The Influence of Solar Radiation on the Lifetimes of Power Transformers

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Abstract

In order to avoid the uncontrolled removal of the power transformers, a special importance is the accurate knowledge of the estimated, consumed and remaining service life of the insulation systems of these equipment taking into account the real loads during their operation. In this paper a method of calculating the lifetimes based on the recommendations of IEEE and IEC loading guides using the values of the hot spot temperature is presented. These are calculated based on the daily load curves of the transformers, as well as the variable temperatures of the environment and the solar radiation. To highlight the effect of ambient temperature and solar radiation, a case study of three transformers operating in different geographical areas, respectively in Romania (Craiova, Suceava, Constanta) and Mauritania (Noukchatt) is presented. It is found that the values of the hot spot temperature calculated in the presence of solar radiation are approx. 3 ºC higher than those calculated in its absence and, for the same daily load regime, the lifetime consumed in one year has higher values for the transformer in Nouakchott, than for those in Craiova (with 231 days) and Suceava (with 256 days).

Keywords: power transformers, oil-paper insulation, solar radiation, hot spot temperature, estimated, consumed and remaining lifetimes

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1. Introduction

Power transformers are some of the most important elements of any regional or national energy system [1] and represent the biggest investment in equipment installed in high-voltage stations (60 % of total investment [2]).

Transformers are relatively reliable equipment with an average life of 20-35 years [2], [3], and with good preventive maintenance, their lifetimes can reach up to 60 years [3]. It is known that unscheduled removal of power transformers from operation (due to a failure) causes significant economic losses, while their destruction (as a result of fires and/or tank destruction) can lead to very large environmental pollution (air, water, soil) [1].

Among the components of a power transformer, the insulation systems of windings is the most frequently defective elements, their failure rate increasing with their service life [1].

During transformers operation, windings and bushings insulations are subjected to constant and/or variable stresses: thermal, electrical, mechanical, environmental, etc. Irreversible chemical reactions occur both in paper and oil, leading to irreversible physical and chemical transformations, resulting in continuous ageing and degradation of the insulation [4].

As a result, the physical and electrical properties of the insulation become worse and, after a certain operation time, their values fall below certain limit values, which can lead to damage and decommissioning of the equipment. The major cause of oil-filled transformer failures related to materials are insulation and bushing deterioration, loss of winding clamping overheating, decomposition of winding insulation, oxygen, moisture, and gases in oil, oil contamination, and partial discharges activity [5].

Loading capability of power transformers is limited mainly by winding thermal stress, the temperature of solid insulation being the main factor of transformer ageing. With temperature and time, the cellulose insulation undergoes a depolymerisation process. As the cellulose chain gets shorter, the mechanical properties of paper such as tensile strength and elasticity degrade. Eventually the paper becomes brittle and is not capable of withstanding short circuit forces and even normal vibrations that are part of transformer life. This situation characterizes the end of life of the solid insulation. Since it is not reversible, it also defines the transformer end of life [6].

Modern transformers make use of thermally upgraded paper (TUP) that has been chemically treated to improve the thermal stability of cellulose structure ([7]).

As can be seen in Figure 1, the values of ageing acceleration factor, determined according to both the IEEE Standard [8] and the IEC Standard [9], are much lower for TUP than for normal Kraft paper (NKP).

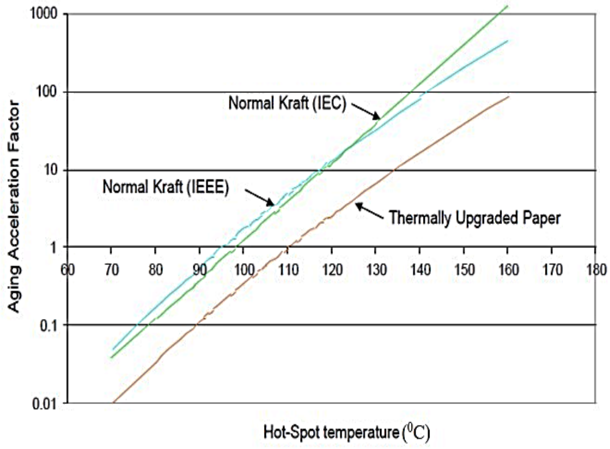


Figure 1. Effect of temperature on paper ageing rate [7]

The rated hot spot temperature for TUP is 110 °C and it can be seen that an increase of 7 °C will double the aging acceleration factor.

For older transformer built with NKP, the rated hot spot temperature is either 95 °C according to IEEE [8] or 97 °C according to IEC [9]. More so, NKP is very sensitive to temperature and in case of emergency (when the hot spot temperature may reach 140°C) the aging acceleration factor may reach 100, which means one hour in this condition is equivalent to 100 hours at the rated temperature [7].

The temperature of the winding is not uniform, and the real limiting factor is actually the hottest section of the winding commonly called winding hot spot. This hot spot area is located somewhere toward the top of the transformer, and not accessible for direct measurement with conventional methods [6-7].

Therefore, for estimating the lifetime of the transformer insulation, in the equations of the lifetimes lines (refer to [1]), the hot spot temperature (HST) (θ_{hs}) must be used. Thus, the equation of the lifetime line, according to the Dakin aging model ($\ln L = a + b/T$, [1]), is as follows:

$$\ln L = a + b/(\theta_{hs} + 273.15), \quad (1)$$

where:

L - the lifetime of the insulation,

a – a material parameter,

$b = E_a/k$, E_a- the thermic activation energy, k - Boltzmann's constant

θ_{hs} - the hot spot temperature (HST).

In [1] the estimated, consumed and remaining insulation lifetimes of transformers were determined based on a hypothetical temperature variation curve over the course of a day. In this paper the consumed and remaining lifetimes are determined using the values of the hot spot temperature, calculated on the basis of the transformer load curve, the ambient temperature and the solar radiation.

2. The hot spot temperature

As it is shown in [7], the determination of hot-spot temperatures involve calculation of three separate elements of thermal gradients which are added to the temperature of the oil entering the bottom of the transformer coil, respective the insulation gradient, the film gradient and the duct gradient.

The insulation gradient is a function of the total thickness of paper between the conductor and the cooling oil, and the thermal conductivity of oil soaked thermally upgraded Kraft paper.

The film gradient is the difference between the temperature of the conductor or paper exposed to the cooling duct and the average temperature of the liquid in the duct.

The duct gradient is the difference between the temperature of the cooled oil entering the duct and the heated oil leaving the duct.

IEEE and IEC loading guides [8-9]) have been providing guidelines for the calculation of the winding hottest spot temperature from data that can be conveniently measured, and parameters derived from temperature rise test or manufacturer calculations.

The basic calculation method relies on the measurement of oil temperature at the top of the transformer tank (top-oil temperature) and a calculation of the temperature difference between the winding hottest spot and the top oil. This temperature rise is provided by the manufacturer, based on his modelling of oil flow and losses distribution in the winding. The hot-spot temperature θ_{hs} can be computed for any load using the standard relation:

$$\theta_{hs} = \theta_{to} + \Delta\theta_{hr} \left(\frac{I}{I_r}\right)^{2m}, \quad (2)$$

where:

θ_{to} - top-oil temperature,

$\Delta\theta_{hs}$- rated hot-spot temperature rise above top oil,

I - the load current,

I_r - rated current,

m - winding exponent.

This simple equation was completed with an exponential function to account for the thermal inertia of the winding when a sudden load increment is applied and has been used for several decades.

However, a more frequent utilisation of transformer overload capability has shown the inadequacy of this method and a revision of the loading guide for power transformers is currently in progress [7].

The hot-spot temperature calculation methods use several assumptions:

a) Oil temperature in the cooling duct is assumed to be the same as the top oil temperature;
b) The change in winding resistance with temperature is neglected;
c) The change in oil viscosity with temperature is neglected;
d) The effect of tap position is neglected;

e) The variation of ambient temperature has an immediate effect on oil temperature.

On the other hand, experimental work has shown that at the onset of a sudden overload, oil inertia induces a rapid rise of oil temperature in the winding cooling ducts that is not reflected by the top oil temperature in the tank.

Therefore, alternate sets of equations are being developed, taking into account all these factors [7].

An important evolution is the disappearance of the IEEE C57.91-1995 Guide on definition of transformer "Thermal Duplicate" that was often used to provide default values for winding temperature rise at rated load [10]. This reference will not be available anymore to provide support to the hot-spot temperature rise estimated by the manufacturer. This might reduce the credibility of transformer manufacturer in providing that critical thermal parameter.

Also, IEC 60076-7 Guide for the calculation of hot spot temperature was improved in time. Still, the correct calculation of the critical temperature difference between winding hottest spot and top oil will depend on manufacturer ability to model properly the oil flow within the winding ducts, the distribution of losses along the winding, the heat transfer characteristics of the various insulation thickness used throughout the winding and the impact of local features restricting the oil flow.

Based on the calculation relationships established in the IEEE and IEC guides [8-9], numerous hot spot temperature calculation models have been developed for different transformer configurations, in different working conditions.[11-18].

Susa *et al.* [11] propose temperature thermal models for more accurate temperature calculations during transient states based on data received in a normal heat run test (i.e., the top oil in the tank of the transformer and the average winding-to-average oil gradient). Also, oil viscosity changes and loss variation with temperature are taken into account.

Kazmi *et al.* presents in [12] thermo-electric calculation models of Top-Oil (TOT) and Hot-Spot (HST) temperatures. The publication provides the state-of-the-art for these models and compares the physics and structure behind the formulation of differential-based models of [8] and [11].

The values obtained for a 6.8 MVA transformer are compared with the values measured. Also, the thermal lifetime of the test transformer is calculated based on its loading and ambient conditions history, using the recommendations of international loading guides.

In [13], Rajini presents an approach to estimate and locate the hotspot accurately by considering the losses distributed across the transformer geometry. The distributed equivalent electrical circuit based on the thermal electrical analogy, is developed for a 50 kVA transformer.

The results are compared with the classical approach of estimating the hot spot temperature.

Harita et al. [14] achieved a thermic model to simulate the thermal behaviour of the transformers. The thermal model is arrived at using the principle of thermal electrical analogy and the fact that the losses in the transformer are distributed rather than lumped. The losses in the core, which are difficult to accurately compute, are calculated by determining the flux densities using Finite Element Analysis and gives the temperature profile across the considered transformer's geometry. The model is implemented for single phase transformer, but the same model can be extended to three-phase transformer.

A computer model, which can predict hot-spot temperatures for different types of cooling regimes and transformer winding geometries is presented by Declercq et al. in [15].

The program realized by the authors can be used as a design tool, to verify if the hot spot temperature is not too high and to verify the influence of different parameters (winding geometry as well as cooling method or number of radiators) on the temperatures.

In [16], Iskender and Mamizadeh, two thermal models for calculating top-oil temperature for indoor and outdoor transformers are suggested, considering nonlinear thermal resistance and the adequate value of thermal capacitance. The ambient temperature change was also considered in deriving the thermal-electric analogy model. The top-oil thermal model for indoor transformer was also derived based on the thermal-electric analogy theory. The experimental results are in a good accordance with the theoretical results both for indoor and outdoor transformers.

A calculation method of the oil temperature at the top of the transformer tank based on the measurement of the surface temperature of the top radiator pipe is suggested by Guo et al. in [17].

The authors find a linear relationship between the two temperatures for an ONAN cooling transformer but consider that this result should be verified on other transformers in operation.

A simple equivalent circuit to represent the thermal heat flow equations for power transformers is presented by Swift et al. in [18].

Key features are the use of a current source analogy to represent heat input due to losses, and a nonlinear resistor analogy to represent the effect of air or oil cooling convection currents. It is shown that the idea of "exponential response" is not the best way to think of the dynamics of the situation and that one can consider ambient temperature to be a variable input to the system, and that it is properly represented as an ideal voltage source.

In [19], Reddy *et al.* propose a novel thermal model to determine the hot spot temperature using the top oil temperature which becomes the ambient temperature for a hot spot equation model.

The equations are modelled in Simulink and validated using transformer data from measurements in the factory, thus a real time online monitoring system can be developed and used. The authors present new and more accurate temperature calculation methods taking into account the losses including the chief cause for hot spot i.e. stray loss (which is evaluated by using finite element method) and the oil viscosity changes and loss variation with temperature.

An originally thermal model, intended to oil power transformers analyses, is presented by Radakovic and Kalic in [20].

The model delivers the value of the insulation hot-spot temperature, as the most critical quantity during transformer loading, and the value of the thermal ageing, both for variable load and variable ambient temperature. The model takes into account the influence of nonlinear thermal characteristics in transient thermal processes; instead of exponential functions and time constants, the numerical solution of differential equations is used. The model delivers one characteristic temperature in copper (solid insulation) and one characteristic temperature in oil.

In [21], the analysis stresses the definition of the hot-spot temperature of the solid insulation by using easily measurable quantities are presented. The authors show that the parameters of the model can be precisely determined from inexpensive measurements in a short-circuit heating experiment and the model can deliver the hot-spot temperature.

The experimental base of this research are the measurements on a 630 kVA, 3 × 10 kV/3 × 6 kV ONAN transformer equipped with 112 temperature sensors (102 inside the central positioned 10 kV winding).

In [22], Roslan *et al.* present an alternative approach to determine the simplified top-oil temperature (TOT) based on the pathway of energy transfer and thermal-electrical analogy concepts. The main contribution of this authors is the redefinition of the nonlinear thermal resistance based on these concepts. An alternative approximation of convection coefficient, h, based on heat transfer theory was proposed, which eliminated the requirement of viscosity.

In addition, the lumped capacitance method was applied to the thermal-electrical analogy to derive the TOT thermal equivalent equation in differential form. The TOT thermal model was evaluated based on the measured TOT of seven transformers with either oil natural air natural (ONAN) or oil natural air forced (ONAF) cooling modes obtained from temperature rise tests.

A comparison between the TOT thermal model and the existing TOT Thermal-Electrical, Exponential (IEC 60076-7), and Clause 7 (IEEE C57.91-1995) models was also carried out. It was found that the measured TOT of seven transformers are well represented by the TOT thermal model where the highest maximum and root mean square (RMS) errors are 6.66 °C and 2.76 °C, respectively. Based on the maximum and RMS errors, the TOT thermal model performs better than Exponential model.

Djamali *et al.* [23-24] calculate the TOT for indoor distribution transformers and extends the findings of Swift and Susa by further addressing the heat transfer due to conduction, radiation and ventilation in the transformer room.

Therefore, the transformer's loadability can be estimated using the room's ventilation temperature. Transformers in offshore platforms can be placed indoors with controlled temperature, therefore the analysis seems practically viable [25].

Like Susa, Josue et al. ([26], [40]) modify the IEC 60076-7 loading guides by investigating the variation of transformer oil viscosity with temperature, along with the dependence of winding losses on temperature. The oil temperature is equated to the HST to determine the change in its viscosity and simulate the extreme condition. Besides the models mentioned above, there are many models that suggest improvements to the loading guides.

Thus, in [27] the influence of weather conditions (including wind speed and solar radiation) on transformer's TOT is investigated, in [28] these models are extended for smaller transformers, while [29] assesses a transformer's overload capability by estimating standardized error in TOT calculation but uses the design information of the transformer to estimate the heat transfer modes in it.

Other methods range from neural networks [30] to neuro-fuzzy ones Hell [31]. Moreover, the practicality of using evolving fuzzy networks is also evaluated [32].

However, the application of such models would require ample training data, which is unfortunately not readily available in today's power systems [29].

For the calculation of TOT and HST, in the above models, the following equations were used:

1) Loading guides IEEE [8] and IEC [9]

$$\tau_0 \frac{d\theta_{ot}}{dt} = \Delta\theta_{or}\left(\frac{1+RK(t)^2}{1+R}\right)^n - \left[\theta_{ot}(t) - \theta_a(t)\right] \tag{3}$$

$$\tau_h \frac{d\theta_{hs}}{dt} = \Delta\theta_{hr} K(t)^{2m} \quad \left[\theta_{hs}(t) \quad \theta_{ot}(t)\right] \tag{4}$$

2) Swith et al. [18], [39]

$$\tau_0 \frac{d\theta_{ot}}{dt} = \Delta\theta_{or}^{\frac{1}{n}} \quad \frac{1+RK(t)^2}{1+R} \quad \left[\theta_{ot}(t) \quad \theta_a(t)\right]^{\frac{1}{n}} \tag{5}$$

$$\tau_h \frac{d\theta_{hs}}{dt} = \Delta\theta_{hr}^{\frac{1}{m}} K(t)^2 \quad \left[\theta_{hs}(t) \quad \theta_{ot}(t)\right]^{\frac{1}{m}} \tag{6}$$

3) Susa et al. [32], [34]

$$\tau_0 \frac{d\theta_{ot}}{dt} = \Delta\theta_{or} \quad \frac{1+RK(t)^2}{1+R} \quad \frac{\theta_{ot}(t) \quad \theta_a(t)}{[\mu_{pu}(t)\Delta\theta_{hr}]^{1 \quad n'}}^{\frac{1}{n'}} \tag{7}$$

$$\tau_h \frac{d\theta_{hs}}{dt} = \Delta\theta_{hr} K(t)^2 P_{pu}(\theta_{hs}) - \left[\frac{\theta_{hs}(t) - \theta_{ot}(t)}{[\mu_{pu}(t)\Delta\theta_{hr}]^{1-m'}}\right]^{\frac{1}{m'}} \quad (8)$$

where:

$\theta_a(t)$ – the ambient temperature (°C),

K - the transformer load current in p.u. with rated load current as base,

θ and θ_h are the calculated

Top Oil and Hot Spot Temperatures respectively, expressed in °C, R is the ratio of load losses to no-load losses at rated load, $\Delta\theta_{or}$ is the TOT rise over ambient temperature θ_a at rated load (°C), $\Delta\theta_{hr}$ is the rated HST rise over TOT for rated load of 1 pu, $P_{pu}(\vartheta_{hs})$ is the variation of load losses with HST (in pu) and μ_{pu} is temperature dependent oil viscosity in pu. The estimation of θ_{hs} can be performed using [33], [34]. The empirically derived exponents n, m, n' and m' have been researched for almost a century and the values vary with the transformer cooling mode (ONAN, ONAF etc.), the mass distribution of transformer components [25] and oil flow type (i.e. the presence or absence of turbulence in oil flow) [9], the values are provided in Table 1 [25], [34], [35].

Table 1. Empirical Constants for IEEE and Susa Models [25]

Transformer Cooling Mode	IEEE C57.91		Susa et al.	
	N	*m*	*n'*	*m'*
Oil Natural Air Natural (ONAN)	0.8	0.8	0.8	0.67
Oil Natural Air Forced (ONAF)	0.9	0.8	0.83	0.67
Oil Forced Air Forced (OFAF)	0.9	0.8	0.83	0.67
Oil Directed Air Forced (ODAF)	1.0	1.0	0.83	0.67

The thermal time constants for oil τ_0 and winding τ_h are usually obtained using the heat run test, but τ_0 can also be estimated using slightly differing methods.

The IEEE guides [36-37], use manufacturer-defined rated losses and $\Delta\vartheta_{or}$ for ODAF cooling (n, m =1) but require additional manipulation for (n < 1).

Similarly, IEC 60076-2 [38] uses real-time load-dependent temperature rise, while IEC 60076-7 [9] recommends using the average oil temperature rise instead. It must also be mentioned that IEC 60076-7 recommends the use of a correction factor (<1) for oil time constants to compensate for the mismatch between the time constants for top oil and average oil in ONAN and ONAF transformers, as scrutinized by Nordman *et al.* in [33].

All of these techniques require detail information regarding the mass and material of different transformer components (winding, oil, core etc.) [25].

Referring to (3)-(8), it can be concluded that the basic structure of the three selected models is similar.

The first-order non-linear differential equations have 3 basic terms: rate of temperature change on the left-hand side, heating-term which is dependent on load losses and cooling-term which is dependent on relevant temperature difference.

The inclusion of oil viscosity in Susa (7)-(8) is accurately reflected in the cooling-term.

The major difference in the 3 models is the location of empirical constants.

The models from loading guides (3)-(4) and Swift (5)-(6) distinctively place these constants on the heat-in term, while the Susa model does otherwise, which appears to be thermodynamically accurate.

In all models, the values of the hot spot temperature are determined according to the values of the load factor and the ambient temperature.

Thus, the IEEE Standard C57.91 provides guideline for oil immersed transformers and recommends, for static rating (“nameplate rating of transformer calculated based on worst case scenario” [37]), the reference hottest-spot temperature for 65 °C and 55 °C average winding rise transformers to be 110 °C and 95 °C, respectively and ambient temperature is typically defined as 30 °C.

However, as the ambient temperature varies, the transformers may present a dynamic load ("the maximum loading which the transformer may acceptably sustain under time-varying load and/or environmental condition") [41], higher than the static load, and the values of the load factor may reach 1.5 or even 2.5 pu [42-43].

However, it cannot take any possible value. To keep a safety margin, IEC 60076-7 provides some limitations, which are presented in Table 2 [9].

Table 2. Current limits (p.u.) applicable to loading beyond nameplate rating [9]

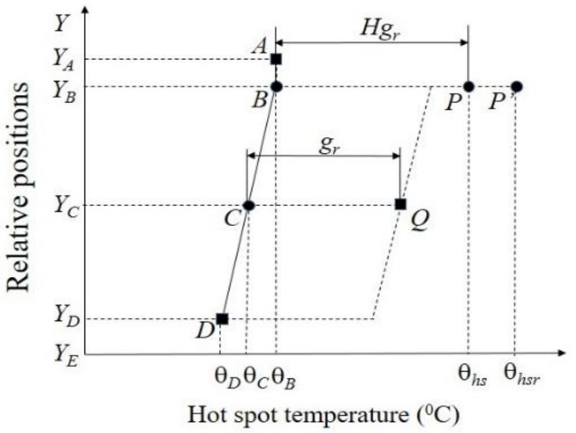
Type of loading	Distribution transformers	Medium power transformer	Large power transformers
Normal cyclic loading	1.5	1.5	1.3
Long-time emergency loading	1.8	1.5	1.3
Short-time emergency loading	2.0	1.8	1.5

3. HST calculation methods

The thermal diagram presented in Figure 2 shows the temperature distribution along the winding height as well as the oil temperature distribution inside the transformer tank [9], [44]. It is assumed that the oil temperature inside the tank increases linearly from bottom to top, whatever the cooling mode.

The temperature rise of the conductor at any position up the winding is assumed to increase linearly, parallel to the oil temperature rise, with a constant difference g_r between the two straight lines (g_r being the difference between the winding average temperature rise by resistance and the average oil temperature rise in the tank).

According to the loading guide [9], the hot-spot temperature in a transformer winding is composed of three contributions: the ambient temperature, the top-oil temperature rise in the tank over the ambient temperature and the hot-spot temperature rise over the top-oil temperature. It is assumed that during a transient period (a change in the load current or in the ambient temperature) the top-oil temperature rise over ambient temperature and hot-spot temperature rise over the top-oil temperature varies instantaneously with transformer loading, thus without time constant [44-45].



Legend: $Y_{A,...E}$: areas for determining the oil temperature;
A- oil temperature measuring point at the top of the tank;
B- point located on the upper part of the winding;
C- point located in the middle of the tank;
D - point from the base of the winding;
E - point located at the lower level of the tank;
P - hot spot temperature in the absence of solar radiation:
P' - hot spot temperature in the presence of solar radiation;
Q- temperature measurement point in the middle of the tank;
$\theta_{A,B...Q}$- temperature values at points *A*, *B*...Q

Figure 2. Thermal diagram according to [9]:

Calculation of the hot spot temperature for a transformer in case of a variation in time of the load current (*K(t)* respectively) and of the surrounding environment temperature ($\theta_a(t)$) can be achieved, according to [9] with the method of exponential equations (M1) or the method of differential equations (M2).

The solution of the differential equations is used, above all, by the transformer manufacturer, and refers to a variation in stages of the load factor *K(t)*. This method renders correct results, if each rising load level is followed by a decreasing one, and in the case of *n* successive increasing load levels ($n \geq 2$) each of the first (n - 1) levels must be sufficiently long, so that $\Delta\vartheta_{hr}$ can stabilise.

The M2 method is recommended in the case of arbitrary variations of *K(t)* and $\theta_a(t)$ [9].

For a variation in stages of *K(t)* and θ_a = const., by using the M1 method, the hot spot temperature at *t* ($\theta_{hs}(t)$) is calculated with the equation:

$$\theta_{hs}(t)=\theta_a+\Delta\theta_{oi}+\ \Delta\theta_{or}\ \frac{1+R\ \ K(t)^2}{1+R}^{\ x}\ \ \Delta\theta_{oi}\ \ f_1(t)+\Delta\theta_{hi}+\left\{Hg_r K^y\ \ \Delta\theta_{hi}\right\}f_2(t) \quad (9)$$

for increasing values of *K* and with the equation:

$$\theta_{hs}(t)=\theta_a+\Delta\theta_{or}\left[\frac{1+R\cdot K(t)^2}{1+R}\right]^x+$$
$$+\left\{\Delta\theta_{oi}-\Delta\theta_{or}\left[\frac{1+R\cdot K(t)^2}{1+R}\right]^x\right\}f_3(t)+Hg_r K^y \quad (10)$$

for decreasing values of *K*, where :

$$f_1(t)=1\ \ e^{(-t)/k_{11}\tau_0}, \quad (11)$$

$$f_2(t)=k_{21}(1\ \ e^{(-t)/k_{22}\tau_w})\ \ (k_{21}\ \ 1).(1\ \ e^{(-t)/(\tau_0/k_{22})}), \quad (12)$$

$$f_3(t)=e^{(-t)/k_{11}\tau_0}, \quad (13)$$

and the constants k_{11}, k_{21}, k_{22}, τ_0 and τ_w are known for each transformer [9].

In case of variations in time of the indicators *K* and θ_a (M_2), the differential heat transfer equations, represented in the block diagram from Figure 3, in which the Laplace variable is used (associated to the operator, d/d*t*) [9].

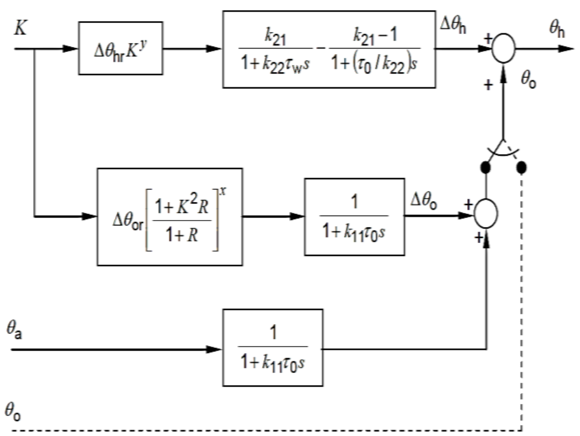


Figure 3. Representation of the block diagram related to differential equations for the calculation of hot spot temperature

4. Solar radiation

The temperature of the insulation (especially of the oil in the upper layers) is influenced by the heat absorbed from the Sun through radiation (even if the transformer is not in use).

As a result, in the equations (3)-(4) and (9)-(10) to the term corresponding to the internal heat sources, one must add the one corresponding to the solar power transmitted through radiation at the moment *t* ($P_s(t)$, respectively).

Thus, in equations (9)-(10), the source term becomes:

$$\left[(1+RK(t)^2)/(1+R)+P_S(t)/(P_{LL}+P_{NL})\right]^x,$$

where:

the quantities P_{LL} and P_{NL} represent the nominal losses in the load and in the idling, respectively.

Due to the absorbed solar power, the temperature will increase at each point of the transformer with a constant difference (maintaining the slope of the BCD line), there will be a shifting to the right of the point *P* in *P*', and the hot spot temperature takes on the value θ_{hsr} (see Figure 2, *supra*).

The calculation for the solar power $P_S(t)$ is achieved with the following equation:

$$P_S(t) = cA_{tr}I(t), \tag{14}$$

where:

c - the absorption factor of solar radiation,
A_{tr} - the collecting surface of solar radiation corresponding to the transformer,
I (≥ 0) is the intensity of the solar radiation at the moment *t* [45].

The absorption factor *c* depends on the nature of the material and the colour of the contact surface (paint layer) of the tank, which affects both the absorbed and emitted radiation [46-47].

Table 3 shows values of *c* for different types of paint of transformer tanks [47].

Table 3. Values of the absorption factor of solar radiation *c* [47]

White lead paint coating	0.25
Light cream paint coating	0.35
Aluminium paint coating	0.55
Grey paint coating	0.75
Mat black paint coating	0.97

Solar radiation represents the global radiation under clean sky conditions, respectively the sum of direct and diffuse radiation (radiation reflected from the earth is neglected).

The intensity of the solar radiation *I(t)* can be estimated using different models [48].

In the case of the Adnot model, the intensity of the global solar radiation is calculated with the equation:

$$I(t) = 951.39 \quad (\sin\alpha(t))^{1.15}, \tag{15}$$

where:

$\alpha(t)$ (≥ 0) - the radiation angle of the sun (altitude-wise).

During the night, the altitude angle is zero, as such $I(t) = 0$ [48].

The α altitude angle represents the angular height of the sun and has the value 0° at sunrise and 90° when the sun is perpendicular to the transformer.

The α angle can be calculated with the following equation:

$$\alpha(t) = \left\{\sin\left[\sin\delta(t)\sin(LAT) + \cos\delta(t)\cos(LAT)\cos(HRA)\right]\right\}^{-1} \tag{16}$$

where:

$\delta(t)$ - the declination angle of the sun (the angle made by the rays of the sun with the equatorial plane),
LAT - the latitude corresponding to the respective area,
HRA - hourly angle (which converts local solar time *LST* according to the movement of the Sun in the sky).

The δ, *LST* and *HRA* parameters are calculated as follows:

$$\delta(^{o}) = 23.45^{o}\sin\frac{360}{365}(DN \quad 81) \tag{17}$$

$$LST = LT + CF \tag{18}$$

$$HRA = 15^{o}\,(LST - 12), \tag{19}$$

where:

DN - the number of days in a year (with values between 1 and 365),
LT – local time, *CF* – a correction factor (for local time adjustment, which usually differs from *LST*, for example due to the use of time zones).

When the Sun is at the highest point in the sky, *LST*=12.

For the correct estimation of *I*, one must also take into account the atmospheric conditions (clouds, rain etc.), the existence of buildings etc., factors that reduce the values of solar radiation [45].

5. Lifetimes

In [1], Notingher *et al.*, a method of calculating the estimated life (*L*), consumed (*LC*) life and remaining (L_R) life is shown, corresponding to the operation of the power transformers at constant and variable temperatures, based on the temperature measured in certain points of their insulation.

In the following, the manner of calculating the lifetimes using the values of the hot spot temperature determined based on the load curve of the transformers, both in the presence and in the absence of solar radiation, will be presented. This method is recommended for new transformers, in order to establish a good maintenance program, as well as for transformers in operation, for which the time variation curve of the hot spot temperature is not known.

The estimated lifetime L_e is calculated as follows:

$$\ln L_e(T) = a + b/T, \tag{20}$$

where:

T - the operating temperature of the transformer (assumed constant),
a and $b = E_a/k$- material constants,
E_a - activation energy,
k - Boltzmann's constant [1].

The calculation relations of the consumed lifetimes are those recommended by IEC 60076-7 [9], obtained in the following hypotheses:

1) the paper represents the least reliable component of an insulation,
2) the diagnostic factors of the aging state of the most representative paper are the resistance to tear by means of traction σ_r and the degree of polymerization of the paper *PD*.

The relative aging rate *V* is calculated as follows:

$$V = 2^{(\theta_{hs} - 98)/6} \tag{21}$$

for non-heat-treated paper and as follows:

$$V = e^{\frac{15000}{110+273} - \frac{15000}{\theta_{hs}+273}} \tag{22}$$

for heat-treated paper.

In the (20)-(21) equations, 98 and 110 °C represent the values of the hot spot temperature for designed lifetime of the insulation [12], [50].

Lifetime consumed in an infinitely short time span Δt (where the hot spot temperature (respectively, the aging rate) can be considered constant, is $V\Delta t$, and for a certain period of time $t_2 - t_1$ it is L_c:

$$L_c = \int_{t_1}^{t_2} V \mathrm{d}t = \sum_{n=1}^{N} V_n \Delta t_n \tag{23}$$

where:
Δt_n represents the n^{th} time sub-interval, resulted from the division of the $t_2 - t_1$ interval into *N* sub-intervals, in which $\theta_{hs}(t)$ = const.

The end-of-life criteria are chosen according to the diagnostic factor and the type of paper [9].

Thus, the normal lifetime of a heat-treated paper-based insulation system operating at 110 ° is 65 000 h, considering the end-of-life criterion the reduction of σ_r to 50 % and 150 000 h, if the reduction of *DP* to 200 is considered [9].

Obviously, as the transformers operate at lower temperatures, the allowable service life is higher (for distribution transformers, up to 180.000 h).

The remaining lifetime L_r is calculated as follows:

$$L_r = L_e - L_c. \tag{24}$$

6. Case study

In order to highlight the influence of solar radiation on the lifetimes of power transformers, the hot spot temperatures and the estimated lifetimes, consumed lifetimes and remaining lifetimes for three transformers considered identical, that have worked for 10 years under different climatic conditions, in Romania (Suceava, Craiova, Bucharest) and Mauritania (Nouakchott) were calculated, both in the absence and in the presence of solar radiation.

The transformers have heat-treated paper and mineral oil insulation, the apparent nominal power S_n=250 MVA, the nominal voltages U_1/U_2=400/220kV/kV, frequency *f*=50 Hz, the ratio between copper and iron losses *R* = 5.7, the heating of the oil in permanent mode, for a given value of the loading factor *K* data - $\Delta\theta_{or}$=45 °C, the heating of the hot spot against the oil at the considered load – *K*, $\Delta\theta_{hr}$ = 35 °C, the exponent corresponding to the heating of the oil *x* = 0.8 and the exponent corresponding to the heating of the windings *y* = 1.3.

Also, the following aspects are known:
- The coordinates of the stations where the transformers operate (Table 4);
- The values of the ambient temperature on different days (Table 5);
- The values of the load factor on different days (Table 6).

Table 4. The geographical coordinates of the transformers

Operation site	Longitude	Latitude
Nouakchott	15°59′ V	18°52′ N
Bucharest	26°06′ E	44°26′ N
Craiova	23°48′ E	44°19′ N
Constanta	26° 06′ E	44°25′ N
Suceava	26°15′ E	47°38′ N

Table 5. Ambient temperature values θ_a in Craiova (CR), Constanta (CO), Suceava (SU) and Nouakchott (NO) at different time's *t* from 10.10.2019

t (h)	0	2	4	6	8	10	12	14	16	18	20	22
θ_{ac} (°C) CR	11	10	9	8	7	13	20	23	24	20	18	17
θ_a (°C) CO	16	16	15	15	15	17	21	23	23	23	21	19
θ_a (°C) SU	10	9	8	8	11	13	17	18	18	16	13	12
θ_a (°C) NO	27	27	26	25	27	29	34	37	37	35	32	30

Table 6. Values of the load factor *K* at different moments in time *t* from 7.10.2019 (M) and 10.10.2019 (T)

t (h)	0	2	4	6	8	10	12	14	16	18	20	22
K (M)	0.92	0.90	0.91	0.95	1.08	1.10	1.03	1.02	0.94	1.01	1.12	1.02
K (T)	0.78	0.69	0.68	0.81	1.07	1.08	1.03	0.95	0.90	0.91	0.99	1.02

Based on this data, the values of the solar power and hot spot temperature and lifetimes were calculated, on different days of a year, in the absence and presence of solar radiation.

6.1. Solar power

By using the equations (14)-(19), the values of the solar power transmitted to the transformers located in the localities of Nouakchott, Craiova, Constanta and Suceava were calculated.

In Figure 4, the time variation of the solar power P_s, on Thursday, October 10th, 2019 can be seen.

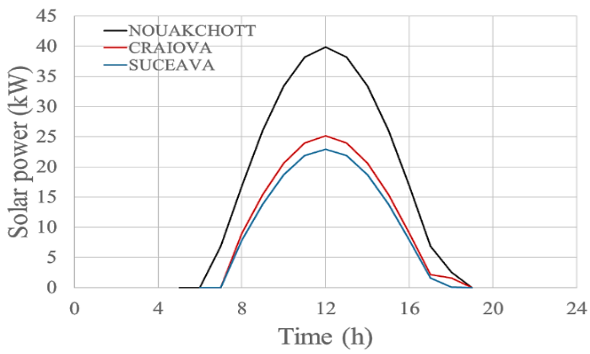


Figure 4. Variation of the solar power P_s during one day (10.10.2019) in Suceava, Craiova and Nouakchott

It is observed that, during the night, where $P_s = 0$, the maximum values are obtained at 12 o'clock and, as expected, the highest value is obtained in Nouakchott and the lowest one in Suceava.

6.2. The hot spot temperature

The calculation of the hot spot temperature was performed, both in the absence of solar radiation (with (3), (4), (9) ... (13)), and in the presence of it (with (3), (4), (9)… (13) modified according to Ch. 4).

Part of results, respectively curves $\theta_{hs}(t)$ are shown in the Figures 5-12.

Figure 5 shows the variation of the hot spot temperature in the transformer located in Nouakchott, recorded in two days from June and October 2019, namely (Monday, June 17th, and Wednesday, October 10th).

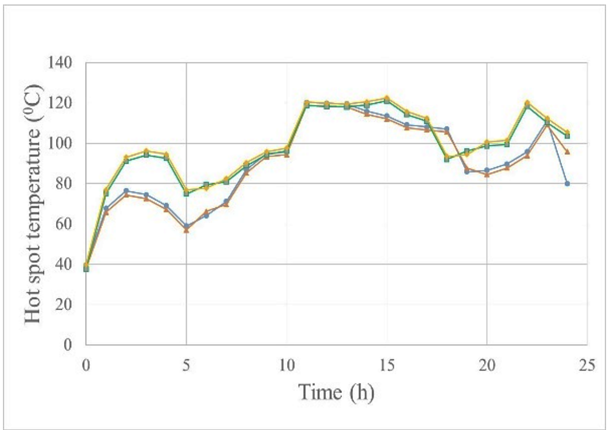


Figure 5. Variation in time of the hot spot temperature θ_{hs} in the presence of solar radiation in the Nouakchott transformer on the 17th (green) and 19th (red) of June and the 7th (yellow) and 10th (blue) of October 2019

It is observed that until 10 o'clock, θ_{hs} values are below 100 °C, then, between 11 and 13 o'clock and around 22 o'clock, θ_{hs} reaches 120 °C in all cases (values that accelerate the degradation reactions of the transformer insulation).

Also, it can be observed that, at the beginning of the week (Monday, June 17th and October 7th), especially, during the night, the values of the hot spot temperature are higher than in the middle of the week (namely, Wednesday June 19th, and October 10th) (see Figure 5, *supra*).

The same types of variations (respectively higher values at noon and at around 22 o'clock) were obtained for the transformers in Suceava (Figure 6) and Craiova (Figure 7).

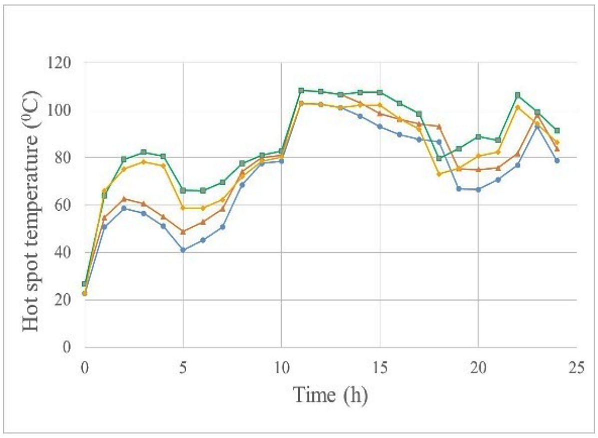


Figure 6. Variation in time of the hot spot temperature θ_{hs} in the presence of solar radiation in the Suceava transformer on the 17th (green) and 19th (red) of June and the 7th (yellow) and 10th (blue) of October 2019

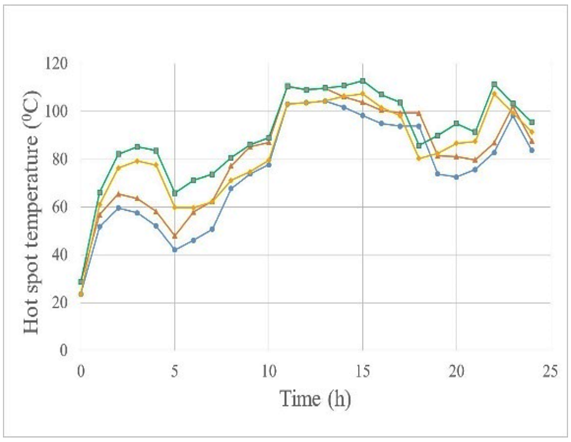


Figure 7. Variation in time of the hot spot temperature θ_{hs} in the presence of solar radiation in the Craiova transformer on the 17th (green) and 19th (red) of June and the 7th (yellow) and 10th (blue) of October 2019

The higher values of θ_{hs} resulted at noon are due to higher values of ambient temperature and solar radiation, and those from 22 o'clock are due to higher loads of the transformers.

On the other hand, the highest values of θ_{hs} are obtained in the case of the transformer in Nouakchott (up to 120.29 °C) and the lowest in the case of the one in Suceava (108.44 °C) (Figure 8 and Figure 9).

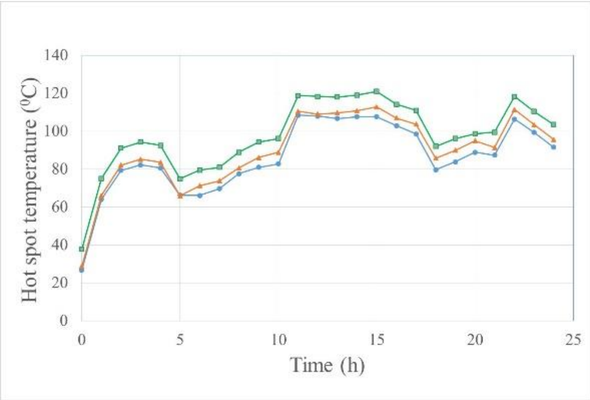


Figure 8. Variation in time of the hot spot temperature θ_{hs} in the transformers from Suceava (blue), Craiova (red) and Nouakchott (green) on June 17th, 2019 (Monday)

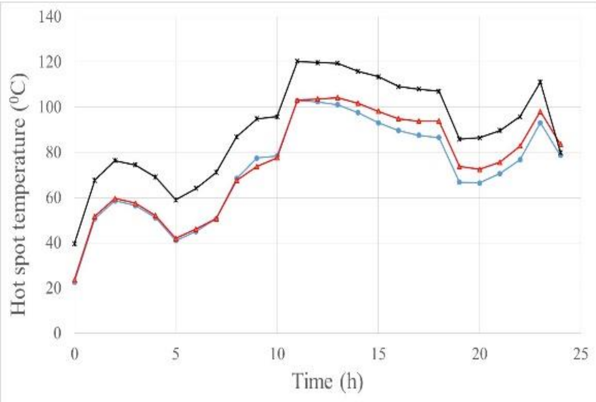


Figure 9. Variation in time of the hot spot temperature θ_{hs} in the presence of solar radiation in the transformers in Suceava (blue), Craiova (red) and Nouakchott (black) on October 10th, 2019 (Thursday)

The relatively significant differences among the values of the hot spot temperature in the transformers in Nouakchott and Craiova and Suceava (12 ºC) are obviously due to the higher values of the ambient temperature (Table 5, *supra*) and solar radiation (Figure 4, *supra*) in Nouakchott, as compared to Suceava and Craiova.

The values of θ_{hs} corresponding to the transformers in Suceava and Craiova are closer to one another, especially in the first part of the day, when the values of ambient temperature do not differ too much (see Figure 8, Figure 9 and Table 5, *supra*).

The presence of solar radiation during the day leads to the increase of the hot spot temperature in all the transformers.

These increases are higher for the Nouakchott transformer (over 3 ºC, see Figure 10) and lower in the transformer in Suceava (below 2 ºC, see Figure 11) and Craiova (below 2 ºC, see Figure 12).

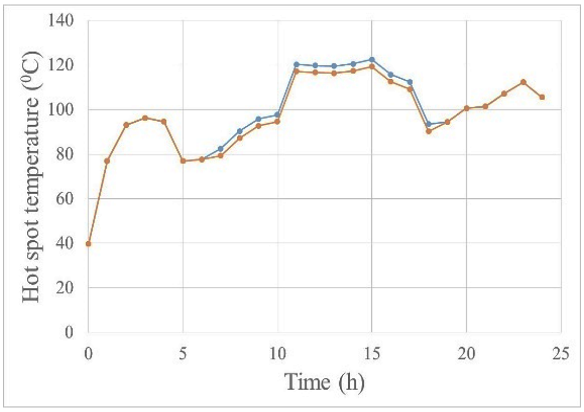


Figure 10. Variation in time of the hot spot temperature in the Nouakchott transformer in the absence (red) and in the presence (blue) of solar radiation, on Monday, October 10th, 2019

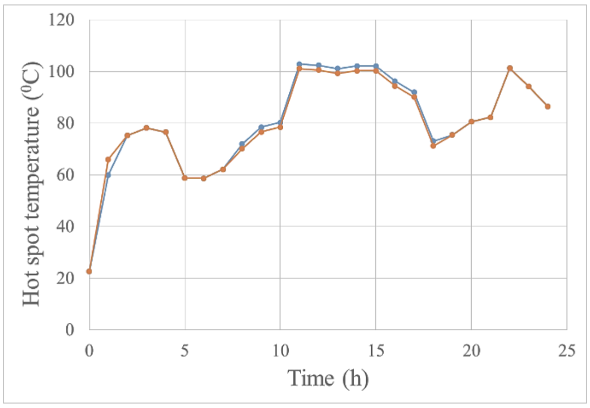


Figure 11. Variation in time of the hot spot temperature in the Suceava transformer in the absence (red) and in the presence (blue) of solar radiation, on Monday, October 10th, 2019

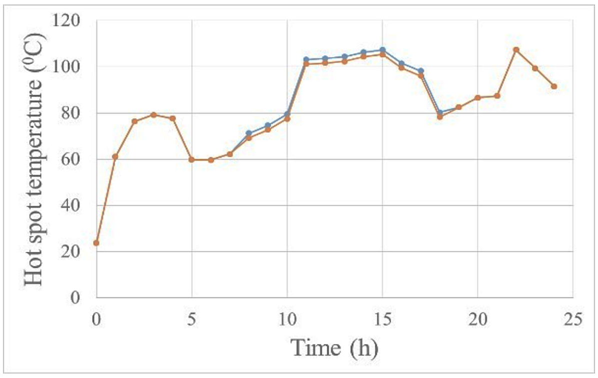


Figure 12. Variation in time of the hot spot temperature in the Craiova transformer in the absence (red) and in the presence (blue) of solar radiation, on Monday, October 10th, 2019

6.3. Estimated lifetime

Considering the diagnostic factor for the aging tests of paper insulation - the degree of polymerization of the paper (PD) and the end-of-life criterion PD = 200, an estimated lifetime for the hypothetical operation at a constant temperature of 110 °C, of L_e = 17.12 years is reached [8].

The activation energy values differ, depending on the diagnostic factor used and the end-of-life criterion chosen [51], but an average value can be ascertained, E_a = 110 kJ/mole [52].

By taking into account equation (19), the parameters of the lifetime line are obtained, namely a = - 22.59 and b = 13218 K, and then the estimated lifetime values for operation at different constant temperatures are obtained, as well (Table 7).

Table 7. L_e lifetime values estimated for different operating temperatures of transformers θ

θ (°C)	90	95	100	105	110	115	120
L_e (years)	84.38	70.14	43.33	29.67	17.12	12.05	7.14

6.4. Consumed lifetime

Using the values of the hot spot temperatures calculated for the variable values of the load factor K, both in the presence and in the absence of the solar radiation, based on (22)-(23), the consumed lifetimes in a year were calculated for the three transformers, respectively between November 2018 and October 2019.

As all the values of the ambient temperature were not known for each hour of all the 365 days, the measured values from June 2019 were considered for the months of April-September and those from October 2019 for the months of October-March.

Also, the values of the ambient temperature measured in 2019 on Monday (for all the days of Monday, Tuesday, Saturday and Sunday) and on Wednesday (for all the days of Wednesday, Thursday and Friday) were considered.

Part of results are shown in Table 8.

Table 8. Lifetime values of transformers consumed in one year, for variable K (in days and %)

City	Without radiation		With radiation	
	Days	%	Days	%
Suceava	59	16.16	67	18.36
Craiova	74	20.27	92	25.21
Nouakchott	226	61.92	323	88.49

It is found that, although the daily loads of the transformers are identical, the values of the consumed lifetimes are higher in Nouakchott, than in Craiova (with 231 days/year) and Suceava (with 256 days/year, Table 8).

This is due to higher values of ambient temperature and solar radiation levels, respectively of hot spot temperature (Figures 8 and 9, *supra*).

On the other hand, for all transformers, the consumed lifetimes calculated in the presence of solar radiation are higher than those calculated without taking into account its presence: by 14% for the transformer from Suceava, 24 % for the transformer from Craiova and 43 % for the one in Nouakchott (locality where solar radiation is the strongest).

Therefore, for calculating the lifetimes of the power transformer insulators, the hot spot temperature values must be used with (9)-(10), completed with the term corresponding to the solar power P_s (Ch. 4).

As shown by the daily load curves of the transformers, the values of K vary, both during the day and from day to another one, between 0.68 and 1.12 (Table 6, *supra*).

Considering that the transformers would work at nominal load (namely K = 1), the consumed lifetimes increase in all cases (in Nouakchott it exceeds 365 days) (Table 9).

Table 9. Lifetime values of transformers consumed in one year, for K = 1 (in days and %)

City	Without radiation		With radiation	
	Days	%	Days	%
Suceava	69.83	19.13	84.39	23.12
Craiova	108.89	29.83	131.64	36.07
Nouakchott	320.82	87.88	407,37	111.6

Thus, in the presence of solar radiation, L_c increases in Suceava, 26 %, in Craiova it increases by 48 % and in Nouakchott by 26.12 %.

Therefore, the transformers located in any of the three cities will have a longer life than that estimated for operating at nominal load.

Considering that, during a 10 year-period, both the climatic conditions and the load curves remain unchanged, the consumed lifetimes during this interval, expressed in days, are obtained by multiplying by 10 the lifetimes calculated for one year (the percentage values remain unchanged, namely those in Tables 8 and 9, *supra*).

6.5. Remaining lifetime

Knowing the estimated lifetimes of the transformer insulations for operation at different constant temperatures (Table 7, *supra*) and the consumed lifetimes L_c and by using equation (24), the remaining lifetimes L_r corresponding to the operation of the transformers for variable and constant daily loads were calculated.

Part of results are shown in Table 10.

Table 10. Values of remaining lifetime L_r for different operating temperatures (θ) of the transformers in Suceava (L_{rS}), Craiova (L_{rC}) and Nouakchott (L_{rN}), after one year of operation with variable load (K = var.) and constant load (K = 1), in the presence of solar radiation

θ (°C)	90	95	100	105	110	115	120
L_e (years)	84.38	70.14	43.33	29.67	17.12	12.05	7.14
L_{rS} (K=var) (years)	84.20	69.96	43.15	29.49	16.94	11.87	6.96
L_{rC} (K=var) (years)	84.13	69.89	43.08	29.42	16.87	11.80	6.89
L_{rN} (K=var) (years)	83.50	69.26	42.45	28.79	16.24	11.17	6.26
L_{rS} (K=1) (years)	84.15	69.91	43.10	29.44	16.89	11.82	6.91
L_{rC} (K=1) (years)	84.02	69.78	42.97	29.31	16.76	11.69	6.78
L_{rN} (K=1) (years)	83.26	69.02	42.21	28.55	16.00	10.93	6.02

It is found that the values of the remaining lifetime after one year of operation are, for all the transformers, lower in the case of operation at nominal load, than in the case of a variable load during a day, when, for relatively important time periods (up to 16 h.) the transformers are under-loaded (Table 6, *supra*).

Therefore, it is expected that the paper-oil insulations of the power transformers in operation will possess real lifetimes higher than those estimated by means of calculation.

In the case of operating for a 10 year-period, under the same climatic and loading conditions, the desired lifetimes are obtained by subtracting from the estimated lifetimes the lifetimes consumed in a year (Tables 8 and 9, *supra*), multiplied by 10.

7. Conclusions

The use of the hot spot temperature for estimating the lifetime of transformers is compulsory, and for the calculation of its values, one can use the methods developed by IEEE and IEC. It should be noted, however, that the calculation correlations in the IEEE and IEC guides must be completed with the term corresponding to solar radiation.

The actual calculations and the results presented in the paper show that the values of solar power, of the hot spot temperature and of the consumed and remaining lifetimes depend on the coordinates of the operating area of the transformer, on the ambient temperature and on the load ratio of the transformer.

Ambient temperature θ_a and solar power P_S had higher values in Nouakchott than in Craiova or Suceava. Thus, in the month of October, the following values applied: θ_a = 37 °C and P_S = 45.5 kW in Nouakchott and θ_a = 18 °C and P_S = 41.11 kW in Suceava.

For the same load regime, the hot spot temperature was much higher in Nouakchott than in Suceava, with approx. 13 °C, in June 2019, and with approx. 20 °C in October 2019.

On the other hand, the values of the hot spot temperature calculated in the presence of solar radiation are approx. 3 °C higher than those calculated in its absence.

The lifetime values estimated at a constant temperature decrease drastically with the increase of temperature: from 43 years for a temperature of 100 °C, to approx. 7 years for a temperature of 120 °C.

For the same daily load regime, the lifetime consumed in one year has higher values for the transformer in Nouakchott, than for those in Craiova (with 231 days) and Suceava (with 256 days).

Taking into account of the solar radiation leads to the increase of the lifetime consumed in one year, by 8 days, for the transformer in Suceava, and 97 days, for the one in Nouakchott.

Therefore, the costs related to the maintenance of the transformers are much higher in Nouakchott than in Suceava.

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