Application of Time/Temperature Fire Curves for the Estimation of Fire Resistance of Transformer within Protective Structures

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Abstract: At each power facility, a number of key elements can be identified thanks to which the power industry functions. One of these elements is transformers, which contain oil in their constructions. Being influenced by such factors as high oil temperature during operation of the device and actual flammability of this dielectric they become hazardous. Fires involving transformers are considered crucial due to the large amount of oil in contact with high-voltage elements. Therefore, it is advisable to prevent fires involving transformers. This condition can be met by maintaining the power equipment of transformer stations in good condition and without overheating. At the same time, transformers are currently a priority target for remote bombing due to Russian aggression against Ukraine. The high failure rate and the corresponding consequences for transformer reliability and safety require in-depth assessment. The paper briefly describes possible preventive measures that are currently being implemented in Ukraine to avoid incidents related to fires involving transformers. The application of standardized time/temperature fire curves is considered when assessing the fire resistance classes of protective structures in which transformers are located in today's conditions. Based on the results of the scientific research, the current state of the art in determining the temperature effect of fire when assessing the fire resistance class of enclosing protective structures within which transformers are located has been analyzed. The purpose of further research, scientific tasks, object and subject of the research and further areas of work are formulated. Scientific research was conducted using analytical methods, in particular analysis and generalization of previously performed works. As the research tools, statistical data on fires, current requirements of regulatory documents, scientific achievements on the researched issue derived by other scientists, and statistical method for processing research results were used.

Keywords: transformer, fire safety, protective structure, time/temperature fire curve, fire resistance.

1. Introduction

In the context of Russian aggression, transformer equipment has become one of the main targets during remote bombing of the Ukrainian territory. In addition to the direct consequences of fires involving transformers, another aspect is the reliability of their operation under today's conditions. Transformers can cause serious concern in the power sector, since the failure of an individual unit can lead to a long interruption in operation and secondary loss, and it can be difficult to quickly replace it. In order to protect transformer equipment, which is facility of infrastructure critical for the life of the population of Ukraine, they are provided for the placement within protective structures.

As a rule, fires involving transformer equipment are accompanied by an emergency spill of oil being used as a coolant in the transformer, and its ignition. Spilling of boiling transformer oil and its combustion contribute to the further development of the fire with its spread over the entire area of the protective structure within which the transformer equipment installed. This necessitates the formation of some requirements for the fire resistance of such enclosing protective structures.

Taking into account the above, conducting research aimed at establishing the temperature regime during a fire involving transformers located within protective structures is a relevant scientific task.

2. Theoretical Framework

The issues of preventing and fighting fires at energy enterprises were studied by Havrish et al. (2024) and Besarab & Yascheritsyn (2022). Methods of effective fighting fires involving electrical transformers and substations were theoretically characterized by such scientists as V. Balanyuk, V. Miroshkin, N. Huzar (2023), and others. The regularities of cooling and stopping the burning of transformer oil depending on the parameters of the gravel backfill of the fire prevention system of a transformer substation were identified by Klimas (2022). The importance of solving the problem of increasing the operational resources of power transformers was determined by Homanova and Bohurina (2020). Diagnostic measures to avoid fires and increase the reliability of transformers in Germany were studied by such scientists as Fritze and Berg (2013). Requirements for the design of fire safety measures for transformers as well as risk assessment of their fire safety status in New Zealand were presented by Anthony K.-L. Ng (2007). However, these and other studies have not sufficiently investigated the specifics of temperature effects on building protective structures for the housing of transformers.

Regulatory legal acts in force in Ukraine and the research having been conducted by scientists studying the behavior of reinforced concrete structures under the thermal influence of fire contain various methods to describe functioning of these structures under certain conditions (Alekseev, 2021; Givlyud et al., 2016; Kaspruk & Zagursky, 2021; Nizhnyk et al., 2023, 2024; Osypenko et al., 2011; Shcherbak et al., 2022; Pastukhova & Yanovskyi, 2023). Substantiation of the time/temperature fire curve during a fire is an important aspect of ensuring fire safety and operational reliability of transformer equipment. It is known that the load bearing structures of the frame and the roof of the protective structure for the transformer should be performed with a fire resistance class not lower than REI 90 under the conditions of influence of hydrocarbon time/temperature fire curve. The analysis of the load bearing structure from the view-point of fire protection is carried out using the models of thermal and mechanical effects established for the given calculation situations as well as the parameters of the supporting structure at elevated temperatures (DSTU-N B EN 1990:2008). In general, fire resistance should be confirmed based on the fulfillment of the following conditions (DSTU-N B EN 1991-1-2:2010): in time, strength, and temperature parameters. Comparison by temperature parameters is the most common method by which the critical temperature for the load is determined. As a rule, this is described using simplified calculation methods.

3. Methodology

Analysis of the research and requirements of the domestic and foreign regulatory frameworks for assessing fire resistance classes of structures in today's conditions makes it possible to assume that improving existing engineering solutions for the arrangement of structures that should perform the function of protection for transformers will create the prerequisites for reliable operation, limiting the spread of fire in the event of its outbreak. Research objective is to analyze the status of the application of standardized time/temperature fire curves for assessing the fire resistance of protective structures for transformers and to establish the prospects for further research.

To achieve the goal, it is necessary to solve the following tasks:

- To analyze and summarize statistical data on fires involving transformer in Ukraine using the databases of the State Emergency Service of Ukraine and the Ministry of Energy of Ukraine;
- To consider the current state of the art in determining the temperature impact of fire when assessing the fire resistance class of protective enclosures for housing transformers taking into account scientific research and the requirements of current regulatory and legal acts that determine the fire protection of mobile communication base stations;

- To determine further areas of research, formulate the goal, scientific objectives as well as object and subject of these studies.
Research object is fire protection of transformers placed in protective structures.
Research subject is physical parameters of a transformer that influence the choice of a standardized time/temperature fire curve for assessing the fire resistance of the protective structure.
The work was carried out using the analysis and generalization of appropriate regulatory documents and previously completed work on the study of temperature regimes of fires involving transformers located within protective structures, the method of mathematical statistics for processing research results.

4. Results And Discussion

One of the main criteria for calculating the fire resistance of any structure is to determine the temperature-time dependence of fire development, which should apply but to a single fire compartment of the building, unless otherwise specified in the design scenario of fire development. There are nominal and parametric time/temperature fire curves. As a rule, in most cases, nominal time/temperature fire curves are used for the design of building structures. At the same time, methods for modelling real (parametric) fire can be used when developing measures for fire protection of buildings and structures.
Nominal temperature-time dependences are generally accepted time/temperature fire curves that are adapted for the classification and confirmation of the fire resistance of various building materials, products, and structures.
The regulatory documents (DSTU-N B EN 1991-1-2:2010; Calculation of steel structures for fire resistance according to Eurocode 3, 2016) regulate the following time/temperature fire curves: standard one; that of external fire; that of hydrocarbon fire. In addition to the regulated time/temperature fire curves, the following are included: one of a slow-developing fire, modified temperature-time dependence of hydrocarbon fire development (HCM), and fire development curves in tunnels (RWS, RABT ZTV).
Standard fire. The standard time/temperature fire curve is determined by the following formula:

$$\theta_g = 345 \log_{10}(8t + 1) + 20 \qquad (1)$$

where
θ_g is the temperature of the gas environment in the fire compartment, °C;
t is the time, min.

External fire. The time/temperature fire curve of an external fire creates less severe conditions than when testing as per standard time/temperature fire curve. This temperature-time relationship is applied when determining the fire resistance rating of external walls of buildings.
The external time/temperature fire curve is determined by the following formula:

$$\theta_g = 660\,(1\text{-}0{,}687e^{0{,}32t} – 0{,}313e^{3{,}8t}) + 20 \qquad (2)$$

Hydrocarbon fire. The hydrocarbon time/temperature fire curve refers to more severe regimes than that of the standard time/temperature fire curve. This regime shall be applied when determining the fire resistance rating of structures used at oil industry facilities, the combustion temperature of which increases much faster and has higher values than when burning any other building and facing materials.
The hydrocarbon time/temperature fire curve is determined by the following formula:

$$\theta_g = 1080\,(1\text{-}0{,}325e^{-0{,}167t} – 0{,}675e^{-2{,}5t}) + 20 \qquad (3)$$

The dependences of some time/temperature fire curves (temperature on time) are presented as curves in Figure 1.

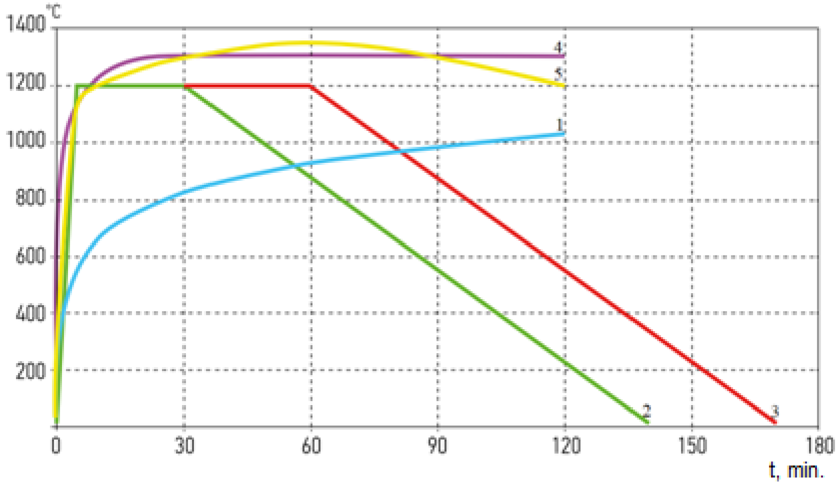

Fig. 1. Time/temperature fire curves

Legend:

1 – Standard time/temperature fire curve
2 –RABT ZTV time/temperature fire curve for roadway tunnels
3 –RABT ZTV time/temperature fire curve for railroad tunnels
4 – hydrocarbon time/temperature fire curve
5 –RWS time/temperature fire curve (simulates burning of a fuel truck (50 m^3) in a tunnel)

It is worth noting that there is a distinction between spatial fires (fires within fire compartments) and local fires. For spatial fires, the temperature distribution depending on time is assumed to be uniform (average by space), and for local fires, it is assumed to be uneven.

The calculation of the temperature of the gas environment for fires within fire compartments should take into account the physical parameters of the premises, specific fire load, ventilation conditions, etc. The calculation of the temperature (thermal effects) of the gas environment of a local fire shall be given if spatial ignition is impossible.

Nominal time/temperature fire curves are: standard one; external one; hydrocarbon one (DSTU-N B EN 1993-1-2:2010). The latter is the most severe fire temperature regime and is used at facilities where large quantities of oil, grease, gasoline, diesel, etc. are present.

Both experimental and calculation methods can be used to determine fire temperature regimes. Calculation methods are more modern, less burdensome and are described in the Eurocodes. In addition, it should be noted that non-standardized fire regimes in confined spaces (e.g. tunnels) have a temperature drop stage, which is mostly caused by the burnout of oxygen (the oxidant of the exothermic combustion reaction), that can similarly occur during a fire involving a transformer located within a protective structure.

Figure 2 schematically shows a cross-section of a protective structure within which the transformer is installed.

Thus, the time/temperature fire curves to be used to assess the fire resistance class of protective structures within which transformers are located do not have proper scientific justification, and the patterns of the influence of the fire load parameter on the temperature change under protective structures within which transformers are installed have not been studied. This determines the relevance of research in the established area.

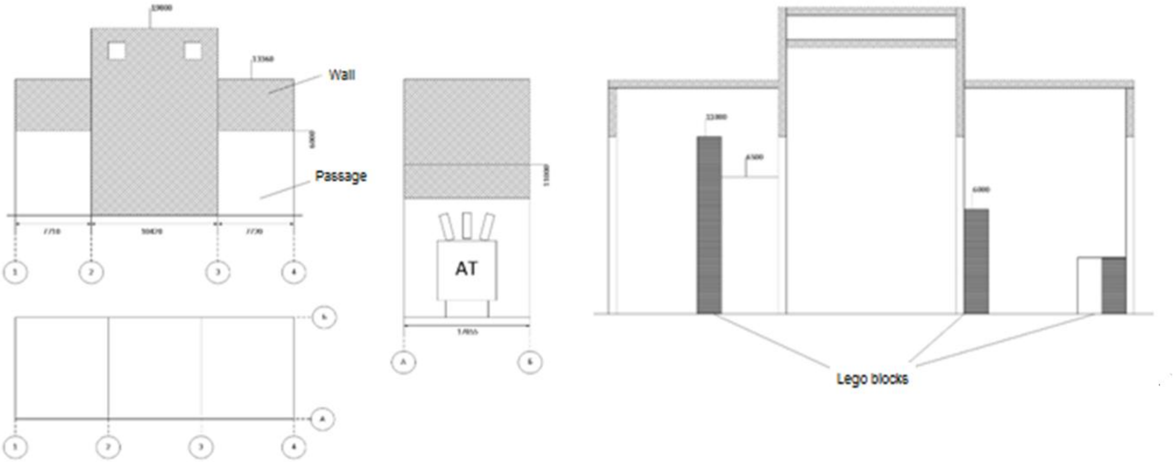

Fig. 2. Schematic cross-sectional view of a protective structure used for a transformer installation

In the future, research on substantiating the parametric time/temperature fire curve during fires involving transformers of different classes placed within protective structures is relevant.
The object of the study should be the temperature change during a fire involving transformers located within protective structures.
The subject of the study should include the influence of the amount of transformer oil and the geometric parameters of the protective structure (possible fire area) on the pattern of temperature changes during a fire involving transformers located within protective structures.
To this end, it will be necessary to solve the following scientific problems:
To analyze the current state of application of standardized time/temperature fire curve when assessing fire resistance classes of protective structures;
To substantiate the criteria for influencing the time/temperature fire curve under protective structures within which transformers are installed;
To calculate the time/temperature fire curve during a fire involving a transformer placed within a protective structure;
To justify the modified time/temperature fire curve during a fire involving a transformer placed within a protective structure;
To develop a program and methodology for experimental research and test the developed modified time/temperature fire curve;
To develop proposals for assessing the fire resistance class of protective structures within which transformers are located.

5. CONCLUSION

The analysis conducted did not reveal that the existing approach using the time/temperature hydrocarbon fire curve fire when assessing the fire resistance class of protective enclosures housing transformers had any scientific basis and was adopted using an expert approach.
The relevance of new scientific research was shown, their goal, object and subject were formulated, and the scientific tasks of such research were set.
In further research, it is necessary: to determine the scenarios of the occurrence and development of fires, in which it is necessary to substantiate the fire regime involving a transformer installed within a protective structure; to substantiate mathematical models that allow detecting the temperature regime of a fire involving a transformer installed within a protective structure; to establish a modified time/temperature hydrocarbon fire curve temperature during the burning of a transformer located within a protective structure and which can be determined through the dependence; to substantiate the fire resistance class of the enclosing protective building structures.

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