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Approach to determining the remaining lifetime of power transformers

Abstract: Insulation of the power transformer windings is the main element which determines the condition and possibility of further operation of the transformer. There is a need to renew the main funds of the electric power industry. Improving the methods of monitoring the condition of the transformer to carry out timely repair work and extend the service life is an urgent task. The residual service life of the transformer is determined based on the combined approach of the probability of failure of the transformer. The probability is determined by assessing the current state and the factors affecting this state, like information about the load and duration of work. The study object is a power transformer. The study aims to develop a fuzzy logic controller for determining the residual life of a transformer based on the physical modelling of thermal processes in the transformer. The article reflects the approach to determining the coordinates of the most heated point of the insulation of the power transformer winding, depending on the mode and temperature of the surrounding environment. Based on this information, a structural diagram of the device based on the fuzzy logic controller was developed to monitor the transformer's residual resource. Transformer load factor, oil temperature and ambient temperature are accepted as input variables for the fuzzy logic controller. At the output, we get the coordinates of the most heated point of the transformer and the remaining service life. The proposed approach will make it possible to determine with high accuracy the remaining service life of the transformer and accordingly plan the date of repair or replacement.

Keywords: the most heated point of the transformer, remaining service life, fuzzy logic controller, winding insulation.

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Підхід до визначення залишкового терміну експлуатації силових трансформаторів

Анотація: Силовий трансформатор є одним із найважливіших та найдорожчих компонентів в електроенергетичних системах і мережах. Ізоляція обмоток трансформатора є головним елементом , за яким визначають стан та можливість подальшої експлуатації трансформатора і погіршення стану якої є основною причиною відмови трансформатора. На ізоляцію обмоток впливають різноманітні фактори, але ключовий є вплив температури. Тому моніторинг температурних режимів та удосконалення методів контроля стану трансформатора з метою вчасного проведення ремонтних робіт та продовження термінів експлуатації є актуальною задачею, особливо в умовах необхідності оновлення основних фондів електроенергетики. Залишковий термін експлуатації трансформатора визначається на основі комбіновано підходу вірогідності відмови трансформатора на основі оцінки його поточного стану та факторів, що на цей стан впливають: інформацію про навантаження та тривалість роботи. В статті відображено підхід до визначення координати найбільш нагрітої точки ізоляції обмотки силового трансформатора в залежності від режиму та температури оточуючого середовища. На основі даної інформації розроблена структурна схема пристрою моніторингу залишкового ресурсу трансформатора на основі нечіткого логічного контролера. В якості вхідних змінних для нечіткого логічного контролера прийнято коефіцієнт завантаження трансформатора, температуру масла та температуру оточуючого середовища. На виході отримуємо координати найбільш нагрітої точки трансформатора та залишковий термін експлуатації. Запропонований підхід дозволить з високою точністю визначити залишковий термін експлуатації трансформатора і відповідно запланувати дату ремонту або заміни, при цьому він не потребує значних капіталовкладень для впровадження і може бути інтегрованим в систему моніторингу всього електроенергетичного обладнання розподільчого пристрою підстанції.

Ключові слова: найбільш нагріта точка трансформатора, залишковий термін експлуатації, нечіткий логічний контролер, ізоляція обмоток.

Abbreviations:

$TLGU$ is transformer load graph unit,

RSL is residual service life,

$MHPC$ are the most heated point coordinates,

FLC is fuzzy logic controller,

$FOTOTS$ is fiber-optic transformer oil temperature sensors,

OPC is operator's personal computer,

ATU is ambient temperature unit.

Introduction

Power transformers are a significant part of power transmission and distribution networks, and their condition directly affects the network's reliability and stability. The process of operating the transformer is undoubtedly accompanied by a change in its technical condition and a decrease in its physical and structural properties. Today, many power transformers in Ukraine's energy facilities have exceeded the standard service life.

Maintenance and replacement of failed transformers can be time-consuming and capital-intensive. Considering the market conditions of power companies, a system for diagnosing the state of the transformer and its residual life with minimal monetary investment is necessary.

The remaining life of a power transformer is the actual time it can operate at a particular load until it is repaired or replaced. Analysis of static information about transformer failure indicates that most equipment failures are related to wear, humidity, and/or insulation contamination (*Rozvodyuk & Vdovichenko, 2019*). In this case, the main reason for the deterioration of insulation is the temperature effect due to the overload of the Transformer (*Palaniuk, 2022*).

According to the research conducted (*Rubanenko et al., 2017*), detecting the development of a defect at the initial stage reduces the cost of repair work by 75% and losses from under-discharge of electric energy by 63%.

A transformer's residual life is usually assessed based on several factors, such as its service life and mode, insulation condition, and wear level. Cellulose insulation is a crucial resource-defining element of a transformer, and its service life depends on many factors, such as temperature, humidity, and the quality of transformer oil. It was found that with increasing temperature, the rate of ageing of cellulose insulation increases (e.g., at a temperature of 98°C – ageing occurs in 20 years, and at a temperature of 110°C – the rate of ageing will be 4 times higher and the operational life of the insulation will work out in 5 years) (*Tenbohlen et al., 2016*). It can be concluded that their replacement after the established service life may not be justified under the regular operation of power transformers.

The scientific community has developed many methods and mathematical models for the diagnostics of power transformers: chromatographic analysis of gases, measurement of partial discharges, analysis of the thermal state, determination of the state of high-voltage transformer inputs, etc. (*Pritiskach, 2017*; *Cao et al., 2024*), which have a different set of the number of detected defects and means of measuring transformer parameters. However, the most significant parameter during transformer insulation ageing is the temperature of the most heated point of the winding. To date, various approaches to determining the thermal parameters of a transformer have been proposed. For example, in (*Grabko et al., 2021*), a mathematical model is formed based on the law of thermal conductivity and a mathematical formula for determining the temperature of the most heated point of the transformer winding. However, to accurately analyse the state of the transformer, you need to use an actual thermal model of the transformer.

One of the leading international standards for determining the residual service life of a transformer is IEC 60076-7 (*2005*). This standard sets out recommendations for determining the residual service life of a transformer based on monitoring its condition, diagnostics and analysis of test results. The basic model of the standard assumes that the most significant ageing of the insulation will be on the side of the winding with the maximum temperature. The temperature of the most heated point on the insulation surface of the power transformer winding θ_h is determined as follows:

$$\theta_h = \theta_a + \Delta\theta_{bt} + \Delta\theta_w,$$

where:

θ_a is ambient temperature;
$\Delta\theta_{bt}$ is excess of the oil temperature over θ_a at the bottom of the tank at a time t;
$\Delta\theta_w$ is exceeding the temperature of the hottest point above $\Delta\theta_{bt}$.

However, the standard's model has several assumptions that do not fully reflect the reality of the transformer's physical processes. For example, the model contains a linear profile of changes in the oil temperature in the middle and along the winding; the sinusoidal dependence of the ambient temperature over time indicates a difference in the maximum and minimum temperatures in the range of 12 hours, which is not valid. There is also an underestimation of the effect of transformer loading.

The temperature of the windings' most heated points determines the reduction of their service life. Data on the temperature of the most heated points at any given time of the transformer's operation under changing load and environmental conditions can be used to perform diagnostics of the transformer's actual exact state.

Most use the methods described in regulatory documents (IEEE and IEC), but equations and methods do not accurately consider processes. Existing regulatory documents are based on statistical data on the maximum load of each day and the average monthly or average daily temperatures during operation. At the same time, significant short-term overloads are not considered.

Therefore, to determine its service life, it is necessary to consider all the features and factors of a particular type of transformer and its operating conditions and use more accurate models and techniques that reflect the actual physical processes occurring in the transformer. You also need to be able to assess the transformer's condition online. M.P. Bolotnyi (*2019*) notes that today, there is a problem of inconsistency in the methods of processing diagnostic information received from monitoring, information measurement, and control systems.

The study object is a power transformer.

The study aims to develop a fuzzy logic controller for determining the residual life of a transformer based on the physical modelling of thermal processes in the transformer.

Based on the purpose of the study, the following tasks were set and solved:

- create a power transformer model in the SolidWorks software environment;
- perform a simulation study of thermal processes in the transformer under different loads and obtain the trajectory of movement of the most heated point of insulation of the winding;
- create an adaptive knowledge base and a fuzzy logic controller to define and fix.

The results of the study

To correctly predict the reduction in the transformer's service life, changes in the transformer's most heated point under various operating conditions were modelled and researched using the SolidWorks computer-aided design software package.

The transformer simulation was performed for the following parameters: the load of the transformer windings varied from 50% to 200% (in increments of 10%), the ambient temperature – from -15°C to +40°C, which corresponds to the actual physical conditions of transformers in Ukraine. As a result of modelling and thermal calculation, it was found that depending on the load factor of the transformer, the ambient temperature, and the presence of symmetry or non-symmetry of the load, the coordinates of the most heated point move. At the same time, for symmetric modes, this point is located on the low-voltage winding, and for unbalanced loads on the high-voltage winding side and at the same time starting from the transformer load by more than 150% and the temperature above 10°C, the coordinates of the most heated point remain unchanged.

Practical approaches to diagnosing electric power system equipment have been widely developed and implemented. These approaches include expert systems, fuzzy logic, and neural networks.

Many scientific papers use neural networks to predict and determine transformer parameters. For example, in the work of Vasylevskyi et al. (*2019*), the neural network is used to predict the humidity of transformer oil in power oil-filled transformers.

As a tool for organising a system for monitoring the technical condition of the transformer, an ANFIS adaptive neural network of neural output is used. This five-layer neural network of direct signal propagation of a particular type has a structure that works as a system of fuzzy logical output Sugeno with appropriate settings for the base of rules and functions of belonging (*Subbotin & Oliinyk, 2019*).

The results obtained from modelling the thermal process and the dependence of the movement of the most heated point of the power transformer are the basis of the neural network model. The appendix (*Figure 1*) shows the dependences of the coordinate displacement of the most heated point of the transformer (KorX, KorY, KorZ) on the ambient temperature and the load factor of the transformer.

Due to the obtained thermal calculation, the value of the coordinates of the most heated point of the transformer is obtained. The corresponding temperature value depends on the transformer load and ambient temperature (*Figure 2*). Thermal modelling of the transformer condition makes it possible to identify internal defects in the windings by installing local heating in the transformer tank, which is associated with local overheating of individual transformer coils. Thanks to the obtained result, it becomes possible to monitor the spent and remaining life of the transformer. When using the proposed approach, it becomes possible to determine the residual service life of the transformer with high accuracy, make an objective forecast of the date of exit from operation, and accordingly plan repairs or replacement.

According to the simulation, the service life of the transformer corresponds to the rated value of 25-30 years (depending on the type of transformer) when the transformer is loaded by no more than 140%, while the temperature value of the most heated point will not exceed 98°C. When the transformer is loaded more than 140%, the temperature of the most heated point increases, and the insulation's thermal ageing rate increases.

According to the reference literature, in the heating range from 80°C to 140°C, an increase in temperature by 6°C reduces the service life of the transformer insulation by almost half (*Rubanenko et al., 2017*).

There are two ways to implement a model for determining the residual life of a transformer, where the temperature of the most heated point is required as input data:

(1) measurements using fibre-optic sensors (Luxtron, ABB, General Electric Co), which will reduce the number of calculations and make it possible to obtain real-time information about the remaining resource;
(2) use the SOLIDWORKS CAD thermal calculation model, which will allow for more straightforward technical means but provides for an increased amount of calculations

The appendix (*Figure 3*) shows a block diagram of the transformer residual life monitoring device, which includes TLGU, RSL, MHPC, FLC, FOTOTS, OPC, and ATU.

For the first method, the operation of the complex involves collecting, processing and receiving data to the input of a fuzzy logic controller relative to the temperature of the transformer windings via a wireless communication channel from measuring devices. The controller input also provides information about the ambient temperature.

For the second option, the controller input must include information about the actual Transformer load graph and ambient temperature.

As a result of information processing, the fuzzy logic controller provides the operator with information about the transformer's residual life, like the coordinates of the point (s) where the greatest thermal ageing of the insulation occurred. Therefore, first of all, during repair work, it is necessary to pay attention to these places.

Discussion

Power transformer condition Diagnostics is a process that uses various methods and technologies based on statistical data and operational experience to determine the transformer's technical condition and assess its remaining life. The main purpose of diagnostics is to ensure the transformer's reliable and safe operation, such as maintenance and repair.

Despite numerous studies of thermal processes and diagnostic systems for power transformers, modern trends lead to further improvement of models and the use of the latest technologies. In order to increase the efficiency of transformer operation, simulation modelling must be combined with accurate monitoring data. A promising approach is using fuzzy logic methods, which allow you to get optimal solutions in conditions of uncertainty or incompleteness of data. Combining simulation results in the SolidWorks software environment with monitoring data provides a synergistic effect. Simulation results can refine the input rules of a fuzzy system, improving the accuracy of its predictions, and actual data allows you to verify the model and improve its parameters. Thus, the proposed approach is the basis for forming adaptive state control systems for transformers. The research results can be used to develop new methods for diagnosing the state of a power transformer, considering both static, i.e., design, and dynamic (operational) factors.

Conclusion

The temperature of the most heated point of the transformer has a significant impact on the residual service life due to the degradation of materials under the influence of high temperatures. Temperature overheating and changes in the transformer windings reduce the service life of insulation, lead to premature failures of power transformers, and cause short circuits.

An approach to determining the most heated point of a transformer and its movement along the windings based on the thermal modelling of SOLIDWORKS CAD is proposed. A 3D model of the transformer was created, considering the geometry and parameters, and thermal modelling algorithms were used to determine the temperature distribution inside the transformer.

From the simulation results, it is concluded that when the transformer is loaded by no more than 140%, the temperature value of the most heated point will not exceed 98°C and the service life, depending on the type of transformer, corresponds to the passport value of 25-30 years. Under transformer overload conditions of more than 140%, the temperature of the most heated point increases and the insulation's thermal ageing rate increases.

In this article, a fuzzy logic controller is formed to analyse the technical condition and continuously determine the residual life of the transformer, taking into account the transformer load and ambient temperature. The controller also includes the ability to receive transformer temperature data from fibre-optic transformer oil temperature sensors, data from which will help form decisions about the need to maintain the transformer replacement unit. Fuzzy controller rules are formed by considering experts' knowledge and analysing 3D modelling data.

The proposed diagnostic method will extend the service life of power transformers and help personnel obtain complete operational information to make appropriate, timely decisions, increasing transformer reliability and safety.

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Appendix

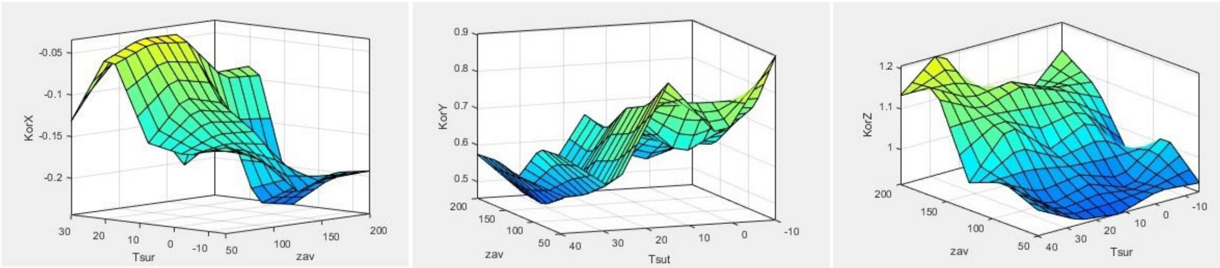

Figure 1. The dependences of the coordinate displacement of the most heated point of the transformer (KorX, KorY, KorZ) on the ambient temperature and the load factor of the transformer

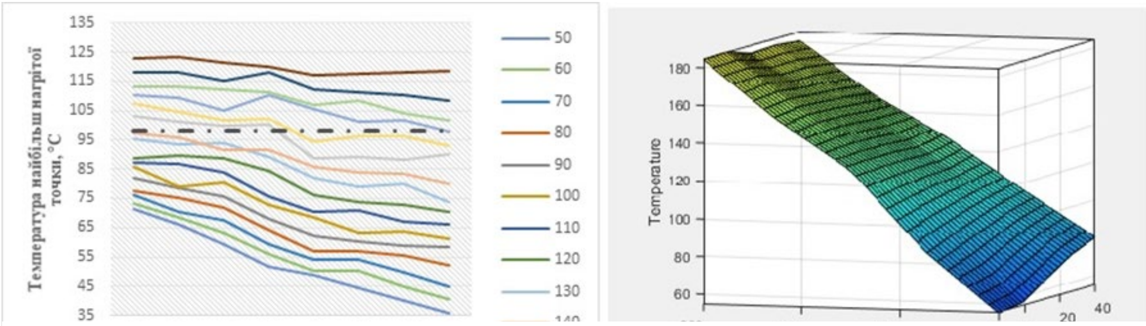

Figure 2. Dependence of the corresponding temperature value on the transformer load and ambient temperature (In Ukrainian)

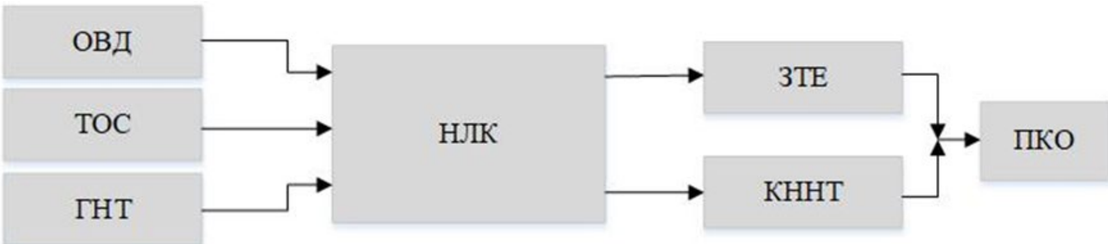

Figure 3. A block diagram of the transformer residual life monitoring device (In Ukrainian)