Reliability and Overload Capacity of Power Transformers

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***Abstract*—The article describes the reliability of transformers, the failure rate and uptime to the first failure, the durability and maintainability of transformers and their service life, the allowable temperature rises and the dependence of steady-state overheating on the load factor of the transformer. An assessment of the effect of ambient temperature on the rated power of the transformer is shown. Dependences of heating on the changing load of transformers are given. The heating time constant is calculated depending on the power and cooling system of the transformer. The winding heating temperature is considered for real daily load schedules of a 33/11 kV transformer, the maximum actual overheats are compared when loaded with full power with allowable overheats. These studies can be used in transformers 33/11 kV and others with subsequent interpolation of values.**

***Keywords* – transformer, reliability, failure rate, uptime, overload, short circuit current, transformer substation, rated power.**

I. Introduction

To investigate this issue were considered relevant foreign sources of literature [5, 9-27].

The authors Gracheva E.I. et al. [6-8] investigate the reliability of power electrical equipment, including power transformers, consider the main characteristics of the topology of power supply schemes and technical condition of low-voltage equipment under their operating conditions.

To study the issue of contactless power transmission, which is very relevant and is not used in all countries of the world, we will use the source [28-29]. To simulate the losses in the power transformer we will use the source [30]. The hybrid storage systems [33] and characterization of parameters of internal synchronous permanent magnet motors to build an algorithm for calculating transformer losses [34] are touched upon.

A mathematical model of fuel cell unit with automobile synchronous electric drive [35] is considered. Power electronics, electric drive and automation are touched upon [36]. Also an experimental study of high-performance real-time control algorithms [37].

The reliability of transformers is determined by the indicators of reliability, durability, and maintainability[1].

Failure rate and uptime before the first damage depends on the quality of workmanship and operating conditions. A number of sources show that within the operating time of up to 5 years, the failure rate decreases, and after 8 years, there is a sharp increase in the probability of failures due to wear of the insulation and elements that provide the mechanical strength of the windings. Direct damage to overhead lines supplying transformers by lightning and induced surges gives 30-50% damage to the longitudinal and main insulation of transformers. Multiple impacts of overvoltage waves lead to accumulated destruction of the insulation in the defective area and their subsequent breakdown [2-4].

Reducing the number of damages during lightning surges is achieved by installing valve arresters on the side of HV and LV transformers.

Short-circuit currents directly lead to the failure of 15-25% of transformers due to mechanical damage to the windings and their fastening parts. Individual transformers are already damaged at 2-5 close short-circuit currents. Systematic overloads in excess of the values allowed by the rules lead to an accelerated loss of mechanical strength and subsequent damage to the winding insulation. The prevention of such damage consists in monitoring the connection of new capacities, determining the permissible loads of transformers in normal and emergency modes of their operation, and timely replacement of transformers.

Long-term operation at temperatures above 75 °C of transformer oil with an acid number of more than 0.4 mg KOH per 1 g can also lead to accelerated aging of the insulation, when sludge forms on the surface of the windings and the magnetic circuit [13, 28-31].

Damages at the HV and the LV taps are responsible for the 15% of all the transformer damages. They are associated with the imperfection of the design of the connections and the errors of the repair and maintenance personnel. The durability of the transformer as a whole is limited by cases of large amounts of destruction and obsolescence, when it is justified to write off the transformer due to the inexpediency of repair or the inability to use it due to low power [32-37]. The service life of the windings or their individual coils is limited by the moment of damage during operation. Cases of winding changes due to insulation wear during scheduled repairs are very rare [8, 25-27].

II. Materials and Methods

Oil in transformers must meet the following standards: acid number - no more than 0.40 mg KOH; the reaction of the water extract is neutral; absence of mechanical impurities; decrease in flash point - no more than 5 °C from the initial one; dielectric strength for transformers up to 15 kV - not less than 20 kV and from 15 kV to 35 kV – not less than 25 kV.

The rate of oil oxidation depends on the oxygen content, temperature, and a number of other factors, and is generally random.

The increased likelihood of oxidation of factory-filled oils is explained by the significant oxygen content in the tank of the new transformers, the presence of varnishes, as well as the use of oils without antioxidant additives. The acid number gives a rough estimate of the chemical state of the oil and a rough estimate of the likelihood of impending sludge, which impairs heat dissipation and destroys solid insulation. Sludge accumulates in places with strong overheating.

Intensive sludge formation begins at an acid number above 0.4 mg KOH and a temperature above 75 °C. If the transformers are not fully loaded and the oil temperature is below 70 °C, then sludge formation is observed only in places and in small quantities even at an acid number oils 0.4-0.5 mg KOH.

The maintainability of power grid transformers is estimated by average statistical indicators. The duration of restoration depends on the volume and technology of repair and is associated with the organization of the repair process [12].

The heating temperature υ of any part of the transformer depends not only on the losses occurring in this part, but also on the temperature of the cooling medium $\upsilon_{a.t.}$ - air.

$$\upsilon - \upsilon_{a.t.} = \theta \quad (1)$$

Difference is the temperature rise of a given part of the transformer relative to the temperature of the cooling medium [21].

The initial data taken when calculating the nominal modes of transformers are the temperature values given in Table I.

TABLE I. Permissible excesses (overheats) of temperature

Resistance-averaged winding temperature above the oil temperature	$\theta_{w.av.oil}$,°C	21
Winding average resistance temperature above the air temperature	$\theta_{w.av.}$,°C	65
Volume-average oil temperature over the cooling air temperature	$\theta_{m.at.}$,°C	44
Oil temperatures in the upper layers above the cooling air temperature	$\theta_{oil.max}$,°C	55
The temperature of the hottest point of the winding above the average resistance temperature of the winding	$\theta_{w.max} - \theta_{w.av.}$, °C	13
Temperatures of the hottest point of the winding above the temperature of the cooling air	$\theta_{w.max}$ °C	78

In Table II are shown the formulas for approximating steady-state overheating from the transformer load factor.

TABLE II. Dependences of steady-state overheating on the load factor of the transformer

Resistance-averaged winding temperature above oil temperature	$18.36(K)^2 + 2.2\,K + 1.2$
Volume-average oil temperature over cooling air temperature	$29.46\,(K)^2 + 14\,K - 0.19$
Oil temperatures in the upper layers above the cooling air temperature	$34.6(K)^2 + 21.6\,K - 1.1$
Temperatures of the hottest point of the winding above the temperature of the cooling air	$48.6(K)^2 + 33\,K - 0.98$

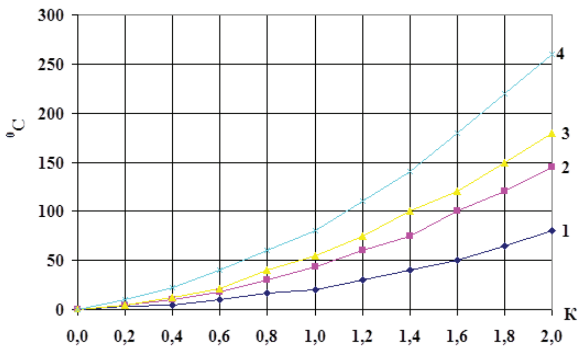

Fig.1. Dependence of steady-state overheating θ_k , °C on the load of transformers

In Fig.1 the graphics are named as follows: 1 – average overheating of the winding above the oil temperature; 2 – average oil overheating above the temperature of the cooling air; 3 – oil overheating above the temperature of the cooling air; 4 – overheating of the most heated point above the temperature of the cooling air.

When a transformer is loaded, its metal parts (steel core, copper windings, etc.) and the insulation of the windings are heated. The metal parts of the transformer can withstand relatively high heating temperatures for quite a long time without any residual deformations. The insulation of the windings, when heated, constantly wears out or, as they say, ages. Insulation aging is characterized by a decrease in its elasticity and mechanical strength. A heavily aged insulation becomes so brittle that, under the influence of vibration and electrodynamic forces that occur during the operation of the transformer, it can crack and break. Such insulation has low electrical strength. The time during which the insulation is completely worn out depends on the temperature of its heating. The higher the latter, the less, ceteris paribus, the total wear of the insulation [15].

Of all the components and parameters of the transformer listed in Table I, the winding is of the greatest importance, since its thermal regime is associated with the process of thermal wear of the insulation and thereby determines the service life of the transformer. The operation of the insulation and the ongoing aging processes depend on the temperature of the most heated winding zone $\upsilon_{w.max}$. This temperature should be used to calculate the aging of the insulation. But such calculations are relatively complicated, so they agreed to be carried out according to the average winding temperature $\upsilon_{w.av.}$, appropriately considering the difference between $\upsilon_{w.max}$ and $\upsilon_{w.av.}$:

$$\upsilon_{w.av.} = \theta_{w.av.} + \upsilon_{a.t.} \quad (2)$$

The operating mode is set and remains constant. In this case, the amount of heat released in the winding, and, therefore, the average overheating of the winding $\theta_{w.av.}$ remains constant. But the temperature of the winding changes in accordance with the change in air temperature during the day and depending on the time of year.

For oil-filled transformers installed in areas where the air temperature fluctuates within ±35 °C (the central strip of Russia), the complete wear of the insulation with a nominal winding temperature exceeding 65 °C is 17-20 years. That is, this service life of 17-20 years is the natural service life of a transformer installed outdoors in a temperate climate and operating continuously at full load in natural conditions of changing air temperature [5].

The natural wear of the insulation is not a constant value but depends on the average annual temperature of the area where the transformer is installed [22].

If the transformer is installed in a climatic zone with maximum temperatures greater than +35 °C, then the annual wear of the insulation will be greater, and the life of the insulation will be less than 17- 20 years. At the same time, the indicated insulation wear and service life can be maintained when the transformer is installed in a climate zone with elevated temperatures, but on condition that the transformer is loaded at a lower power than that allowed at +35 °C [17-18].

Therefore, the rated power of the transformer is not a constant value but depends on the highest air temperature of the area where it is installed. The value of the rated power of the transformer at an air temperature other than +35 °C, $S_{nom.\upsilon}$ is determined by recalculating the power $S_{nom.}$, indicated on the rating plate:

$$S_{nom.\upsilon} = S_{nom.}\,[1 - 2(\upsilon_{a.t.max} - 35)/100] \quad (3)$$

When $\upsilon_{a.t.max} = 55$ °C, $S_{nom.\upsilon} = 0.6\,S_{nom}$.

Calculations of heating of windings and oil of transformers under time-varying loads are based on the following relationship:

$$\theta_k(t) = \theta_0 \exp[-(t / T_0)] + \theta_k \{1 - \exp[-(t / T_0)]\} \quad (4)$$

where $\theta_k(t)$ – overheating of the transformer part at the moment t; θ_0 – the same at time t=0; θ_k – final superheat, which will be established after $3T_0$ if the load remains unchanged.

Overheating of the windings above the oil temperature is set for no more than 15 minutes, and a further increase in the temperature of the windings is due to an increase in the temperature of the oil, magnetic circuit and transformer tank with coolers. The heating time constant of a 20 MVA transformer installed at the substation T_0 = 2.5 h. Initial superheat θ_0 at time t=0 varies depending on the load of the transformer at the previous time. As the calculations showed, we can assume that θ_0 =30 °C [9-10].

For the climatic conditions, the equivalent annual temperature is $\upsilon_{a.t.eq.}$ =32 °C.

Steady temperature of the average heating of the winding:

$$\upsilon_{w.av.k} = \upsilon_{a.t.eq.} + \theta_{w.av.k} \quad (5)$$

Overheating of the winding relative to air $\theta_{w.av.k}$ is equal to the sum of overheating of the winding relative to oil $\theta_{w.av.oil}$ and overheating of oil relative to air $\theta_{av.oil}$.

In Table II shows the dependencies of the final overheating on the load factor, using which it is possible to calculate the dependence of the steady-state heating temperature of the winding $\upsilon_{w.av.k}$, °C of the 33/11 kV transformer of substation on the load factor K

The nominal temperature of the winding temperature, average in terms of resistance, is $\upsilon_{w.av.}$= 85 °C, therefore, at K > 0.5, the final heating is exceeded in excess of the permissible value.

Note that the final overheating occurs if the corresponding load exists for a period greater than $3T_0$, that is, with a duration of 7.5 h.

With the duration of the existence of any value of the load t =1 h, at T_0 =2.5 h, θ_0 = 30 °C, overheating at the end of the hour is less than the steady state is determined in accordance with (4) and Table II.

$$\theta_{w.av.oil.(t=1)} = 30e^{-(1/2,5)} + [18,36(K)^2 + 2,2K + 1,2][1 - e^{-(1/2,5)}] \quad (6)$$

$$\theta_{av.oil.(t=1)} = 30e^{-(1/2,5)} + [29,46(K)^2 + 14K - 0,19][1 - e^{-(1/2,5)}] \quad (7)$$

$$\theta_{w.av.\,(t=1)} = \theta_{w.av.oil.\,(t=1)} + \theta_{av.oil(t=1)} \quad (8)$$

Winding heating temperature:

$$\upsilon_{w.av.\,(t=1)} = 32 + \theta_{w.av.k\,(t=1)}. \quad (9)$$

III. Results and Discussions

On Fig. 1and shows dependence of the steady-state temperature of the average heating of the winding on the load factor of the 33/11 kV transformers.

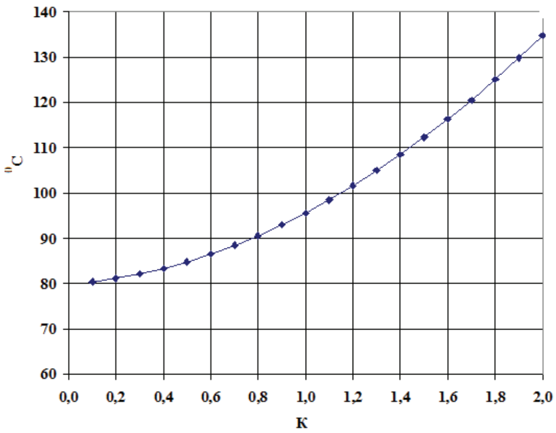

Fig.2. Dependence of the steady-state temperature of the average heating of the winding $\upsilon_{w.av.k}$, °C on the load factor of the 33/11 kV transformers

Where 1 – average overheating of the winding above the oil temperature; 2 – average oil overheating above the temperature of the cooling air; 3 – oil overheating above the temperature of the cooling air; 4 – overheating of the most heated point above the temperature of the cooling air.

Table III shows that the maximum actual superheats do not exceed the allowable for the oil and the most heated part of the winding, but are significantly greater for the average superheat of the winding above the oil temperature.

TABLE III. Comparison of the actual maximum actual superheats when loading transformers 33/11 kV with full power with allowable superheats

Overheat	Designation	Max θ, °C	Allowable θ, °C
Resistance-averaged winding temperature above oil temperature	$\theta_{w.av.oil}$	32	21
Volume-average oil temperature over cooling air temperature	$\theta_{av.oil}$	38	44
Oil temperatures in the upper layers above the cooling air temperature	$\theta_{oil.max}$	42	55
Temperatures of the hottest point of the winding above the temperature of the cooling air	$\theta_{w.max}$	51	78

Table IV shows the service life of transformers at different load factors, at full power and with reactive power compensation and consumer restrictions.

On Fig. 3 shows dependence of the relative service life of 33/11 kV transformers on the load factor.

IV. Conclusion

Transformers are designed for a load that is long-term constant in time, which is called nominal and is indicated by the manufacturer to count deviations from it during operation and testing. Exceeding the rated value is an overload. For transformers, including components, emergency and systematic overloads are allowed depending on the load curves and the temperature of the cooling medium [14; 20].

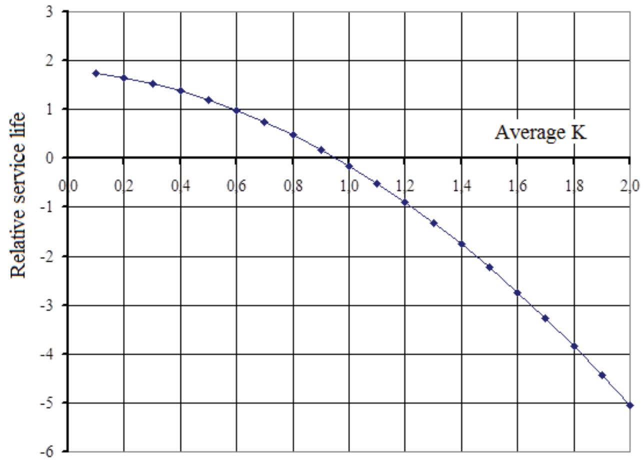

Fig.3. Dependence of the relative service life of 33/11 kV transformers on the load factor

TABLE IV. Service life of transformers at various load factors

Load characteristic	Transformer load factor		Winding heating temperature		Relative service life
	max	*average*	*max* $\upsilon_{w.max.}$	*average* $\upsilon_{w.av.}$	
Full power	1.2	0.8	102	92	0.34
Reactive power compensation	1.05	0.72	98	90	0.54
Reactive power compensation and consumer restrictions	0.72	0.53	87	86	1.05

The value of systematic overloads is determined by two conditions:

1. The thermal wear of the insulation under varying load should be the same as with a long-term constant temperature of the winding at the most heated point of 98 °C.

2. The highest oil temperature in the upper layers and the hottest point of the winding during the transient daily heating process is not higher than 95 °C and 140 °C, respectively.

The service life of a transformer is determined by the aging of its insulation, which increases sharply with increasing winding temperature. When the temperature of the insulation changes by 6 °C, its service life is doubled (it is reduced when the temperature rises or increases when it is lowered).

The temperature conditions under which the transformer can operate continuously throughout its entire service life: ambient temperature is 20 °C; the excess of the temperature of the most heated point of the winding over the average temperature of the winding 13 °C.

Short-term overloads according to the temperature criterion are emergency. They are determined from the following conditions: before the overload, the transformer was in nominal mode; overload is released when the hottest point temperature reaches 140 °C.

A temperature of 140 °C is significantly higher than the nominal temperature, but it can be tolerated for a short time. Exceeding this temperature is undesirable due to its proximity to the ignition temperature of oil vapors.

Permissible systematic overloads of transformers are determined depending on the characteristics of the load curve and the equivalent annual ambient temperatures. The duration of systematic overload is also taken into account: 1, 2, 4, 6 hours. The coefficient of systematic overload $k_{c.p.}$ is measured within 1.1-1.5. Emergency overloads are allowed in exceptional cases, for example, when one of the operating transformers fails. Transformers must allow emergency overloads by 30% above the rated current for no more than 3 hours a day, if the long-term preload was not more than 70% of the transformer's rated current.

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