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Impact of Long-Term Climatic Conditions on the Ageing and Cost Effectiveness of the Oil-Filled Transformer

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***Abstract*—The major concern to evaluate the transformer loading ability to feed a load is the capability to transfer the internal generated heat of the windings, core, and structural parts to its ambient. The climatic conditions play an important role for evaluating the loading ability of a transformer. Hence, in the planning stage, the long-term climatic characteristics are a crucial issue. The thermal limit of the loading capability is referred to the winding hottest spot temperature. This paper is aiming to present the long-term ambient temperature change effect on the loss of life and cost effectiveness of a transformer located in two different regional climatic conditions. The climatic conditions are modeled on basis of daily ambient temperature. The transformer loading was measured for a 2.5 MVA, mineral oil, and ONAN cooling type transformer at certain region. The same loading is considered for the same transformer size and type at another region to show the impact of the diversity of regional climatic characteristics on the thermal performance. The results demonstrate the loss of life and cost effectiveness of the transformer is a function of the ambient temperature. The considered transformer is a 2.5 MVA, mineral oil, and ONAN cooling type.**

***Keywords*—Transformer aging, climate conditions, hot spot temperature, loss of life, cost effectiveness**

I. INTRODUCTION

Transformer plays a vital role in electrical utility by converting the electrical power at voltage level to another voltage level. The transformer loading capability can be investigated by evaluating the winding hottest spot temperature (HST). Hence, HST profile at each instant of the transformer operation needs to be calculated for various conditions including loading conditions and ambient ones [1]. More precise thermal models allow the electrical utilities to operate the transformer near its thermal limit to mitigate the unused capacity [2]. If HST exceeds the reference thermal limit of 110 °C, this will accelerate the ageing of the transformer and causing the real life is half of its normal life. Hence, the ageing acceleration factor is used to indicate the transformer loss of life [3]. In [4] the transformer oil ageing was enhanced by dispersion of TiO_2 nanoparticles with different concentration with the base oil to reuse it in the transformer. Also in [5] the heat transfer coefficient was enhanced by suspension of Al_2O_3 nanoparticles with the transformer oil. This development for the transformer thermal performance can cause transformer overloading without affecting the transformer ageing.

The electrical utility concern is to install more cost-efficient transformers across their networks. The total owning cost (TOC) of transformers is determined based on the transformer bid price in addition to the present value of the transformer considering operation and maintenance costs throughout the transformer lifetime [6]. As the internal heat generated of the windings, core, and structural tanks will transfer to its ambient, hence the climatic characteristics have significant impact on HST which can cause loss of life in case of exceeding the thermal limit [7]. The transformer losses should be corrected due to temperature change which lead to increasing the transformer losses cost [8].

This paper demonstrates to what extent the loss of life and cost effectiveness of mineral oil filled-transformer will be affected under regional climatic changes in Egypt. The ambient temperature profile at Cairo and Aswan is found to be the most appropriate characteristics for this study. The daily ambient temperature is an average for the month at Cairo and Aswan. The study is applied on 2.5 MVA, mineral oil, and ONAN cooling type transformer by using MATLAB. The data of ambient temperatures have been taken from [9].

II. REGIONAL CLIMATIC CONDITIONS

In the planning stage, more exhaustive evaluation is crucial in terms of both regional climatic characteristics and energy demand needs of the area. In [9] latitude and longitude coordinates for Cairo are 30.13 ^{o}N and 31.4 ^{o}E respectively and that for Aswan are 23.97 ^{o}N and 32.78 ^{o}E respectively. Fig. 1 shows the daily ambient temperatures as an average for the month at Cairo and that at Aswan is shown in Fig. 2. For Cairo, the temperature ranges between 11 and 18 °C during the coldest month and between 22 and

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34 °C during the hottest one. For Aswan, the temperature range is higher than Cairo, where it ranges between 11 and 21 °C for the coldest month and between 27 and 40 °C for the hottest one. Fig. 3 shows monthly deviation of maximum ambient temperature at Cairo and Aswan.

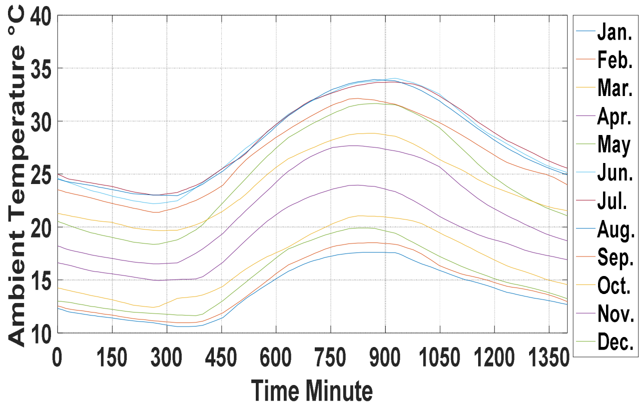

Fig. 1. The daily ambient temperatures as an average for the month at Cairo.

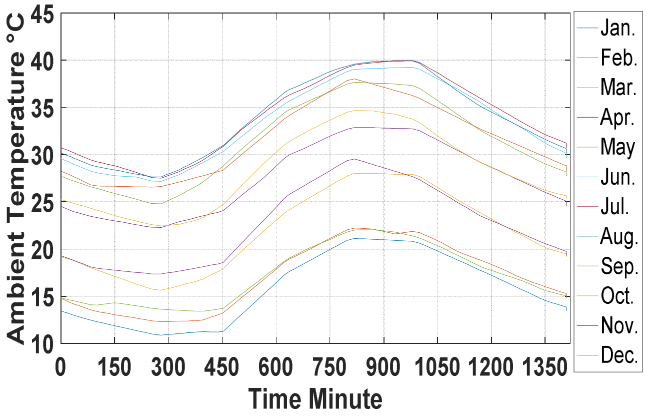

Fig. 2. The daily ambient temperatures as an average for the month at Aswan.

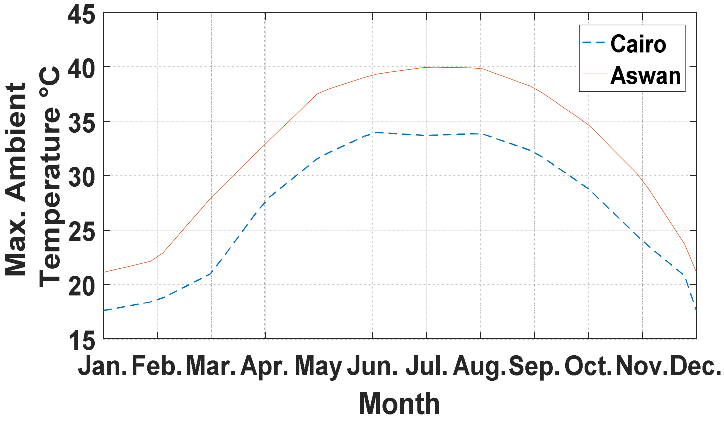

Fig. 3. Monthly maximum ambient temperature at Cairo and Aswan.

III. TRANSFORMER THERMAL MODEL

A transformer thermal modeling approach is based on the heat transfer theory in the form of an equivalent circuit. A heat source analogy is used to present heat input due to electrical losses and a nonlinear thermal resistance analogy to present the impact of air or oil convective cooling. The transformer thermal modeling approach is verified in [10].

Actually, the transformer loading is variable at each moment. The same loading is considered for two regions to demonstrate the impact of their climatic conditions on the ageing and cost effectiveness of the transformer. We measured the loading of 2.5 MVA, mineral oil, and ONAN cooling type transformer. As shown in Fig. 4, the loading exceeded 1 p.u for duration of 394.3 minutes. In this study, we will present the overloading period impact on the transformer thermal performance for the two regions. The thermal model parameters of 2.5 MVA mineral oil-filled transformer are shown in Table I. Table II shows the exponents n and n' used in TOT and HST thermal model respectively.

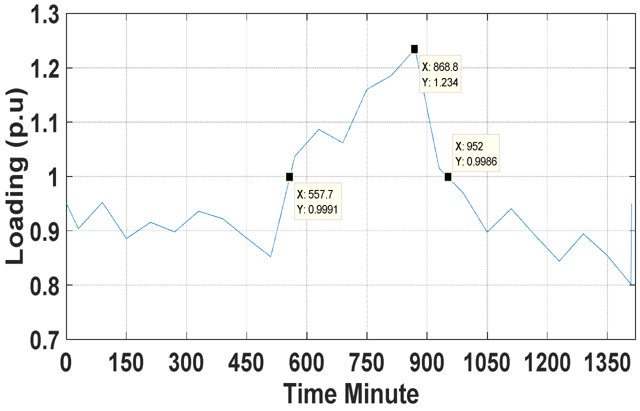

Fig. 4. The measured daily pu loading.

TABLE I. THERMAL MODEL PARAMETERS OF 2.5 MVA OIL-FILLED TRANSFORMER

Rated top oil rise over ambient	48 °C
Rated hot spot rise over top oil	24.5 °C
Ratio of load losses to no load losses	3.57
Top oil time constant	126 min
Hot spot time constant	7.5 min
Exponent n	0.25
Exponent n'	0.25
No Load loss	5100 W
(I^2R) losses	16028 W
P_{EC-R} (eddy current losses)	1170 W
P_{OSL-R} (other stray losses)	1041 W
P_{TSL} (total stray losses)	2211 W
Rated total loss	23339W
pu eddy current losses at the hot spot location	0.7

TABLE I. EXPONENTS USED IN THERMAL MODEL [11]

Type of cooling	*n*	*n'*
Without external cooling	0.25	0.25
With external cooling	0.5	2

A. Thermal Model of Top Oil Temperature

This model calculates instantly the top oil temperature (TOT) variations as a function of ambient temperature variations and loading variations with top oil thermal time constant. The following differential formula is used to calculate the TOT variations: [10]

$$\frac{1+RxK^2}{1+R} x\mu_{pu}{}^{n} x\Delta\theta_{oil,rated} = \mu_{pu}{}^{n} x\tau_{oil,rated} x \frac{d_{\theta_{oil}}}{dt} + \frac{(\theta_{oil}-\theta_{amb})^{1+n}}{\Delta\theta_{oil,rated}{}^{n}} \quad (1)$$

$$\tau_{oil,rated} = C_{th-oil,rated} \frac{\Delta\theta_{oil,rated}}{q_{tot,rated}} x60 \quad (2)$$

where:

R	ratio of rated load losses to no-load losses
K	ratio of the specified load to rated load
μ_{pu}	oil viscosity (per-unit value)
$\Delta\theta_{oil,rated}$	rated top-oil temperature rise over ambient
θ_{oil}	top-oil temperature
$\tau_{oil,rated}$	rated oil time constant
θ_{amb}	ambient temperature
n	cooling constant if the moving fluid is air
$C_{th-oil,rated}$	thermal capacitance of the oil at the rated hot-spot temperature
$q_{oil,rated}$	total losses at rated load, corrected for the extra heat generated at the rated hot-spot temperature

For external cooling of transformers and zigzag oil flow across the windings, the thermal capacitance of the oil is given by [11]:

$$C_{th-oil} = Y_{wdn} x\, m_{wdn} x\, c_{wdn} + Y_{fe} x\, m_{fe} x\, c_{fe} + Y_{st} x\, m_{mp} x\, c_{mp} + O_{oil} x\, m_{oil} x\, c_{oil} \qquad (3)$$

Where:

m_{wdn}	the winding material weight
m_{fe}	the core weight
m_{mp}	the tank and fittings weight
m_{oil}	the oil weight
c_{wdn}	specific heat capacity of the winding material ($c_{cu} = 0.11$ *and* $c_{al} = 0.25\ Wh/kg°\text{C}$)
c_{fe}	specific heat capacity of the core ($c_{fe} = 0.13\ Wh/kg°\text{C}$)
c_{mp}	specific heat capacity of the tank and fitting ($c_{mp} = 0.13\ Wh/kg°\text{C}$)
c_{oil}	specific heat capacity of the oil ($c_{oil} = 0.51\ Wh/kg°\text{C}$)
O_{oil}	correction factor for the oil in the ONAF, ONAN, and OFAF cooling modes ($\text{O}_{\text{oil}} = 0.86\ \text{Wh/kg°C}$)
Y_{wdn}	portion of the winding losses in the total transformer losses
Y_{fe}	portion of the core losses in the total transformer losses
Y_{st}	portion of the stray losses in the total transformer losses

Without external cooling of transformers, the thermal capacitance of the oil for transformers is as follow [11]:

$$C_{th-oil} = m_{wdn} x\, c_{wdn} + m_{fe} x\, c_{fe} + m_{mp} x\, c_{mp} + + m_{oil} x\, c_{oil} \qquad (4)$$

TOT variations are calculated for each month on the basis of daily ambient temperature and the same loading as shown in Fig. 5 for Cairo and that for Aswan is shown in Fig. 6. Fig. 7 shows monthly maximum TOT variations at Cairo and Aswan.

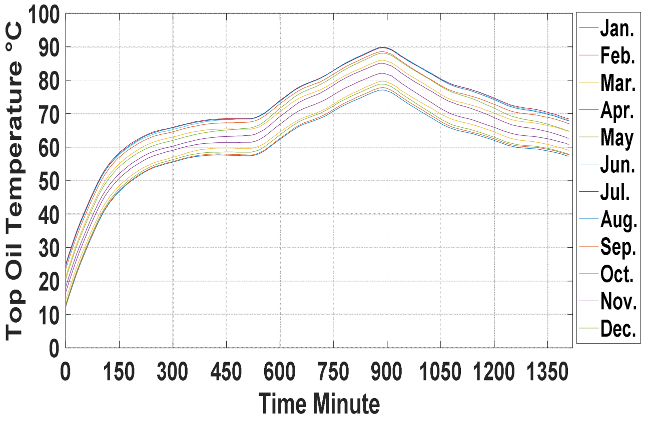

Fig. 5. TOT variations at Cairo.

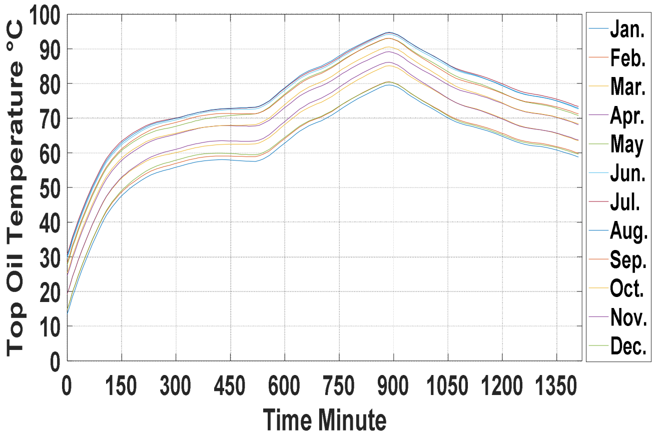

Fig. 6. TOT variations at Aswan.

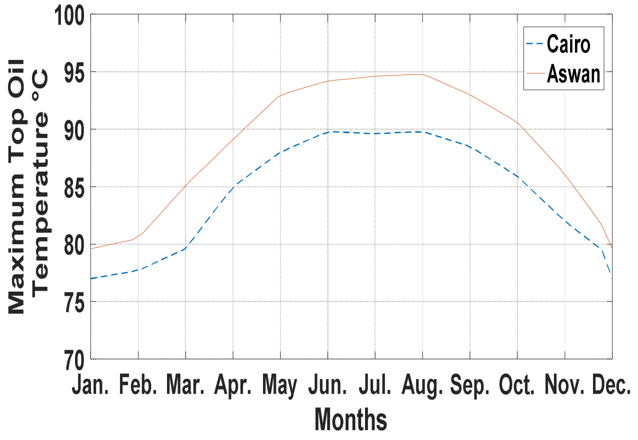

Fig. 7. Monthly Maximum TOT variations at Cairo and Aswan.

B. Thermal Model of Winding Hottest Spot Temperature

Winding HST model calculates at each moment HST changes as a function of loading variations and TOT changes with winding thermal time constant. The following formula is used to calculate the HST variations [10]:

$$K^2 x \left(K_\theta + \frac{P_{EC-R\,pu}}{K_\theta}\right) x \mu_{pu}{}^{n} x \Delta\theta_{hs,rated} = \mu_{pu}{}^{n} x \tau_{wdg,rated} x \frac{d\theta_{hs}}{dt} + \frac{(\theta_{hs} - \theta_{oil})^{1+n'}}{\Delta\theta_{hs,rated}{}^{n'}} \qquad (5)$$

$$K_\theta = \frac{\theta_K + \theta_{hs}}{\theta_K + \theta_{avg}} \qquad (6)$$

Where:

K_θ	resistance correction factor
$P_{EC-R\,pu}$	pu unit eddy current losses at rated load and hot spot location
$\Delta\theta_{hs,rated}$	rated hot spot temperature rise over top oil temperature
θ_{hs}	hot spot temperature
$\tau_{wdg,rated}$	rated winding time constant
n'	cooling constant if the moving fluid is oil
θ_K	temperature factor for the loss correction
θ_{avg}	average winding temperature at rated load

$\theta_K = 235$ for Copper

$\theta_K = 225$ for Aluminum

HST variations are calculated for each month as a function of daily TOT and the same loading as shown in Fig. 8 for Cairo and that for Aswan is shown in Fig. 9. Fig. 10 shows monthly maximum HST variations at Cairo and Aswan.

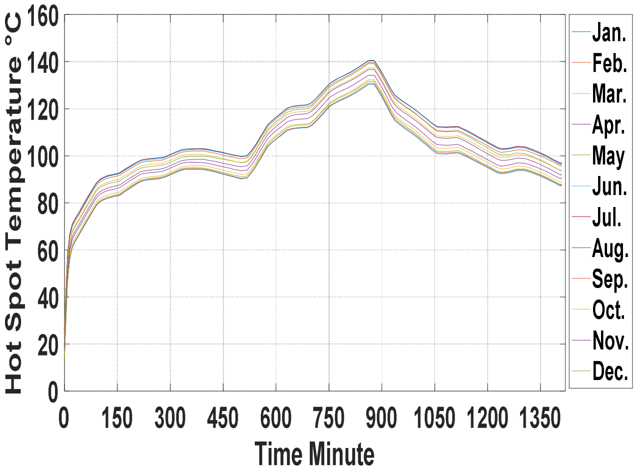

Fig. 8. HST variations at Cairo.

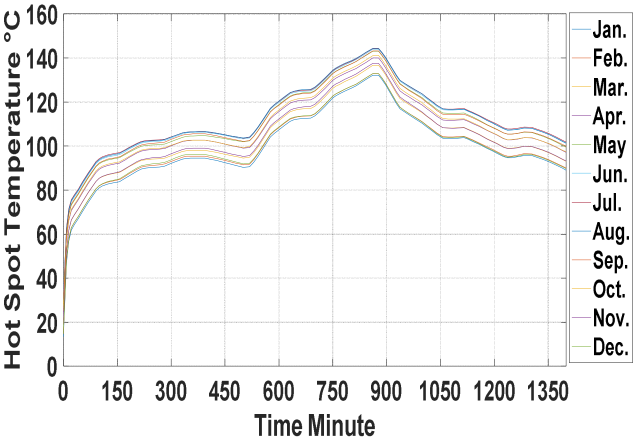

Fig. 9. HST variations at Aswan.

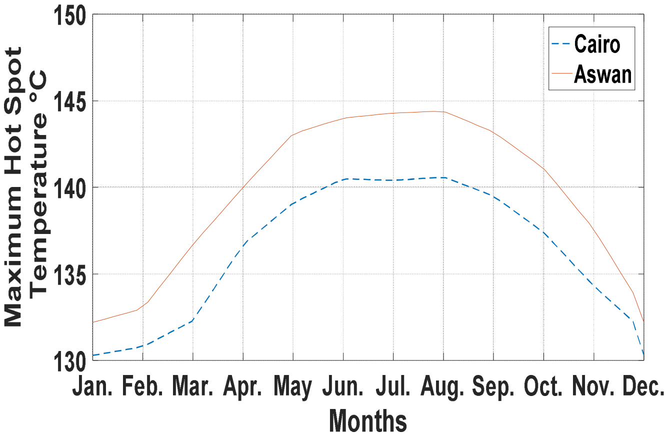

Fig. 10. Monthly Maximum HST variations at Cairo and Aswan.

IV. TRANSFORMER THERMAL AGEING

The winding HST will accelerate the transformer ageing in the periods of exceeding the reference temperature value of 110 °C. Hence, it's necessary to mitigate exceeding this thermal limit by reducing ambient temperature or loading as in [12]. The ageing acceleration factor (F_{AA}) is modeled as a function of HST in (7). The life loss (L) for an interval dt can be calculated as follows [3]:

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]} \tag{7}$$

$$dL = F_{AA}dt \tag{8}$$

Thus, the total life loss over a certain load cycle (T) is given by [3]:

$$L = \frac{1}{T}\int_0^T F_{AA}\,dt \tag{9}$$

In [13], the transformer tests show that the expectancy of the normal life at a continuous HST of 110 °C is 20.55 years. Fig. 11 shows the climatic conditions impact on monthly loss of life of a transformer at Cairo and Aswan. The results show the transformer real life at Cairo is 11 years, 10 months and 17 days. But at Aswan, the transformer real life is 8 years, 6 months and 25 days.

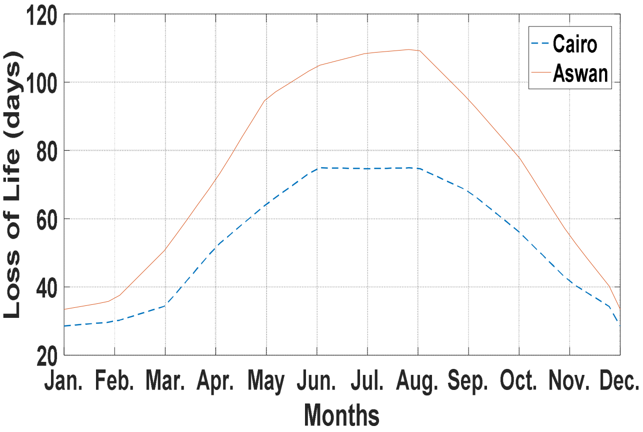

Fig. 11. Monthly loss of life at Cairo and Aswan.

V. COST EFFECTIVENESS OF OIL-FILLED TRANSFORMER

More cost-efficient transformer is a vital issue for both the electrical utility and the owner (end customer). The cost-effectiveness of transformers is based on the transformer total owning cost (TOC) throughout its life time. Equation (10) shows TOC is the sum of transformer bid price (BP) into USD and the present value of the transformer total losses (PV_{TL}) into USD [6].

$$TOC = BP + PV_{TL} \tag{10}$$

$$PV_{TL} = C_{TL} * PV_m \tag{11}$$

$$C_{TL} = (NLL + LL * K^2) * ET * HPY \tag{12}$$

$$LL = P * K_\theta + \frac{P_{EC-R}}{K_\theta} + P_{OSL} \tag{13}$$

$$PV_m = \frac{(1+d)^N - 1}{d*(1+d)^{N-1}} \tag{14}$$

Where:

C_{TL}	annual cost (\$/year) of transformer total loss
PV_m	present value multiplier
NLL	no-load losses (kW)
LL	rated load losses (kW)
P	ohmic losses (kW)
P_{EC-R}	rated eddy current losses (kW)
P_{OSL}	other stray losses (kW)
ET	energy tarrif (\$/kWh)
HPY	hours per year (hr)
d	discount rate
N	transformer real life time (years)

It was found the bid price of a 2.5 MVA, ONAN cooling type, mineral oil-filled transformer is 25,300 USD. In [14], the average energy tariff for industrial applications at 11 and 22 kV is 0.043 USD/kWh and the capacity tariff is 2.78 USD/kW-month.

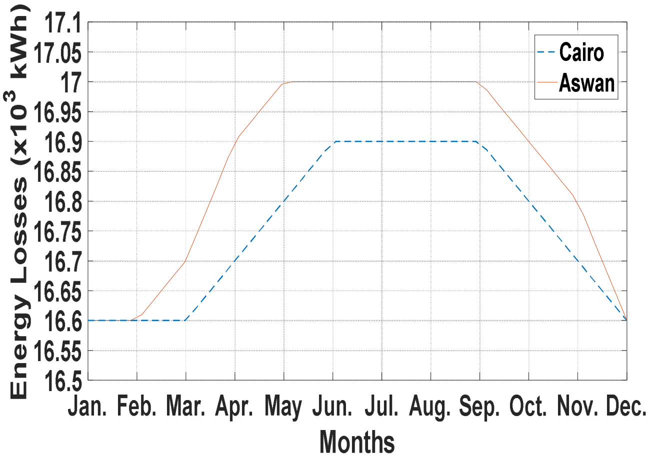

Fig. 12. Monthly energy losses at Cairo and Aswan.

Fig. 12 shows the impact of the climatic characteristics of Cairo and Aswan on energy losses. The results show the energy losses at colder region (Cairo) are less than that at Aswan for nine months (Mar – Nov.) but approximately equal for three months (Jan., Feb., and Dec.). The annual energy saving between the two regions is 1.1 MWh. TOC of the transformer at Cairo throughout its real life time is 138,800 \$ and that at Aswan is 125,000 \$. TOC of the transformer at Cairo is higher than that at Aswan as the transformer real life at Cairo is higher than that at Aswan. The results show the transformer is more cost effective in Cairo which is the coldest climatic conditions.

VI. TRANSFORMER LOADING

The results have shown the overloading accelerates transformer ageing. Hence, it's necessary to evaluate the loading during overloading periods according to the climatic characteristics to mitigate the transformer thermal ageing. When HST exceeds the reference temperature 110 ^{o}C, the loading shall be derated. On the other side, transformer may be overloading without exceeding the reference temperature.

Fig. 13 shows the loading capability for the two regions Cairo and Aswan without exceeding the thermal limit and maintain normal life. The results show the maximum loading at Cairo is higher than that at Aswan as the Cairo climatic conditions are colder than that at Aswan throughout the year.

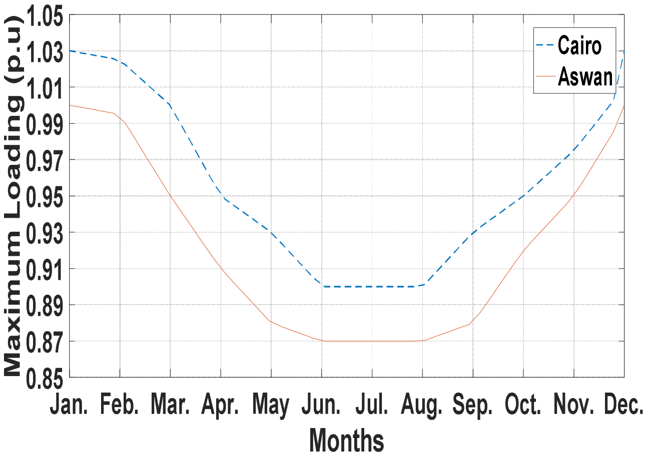

Fig. 13. Monthly maximum pu loading during periods of exceeding thermal limit at Cairo and Aswan.

CONCLUSIONS

This paper is aiming to evaluate the impact of long-term regional climatic conditions on the ageing and cost effectiveness of a 2.5 MVA, mineral oil, and ONAN cooling type transformer which is located at Cairo. The transformer loading was measured and found to be overloaded for 394.3 minutes. The same loading is considered for the same transformer size and type at Aswan to show the impact of the diversity of regional climatic characteristics based on daily ambient temperature on the transformer thermal performance. The results have been shown the transformer real life in colder region (Cairo) is higher than that at warmer region (Aswan). As the capability of transferring the internal generated heat at Cairo is higher than that at Aswan. This led to HST profile at Cairo is lower than that at Aswan. Also, the results have been shown the transformer at Cairo is more cost effectiveness and loading capability than that at Aswan. Hence, in the planning stage the long-term regional climatic conditions should be considered.

REFERENCES

[1] D. G. Ece and H. Akçay, “An analysis of transformer excitation current under nonsinusoidal supply voltage,” *IEEE Trans. Instrum. and Meas.*, vol. 51, pp. 1085-1089, 2002.

[2] J. Rosenlind, *Lifetime modeling and management of transformers*, Doctoral Thesis, KTH Royal Institute of Technology, Sweden, 2013.

[3] Y. Biçen, F. Aras and H. Kirkici, "Lifetime estimation and monitoring of power transformer considering annual load factors," *IEEE Trans. Dielectr. Electr. Insul.*, Vol. 21, pp. 1360-1367, 2014.

[4] M. M. Emara, D. A. Mansour and A. M. Azmy, "Mitigating the impact of aging byproducts in transformer oil using TiO2 nanofillers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, pp. 3471-3480, 2017.

[5] D. A. Mansour and A. M. Elsaeed, "Heat transfer properties of transformer oil-based nanofluids filled with Al_2O_3 nanoparticles," *IEEE Int'l. Conf. Power and Energy (PECON)*, Malaysia, pp. 123-127, 2014.

[6] P. S. Georgilakis, *Spotlight on modern transformer design*, Springer-Verlag London, 2009.

[7] W. H. Tang, Q. H. Wu and Z. J. Richardson, "A simplified transformer thermal model based on thermal-electric analogy," *IEEE Trans. Power Del.*, vol. 19, pp. 1112-1119, 2004.

[8] A. Elmoudi, M. Lehtonen, Hasse Nordman, "Effect of harmonics on transformers loss of life," *IEEE Int'l. Symp. Electr. Insul.*, Canada, pp. 408-411, 2006.

[9] https://sam.nrel.gov/weather, Thursday, 29-3-2018, 10:00 am.

[10] D. Susa, M. Lehtonen and H. Nordman, "Dynamic thermal modeling of distribution transformers," *IEEE Trans. Power Del.*, vol. 20, pp. 1919-1929, 2005.

[11] D. Susa and M. Lehtonen, "Dynamic thermal modeling of power transformers: Further development—Part I," *IEEE Trans. Power Del.*, vol. 21, pp. 1961-1970, 2006.

[12] A. Abbas, E. Abou Elzahab, and A. Elbendary, "Thermal modeling and ageing of transformer under harmonic currents," *23rd Int'l. Conf. Electricity Distribution*, France, pp. 1-5, 2015.

[13] IEEE, "IEEE guide for loading mineral-oil-immersed transformers," IEEE Standard C57.91-1995, 1996.

[14] www.egyptera.org, Wednesday, 4-4-2018, 11:00 am.