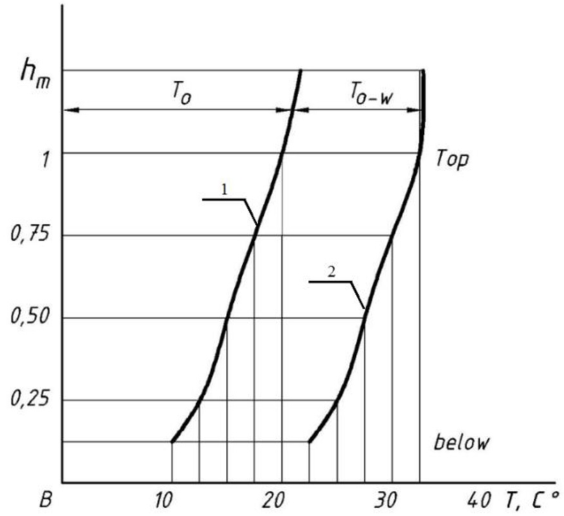

Fig. 1. 1- the winding temperature exceeds the oil temperature; 2- the oil temperature exceeds the ambient air temperature; T_o - oil temperature; $T_{-o\text{-}w}$ - temperature difference between windings and oil

The insulation of the transformer, including the insulation of the windings, is gradually destroyed during the operation. With an increase in the temperature of the transformer insulation, chemical processes and wear occurring under thermal action in the insulation accelerate [15,16,17]. The insulation gradually loses its mechanical strength and elasticity; under the influence of an electromagnetic field and vibrations, microcracks appear, and the insulation resistance decreases. The average duration of operation of insulating materials at an average operating temperature of 80-140^{0}C is determined from the following expression:

$$V = A_1 e^{-\alpha T} \tag{2}$$

here: A_1, α - are constant coefficients;

T - is the temperature of the insulating material.

When calculating the temperature mode of the transformer, the temperature of the most heated point is considered. At the nominal temperature of the transformer 95^{0}C, the insulation service life is:

$$V_n = A_1 e_n^{-\alpha T} \tag{3}$$

The relative service life of the transformer insulation is:

$$V_* = \frac{V}{V_n} = e^{-\alpha(T-T_n)} \tag{4}$$

The inverse value of the relative insulation life determines the relative insulation breakdown:

$$L = e^{\alpha(T-T_n)}$$

$$L = 2^{\frac{\alpha(T-T_n)}{0.693}} = 2^{\frac{\alpha(T-T_n)}{\Delta}} \tag{5}$$

here: $\frac{ln_e}{ln_2} = \frac{1}{0.693}$, $\quad \Delta = \frac{0.693}{\alpha}$

At the nominal temperature, the relative insulation breakdown is equal to one. If the relative insulation breakdown is equal to two, the insulation is destroyed twice as fast. If

$\Delta T=6^0C$, i.e. for every 6-degree change in temperature, the relative insulation breakdown (service life) changes by a factor of two. In the general condition, the insulation breakdown over time Δt is determined from the following expression [18,19,20]:

$$L_i = \frac{1}{T}\int 2^{\frac{(T_{cur}-T_{bas})}{\Delta}} dt \qquad (6)$$

here: T_{cur}, T_{bas} -are the current and basic conditional temperature constants of the most heated point of the transformer, where the relative insulation breakdown is equal to 1.

To determine the value of the relative turn insulation failure of the transformer, depending on the temperature of the most heated point of the transformer, the change in this temperature over time (during the load duration of Δt) was observed and the following expression was obtained:

$$L_1 = \frac{\Delta t}{T} 2^{\frac{(T_{cur}-T_{bas})}{\Delta}} \qquad (7)$$

The sum of insulation breakdown can be defined as the sum of transformer breakdown for the entire period of operation: $L = \sum L_i$

The relative turn insulation failure of the transformer winding with a two-stage daily load pattern can be determined by controlling the time change in temperature of the most heated point of the transformer under various loads. The measurements were obtained for the following operating parameters of the transformer:
- the base conditional temperature for the most heated point of the transformer is 95^0C;
- maximum heating temperature: for systematic overloads 105^0C, for emergency overloads 120^0C;

The maximum temperature in the upper layers of transformer oil is:
- under allowable systematic loads 85^0C;
- under emergency loads 95^0C.

3 Research results, recommendations, and suggestions

The cooling conditions of the transformer depend on the temperature of the cooling medium. At a negative temperature of the cooling medium, the change in the temperature of the transformer has an exponential form. The influence of the deviation of the equivalent temperature of the cooling medium on the value of the constant coefficient of insulation breakdown (f) is given in Table 1 and Fig.2.

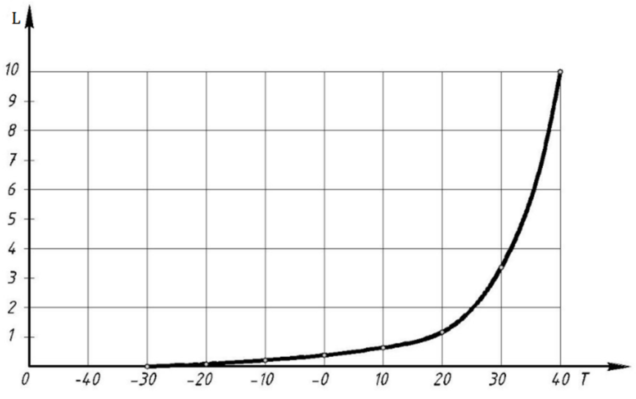

Fig. 2. Dependence of the constant coefficient of the transformer insulation breakdown on the deviation of the equivalent temperature of the cooling medium (ambient medium)

Table 1. The influence of the deviation of the equivalent temperature of the cooling medium on the value of the constant coefficient

T, ^{0}C	40	30	20	10	0	-10	-20	-30	-40
f	10	3.2	1.0	0.32	0.1	0.032	0.01	0.001	0.0003

As seen from the results, the transformer insulation breakdown is significant at a positive temperature difference, that is, in the summer season of operation. Therefore, summer overloads of the transformer are of particular danger.

Heating and cooling, i.e. the temperature setting of the transformer, are determined from the step loading pattern. The voltage of the power transformer varies depending on its load (Fig.3). On the graph, we draw a line of rated power and determine the duration of the overload of the transformer.

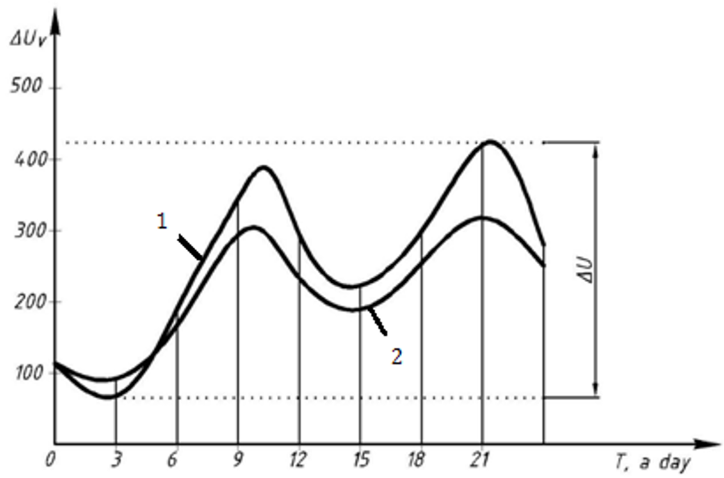

Fig. 3. Change in voltage at the output of a power transformer with a mixed load during the day.

1-first stage load transformerS_1, 2-second load stage transformer S_2, what does$S_1 > S_2$.

As seen from the graph, the voltage at the output of the power transformer is automatically adjusted depending on the voltage drop when the load changes. During peak hours, to maintain the rated voltage for consumers, the voltage at the transformer output rises to 4-5% of the rated voltage. To smooth out voltage fluctuations on the low voltage side (10 kV), a compensating capacitor unit with a capacity of 1 MVar, is included, a transformer capacity is10 MVA.

The equivalent load value is determined from the load steps:

$$S_{eqv} = \frac{\frac{\sqrt{S_1^2 \Delta t_1 + S_2^2 \Delta t_2 + S_3^2 \Delta t_3 + \cdots + S_n^2 \Delta t_n}}{\sum \Delta t_i}}{S_n} \quad (8)$$

The equivalent load S_2 is compared with the maximum load S_{max}.
If $S_2 > S_{max}$, it is assumed that $S_2 = S_{max}$.
If $S_2 < S_{max}$, it is assumed that $S_2 = 0.9 \cdot S_{max}$.
The duration of the transformer overload is adjusted.

During the operation, it is necessary to know the degree of wear of the transformer insulation. The actual degree of breakdown (obsolescence) is determined relative to the nominal or normalized degree of wear of electrical insulation (on average over 25 years)

[15]. This value usually remains unknown since the load of the transformer during operation is not constantly monitored; it is fixed only during peak hours (except for main transformer substations). In some periods, transformers can work with overloads, and information about their technical condition may be insufficient. In real conditions, transformers operate with a load of $(0.3 - 0.6)S_n$ and their power is not fully used. In large transformers, the load and temperature are monitored by an overload alarm. For low-power transformers with a voltage of 10 kV, the load is controlled by a thermometer and a temperature sensor is installed in the upper part of the tank. For the conditions of our Republic, the temperature of the upper layers of oil is controlled; the temperature of the most heated point of the transformer (T_{hp}) to the temperature of oil (T_o) is added to the temperature exceeding the most heated point or exceeding the temperature of the transformer (T_{exc}) [18,21]:

$$T_{hp} = T_o + T_{exc} \tag{9}$$

The temperature value is controlled using a resistor voltage sensor. Here, the first reading informs about the temperature of the upper layer of oil, and the second reading is proportional to the rise in temperature of the most heated point. The temperature of the most heated point of the transformer was also controlled by the difference in sensor voltages. These indications are received by means of functional converters. The first sensor works according to the oil temperature, and the second one works according to the relative load. To control the resource of the transformer, a block diagram was used (Fig.3) [22,23].

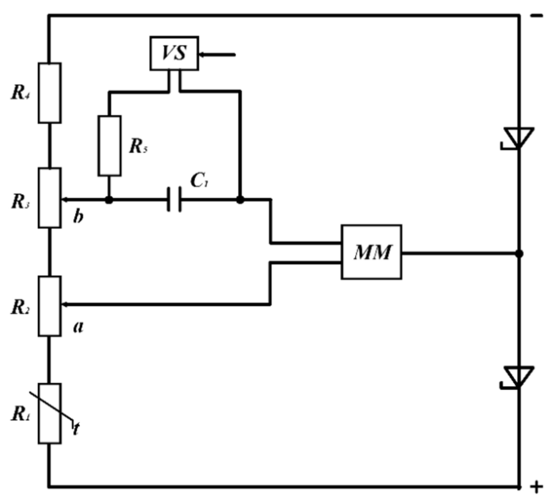

Fig. 4. Circuit of the device for monitoring the resource of the transformer. R_1-temperature resistor; R_2...R_5-resistors; VS - voltage sensor; MM - measuring mechanism; C1 - sensor capacitor.

The measuring body controls the potential difference between two points. When the load of the transformer in the capacitor C1 changes, the voltage changes according to the constant time R_5 C1, this value is equal to the time constant of the transformer winding. Thus, by controlling the temperature of the most heated point and the chemical composition of the transformer oil, the degree of breakdown (wear) of the transformer insulation is determined. The degree of transformer insulation failure is determined from expression $L_1 = 2^{\frac{T_{hp}-95}{6}}$ [24,25].

Using this device, pulses, which changed in proportion to the degree of wear of the transformer insulation were controlled, the pulses were summed up using a digital counter, which showed the degree of wear (breakdown) of the transformer insulation:

$$L = \int L_i dt \quad (10)$$

At the constant operation of the fans of the cooling system of transformers with a capacity of 10 mVA, the loss of electrical energy is within 16000 kWh/year [26,27,28]. To reduce energy losses, the fans of the transformer cooling system are switched on in stages: one group of fans is switched on at a temperature of 70-75^{0}C, the second group of fans is switched on at a temperature of 80-85^{0}C, and the third group of fans is switched on at a temperature of 90-95^{0}C. The monitoring device of the transformer insulation resource also protects the transformer against overload conditions. In this case, certain boundaries are set for the elements of the device. When the parameters exceed the set limits, an emergency signal is turned on and, if necessary, a command to turn off the network is given. Load break switches disconnect part of the transformer feeders. The technical condition of the transformer is checked, the degree of wear of the insulation is determined, the necessary measures are taken, and the parameters are restored [29,30,31]. If necessary, the transformer is sent for repair.

4 Conclusions

1. To increase the reliability of power transformers during operation, it is necessary to regularly monitor the load and the temperature of oil and windings. The control system must work together with relay protection and, if necessary, take appropriate measures.
2. The temperature setting of the transformer is determined by its constantly changing load. When the load changes, the voltage of the transformer also changes, and later is restored by automatic regulators and compensating devices.
3. By measuring the temperature of the most heated point and the chemical composition of the transformer oil, it is possible to determine the degree of wear of the power transformer insulation during operation.
4. Fans of the cooling system in power transformers, in the absence of control over the condition of the insulation, operate continuously and consume an average of 15,000 kWh/year of electrical energy. In order to reduce the consumption of electrical energy, it is proposed to turn on the fans in steps, for example, in three steps. They are automatically switched on depending on the temperature of the transformer.
5. To improve the energy efficiency of transformers and power lines, it is necessary to compensate for reactive powers. Capacitor batteries are installed directly at the electric motors or on the busbars of the feed transformer. When compensating for the reactive power of the network, the losses of electrical energy are reduced, a stable voltage of the network is established, and the quality of electrical energy is improved.

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