

THE EFFECT OF TEMPERATURE AND TEMPERATURE RISE TEST OF DISTRIBUTION TRANSFORMERS

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Abstract

The actual lifetime or failure-free operation of the power electrical devices is strongly dependent on mode of operation and service conditions. In many cases, power devices contain the organic or inorganic insulation system. In addition to the electric field intensity, partial discharges and other similar electrical phenomenas as a consequence of its action, the temperature is an important service factor, which mainly affects the lifetime of electrical insulation system. The temperature can then be considered as particularly significant ageing factor of power devices. During the long-term extremely hot summer months and at the full loaded equipment, temperature increases the rate of ageing of the insulation system contained in electrical equipment. Extremely high long-term external temperatures can overheat technological buildings, transformer stations, and in some cases even the soil into the great depths, and thus even the cable networks buried underground. In this paper, we will attempt to show that specific instances of such electrical equipment failures could be caused by temperature rise in prefabricated substation.

Key words

prefabricated substation, temperature rise, lifetime, failure

Introduction

Prefabricated substations (transformer stations) as well as other equipment with the respective protection and measurement devices are usually used for transformation of electrical power from classical transmission lines or power transmission from photovoltaic, biogas or other type of power plants. Photovoltaic or other non-conventional power plants up to several MW output power to the existing 22 kV distribution lines often use these prefabricated substations.

The electrical equipment life time indicator (lifetime) of these appliances is given by means of statistical values, for example gamma–percentage lifetime, mean lifetime, mean time between failures, mean accumulated lifetime and others. The failure rate statistic based indicators are processed by manufacturing companies and sometimes even big operators of equipment. Technical documentation of manufactured equipment should provide instructions for operation, maintenance procedures, proposals and time schedules of periodic inspections of individual equipment components, respectively of the whole equipment. We must note, that only the minimum number of manufacturers introduce the overall equipment service lifetime directly in the technical documentation. However, based on the endurance lifetime tests, experience and also the competitive pressures, manufacturers determine the extent of the guarantee and after-warranty inspections. The inspections also result from the respective operating rules of distribution companies. More rarely, the respective maintenance conditions or prophylactics procedures for the given equipment type are recommended. In the case of power transformers, individual lifetime comparison for various manufacturers is difficult. On our market, there is a large amount of various transformer manufacturers` types, of course with various thermal properties.

Significance of the accelerated lifetime tests

The process of the transformer operation causes gradual deterioration of the transformer insulation system dielectric properties. After a certain time, deterioration may lead to the failure. Dielectric properties of the electrical insulation system are frequently the subject of prophylactic measurements. Detection of the initial failure may prevent further development of the total transformer failure. Sophisticated quality technological production process and, of course, available knowledge of lifetime and degradation processes are of great importance in terms of the device lifetime. Therefore, during the pre-production technological process, accelerated lifetime tests are used. The aim of the accelerated lifetime tests is to determine the lifetime of a selected group of materials, components, products or equipment, at the given significance level in a technically feasible time interval.

In the case of transformers, the accelerated lifetime tests with respect to their financial demands are mainly carried out before the introduction of a new insulation system of transformer. The accelerated lifetime tests are not often performed after partial changes in the transformer insulation system. However, the interaction between the new used insulation materials may be significant, especially in oil-filled transformers and similar devices. Influence of the different materials of the insulation system can theoretically cause positive or negative synergistic effect in terms of lifetime. Due to the diffusion processes in the insulation systems containing electro-insulating oils and various other insulation and other materials, more significant degradation may occur than for example in the dry insulation systems. Intercourse of a material yet not used and tested with oil may activate a significant degradation process.

To illustrate that some producers do not perform the accelerated life tests, we introduce a problem which we solved in our department in the past. Failure was related to the high voltage equipment tap changer. Inappropriate construction materials used in the equipment caused degradation of electrical insulating oil, leading to the subsequent breakdown and failure. After repairing and completely cleaning up the tap changer and exchanging oil several times, the failure "incomprehensibly" repetitively re-occurred. The reason was the continual diffusion processes of the new insulation material used for the first time. We point out, that the equipment construction design was complied and the tap changer was a product of a

renowned manufacturer. Inappropriate mechanical construction materials were determined as a cause of failures.

Degradation processes in electrical insulation systems caused by temperature

Degradation processes in electrical insulation systems containing mainly organic materials are significantly accelerated by increased temperature. Effect of temperature on the thermal, mechanical, electrical and some physical properties is closely tied to the rate of the 1st order chemical reactions. During the reactions (device operation), the concentration of reactants is changing. The concentration of selected substances entering the reaction decreases, while the concentration of the final "product" of reaction increases. The local chemical reaction speed c changes, thus the dc/dt is not a constant. The reaction rate of processes is strongly dependent, inter alia, on the temperature. The dependence of the time concentration changes is given by the differential equation $dc/dt = -k \cdot c^n$, where k is the rate constant.

The exponent n has usually the value 1 (1st order reactions), the maximum value reaches 3. Concentration depends on the temperature only through the constant k , which is the function of temperature. Based on it, derived can be the temperature-time dependence at which the material will age to a certain degree. The rate of ageing is the value of the selected property. When the selected property x reaches a certain limit value, material functional lifetime (life) ends. The time elapsed from the beginning to the end of the material or equipment function is called lifetime τ (also L). Lifetime τ (1) can be expressed by the following equation:

$$\tau = A \exp^{\frac{B}{T}} \quad (1)$$

where L – is the lifetime,

T – is the absolute temperature,

A – is the constant depending on the critical value of the observed property,

B – is the constant determined by the activation energy of the reaction (failure).

For most of the organic electrical insulating materials as well as parts and equipment it follows that by increasing the temperature by about 7 Kelvin's, the lifetime is reduced by a half. Although, this statement does not apply exactly to all materials and material systems; it can be used informatively only. On this basis, relationships are conducted through accelerated life tests, so called thermal aging tests. What is more essential, the real thermal ageing of the equipment in service is also based on this knowledge.

We found, that a simple increase in temperature could cause a significant decrease of electrical strength of some insulating varnishes. On other side, for the most insulating materials breakdown, voltage slightly decreases with the increasing temperature, except for the materials in which so-called thermal electric breakdown is developing. At short time, extremely higher exposure temperatures of some insulating materials change its colour, and dielectric strength could even increase.

Therefore, the impact of temperature on the equipment lifetime is conditioned in particular by the insulation system lifetime, and then the service duration may be crucial.

Prefabricated substations

Prefabricated substations (Fig.1) are usually used for distribution transformers (22/0.4 kV) and other equipment. The devices are located on the places accessible to the public, such as housing estates, small renewable power plants, small factories, and so on. To supply the transformer, typically a 22 kV cable line is used.



Fig. 1 *An example of prefabricated substation.*

Prefabricated substations, in the terms of normative references, refer to the normative standard (STN EN 62271-202, 2007). Standard (STN EN 62271-202, 2007) establishes operating conditions, nominal values, general design requirements, measurement methods and temperature rise test methods for prefabricated substations with cable input voltage from 1 kV to 52 kV up to 1600 kVA nominal output power. Prefabricated substation is defined as a type-tested assembly comprising an enclosure that includes:

- transformer,
- LV switchgear,
- HV switchgear,
- HV and LV interconnections,
- auxiliary equipment.

Such block substations may be placed either at the ground level, or partially or completely below the ground level. Substation must be designed to ensure the common operation, revision and maintenance purposes. All transformer substation components must be under common enclosure or a system of enclosures. Substation components must conform to the following STN EN standards:

- HV switchgears: STN EN 62271-200 or STN EN 62271-201,
- LV switchgears: STN EN 61439-1 and STN EN 60947-1,
- Transformers: STN EN 60076-2 (liquid-immersed) or STN EN 60076-11 (dry-type).

The Slovak market provides many types and manufacturers of prefabricated substations with competitive advantage regarding the minimisation of dimensions and elegant external appearance. The substations may be made of different materials such as concrete, steel, and others, respectively of combination of materials.

The issue of heat dissipation may be worse. It is necessary to remember that such substations must provide loss heat dissipation due to transformer losses which consist of the open-circuit and short-circuit losses. It is also necessary to consider that the additional power losses are caused by the switchgear and auxiliary circuits. These losses depend on the product type and load conditions of the transformer. They typically reach the values of several kW.

This may lead to an increase in the internal temperature of substation, thereby reducing the transformer cooling ability. Transformer substations do not generally have a forced ventilation system and are designed only for the cooling based on the natural air exchange and heat dissipation by convection.

The tests of prefabricated substation and its components include the requirements for the components such as degree of protection, mechanical tests, electromagnetic compatibility tests, arcing due to the internal fault tests, functional tests or temperature rise tests discussed below.

Temperature rise test

This contribution deals with the effects of temperature. Let us therefore describe the test procedures and objectives for prefabricated substations with respect to the requirements specified in (STN EN 62271-202, 2007). The aim of temperature rise test of prefabricated substations is to:

- determine enclosure class,
- verify if the temperature of individual parts of the prefabricated substations including external enclosure parts accessible to touching does not exceed defined limits,
- ensure the guaranteed lifetime of the device insulation system, and thereby the safety and reliability of transformer substations during the period of operation.

One of the main tests of prefabricated substations is the objective temperature rise test. The test shows, if design and construction prefabricated substation are suitable and appropriate.

Poor enclosure construction and then overheating of substation may have a major impact on the used components' lifetime as discussed above. The temperature rise tests are therefore focused mainly on the temperature measurement of transformer insulation system (coolant or oil) and windings. Measurements on HV components are not considered necessary because the nominal values of HV circuits (HV switchgear) are practically given by the nominal power of the transformer used, with regard to the enclosure class. The temperature rise tests of transformer and LV equipment (LV switchgear) are performed simultaneously.

Loading tests should demonstrate that the temperature rise of the transformer of the same type and at the same load does not differ more than 10 K, 20 K or 30 K, whether the transformer is placed into enclosure or it is freestanding (i.e. without any enclosure – see Fig. 2).

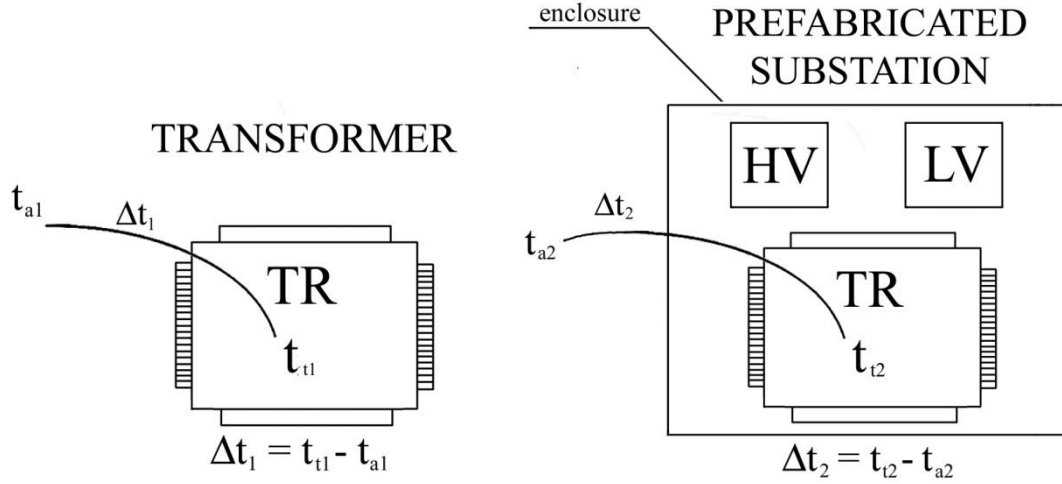


Fig. 2 Measurement of temperature rise in the transformer without enclosure Δt_1 (left) and with enclosure Δt_2 (right). Indexed $t_{a,n}$ represents ambient temperature and $t_{t,n}$ transformer temperature

This number determines the enclosure class of block transformer. The loading tests of transformers are performed at the short-circuited the low-voltage terminals, while the high-voltage terminals are supplied by voltage to reach the nominal current value on the transformer low-voltage side. After stabilization of conditions (steady-state), measurement of transformer coolant temperature (insulation system – oil), windings temperature and ambient temperature is performed.

The highest and the average temperature rise measurement of the liquid-immersed transformers windings is performed in accordance with (STN EN 60076-2, 2012). Measurement of the average temperature rise of the dry transformers windings is performed in accordance with (STN EN 60076-11, 2005). Measurement of the temperature rise of the LV switchgear is performed in accordance with (STN EN 61439-1, 2010).

The ambient temperature measurement is performed using four temperature measuring devices (e.g. thermocouples) placed uniformly around the prefabricated substation at a distance of 1 meter. The ambient temperature of the test area during the test must be higher than + 10 °C and less than + 40 °C with a maximum fluctuation of 1 °C/hour during the test. The ambient temperature around prefabricated substation is measured during the last quarter of the duration of the temperature rise test.

The results of temperature measurement are the values of temperature rise Δt , where $\Delta t = \Delta t_2 - \Delta t_1$. Based on the calculated values, prefabricated substation can be then classified into three classes (STN EN 62271-202, 2007):

class 10: $\Delta t \leq 10$ K

class 20: $\Delta t \leq 20$ K

class 30: $\Delta t \leq 30$ K

Prefabricated substation is considered satisfactory if the:

transformer temperature rise does not exceed the corresponding temperature rise measured on the same transformer without enclosure more than one temperature class of prefabricated substation,

temperature rise and the local temperature of LV switchgear, interconnections and terminals do not exceed the values specified in (STN EN 61439-1, 2010) and (STN EN 62271-1, 2009).

Conclusion

It should be concluded, that correct operation of transformers in terms of total lifetime is critical. It was proved that the lifetime of organic electrical insulation with the temperature rise of 7 °C is reduced by half. These facts should lead the operators of transformers to responsible temperature monitoring and managing, but also to the choice of the correct transformers' location.

The Institute of Power and Applied Electrical Engineering, Slovak University of Technology in Bratislava is equipped, inter alia, for using the temperature rise test. Based on our experience, however, many manufacturers of substations do not perform such tests. In better cases, the temperature rise is documented only by theoretical thermal calculations. It should be noted that the determination of thermal calculation coefficients may lead to inaccurate results. In practice this means that the transformers located in such station may be thermally overloaded with all the consequences in terms of their lifetime.

It is evident, that the distribution transformers are rarely fully loaded; however this "advantage" at the time of global warming and the increasing use of air conditioning may not be permanent. During the summer months, especially at the long-term extreme outdoor temperatures, this may lead to the frequent failures of transformers. The solution is, for example, continuous in-situ monitoring of the transformers' temperature using a suitable thermometer placed in the transformer station area and on the surface or inside the transformer tank.

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Acknowledgements

This publication is the result of implementation of the project: “Increase of Power Safety of the Slovak Republic” (ITMS: 26220220077) supported by the Research & Development Operational Programme funded by the ERDF.



Supporting the research in Slovakia. The project is co-financed by EU funds.