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Ambient temperature as the reason for MV/LV power transformer damage

ANDRZEJ ŁUKASZ CHOJNACKI

Department of Power Engineering, Power Electronics and Electrical Machines
Kielce University of Technology
Poland
e-mail: a.chojnacki@tu.kielce.pl

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Abstract: The paper presents an evaluation of MV/LV power transformer damage risk due to the impact of ambient temperature at their operation location. It features a presentation of the method of evaluating the power structures' reliability in the conditions of the structures' variable durability and exposure values. Based on perennial observations of ambient temperature and failure rate of MV/LV transformers, it was demonstrated that temperature is a factor that causes damage or is jointly responsible for the damage caused in all of the devices' other failures.

Key words: damage, distribution grids, reliability, temperature, transformers

1. Introduction

A contemporary consumer of electricity has very high requirements concerning the quality and continuity of electricity supply. The systematically increasing unit power rating of power stations and lines increases the danger of higher power value shutdowns in the case of their failure, thus leading to increasing limitations in electricity supply for consumers. This causes substantial material losses and in extreme cases can result in health or life hazards. In order to avoid the aforementioned threats, design engineers must know the principles applicable to power device reliability and strive to select optimally the structural materials and device parameters that ensure their reliable operation. The timeliness of the aforementioned aspects and the necessity of conducting further research on the reliability of power structures are confirmed, among others, by numerous publications on the subject matter [2, 6, 9, 13].

According to the definition presented in [8, 12], reliability is the ability of elements (objects) to perform the set functions in specific conditions and in a specific time, with simultaneous adherence to the acceptable loads. Usually, "specific conditions" are adopted as constants, while reliability is considered only in the operation time function. Meanwhile, it is necessary to note that time does not directly affect the structures' reliability. Any changes in the elements' ability to perform the set functions are an effect of internal and external (environmental) exposure. Exposure changes in time and the changes are usually random. An additional simplification in the conducted analysis is the assumption of the studied structures' constant durability. Meanwhile, durability is also random for any population. The problems of the relations between the structure's instantaneous durability and the exposure take place at the same time. This notion is most often omitted in power device reliability analyses.

Environmental impact on the behaviour of structures has been known for a long time. Many years before the development of the reliability theory, standardisation acts concerning environmental studies were established with the aim of checking whether a given structure is able to perform its task if specific environmental exposure is to affect the structure with specific intensity and for a specific time period. When designing structure reliability, two components are often taken into consideration: temperature impact and total impact of other environmental exposure [7, 8]. Unfortunately, the literature features a relatively low number of up-to-date elaborations on the ambient conditions' impact on the operation of power devices and structures. The only publications known to the Author of this paper, published in the last five years are [2, 11]. It is more often possible to find publications concerning the impact of weather on the variation of electrical loads or energy production in renewable sources (photovoltaic power plants, wind power plants), e.g. [1, 5, 10]. Furthermore, in most reliability studies, ambient temperature is not considered at all as the cause of power device damage [14, 15]. Electricians that remedy power distribution grid failures usually do not have sufficient knowledge to recognise the temperature-related mechanism of the device's damage. They therefore specify "Ageing processes" or "Unknown reasons" as the cause of damage on the failure sheet. Only specific visual inspection of the damaged transformer by the Author of this elaboration (and other researchers) allows for the assumption that the transformer was damaged due to long-term ambient temperature impact. The temperature impact is indirectly taken into consideration in the failure rate statistics, e.g. by specifying icing and soot, strongly correlated with negative temperatures, as the cause of failure.

In the paper, the author presents the evaluation of MV/LV power transformer damage risk due to the impact of ambient temperature on the devices at their operation location. The author demonstrates that temperature is a factor that causes damage or is jointly responsible for the damage caused in all of the devices' other failures.

2. Impact of environmental conditions represented by ambient temperature on the operation of power devices

The range of temperatures occurring on Earth is very large. The maximum air temperature in the shade, in open space, is around 60°C (the highest observed temperature amounted to 56.7°C – Death Valley, USA – 10.07.1913). On the other hand, the lowest temperatures reach nearly –90°C (the lowest observed temperature amounted to –89.2°C – Vostok Research Station, Antarctica – 21.07.1983). The range of occurring temperatures obviously depends on the latitude. The highest temperature observed in Poland amounted to 40.2°C (Prószków near Opole – 29.07.1921), while the lowest observed temperature reached –41.0°C (Siedlce – 11.01.1940). The above data are derived from the databases of the World Meteorological Organization of Arizona State University as well as the Institute of Meteorology and Water Management.

High temperature can be the cause of numerous forms of damage in power devices and structures, because it degrades the properties of their structural materials by causing their softening, melting, sublimation, evaporation, reduction in viscosity, changes in sizes and thermal ageing.

Mechanical deformation caused by material expansion is especially large in the case of combining materials with various expandability factors or uneven heating of a structural element made from a single material, but with substantial dimensions. Mechanical deformation is the cause of numerous forms of mechanical damage and leads to changes in the devices' electrical parameters. Softening and melting of plastic materials leads to structural weakening or damage, and to resin filling leaks. On the other hand, the thermal ageing of materials leads to their shortened durability. For electric devices, the impact of high temperatures is substantial in terms of the following [7]: reduction in the vertical and surface electrical resistivity of dielectrics, reduction in the withstand voltage of dielectrics, change in the dielectric constant of all dielectrics, increase in the dielectric loss and resistivity of metals.

It is necessary to note that the surface temperature of electric devices placed in open air, without covers, can substantially exceed the air temperature in the shade and reach above 100°C.

On the other hand, negative temperatures cause increased material fragility, increased liquid viscosity and solidification, reduced mechanical durability and material shrinking. Dimensional changes cause mechanical damage based, among other things, on the jamming and seizure of interoperating moving parts. The shrinking of materials, and simultaneously of the devices' structural elements, can cause the weakening of joints as well as fractures and cracks. Most materials become hardened and more fragile in negative temperatures. The change in the seals' hardness and dimensions can cause the devices to become unsealed. The viscosity of lubricants and oils is increased, thereby hindering the operation of moving parts and their damage if the lubricants free. Negative temperatures also lead to changes in the materials' electrical parameters, such as electrical conductivity, dielectric loss, dielectric constant and magnetic permeability. It is also necessary to note that the temperature of the surfaces of devices placed in open air can reach values significantly below the ambient temperature as a result of heat radiation [7].

Rapid temperature changes are also a factor that can cause power structure damage. Changes in temperature are a result of daily changes in air temperature, varying insolation, sudden wetting of the device, etc. The highest daily temperature amplitude observed on Earth amounts to 55.5°C (Browning, USA).

Sudden temperature changes affect devices subjected to the direct impact of solar radiation (surface temperature above 100°C) and then wetted by rain (in the case of hail, the temperature amounts to approx. 0°C).

Changes in temperature can cause dangerous mechanical stress in structural materials. Fast expansion and shrinking of materials lead to the weakening of joints, cracks and fractures. Sealed devices can become unsealed [7].

3. Analysis of reliability in the conditions of the structure's variable durability and exposure values

The analysis of the power structures' durability and their environmental loads (exposures) occurring in their operation location allows for distinguishing three specific cases of the mutual relation of their probability density function (Fig. 1):

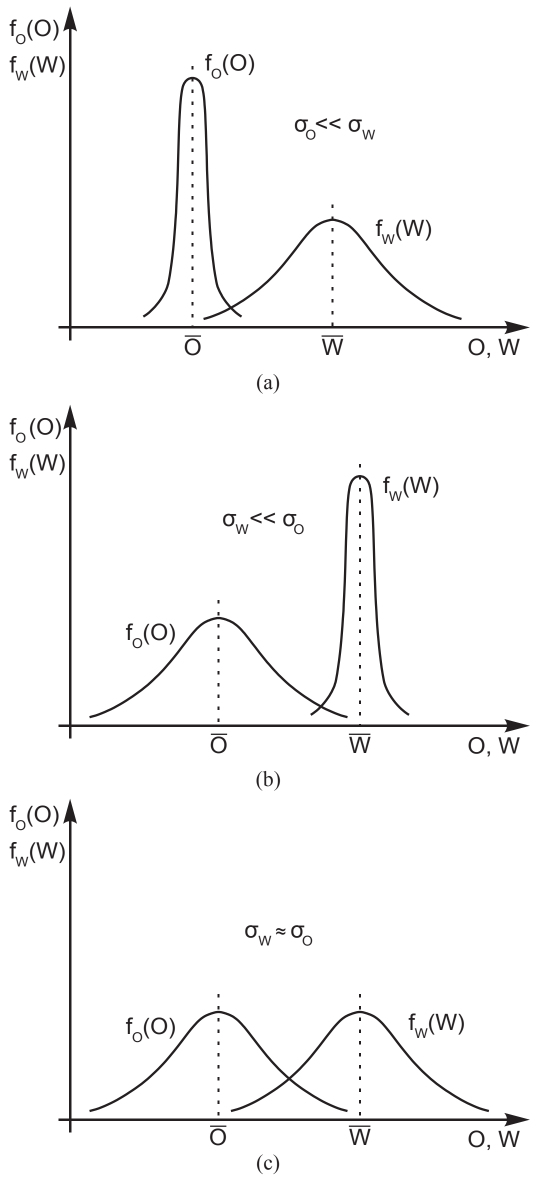

Fig. 1. Probability density functions for loads (exposures) $f_O(O)$ and element durability $f_W(W)$

1. Relatively low load dispersion

$$\sigma_O \ll \sigma_W \,. \tag{1}$$

2. Relatively low durability dispersion

$$\sigma_O \gg \sigma_W \,. \tag{2}$$

3. Comparable dispersion of load and durability

$$\sigma_O \approx \sigma_W \,, \tag{3}$$

where σ_O stands for the standard deviation of load, and σ_W stands for the standard deviation of durability.

In the case represented in Fig. 1(a), i.e. for a concentrated load, the reliability of structure R can be expressed with the following dependency.

$$R \cong \int\limits_{\overline{O}}^{\infty} f_W(W)\,\mathrm{d}W. \tag{4}$$

If we are dealing with concentrated durability values (Fig. 1(b)), then the structure's reliability will amount to the following.

$$R \cong \int\limits_{0}^{\overline{W}} f_O(O)\,\mathrm{d}O. \tag{5}$$

For case 1(c), it is necessary to consider the mutual situation of the probability distributions of adequate structure load and durability values. The probability that the load does not exceed the structure's durability values is the probability of the simultaneous occurrence of two independent events (Fig. 2):

– structure load equal to O_g

$$P(O = O_g) = f_O(O_g)\,\mathrm{d}O, \tag{6}$$

– structure durability of no less than $W_g = O_g$

$$P\left(W \geq O_g\right) = \int\limits_{O_g}^{\infty} f_W(W)\,\mathrm{d}W. \tag{7}$$

Due to the fact that these are independent random events, the probability of their simultaneous occurrence is equal to the product of the events' occurrence probability.

$$R = f_O(O_g)\,\mathrm{d}O \cdot \int\limits_{O_g}^{\infty} f_W(W)\,\mathrm{d}W. \tag{8}$$

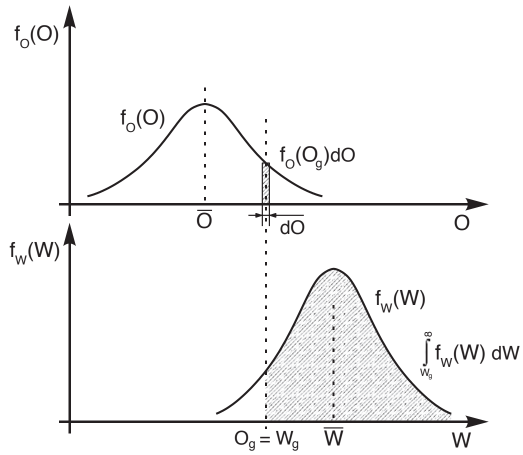

Fig. 2. Simultaneous occurrence of two independent events: structure load equal to O_g and structure durability higher than $W_g = O_g$

The damage occurrence risk evaluation is conducted in this case by the determination of the probability of damage to structure F, which is complementary for the probability R to single digits.

$$F = 1 - R = 1 - f_O(O_g)\,\mathrm{d}O \cdot \int_{O_g}^{\infty} f_W(W)\,\mathrm{d}W. \tag{9}$$

If we analyse power devices, we are usually dealing with case 1(c). This is due to the fact that these devices are manufactured with precision and care in a homogeneous manufacturing process. Therefore, they demonstrate a relatively low dispersion of durability features. In practice, they must resist loads with significantly dispersed values. In the basic scope, we can treat current and voltage load as the device's load. However, in a broader range, it is also possible to treat the device's mechanical and environmental (temperature, wind, etc.) exposure as load.

The structure's reliability measure is the probability that its durability will be higher than the applied load.

$$R = P(W > O) = \int_{0}^{\infty} f_O(O) \cdot \int_{O}^{\infty} f_W(W)\,\mathrm{d}W\,\mathrm{d}O, \tag{10}$$

or

$$R = P(W > O) = \int_{0}^{\infty} f_W(W) \cdot \int_{0}^{W} f_O(O)\,\mathrm{d}O\,\mathrm{d}W. \tag{11}$$

In some analyses, instead of analysing the variables W and O, they are replaced by a single variable, Z.

$$Z = W - O. \tag{12}$$

In such a case, the dependencies (10) and (11) take the following form:

$$R = P(Z > 0). \tag{13}$$

Depending on the type of analysed loads, the distributions $f_O(O)$ and $f_W(W)$ take various forms. Usually, it is possible to express them with a model in the form of a normal distribution with relatively good approximation.

If we assume a normal distribution in the form of $N(m_W, \sigma_W)$ for the structure's durability and a normal distribution in the form of $N(m_O, \sigma_O)$ for the load, then the random variable Z, constituting the difference of the random variables W and O, also has a normal distribution in the following form:

$$N\left(m_Z = m_W - m_O,\ \sigma_Z = \sqrt{\sigma_W^2 + \sigma_O^2}\right). \tag{14}$$

In this situation, the dependency (13) will take the following form:

$$R = P(Z > O) = \int_0^{\infty} \frac{1}{\sigma_Z \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{1}{2}\cdot\left(\frac{Z-m_Z}{\sigma_Z}\right)^2} \mathrm{d}Z. \tag{15}$$

As result of standardisation of the dependency (15), we obtain the following:

$$R = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \int_{\frac{0-m_Z}{\sigma_Z}}^{\infty} e^{-\frac{1}{2}\cdot K^2} \mathrm{d}K, \tag{16}$$

where:

$$K = \frac{Z - m_Z}{\sigma_Z}, \tag{17}$$

$$\sigma_Z \,\mathrm{d}K = \mathrm{d}Z. \tag{18}$$

After simple transformation, we obtain.

$$R = 1 - \Phi\left(\frac{m_O - m_W}{\sqrt{\sigma_O^2 + \sigma_W^2}}\right), \tag{19}$$

where $\Phi(y)$ stands for the probability function for the cumulative standardised normal distribution, defined by the following formula:

$$\Phi(y) = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \int_{-\infty}^{y} e^{-\frac{u^2}{2}} \mathrm{d}u. \tag{20}$$

4. Analysis of ambient temperature impact on the reliability of MV/LV power transformers – a case study

The use of the presented model in practice requires the specification of the theoretical probability density function for the occurring ambient temperatures, which in this case constitute a threat, as well as the theoretical probability density function for the ambient temperature at the time of the MV/LV power transformer failure, determining the limit resistance in the analysed model. The models were implemented by the Author by using parametric and non-parametric estimation bases, which are described broadly in the literature on the basis of mathematical statistics and probability theory. In order to determine the credibility of both models, the posed statistical hypotheses with the model's functional form were verified at the significance level $\alpha = 0.05$ by using the Kolmogorov test λ, Pearson's χ^2 and the character test.

The distribution of the probability density of exposure comprised of the ambient temperature in which MV/LV transformers are operated was determined based on data received from the meteorological services. Temperature values were observed in the Świętokrzyskie Province. The random ambient temperature sample collected during 10 years of observations includes a total of 87 648 samples. The ambient temperature's empirical distribution is presented in Fig. 3.

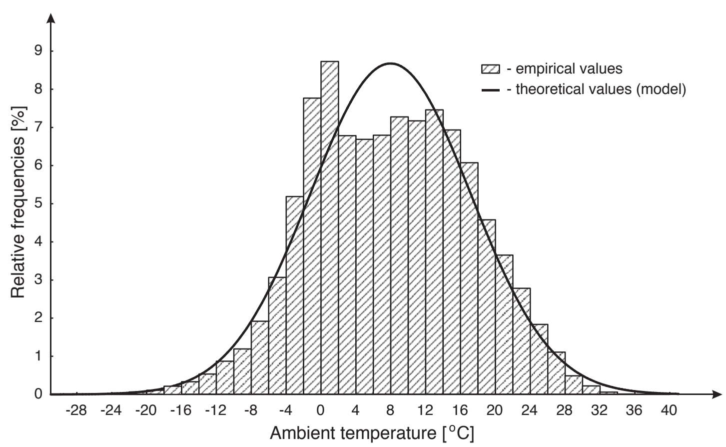

Fig. 3. Empirical and theoretical probability density function for the ambient temperature in the MV/LV transformers' operation locations

It was hypothesised that the distribution can be modelled using normal distribution in the following form:

$$f(T) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(T-m)^2}{2 \cdot \sigma^2}} \qquad (-\infty < T < +\infty), \tag{21}$$

where m is the expected value of random variable T, and σ is the standard deviation of random variable T.

The designated distribution parameters amount to: $m_o = 7.9689$ and $\sigma_o = 8.3051$.

The hypothesis was verified at the level of significance $\alpha = 0.05$ using the λ-Kolmogorov tests and χ^2 Pearson's tests. The following results were obtained: $\chi^2 = 12.41 < \chi^2_\alpha = 16.9$;

$\lambda = 1.095 < \lambda_\alpha = 1.358$. Based on the conducted tests, there is no reason to reject the hypothesis about the normal distribution $N(7.9689; 8.3051)$ of ambient temperature in the MV/LV transformer operation locations.

Based on empirical data encompassing a 10-year period of MV/LV transformer observations, the study also featured testing of the transformers' failure rate depending on the ambient temperature in the time period preceding the failure. The research was conducted in the area of functioning of one of the large electricity distribution companies in Poland. The tests served as the basis for determining the probability density functions for the MV/LV transformers' durability (resistance) against the external factor (exposure) of ambient temperature. For this purpose, the empirical data required standardisation, because the time intervals for the occurrence of particular ambient temperatures are not identical. The empirical values and the theoretical probability density function for the transformers' durability against ambient temperature are presented in Fig. 4.

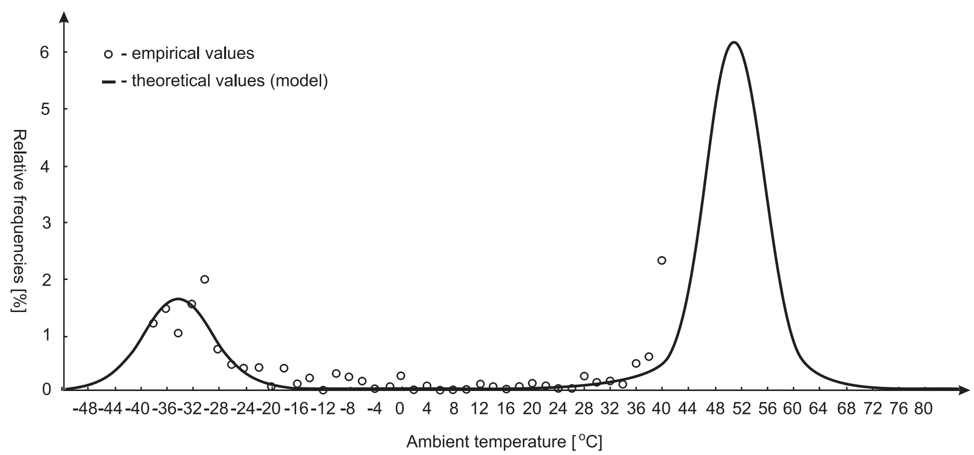

Fig. 4. Empirical and theoretical probability density function for the transformers' durability against load (exposure) in the form of ambient temperature occurring in the MV/LV transformers' operation location

It was attempted to implement the theoretical model of the failure probability density function's empirical distribution depending on ambient temperature. Based on a detailed analysis of the obtained results, it was assumed that the function is a superposition of two density functions $f_1(T)$ and $f_2(T)$ in the following forms:

$$f(T) = k_1 \cdot f_1(T) + k_2 \cdot f_2(T), \tag{22}$$

where k_1, k_2 stand for the shares of failures that took place in negative and positive temperatures, accordingly, expressed with the following dependencies:

$$k_1 = \frac{l_1}{l} \qquad \text{and} \qquad k_2 = \frac{l_2}{l}, \tag{23}$$

l_1 is the number of MV/LV transformer failures that occurred in negative temperatures, l_2 is the number of MV/LV transformer failures that occurred in positive temperatures, and l is the number of all MV/LV transformer failures.

The normal distribution was adopted as the probability density functions for both the first and second fractions. The normal distribution's probability density function is expressed using the dependency (21).

Based on the analysis of empirical data, the following quantities of particular fractions were designated: $l_1 = 93$, $l_2 = 353$, $l = 446$ as well as failure shares in particular fractions.

$$k_1 = \frac{93}{446} = 0.21 \qquad \text{and} \qquad k_2 = \frac{353}{446} = 0.79. \tag{24}$$

The designated normal distributions' parameters are as follows: $m_1 = 34.8451$, $\sigma_1 = 4.4108$ and $m_2 = 50.4698$, $\sigma_2 = 4.1776$.

After applying the designated values to the dependency (22), the transformer failures' theoretical probability density function takes the following form:

$$f(T) = 0.0190 \cdot e^{-\frac{(T+34.8451)^2}{38.9103}} + 0.0754 \cdot e^{-\frac{(T-50.4698)^2}{34.9047}}. \tag{25}$$

The theoretical probability density function for MV/LV transformer failures is presented in Fig. 4.

The distribution hypothesis verification was conducted using the signed-rank test at the level of significance $\alpha = 0.05$. The obtained verification results are as follows:
$l_0 = \min(l^+,\ l^-) = \min(24, 16) = 16$; $l_0 = 16 > 13 = l_\alpha$; $l_o \notin R_\alpha = (-\infty,\ 13)$. Based on the test conducted for the level of significance $\alpha = 0.05$, there is no reason to reject the hypothesis that the probability density function is a superposition of two distributions presented using the dependency (25).

The discussed case features two danger zones: for high and low temperatures. Exceeding the positive limit temperature upwards and negative limit temperature downwards can lead to MV/LV transformer damage or substantially accelerate the damage process. The impact of positive and negative temperatures can be examined independently. By applying the dependency (19), it is possible to designate the transformers' reliability:

– for positive temperatures

$$R_+ = 1 - 0.79 \cdot \Phi\left(\frac{7.9689 - 50.4698}{\sqrt{8.3051^2 + 4.1776^2}}\right) = 0.99999807,$$

– for negative temperatures

$$R_- = 1 - 0.21 \cdot \Phi\left(\frac{-7.9689 - 34.8451}{\sqrt{8.3051^2 + 4.4108^2}}\right) = 0.99999944.$$

In this case, the damage occurrence risk measure is the probability of damage to structure F, which is complementary for the probability R to single digits. The dependency (9) provides the following:

– for positive temperatures

$$F_+ = 1 - R_+, \tag{26}$$

therefore,

$$F_+ = 1 - 0.99999807 = 1.93 \cdot 10^{-6},$$

– for negative temperatures

$$F_{-} = 1 - R_{-}, \tag{27}$$

therefore,

$$F_{-} = 1 - 0.99999944 = 0.56 \cdot 10^{-6}.$$

The total probability of MV/LV power transformer damage due to the impact of ambient temperature amounts to

$$F = F_{+} + F_{-}. \tag{28}$$

After data substitution,

$$F = 1.93 \cdot 10^{-6} + 0.56 \cdot 10^{-6} = 2.49 \cdot 10^{-6}.$$

Based on the results of transformer reliability studies in the available science literature [2–4, 14, 15], it is possible to state that the total probability of MV/LV transformer damage amounts from $3.56 \cdot 10^{-6}$ to $6.11 \cdot 10^{-6}$. Therefore, in the most favourable situation, temperature is the cause of damage or a factor that facilitates damage in approx. 41% of MV/LV transformer failures (70% in extreme situations). This points to the necessity of conducting further research on increasing the resistance of the materials used to build MV/LV transformers against ambient temperature. Research on combining various structural materials also seems important. Incorrect combination of various materials, e.g. materials with substantially different thermal expandability, can quickly lead to transformer damage.

5. Conclusions

Based on perennial research, the author found that despite the substantial progress in material engineering and many structural changes in transformers, the devices are still insufficiently resistant against extreme ambient temperatures occurring at their operation location. In his reliability studies based on several thousand failures, the author demonstrated that the MV/LV transformer damage intensity increases substantially for extreme positive and negative temperatures [2,3]. This paper features an analysis of the mutual relations of load, represented by the occurring ambient temperature, and of the durability of a transformer, which constitutes a complex reliable system. The risk of transformer damage due to the impact of ambient temperature was determined based on the analysis. For this purpose, the author has determined the probability density distributions of ambient temperature that occur in the transformers' operation location and the distribution of ambient temperature featuring the occurrence of damage, the cause or facilitating factor of which was the ambient temperature.

The conducted studies demonstrated that ambient temperature is a factor causing damage or factors jointly responsible for the damage in approx. 41% of MV/LV transformer failures. This share is very high. It should be emphasized that the impact of negative temperatures is lower than positive temperatures. The probability of damage to the MV/LV transformer as a result of negative temperatures' impact is almost four times lower than as a result of positive ones ($0.56 \cdot 10^{-6}$ and $1.93 \cdot 10^{-6}$). To a large extent, this should be explained by the overheating of transformers at high positive temperatures, while at negative temperatures the cooling efficiency is very high.

The obtained results allow for the statement that the issue of the impact of ambient temperature on MV/LV transformer damage is not yet sufficiently recognised. It is necessary to conduct further research in order to use new materials in transformer structures or introduce technological changes that would reduce the negative impact of ambient temperature in which the devices are operated.

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