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CALCULATION OF THE TEMPERATURES AND LIFETIMES FOR DISTRIBUTION TRANSFORMERS

PETRU V. NOTINGHER, CRISTINA STANCU, IONUT DRAGAN, MAAYA ISSEDOU BEY

Key words: Power transformers, Oil-paper insulation, Solar radiation, Oil and hot spot temperatures, Consumed and remaining lifetimes.

The paper presents the methods of exponential functions and differential equations recommended by IEC and IEEE for the calculation of the oil θ_o and hot spot θ_h temperatures in power transformers, in the absence and presence of solar radiation. Considering the case of distribution transformers, for which the load factor K shows variations in small time intervals, the authors propose a new (analytical) method for calculating temperatures (θ_o and θ_h), both in the absence and in the presence of solar radiation. To highlight the importance of the calculation method and solar radiation, the quantities θ_o and θ_h are calculated (in two days from 2019) by three methods, as well as the consumed and remaining lifetimes for two transformers, with the same load and located in areas with different values of temperature and solar radiation. Finally, the influence of solar radiation, place of operation of the transformer and calculation method on the values of temperatures and lifetimes are analyzed.

1. INTRODUCTION

Power transformers are some of the most important elements of any electric power transmission and distribution systems [1] and represent the biggest investment in equipment installed in high-voltage stations (60 % of total investment [2]). The average life of power transformers is 20-35 years, and with good preventive maintenance, even 60 years [3]. On the other hand, the unscheduled removal of power transformers from operation (due to a failure) causes significant economic losses, while their destruction (because of fires and/or tank destruction) can lead to very large environmental pollution (air, water, soil) [1].

The insulation systems of windings (in general, oil-paper) are the most frequently defective elements, their failure rate increasing with their service life, due to electrical, mechanical and especially thermal stress. As a result, during transformers operation, irreversible chemical reactions occur both in paper and oil, leading to a continuous ageing and degradation of the insulation. 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 [4–5]. Under the effect of heat, in time, the cellulose insulation undergoes a depolymerisation process [6]. As the cellulose chain gets shorter, the mechanical properties of paper (tensile strength and elasticity) degrade, the paper can become brittle and is not capable of withstanding short circuit forces and even normal vibrations that are part of transformer life [7]. This situation characterizes the end of life of the solid insulation, and it also defines the transformer end of life [6,8].

The temperature of the winding is not uniform, and the real limiting factor is the hottest section of the winding commonly called winding hot spot. This hot spot temperature is located somewhere toward the top of the transformer, and it is not accessible for direct measurement with conventional methods [9,10]. Therefore, for estimating the lifetime of the transformer insulation L_e, according to the Dakin aging model [11], the following equation is used:

$$\ln L_e = a + b/\theta_h + 273.15, \tag{1}$$

where L_e is estimated lifetime for operating at constant temperature (θ_h), a – a material parameter, $b = E_a / k$, E_a – the thermal activation energy, k – Boltzmann's constant and θ_h – the hot spot temperature.

In eq. (1) the hot spot temperature is assumed to remain constant during transformer's operation, respectively the load and the ambient temperature also remain constant. As a result, consumed lifetime over a period $\Delta t(L_c)$ is equal to its service lifetime (Δt), and remaining lifetime L_r is the difference between L_e and L_c. Then, during operation of power transformers, both the load factor K (respectively, the ration between apparent power and nominal apparent power), and ambient temperature varies over time [12]. As a result, oil temperature (θ_o) and hot spot temperature (θ_h) and, consequently, the consumed lifetime of the insulation varies over time. For the calculation of θ_o and θ_h the differential equations recommended by IEEE Std. C57.91-2011 [13], are used:

$$\tau_o \frac{\mathrm{d}\theta_o}{\mathrm{d}t} = \Delta\theta_{or}\left(\frac{1+RK(t)^2}{1+R}\right)^n - \left[\theta_o(t) - \theta_a(t)\right], \tag{2}$$

$$\tau_w \frac{\mathrm{d}\theta_h(t)}{\mathrm{d}t} = \Delta\theta_{hr}K(t)^{2m} - \left[\theta_h(t) - \theta_o(t)\right], \tag{3}$$

where $\theta_a(t)$ is the ambient temperature ($^{\circ}$C), $K(t)$ is the transformer load current in p.u. with rated load current as base, $\theta_o(t)$ and $\theta_h(t)$ are the calculated top oil and hot spot temperatures respectively at time t (expressed in $^{\circ}$C), R is the loss ratio (ratio between the load losses PLL and no-load losses PNL), $\Delta\theta_{hr}$ is the oil temperature rise over ambient temperature θ_a at rated load ($^{\circ}$C), $\Delta\theta_{hr}$ is the rated hot spot temperature rise over θ_o for rated load of 1 p.u., τ_o is the average oil time constant, τ_w is winding time constant, n and m are empirically derived exponents dependent on the transformer's cooling system [1]. It should be noted that the equations (2) – (3) consider as heat source the transformer's losses and it's not considered the insulation heating by solar radiation. Also, the harmonic load current and the changes in the viscosity of oil under varying temperature conditions are not considered [14].

"Politehnica" University of Bucharest, Department of Electrical Materials and Drives, Bucharest, Romania, Email: petrunot@elmat.pub.ro, stcris2003@yahoo.co.uk, niculaie.dragan@stud.electro.upb.ro, isseydou@yahoo.fr

In IEC 60076-7 [12] and IEEE Std. C57.91-2011 [13] it is considered that θ_h is the temperature of the oil from the interior of winding (at the oil winding interface) at the top of the tank, which may differ from the oil temperature from the top part of the tank (θ_o) with up to 15 K. Also, the oil heating at the top of the tank relative to the ambient temperature θ_a (respectively, $\Delta\theta_{or}$) and the heating of the hot spot relative to the oil temperature at the top of the tank (respectively, $\Delta\theta_{hr}$) are considered known for transformer's nominal operation. It is assumed that, in the interior of the cooling system, oil temperature and winding temperature grow linearly, the two lines ($\theta_o(t)$ and $\theta_h(t)$) being parallel and located at distance g_r from each other (Fig. 1). The hot spot heating is superior to the heating of the conductor in the top of the winding with $\Delta\theta_{hr} = H \cdot g_r$, H being the hot spot factor (with known values, between 1.0 and 2.1, depending of the size, short circuit impedance and type of the transformer winding) [12].

In previous papers the estimated, consumed, and remaining insulation lifetimes of power transformers were determined admitting different hypotheses. Thus, in [15] the operation of the transformer at constant load and constant temperature is considered, also in [1] it is considered a gradual variation of the insulation temperature during a day. In [11] the hot spot temperatures, the consumed and remaining lifetimes of the insulations of 3 transformers were calculated, operating with loads in identical steps, but in areas with different values of the ambient temperature and of the solar radiation. The relations used to calculate solar power are simplified and allow the calculation of solar power only in the days of the first half of the year.

In [16] the solar power of a transformer with the same simplified relations was calculated and its influence on reducing the degree of polymerization of the paper insulation and increasing the probability of transformer failure was analysed. In all cases it was considered that the load factor varies in steps and that the intervals at which its values change is relatively large (from tens to hundreds of minutes). Therefore, the method of exponential equations was used to calculate the hot spot temperature [12].

If the load factor K changes after shorter intervals or if it varies almost continuously over time the use of the method of exponential functions can lead to large errors. In this case, in [12] it is recommended to integrate the differential equations (2), (3) modified (by considering the thermal characteristics of the transformers, respectively the values of the constants k_{11}, k_{22}, *etc.*) by finite differences. This method requires the use of variations in steps of the loading factor K and of the ambient temperature θ_a on relatively small-time intervals (less than half of the thermal constant of the winding [12]). Even if the time intervals are reduced, the step variations of the quantities K and θ_a cause errors in the calculation of the quantities $\theta_o(t)$ and $\theta_h(t)$.

To reduce these errors, in the paper an analytical method for calculating the oil and hot spot temperatures applicable in the case of distribution transformers with OF cooling system is proposed. By integrating the differential equations on small intervals (in which linear variations of the quantities K and θ_a are considered) the expressions of the quantities $\theta_o(t)$ and $\theta_h(t)$ are obtained as sums of exponential and rational functions. Finally, a case study on two 105 MVA distribution transformers that operate in two areas with different climatic conditions is presented. It is found that the results obtained by solving the differential equations with finite differences and analytic are relatively close, but much different from those obtained with the method of exponential functions. On the other hand, it was found that the values of the oil and hot spot temperatures in the presence of solar radiation are much higher than those in the absence of this and that the lifetimes consumed in the same time interval are longer in areas with solar radiation and higher ambient temperatures.

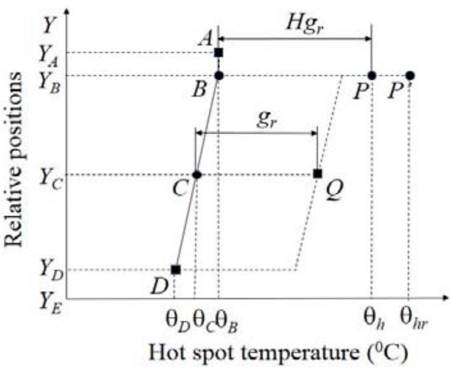

Fig. 1 – Thermal diagram according to [12]: $Y_{A,..E}$ – areas for determining the oil temperature; A – oil temperature measuring point at the top of the tank; B – point located on the upper part of the winding; C – point located in the middle of the tank; D – point from the base of the winding; E – 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; $\theta_{A,B\ldots Q}$ – temperature values at points A, $B\ldots$Q [1].

2. OIL AND HOT SPOT TEMPERATURES

The methods of exponential and of differential equations are used to calculate the values of oil (θ_{oi}) and hot spot (θ_{hs}) temperatures. The characteristics of the transformer and the time variation curves of the quantities K and θ_a are considered known.

2.1. EXPONENTIAL FUNCTIONS METHOD

The method of exponential functions (M1) is recommended [9] for step variations of the load factor K and gives good results for the power transformers if the following conditions are satisfied: a) Each of the increasing load steps is followed by a decreasing load step or vice versa, and b) In case of N successive increasing load steps ($N \geq 2$), each of the ($N - 1$) first steps has to be long enough for the hot-spot-to-top-oil gradient $\Delta\theta_h$ to obtain steady state [12]. The value of the hot spot temperature at a given moment t from a time interval $\Delta t = t - t_1 \left(t \subset \left[t_1, t_2\right]\right)$, where the quantities K and θ_a are constant ($\theta_h(t)$), can be calculated using the following equation:

$$\begin{gathered}\theta_h(t) = \theta_a(t_1) + \Delta\theta_{oi} + \\ + \left\{\Delta\theta_{or}\left[\frac{1 + R \cdot K(t_1)^2}{1+R}\right] - \Delta\theta_{oi}\right\} f_1(\tau) + \\ + \Delta\theta_{hi} + \left\{Hg_r K^y - \Delta\theta_{hi}\right\} f_2(\tau),\end{gathered} \tag{4}$$

if the value of $K(t_1)$ is higher than its value from the previous interval and with the equation:

$$\theta_h(t)=\theta_a(t_1)+\Delta\theta_{or}\left[\frac{1+R\cdot K(t_1)^2}{1+R}\right]^x+$$
$$+\left\{\theta_{oi}-\Delta\theta_{or}\left[\frac{1+R\cdot K(t_1)^2}{1+R}\right]^x\right\}f_3(\tau)+Hg_rK^y, \quad (5)$$

if the value of $K(t_1)$ is smaller than its value from the previous interval, where:

$$f_1(\tau)=1-\mathrm{e}^{(-\tau)/k_{11}\tau_0}, \quad (6)$$

$$f_2(\tau)=k_{21}\left(1-\mathrm{e}^{-\tau/k_{22}\tau_w}\right)(k_{21}-1)\left(1-\mathrm{e}^{-\tau/(\tau_0/k_{22})}\right), \quad (7)$$

$$f_3(t)=\mathrm{e}^{-t/\mathrm{k}_{11}\tau_0}, \quad (8)$$

$\tau=t_2-t$ (respectively $t\subset[0,t_2-t_1]$), $\Delta\theta_{oi}$ is top-oil (in tank) temperature rise to the ambient temperature at start K, $\Delta\theta_{hi}$ – hot-spot-to-top-oil (in tank) gradient at start K, τ_o – average oil time constant, τ_w – winding time constant, x – exponential power of total losses *versus* top-oil (in tank) temperature rise (oil exponent), y – exponential power of current versus winding temperature rise (winding exponent) and k_{11}, k_{21}, and k_{22} are thermal model constants (known for each transformer) [12].

The top-oil temperature (in the tank) at the load considered K ($\theta_o(t)$) is calculated with the equation:

$$\theta_o(t)=\theta_h(t)-\Delta\theta_h(t), \quad (9)$$

where $\Delta\theta_h(t)$ is hot-spot-to-top-oil (in tank) gradient at the load K and it is calculated with the equation:

$$\Delta\theta_h(t)=\Delta\theta_{hi}+(Hg_rK(t_1)^y-\Delta\theta_{hi})f_2(\tau), \quad (10)$$

if the value of $K(t_1)$ is higher than its value from the previous interval and with the equation:

$$\Delta\theta_h(t)=Hg_rK(t_1)^y, \quad (11)$$

if the value of $K(t_1)$ is smaller than its value from the previous interval.

2.2 DIFFERENTIAL EQUATIONS METHOD

The method of differential equations (M2) is recommended for calculation of the quantities $\theta_o(t)$ and $\theta_h(t)$ for the transformers with arbitrarily time-varying load factor K and ambient temperature θ_a, especially for on-line monitoring [12, 18]. The differential equation for top-oil temperature $\theta_o(t)$ is:

$$k_{11}\theta_o\frac{\mathrm{d}\theta_o(t)}{\mathrm{d}t}+[\theta_o(t)-\theta_a(t)]=\left[\frac{1+R\cdot K(t_1)^2}{1+R}\right]^x\Delta\theta_{or}. \quad (12)$$

The hot-spot temperature rise $\Delta\theta_h(t)$ is given by:

$$\Delta\theta_h(t)=\Delta\theta_{h1}(t)-\Delta\theta_{h2}(t), \quad (13)$$

the quantities $\Delta\theta_{h1}(t)$ and $\Delta\theta_{h2}(t)$ being the solutions of differential equations [12] :

$$k_{22}\theta_w\frac{\mathrm{d}\Delta\theta_{h1}(t)}{\mathrm{d}t}+\Delta\theta_{h1}(t)=k_{21}K(t_1)^y\Delta\theta_{hr}, \quad (14)$$

$$\frac{\theta_o}{k_{22}}\frac{\mathrm{d}\Delta\theta_{h2}(t)}{\mathrm{d}t}+\Delta\theta_{h2}(t)=(k_{21}-1)K(t_1)^y\Delta\theta_{hr}. \quad (15)$$

The following equation is used for the calculation of the hot spot temperature $\theta_h(t)$:

$$\theta_h(t)=\theta_o(t)+\Delta\theta_h(t). \quad (16)$$

The solutions of the equations (12), (14) and (15) can be obtained by numerical approach – by using finite differences method (recommended by IEC 60076-7 [9] – or by analytical approach (proposed in this paper).

2.2.1. FINITE DIFFERENCES METHOD

The use of the finite difference method involves dividing the interval $[t_1, t_2]$ in N sub-intervals of size $\mathrm{D}t=(t_2-t_1)/N$ less than half the winding time constant τ_w, in which the quantities K and θ_o are considered constant. The method is presented more detailed in [12].

The variation of oil temperature in a sub-interval k (k = 1,2,3…N) defined by the values t_{k-1} and t_k of t, noted with $\mathrm{D}\theta_o(k)$ is calculated with the equation:

$$\mathrm{D}\theta_\mathrm{o}(k)=\frac{\mathrm{D}t}{k_{11}\tau_o}\left[\begin{array}{l}\left(\dfrac{1+K^2(t_{k-1})R}{1+R}\right)^x\Delta\theta_{or}-\\-\left(\theta_\mathrm{o}(t_{k-1})-\theta_a(t_k)\right)\end{array}\right] \quad (17)$$

and the oil temperature at a given time t_k ($\theta_o(t_k)$) is :

$$\theta_\mathrm{o}(t_k)=\theta_o(t_{k-1})+\mathrm{D}\theta_\mathrm{o}(t_k), \quad (18)$$

where $K(t_{k-1})$ represents the value of the load factor at the moment t_{k-1}.

The overheating of the hot spot to the oil temperature in the interval k ($\Delta\theta_h(t_k)$) is given by:

$$\Delta\theta_h(t_k)=\Delta\theta_{h1}(t_k)-\Delta\theta_{h2}(t_k), \quad (19)$$

where

$$\Delta\theta_{h1}(t_k)=\Delta\theta_{h1}(t_{k-1})+\mathrm{D}\Delta\theta_{h1}(t_k) \quad (20)$$

$$\Delta\theta_{h2}(t_k)=\Delta\theta_{h2}(t_{k-1})+\mathrm{D}\Delta\theta_{h2}(t_k), \quad (21)$$

$$\mathrm{D}\Delta\theta_{h1}(t_k)=\frac{\mathrm{D}t}{k_{22}\tau_w}\left[k_{21}K^y(k-1)\Delta\theta_{hr}-\Delta\theta_{h1}(t_{k-1})\right], \quad (22)$$

$$\mathrm{D}\Delta\theta_{h2}(t_k)=$$
$$=\frac{\mathrm{D}t\cdot k_{22}}{\tau_w}\left[(k_{21}-1)K^y(k-1)\Delta\theta_{hr}-\Delta\theta_{h2}(t_{k-1})\right], \quad (23)$$

and $\mathrm{D}\Delta\theta_{h1}(t_k)$ and $\mathrm{D}\Delta\theta_{h2}(t_k)$ represents the variations of the quantities $\Delta\theta_{h1}(t)$ and $\Delta\theta_{h2}(t)$ in the interval $[t_{k-1}, t_k]$, see [12].

The hot spot temperature at the moment t_k ($\theta_h(t_k)$) is:

$$\theta_h(t_k)=\theta_o(t_k)+\Delta\theta_\mathrm{h}(t_k). \quad (24)$$

2.2.2. ANALYTICAL METHOD

In the case of distribution transformers to which several low power consumers are connected (micro-enterprises, households, etc.) there may be small variations of K and θ_o even within the N sub-intervals used in the finite difference method. On the other hand, for transformers with OF (oil forced) cooling systems $x = 1$, and in the case of OD (oil directed) type $x = 1$ and $y = 2$ [12]. As a result, eqs. (12), (14) and (15) can be solved by an analytical method (AM). To obtain the solutions, it was considered that inside each sub-interval k, load factor K_k and ambient temperature θ_k vary linearly on time, respectively:

$$K_k(\tau) = m_{1k} + n_{1k}\tau, \qquad (25)$$

$$\theta_{ak}(\tau) = m_{2k} + n_{1k}\tau, \qquad (26)$$

where $n_{1k} = [K(t_k) - K(t_{k-1})]/(\theta_k - \theta_{k-1})$, $m_{1k} = K(t_{k-1})$, $m_{2k} = \theta_{ak}(t_{k-1})$ and $\tau = t - t_{k-1}$.

For the oil temperature $\theta_o(t)$, $t \subset [t_{k-1}, t_k]$, the following expression was obtained:

$$\theta_o(t) = \left[\theta_o(t_{k-1}) - \frac{d_3^2}{d_3 + bd_4}\right]\cdot \mathrm{e}^{-\tau/b} + \frac{\left(d_3 + d_4\tau + d_5\tau^2\right)^2}{d_3 + bd_4 + \left(d_4 + 2bd_5\right)\tau + d_5\tau^2}, \qquad (27)$$

where: $a = \Delta\theta_{or}$, $b = k_{11}\tau_o$, $p = m_1^2$, $d_1 = a/(1+R)$, $d_2 = a\cdot R/(1+R)$, $d_3 = m_2 + d_1 + d_2 p$, $d_4 = n_2 + d_2 q$, $q = 2m_1 n_1$, $d_5 = d_2 \cdot s$ and $s = n_1^2$.

For the calculation of the hot spot temperature $\theta_h(t)$ $\left(t \subset [t_{k-1}, t_k]\right)$, the following equations were obtained:

$$\theta_h(t) = \theta_o(t) + \Delta\theta_h(t), \qquad (28)$$

$$\Delta\theta_h(t) = \Delta\theta_{h1}(t) - \Delta\theta_{h2}(t), \qquad (29)$$

$$\Delta\theta_{h1}(t) = \left[\Delta\theta_{h1}(t_{k-1}) - \frac{b_1 p^2}{p + b_2 q}\right]\cdot \mathrm{e}^{-\tau/b_2} + \frac{b_1\left(p + q\tau + s\tau^2\right)^2}{p + b_2 q + \left(q + 2b_2 s\right)\tau + s\tau^2}, \qquad (30)$$

$$\Delta\theta_{h2}(t) = \left[\Delta\theta_{h2}(t_{k-1}) - \frac{b_3 p^2}{p + b_4 q}\right]\cdot \mathrm{e}^{-\tau/b_4} + \frac{b_3\left(p + q\tau + s\tau^2\right)^2}{p + b_4 q + \left(q + 2b_4 s\right)\tau + s\tau^2}, \qquad (31)$$

where $b_1 = k_{21}\Delta\theta_{hr}$, $b_2 = k_{22}\tau_w$, $b_3 = k_{21} = 1$ and $b_4 = \tau_o / k_{22}$.

The solutions obtained by the analytical method ($\theta_o(t)$ and $\theta_h(t)$) contain besides some exponential functions (as in the case of the method of exponential functions) and a rational function (which, in case of linear variations in time of the quantities K and θ_a has the fourth order numerator and the second order denominator).

Initial values (at $t = 0$) of the quantities $\theta_o(t)$, $\Delta\theta_{h1}(t)$ and $\Delta\theta_{h2}(t)$ are calculated, in all three methods, using the following equations:

$$\theta_o(0) = \left[\left(\frac{1 + K^2(0)R}{1+R}\right)^x \Delta\theta_{or} + \theta_a(0)\right], \qquad (32)$$

$$\Delta\theta_{h1}(0) = k_{21}K^y(0)\Delta\theta_{hr}, \qquad (33)$$

$$\Delta\theta_{h2}(0) = \left(k_{21} - 1\right)K^y(0)\Delta\theta_{hr}, \qquad (34)$$

where $K(0)$ represents the value of the load factor at moment $t = 0$.

3. REMAINING AND CONSUMED LIFETIME

Knowing the values of the hot spot temperature, the consumed lifetime of the transformer insulation in $\Delta t = t_2 - t_1$ (L_c) is calculated with the equation [1]:

$$L_c = \int_{t_1}^{t_2} V \,\mathrm{d}t = \sum_{k=1}^{N} V_k \Delta t_k, \qquad (35)$$

where Δt_k represents the k^{th} time sub-interval, resulted from the division of the $t_2 - t_1$ interval into N sub-intervals, in which $\theta_h(t)$ is considered constant and equal to $\theta_h(t_{k-1})$, and V_k – the relative aging rate of the insulation made of heat-treated paper in the sub-interval k [12]:

$$V_k = \mathrm{e}^{\left(\frac{15000}{110+273.15} - \frac{15000}{\theta_h(t_{k-1})+273.15}\right)}, \qquad (36)$$

110 ºC being the value of the hot spot temperature for designed lifetime of the insulation [1,12].

The remaining lifetime L_r is calculated as difference between the estimated L_e and consumed lifetime L_c.

4. INFLUENCE OF SOLAR RADIATION

The temperature of the insulation 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 (2), (4), (5), (12), (17) and (32) the term corresponding to the internal heat sources is modifying, becoming:

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

where $P_s(t)$ is the solar power transmitted through radiation at t and P_{LL} and P_{NL} are the nominal losses in the load and in the idling, respectively.

As a result, the temperature will increase at each point of the transformer with a constant difference (maintaining the slope of the BCD line, Fig. 1), there will be a shifting to the right of the point P in P', and the hot spot temperature takes on the value θ_{hr} (Fig. 1).

The solar power $P_S(t)$ is calculated using the equation:

$$P_S(t) = cA_{tr}I(t), \qquad (37)$$

where c is the absorption factor of solar radiation, A_{tr} – the collecting surface of solar radiation corresponding to the transformer and $I(\geq 0)$ is the intensity of the solar radiation at t [1, 19–21].

The intensity of the solar radiation $I(t)$ is calculated with the equation:

$$I(t) = 951.39(\sin\alpha(t))^{1.15}, \qquad (38)$$

where $\alpha(t)(\geq 0)$ is the radiation angle of the sun (altitude-wise) [20] and it is calculated using the equation:

$$\alpha(t) = \left\{\sin\left[\sin\delta(t)\sin L + \cos\delta(t)\cos L\cos\beta\right]\right\}^{-1}, \qquad (39)$$

were: $\delta(t)$ is the declination angle of the sun (the angle made by the rays of the sun with the equatorial plane), L –

the latitude corresponding to the respective area and β – hourly angle of the Sun [11].

The declination angle δ is obtained using the equation [22]:

$$\delta(y)=0.3948-23.25559\cos(y+9.1°)-\\-0.3915\cos(2y+5.4°)-0.1764\cos(3y+105.2°) \quad (40)$$

where $y=360n/365$ represents the day angle, and n – day number in year.

Hourly angle of the Sun β (in degrees) is obtained using the equation:

$$\beta=(12-t_s)\ \ [°], \quad (41)$$

where $t_s=(t_a+t_e)/2$ is solar hour, $t_a=t-t_z+4\lambda$ – apparent local hour, t – local hour, t_z – time zone, λ – longitude of the respective area and t_e – the annual difference between the time indicated by a solar clock and a usual one, calculated with the equation [23] :

$$t_e(y)=0.0066-7.3525\cos(y+85.9°)+\\+9.9359\cos(2y+108.9°)+0.3387\cos(3y+105.8°). \quad (42)$$

5. CASE STUDY

In order to highlight the influence of the calculation method on the values of temperatures and lifetimes of power transformers, the hot spot temperatures and the estimated, consumed and remaining lifetimes were calculated for two identical distribution transformers that operate, one in Mauritania (Nouakchott, noted with T1) and another one in Romania (Suceava, noted with T2), both in the absence and in the presence of solar radiation on 07.06.2019 and 10.10.2019, for sub-intervals Δt = 3 min (corresponding to τ_w = 7 min).

Table 1

Geographical coordinates of the transformers

Operation site	Longitude	Latitude
Nouakchott	15°59′ V	18°52′ N
Suceava	26°15' E	47°38' N

Table 2

Values of the load factor K

t (h)	0	2	4	6	8	10
K	0.92	0.90	0.91	0.95	1.08	1.10

Table 2 (continued)

t (h)	12	14	16	18	20	22	24
K	1.03	1.02	0.94	1.01	1.12	1.02	0.92

Table 3

Ambient temperature values in 17.06.2019 and 10.10.2019, in Suceava ($\theta_{aS17}(t)$ and $\theta_{aS10}(t)$) and Nouakchott (($\theta_{aN17}(t)$ and $\theta_{aN10}(t)$)

t (h)	0	2	4	6	8	10
θ_{aS17} (°C)	10	9	8	8	11	13
θ_{aS10} (°C)	27	27	26	25	27	29
θ_{aN17} (°C)	25	25	24	23	25	27
θ_{aN10} (°C)	27	27	26	25	27	29

Table 3 (continued)

t (h)	12	14	16	18	20	22	24
θ_{aS17} (°C)	17	18	18	16	13	12	14
θ_{aS10} (°C)	34	37	37	35	32	30	10
θ_{aN17} (°C)	32	35	35	33	30	28	25
θ_{aN10} (°C)	34	37	37	35	32	30	27

The transformers have the apparent nominal power S_n = 105 MVA, A_{tr} = 64 m^2, c = 0.75, P_{LL} = 308 kW, P_{NL} = 54 kW, heat-treated paper – mineral oil insulation (110 °C), OD cooling system type, x = 1, y = 1.3, k_{11} = k_{21} = k_{22} = 1, $\Delta\theta_{or}$ = 48 °C, $\Delta\theta_{hr}$ = 14.3 °C, H = 1.4, g_r = 14.35 °C, τ_o = 90 min and τ_w = 7 min. The coordinates of the stations where the transformers operate are presented in Table 1 and the values of the K and θ_a in Table 2.

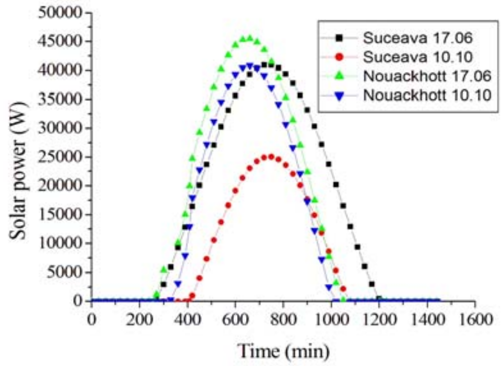

Fig. 2 – Time variation of solar power in Nouakchott (green/blue curves) and Suceava (black/red curves), on 17.06.2019 (green/black curves) and on 10.10.2019 (red/blue curves).

The values of K are influenced by many factors [24], but to highlight the effect of solar radiation, the same values of K were considered, regardless of the date and place of operation of the transformers. Within the subintervals Δt linear variations of the quantities K and θ_a were assumed.

5.1. SOLAR POWER

In Fig. 2 the time variations of the solar power P_s, on 17.06.2019 and 10.10.2019, in Nouakchott (Mauritania) and Suceava are presented. The values of P_s depend on the geographical coordinates of the transformer station, on the day and on the hour at which are calculated. It can be noted that the maximum value of P_s is obtained in Nouakchott (in June) and the minimum value in Suceava (in October). On the other hand, the values of P_s in June are higher than in October in both localities.

5.2. OIL AND HOT SPOT TEMPERATURES

The calculation of the oil (θ_o) and hot spot (θ_h) temperatures was performed for the two transformers with all three methods: exponential functions, finite differences, and analytical method. Part of the results respectively curves $\theta_o(t)$ and $\theta_h(t)$ are shown in the Figs. 3–12 and Table 1. It is found that the values of $\theta_o(t)$ and $\theta_h(t)$ depend (through the values of solar power and ambient temperature) on the geographical coordinates of the transformer station, on the day and hour at which it is calculated. Thus, on both days analysed, $\theta_o(t)$ and $\theta_h(t)$ presents two maxims: the first around 2 pm – when the load factor K is above unit (1.02 – 1.03), and the ambient temperature and solar radiation have high values and the second maximum, around 9 pm – when the load factor has the largest values (over 1.1).

5.2.1. INFLUENCE OF THE SOLAR RADIATION

The variations of the oil and hot spot temperatures in the two transformers (T1 and T2) in June and October 2019, calculated with the finite difference method, both in the absence and in the presence of solar radiation are presented in Figs. 3 – 6. It can be seen that in all cases, the values of θ_o and

θ_h are higher in the presence of solar radiation, than in its absence, respectively for $t \in [270, 1020]$ in June and $t \in [330, 990]$ in October – for T1 (Figs. 3 and 4) and $t \in [270, 1200]$ in June and $t \in [420, 1050]$ in October – for T2 (Figs. 5 and 6). As a result, the use of the hot spot temperature equations indicated in the IEC [12] and IEEE [13] standards – in which $P_s = 0$ – leads to lower values of θ_h and, respectively, lower values of the consumed lifetimes (§ 5.2.3).

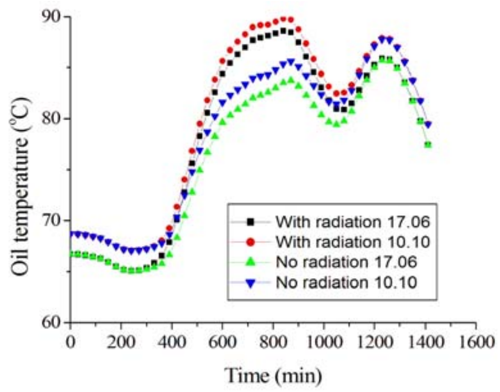

Fig. 3 – Time variation of the oil temperature for T1 on 17.06.2019 (black/green curves) and on 10.10.2019 (red/blue curves), both in the absence (green/blue curves) and in the presence of solar radiation (black/red curves).

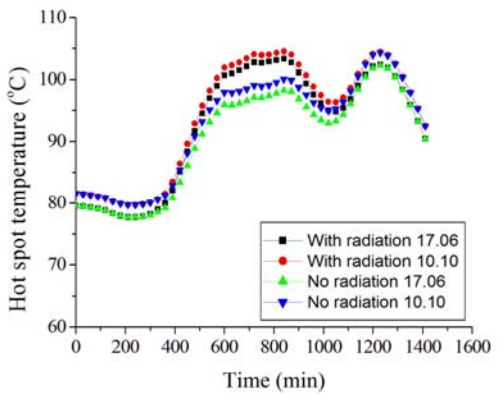

Fig. 4 – Time variation of the hot spot temperature for T1 on 17.06.2019 (black/green curves) and on 10.10.2019 (red/blue curves), both in the absence (green/blue curves) and in the presence of solar radiation (black/red curves) calculated with M2 method.

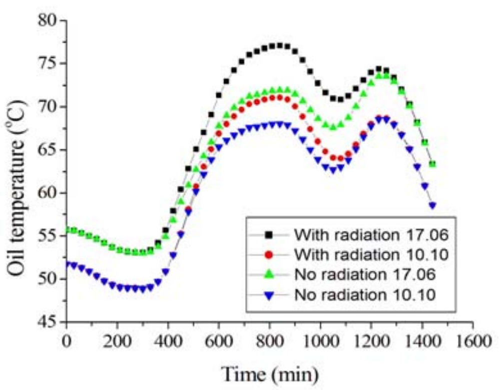

Fig. 5 – Time variation of the oil temperature for T2 on 17.06.2019 (black/green curves) and on 10.10.2019 (red/blue curves), both in the absence (green/blue curves) and in the presence of solar radiation (black/red curves) calculated with M2 method.

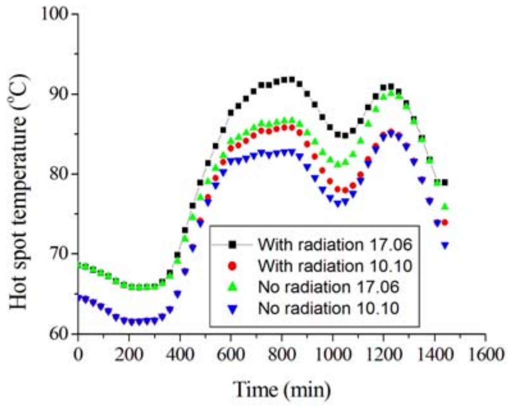

Fig. 6 – Time variation of the hot spot temperature for T2, on 17.06.2019 (black/green curves) and on 10.10.2019 (red/blue curves), both in the absence (green/blue curves) and in the presence of solar radiation (black/red curves) calculated with M2 method.

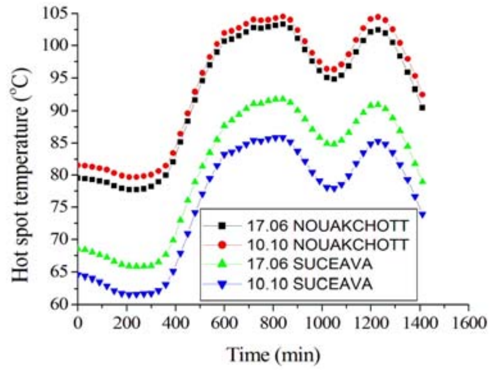

Fig. 7 – Time variation of the hot spot temperature in the presence of solar radiation for T1 (black/red curves) and T2 (green/blue curves), on 17.06.2019 (black/green curves) and on 10.10.2019 (red/blue curves) (obtained using finite differences method) calculated with M2 method.

For T1, $\theta_o(t)$ and $\theta_h(t)$ take maximum values in the time interval 13h30 – 14 h (θ_o over 88 °C and θ_h over 103 °C) in June and in the time interval 13h – 14h 30 (θ_o over 89 °C and θ_h over 104 °C) in October (Figs. 3 and 4). For T2 the maximum values of the quantities $\theta_o(t)$ and $\theta_h(t)$ are obtained, both in June (θ_o over 77 °C and θ_h over 91 °C), and in October (θ_o over 71 °C and θ_h over 85 °C) for $t \in [780, 840]$ (Figs. 5 and 6). It should be noted that the differences between the maximum values of the hot spot temperature are relatively important, respectively over 5 °C for T1 (on both days) and over 5 °C – in June – and over 3 °C – in October – for T2.

5.2.2. INFLUENCE OF PLACE OF OPERATION

The values of the hot spot temperatures depend on the coordinates of the geographical areas in which the transformers operate, areas which present different values, both ambient temperature and of the solar power. Thus, on 17.06.2019, the hot spot temperature – calculated with the finite difference method – had a maximum value of 103.33 °C for T1 (Nouakchott) and 91.79 °C for T2 (Suceava), and on 10.10.2019, it had a value of 104.59 °C for T1 and 85.64 °C for T2 (Fig. 7). Therefore, on 17.06.2019 the maximum value of the hot spot temperature was approx. 12 °C higher for T1 than for T2, and on 10.10.2019 with approx. 19 °C. Obviously, the higher values of θ_h for T1 than for T2 are due to the higher values of ambient temperature (Table 2) and solar power (Fig. 2) in Nouakchott compared to those in Suceava.

5.2.3. INFLUENCE OF CALCULATION METHOD

The calculated values of the oil and hot spot temperatures depend on the calculation method used. As can be seen in Fig. 8–11 the highest values of $\theta_h(t)$ at any time of the day and for both transformers are obtained with the method of exponential functions (EFM), and the lowest with the method of finite differences (DFM). The values of $\theta_h(t)$ obtained with the analytical method (AM) are located between those obtained with EFM and those obtained with EFM. The use of analytical functions involves stepwise variations of the load factor and over relatively large sub-intervals Δt, so that the thermal regime stabilizes. Or this condition could not be satisfied for sub-intervals Δt less than half the winding time constant (τ_w = 7 min). As a result, in the case of distribution transformers (which corresponds to continuous variations of K) the values of $\theta_h(t)$ obtained using EFM can present, significant differences compared to the real ones.

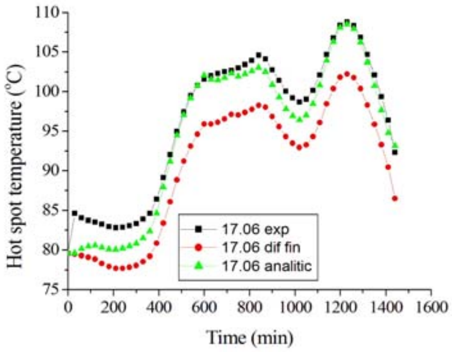

Fig. 8 – Time variation of the hot spot temperature for T1 on 17.06.2019, calculated using exponential functions method (black curve), analytical method (green curve) and finite differences method (red curve) (in the absence of the solar radiation).

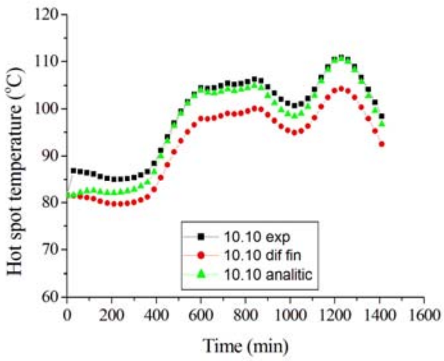

Fig. 9 – Time variation of the hot spot temperature for T1 on 10.10.2019, calculated using exponential functions method (black curve), analytical method (green curve) and finite differences method (red curve) (in the absence of the solar radiation).

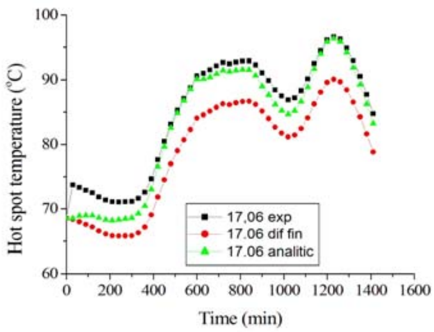

Fig. 10 – Time variation of the hot spot temperature for T2 on 17.06.2019, calculated using exponential functions method (black curve), analytical method (green curve) and finite differences method (red curve) (in the absence of the solar radiation).

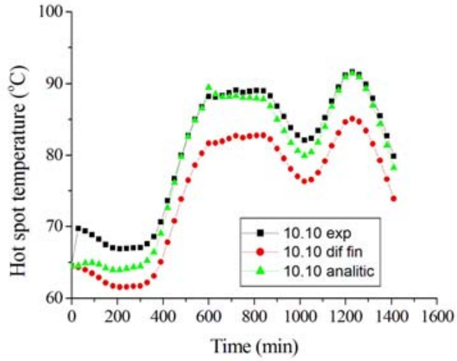

Fig. 11 – Time variation of the hot spot temperature for T2 on 10.10.2019, calculated using exponential functions method (black curve), analytical method (green curve) and finite differences method (red curve) (in the absence of the solar radiation).

In these cases, IEC 6076-7 recommends DFM. However, the values of $\theta_h(t)$ obtained with DFM also depend on the discretization step Δt. For example, for T2, the values of $\theta_h(t)$, calculated on 17.06.2019 in the absence of radiation decrease by 0.028… 1.03%, if Δt decreases from 3 to 1 min.

Table 4

Maximum values of the hot spot temperature calculated in the absence of solar radiation with the methods of exponential (EFM), analytical (AM) and finite difference (FDM) functions, at noon (θ_{hsmax1}) and at night (θ_{hsmax2}) for T1

Method	EFM	EFM	AM	AM	FDM	FDM
Day	17.06.2019	10.10. 2019	17.06. 2019	10.10. 2019	17.06. 2019	10.10. 2019
θ_{hmax1} (°C)	104.59	106.29	103.05	104.45	98.26	100.07
θ_{hmax2} (°C)	108.81	110.87	108.52	110.57	102.24	104.30

Table 4 (continued)

Method	EFM	EFM	AM	AM	FDM	FDM
Day	17.06. 2019	10.10. 2019	17.06. 2019	10.10. 2019	17.06. 2019	10.10. 2019
θ_{hmax1} (°C)	92.91	89.02	90.09	89.44	86.67	82.78
θ_{hmax2} (°C)	96.64	91.66	96.38	91.43	90.07	85.09

Table 4 shows the maximum values of the hot spot temperature θ_{hmax} for the two transformers. It is observed that, regardless of the calculation method, the values of θ_{hmax} exceed 100 °C for T1 and do not reach 100 °C for T2. It should be noted that, if the calculated values of θ_h depend on the calculation method, the calculated values of θ_o do not depend, practically, on the method. The curves $\theta_o(t)$ obtained by the three methods being, practically, identical (Fig. 12).

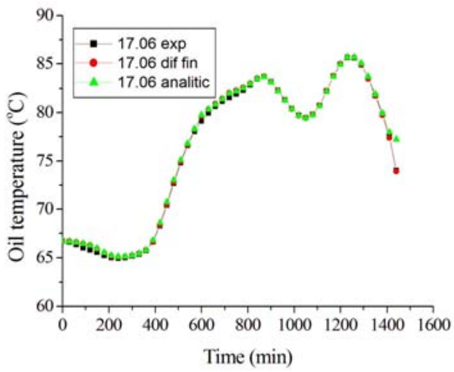

Fig. 12 – Time variation of the oil temperature for T1 (P_s = 0), calculated with EFM (black curve), FDM (red curve) and AM (green curve).

In the case of the analytical method, the expression of $\theta_h(t)$ contains, besides the exponential function, also a rational function, because of the hypothesis that on the sub-intervals Δt linear variations of the quantities K and θ_a take place. The rational function allows a correction of the values of $\theta_h(t)$, these being, in general, inferior to the values obtained with EFM (Figs. 8–11, green curves).

However, a conclusion regarding the correctness of this method can be drawn only after measuring the hot spot temperature during the operation of the transformers [25].

5.3. LIFETIMES

Using the equations (35) and (36) the values of the consumed L_c and remaining L_r lifetimes were calculated for the two transformers on 17.06.2019 and 10.10.2019, both in the presence and in the absence of solar radiation (with the values of θ_h calculated by all three methods). Some of the results, obtained by DFM are presented in Figs. 13 to 15. It is found that the values of the consumed lifetimes depend on the location of the transformer, the presence of solar radiation and the day on which it operates. Thus, the presence of solar radiation causes a faster increase of the consumed lifetimes for both transformers, regardless of the day of operation (Figs. 13 and 14). For example, on 17.06.2019, the values of L_c increase in 24 hours, due to the solar radiation by approx. 34 % for T1 and with approx. 47 % for T2. Therefore, the use of the relations recommended in [9, 10] for the calculation of θ_h, may lead to errors of almost 50 % in estimating the consumed lifetime. On the other hand, L_c has higher values on 10.10.2019 than on 17.06.2019 for T1 (in the presence of solar radiation with approx. 18 in 24 h), but lower for T2 (in the presence of solar radiation with approx. 94 %). It should be noted that on both days (both in the presence and in the absence of solar radiation) the values of L_c are higher for T1 than for T2. For example, in the presence of solar radiation, on 10.10.2019, the value of L_c for T1 is over 5 times higher than that for T2.

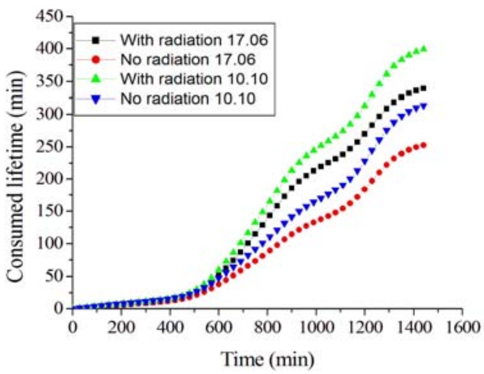

Fig. 13 – Time variation of the consumed lifetime for T1 on 17.06.2019 (black/red curves) and on 10.10.2019 (green/blue curves), both in the presence (black/green curves) and in the absence of the solar radiation (red/blue curves), θ_h – calculated with FDM.

The values of L_c calculated based on the temperature obtained with DFM depend on the values chosen for Δt. Thus, in the case of transformer T2, on 17.06.2019 in the absence of radiation, the reduction of the value of Δt from 3 min to 1 min determines a reduction of the consumed lifetime by up to 5.2%. Environmental temperature differences in design and real conditions make a transformer very risky to operate to reach its maximum capacity [26].

The time variations of the consumed lifetimes obtained with EFM and AM are similar to those obtained with FDM (Figs. 13 and 14), but the numerical values of L_c are higher. A comparison between the FDM and AM methods regarding the variation of the consumed lifetime is presented in Fig. 15. It is found that the values of the consumed lifetime obtained with the AM method are higher than those obtained with FDM (especially for $t > 600$ min).

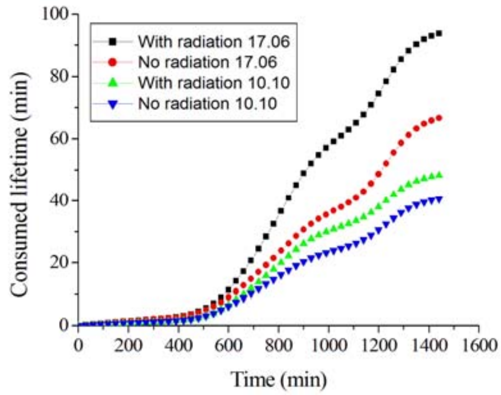

Fig. 14 – Time variation of the consumed lifetime for T2 on 17.06.2019 (black/red curves) and on 10.10.2019 (green/blue curves), both in the presence (black/green curves) and in the absence of the solar radiation (red/blue curves), θ_h – calculated with FDM.

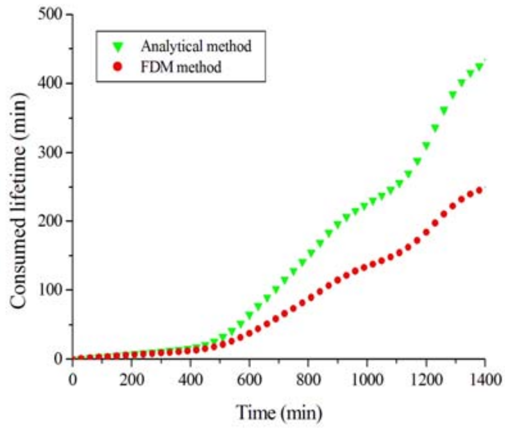

Fig. 15 – Time variation of the consumed lifetime for T2 on 17.06.2019 in the absence of the solar radiation, calculated with FDM (green curve) and analytical method (red curve).

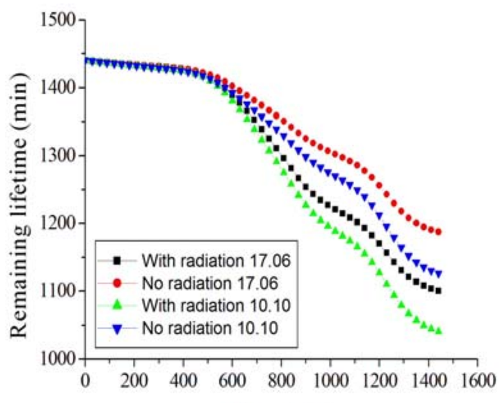

Fig. 16 – Time variation of the remaining lifetime for T1 on 17.06.2019 (black/red curves) and on 10.10.2019 (green/blue curves), both in the presence (black/green curves) and in the absence of the solar radiation (red/blue curves) (θ_h – calculated with FDM).

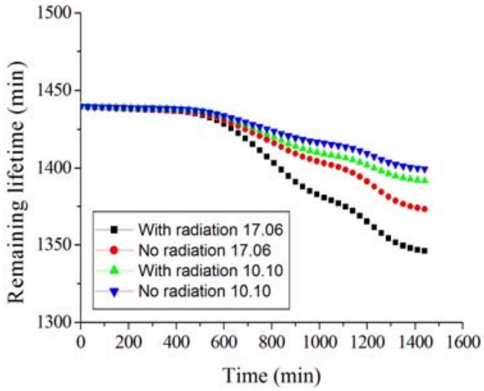

Fig. 17 – Time variation of the remaining lifetime for T2 on 17.06.2019 (black/red curves) and on 10.10.2019 (green/blue curves), both in the presence (black/green curves) and in the absence of the solar radiation (red/blue curves) (θ_h – calculated with FDM).

Considering that the transformers would work at nominal load (K = 1) at a constant temperature of 110 °C, the estimated lifetime can be considered L_e = 180 000 h [9]. Consumed lifetime for operation at this temperature, in one day, would be L_c(24 h) = 24 h, and the remaining lifetime after operation for one day would be L_r(24 h) = 0. In the cases of operation at the variable load considered in Table 2, the consumed lifetimes in one day have different values, and the values of the remaining lifetimes of the two transformers vary in time according to Figs. 16 and 17.

It is found that the lowest values of the remaining lifetime L_r are obtained for the transformer in Nouakchott for its operation in the presence of solar radiation on 10.10.2019 (Fig. 16), and the highest values (about 27 %) are obtained for the one from Suceava on the same day, in the absence of radiation (Fig. 17).

It should be noted that when using FDM the values of L_r are influenced by the values of Δt. Thus, for the transformer in Suceava, if Δt decreases from 3 min to 1 min, the remaining lifetime after 24 h increases by 0.0175%. The time variations of the remaining lifetimes obtained with EFM and AM are similar to those obtained with FDM (Figs. 16–17), but the numerical values of L_r are lower. Higher ambient temperatures and more intense solar radiation reduce the remaining lifetime of the insulation systems in Nouakchott transformers.

They need to be monitored more carefully [27] and eventually subjected to repairs or replacements at shorter intervals [28]. As a result, costs for electricity transmission and distribution are higher in Mauritania than in Romania.

6. CONCLUSIONS

The IEC and IEEE standards recommend certain equations for calculating the hot spot temperature and the consumed lifetimes of the power transformers. These equations do not consider the influence of solar radiation, which differs from one geographical area to another. Therefore, their use can lead to important errors in the assessment of the consumed and remaining lifetimes of the transformers.

In geographical areas with lower values of ambient temperature and solar radiation, hot spot temperatures and consumed lifetimes of transformers are higher than in areas with lower temperatures and lower solar radiation.

In the case of distribution transformers, the load factor has variations over relatively small intervals, which leads to large differences in the calculated values of the hot spot temperature and the lifetimes obtained by the method of exponential functions and the method of finite differences.

The use of the analytical method proposed in this paper involves the use of more complex functions for time variations of oil temperature and hot spot temperature, consisting of an exponential and a rational function.

The values of the temperatures obtained with AM are lower than those obtained by EFM, but higher than those obtained by FDM. However, a conclusion regarding the correctness of this method can be drawn only after measuring the hot spot temperature during the operation of the transformers.

The values of hot spot temperatures and lifetimes calculated with the three methods may have important differences from those obtained by direct measurement. Therefore, the new transformers must be equipped with devices for the correct measurement of the hot spot temperatures.

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