Graphical Abstract

Impact of the tap-changer positioning on the aging and the loading of the oil-immersed transformer

Mohamed Moenes Mohamed Salama, Diaa-Eldin A. Mansour, Samir Mohamed Abdelkasoud, Ahmed Abdelmoneim Abbas

Engineering Science and Technology,
an International Journal

journal homepage: www.elsevier.com/locate/jestch

Impact of the tap-changer positioning on the aging and the loading of the oil-immersed transformer

Mohamed Moenes Mohamed Salama [a], Diaa-Eldin A. Mansour [b], Samir Mohamed Abdelkasoud [a] and Ahmed Abdelmoneim Abbas [a,]*

[a] *Department of Electrical Power and Machines Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt*
[b] *Department of Electrical Power and Machines Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt*

ARTICLE INFO

Article history:
Received
Received in revised form
Accepted

Available online

Keywords:
hot spot temperature
top oil temperature
tap changer
loss of life

ABSTRACT

Adequate voltage in the medium and low voltage electrical network is a mandatory issue. The transformers tap-changer (TC) is used to achieve this vital issue. The increasing of the power demand and the integration of the distributed generation with the electrical grid led to adjusting the TC of the transformer. Adjusting TC leads to adjusting the thermal parameters of the transformer, which affect directly the winding hottest spot temperature of the transformer. In addition, the winding hottest spot temperature is a function of the ambient temperature and the load profile. The transformer aging is a function of the winding hottest spot temperature. The cost-effectiveness of the transformer is based on the transformer total losses cost. Hence, TC plays a vital role in determining the loading capacity, the aging, and cost-effectiveness of the transformer. In this paper, a 630 kVA, ±5% voltage tap at the low voltage winding, ONAN cooling type, oil – immersed transformer is considered. The derivation of the impact of the TC position is based on the variation of the voltage at the medium voltage side. The winding hottest spot temperature, the aging, the energy losses, and the loading of the transformer with varying the TC positions are simulated in MATLAB programming language. The results show the TC position has a great impact on the aging, the cost-efficient, and the loading of the transformer.

1. Introduction

In the electrical network, the voltage regulation should be guaranteed to avoid malfunction of the connected equipment. Hence, the disturbance into the voltage profiles at any point in the electrical network can cause a decline for the power quality [1, 2]. The continuous increasing in the electrical energy and the integration of the distributed generation (DG) with the electrical grid can cause a disturbance into the voltage profile at the end user [3]. The transformer tap-changer (TC) is used to guarantee a convenient voltage level for the end consumer. Hence, TC is available with a variety of tapping positions to provide a variety of the output voltages, which guarantee a good power quality at all voltage levels [4]. TC may be no-load or on-load. No-load TC also called as an off-circuit TC or de-energized TC. This type is used for not frequent changing of the voltage and will interrupt the service to change the tap. On-load TC is also called on-circuit TC. This type is used for frequent controlling of the voltage without interrupting the power for changing the tap. This type may be mechanical TC, hybrid (mechanical/electronic) TC, or fully electronic TC. The tapping for distribution and small auxiliary transformers will be no-load TC with ±5% variation. But for the tapping of larger transformers will be on-load TC with ±10% variation [5]. In [6], different schemes are used to monitor the voltage profiles by using voltage sensors and control the voltages via using TC.

The variation of the transformer TC leads to changing the winding resistance which varies the losses. The internal heat generation due to the losses will be transferred to the ambient. This heat will increase the winding hottest spot temperature (HST) and the top oil temperature (TOT). HST is the limit for the loading of the transformer which is 110°C. As if HST increased more than 110°C, the aging of the transformer will increase and the real life will be less than the normal life [7]. In this paper, the impact of TC positions on the aging and the loading of a 630 kVA, ±5% voltage tap at the low voltage (LV) winding, ONAN cooling type, oil – immersed transformer is demonstrated.

2. Transformer tap changer

The main objective of the transformer equipped with TC is to get back the voltage on the LV side to the desired value to ensure a good power quality. This denotes the TC needs to respond to the changes of the voltage on the LV and MV side of the transformer by moving the tap up or down [8]. The TC is more effectiveness and economical than the utility reinforcement to ensure a good power quality. On the other hand, TC motivated the researcher to maximize the size of the photovoltaic (PV) system. The voltage of most buses may come to the upper limit in the presence of PV. Hence, TC can get back the busses voltage to the nominal value and maximize the penetration of PV [9]. The selection of TC mainly relies on the voltage steps especially the maximum voltage step [10]. Due to the complexity of mechanical and electrical structures of TC, faults are often occurred [11].

The adjusting of TC step adjusts the number of turns of the winding which reflect on increasing or decreasing of the transformer losses. Eq. (1) shows the length of LV winding is proportional to the number of the turns. Eq. (2) shows the resistance of LV winding is proportional to the length of LV winding. Eq. (3) shows the proportionality relation of LV winding losses with LV winding resistance and the square of loading [4].

$$CL_{LV} = MT_{LV} x turns_{LV} \tag{1}$$

$$R_{LV} = \frac{\rho_{LV} x \, CL_{LV}}{area_{LV}} \quad (2)$$

$$LL_{LV} \; \alpha \; R_{LV} \; x \; I_{LV}^2 \quad (3)$$

Where:

CL_{LV}	LV winding length (m)
MT_{LV}	LV winding mean turn length (m)
$turns_{LV}$	number of turns of LV winding
R_{LV}	LV winding resistance (Ω)
ρ_{LV}	LV winding resistivity (Ω.m)
$area_{LV}$	LV winding cross section area (m^2)
LL_{LV}	LV winding ohmic losses (watt)
I_{LV}	LV winding current (A)

There are two types of TC mounting. The first type is called in tank TC. This type is used for higher currents and voltage levels. The change-over and selector switches are mounted at the bottom of TC but at the top of TC the diverter switch is mounted in a segregated compartment. The second type is called separate compartment TC. In this type, the diverter, change-over, and selector switches are located in a compartment. This type is bolted to the side of the tank. Fig. 1 shows the regulation types. Whereas S indicates the selector, R indicates reversing switch, and C indicates change-over switch. For linear type, the tapped turns are added to the main turns. Hence, the tap voltage will add to the main winding voltage. The tapped turns will be totally bypassed for minimum voltage. Change-over switch isn't required for this type. For reversing type, the tapped turns are connected with the main turns in reverse or additive polarity with the main turns. This type is giving larger tapping range with a disadvantage of higher copper losses at the minimum tap position. Coarse-fine type provides advantage of reversing type with lower copper losses. Bias winding is hassling to the coarse-fine but with number of turns is half the turns of one section of the tapped winding [12, 13].

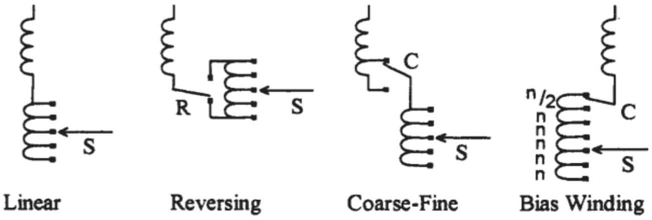

Figure 1. Main regulation types of TC.

In this paper, the response of TC at the LV side will be done as per the variation of the voltage on the medium voltage (MV) network. If the voltage at MV increased by 5% of the nominal voltage, TC at LV side tap down at -5% reducing the winding resistance, reducing the internal heat generation, reducing the transformer aging, and increasing the transformer loading capability vice versa.

3. Transformer thermal model

The transformer thermal model is used to simulate the winding HST and TOT. It can be used to monitor the loading of the transformer and study the capability to increase the loading or shed it. Hence, it is mandatory to be accurate [14]. The transformer internal heat generation is due to the transformer losses. The transformer losses are the ohmic losses, winding eddy current losses, other stray losses, and no-load losses. The ohmic losses are due to the flowing of the current through the resistance of the transformer winding. The winding eddy current losses are due to the linkage of the leakage flux and the winding. The other stray losses are due to the linkage of the leakage flux with the structural parts and the fittings of the transformer. The no-load losses are due to the linkage of the flux with the transformer core causing hysteresis and eddy current losses. The ohmic losses can be reduced by increasing the conductor cross section area but this will lead to increasing the winding eddy current losses [15]. This model is based on the thermal-electrical analogy for applying the heat transfer approach. The thermal performance of the transformer responds to the loading and the ambient temperature instantaneous changes. The thermal modeling of the transformer is considered as two intertwined models. TOT model is the first model to simulate TOT changes with the loading and ambient temperature changes with the oil time constant. The second model is HST which is interrelated with TOT model. The output of TOT model is used as feed in for HST model. HST model is used to emulate the changes of the winding HST with the loading and TOT instantaneous variations considering the winding time constant [16]. Fig. 2 shows the profile of the ambient temperature changes through the whole day. Fig. 3 shows the profile of the transformer loading through the whole day. Table 1 shows the thermal parameters of a 630 kVA, 0% voltage tap at the low voltage winding, ONAN cooling type, and mineral oil-filled transformer. Table 2 shows the cooling exponents variation according to the cooling type.

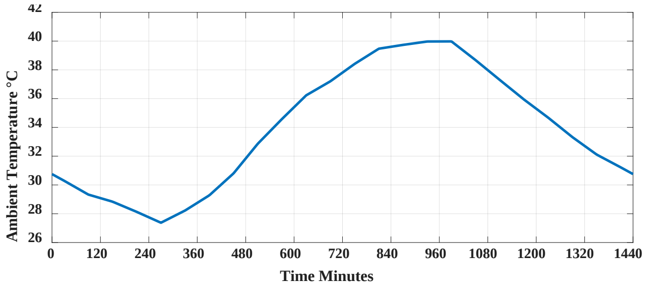

Figure 2. The profile of the ambient temperature changes through the whole day.

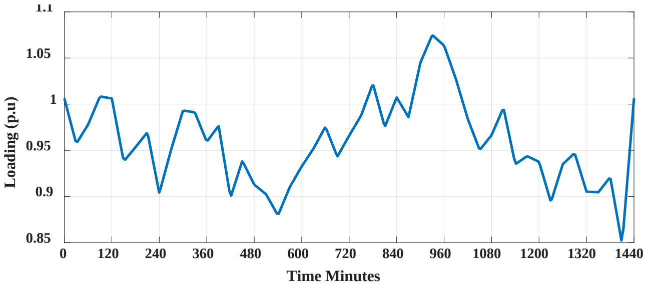

Figure 3. The profile of the transformer loading through the whole day.

Table 1. Thermal parameters of a 630 KVA, 0% voltage tap at the low voltage winding, oil-filled transformer

Rated ohmic losses ($\boldsymbol{I^2R}$)	9023 W
Windings eddy current losses under rated conditions ($\boldsymbol{P_{EC-R}}$)	665 W
Other stray losses in the structural parts under rated conditions ($\boldsymbol{P_{OSl-R}}$)	1350 W
No Load losses	1195 W
P.U eddy current losses at the hot spot location	0.72
Ratio of load losses under rated conditions to no load losses	9.24
Cooling constant n'	0.25
Cooling constant n	0.25

Table 2. Exponents used in temperature determination equations [7]

Type of Cooling	n'	n
In case of No external cooling	0.25	0.25
In case of external cooling	2	0.5

3.1 Top Oil Temperature (TOT) Model

The oil of the transformer is used as a cooling and an insulating medium. Hence for the transformer thermal model, the oil thermal properties such as the specific heat, thermal conductivity, dynamic viscosity, and density shall be considered [16]. Some of the total internal heat generated in the transformer will be transferred to the ambient temperature and some will be stored in the oil causing increasing or decreasing of TOT. The response of TOT with changing the loading and the ambient temperature is not instantaneously but with time constant which is called oil time constant. The time constant is a function of the total transformer losses which vary with the transformer TC position. The calculation of the top oil temperature can be as follows: [17]

$$\frac{1+RxK^2}{1+R} x \mu_{pu}^n x \Delta\theta_{oil,rated} = \mu_{pu}^n x \tau_{oil,rated} x \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil}-\theta_{amb})^{1+n}}{\Delta\theta_{oil,rated}^n} \quad (4)$$

$$\tau_{oil,rated} = C_{th-oil,rated} \frac{\Delta\theta_{oil,rated}}{q_{tot,rated}} x60 \quad (5)$$

Where:

$\Delta\theta_{oil,rated}$	TOT over the ambient temperature under rated conditions (°C)
θ_{amb}	ambient temperature of the whole day (°C)
$\tau_{oil,rated}$	rated of oil time constant (minutes)
K	the per unit of the transformer actual loading to the loading under rated conditions

$q_{tot,rated}$	total losses (load and no-load losses) of the transformer at rated condition (watt)
R	dividing of transformer load losses and no-load losses at rated condition
μ_{pu}	dynamic viscosity of the oil (per-unit)
$C_{th-oil,rated}$	thermal capacitance of the oil at rated condition (joules /°C)
n	cooling constant in case of air moving fluid

The thermal capacitance of the transformer oil in case of existing the external cooling can be formulized as follows: [16]

$$C_{th-oil} = Y_{fe} x\, m_{fe} x\, c_{fe} + Y_{wdn} x\, m_{wdn} x\, c_{wdn} + O_{oil} x\, m_{oil} x\, c_{oil} + Y_{st} x\, m_{mp} x\, c_{mp} \quad (6)$$

Where:

Y_{fe}	core losses of the transformer ratio to the entire losses
Y_{wdn}	winding losses ration to the entire losses
Y_{st}	stray losses proportion to the entire losses
m_{fe}	transformer core weighting (kilograms)
m_{wdn}	transformer winding weighting (kilograms)
m_{mp}	transformer tank and fittings weighting (kilograms)
m_{oil}	transformer oil weighting (kilograms)
c_{fe}	transformer core specific heat $(c_{fe} = 0.13\ Wh/kg°C)$
c_{wdn}	transformer winding specific heat $(c_{Cu} = 0.11\ and\ c_{Al} = 0.25\ Wh/kg°C)$
c_{oil}	transformer oil specific heat $(c_{oil} = 0.51\ Wh/kg°C)$
c_{mp}	transformer tank and fittings specific heat $(c_{mp} = 0.13\ Wh/kg°C)$
O_{oil}	correction factor of the oil for the ONAF and OFAF cooling types $(O_{oil} = 0.86\ Wh/kg°C)$

The thermal capacitance of the transformer oil in case of no external cooling can be expressed as follows: [18]

$$C_{th-oil} = m_{fe} x\, c_{fe} + m_{wdn} x\, c_{wdn} + m_{oil} x\, c_{oil} + m_{mp} x\, c_{mp} \quad (7)$$

MATLAB programming language is used to model (4) to simulate TOT through the whole day for the three scenarios of TC positions as shown in Fig. 4. The results show TOT for -5% tap is lower than that at 0% tap by 1.1°C at the instant of the peak load. But in case of +5% tap, TOT is higher than at 0% tap by 2.1°C.

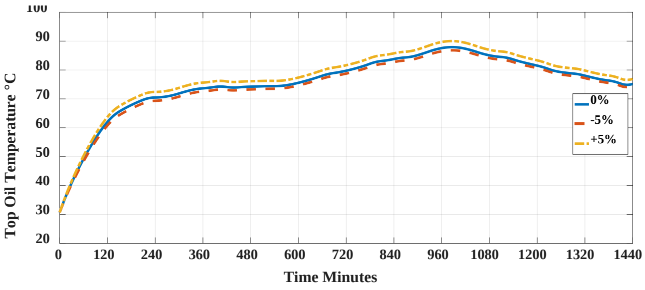

Figure 4. TOT for the different TC positions.

3.2 *Winding Hot Spot Temperature (HST) Model*

Some of the heat generated due to the losses in the windings will be transferred to the surrounding medium which is the oil and some will be stored in the winding causing increasing or decreasing of the winding HST. This model is used to calculate the winding HST which doesn't vary instantly with TOT and the loading variation but with time constant. The transformer thermal limit which is the winding HST at 110°C governs the transformer loading capability. Hence, HST model is used to determine the unused capacity of the transformer [19]. The winding HST can be calculated as: [17]

$$K^2 x \left(K_\theta + \frac{P_{EC-R\,pu}}{K_\theta}\right) x \mu_{pu}^n x \Delta\theta_{hs,rated} = \mu_{pu}^n x \tau_{wdg,rated} x \frac{d\theta_{hs}}{dt} + \frac{(\theta_{hs}-\theta_{oil})^{1+n'}}{\Delta\theta_{hs,rated}{}^{n'}} \quad (8)$$

$$K_\theta = \frac{\theta_K+\theta_{hs}}{\theta_K+\theta_{avg}} \quad (9)$$

Where:

θ_{hs}	variation of winding HST (°C)
$\Delta\theta_{hs,rated}$	winding HST rise over TOT at rated condition (°C)
$P_{EC-R\,pu}$	eddy current losses of the winding as a per unit at hot spot location at rated conditions
n'	cooling exponent for moving fluid (oil)
$\tau_{wdg,rated}$	winding time constant at rated conditions (minutes)
K_θ	correction of the resistance on account of temperature change
θ_K	temperature factor for the loss correction
θ_{avg}	average temperature of the winding under rated conditions

$\theta_K = 225$ for Aluminum
$\theta_K = 235$ for Copper

Eq. (8) is used for the calculation of the winding HST for the three scenarios of TC positions as shown in Fig. 5. Fig. 6 shows the winding HST for -5% tap is lower than that at 0% tap by 2.7°C but for +5% tap is higher than that at 0% tap by 5.2°C at the instant of peak load. This means that HST at -5% tap is lower than that at +5% tap by 7.9°C. The results show -5% tap led to higher loading capacity than that at +5% tap.

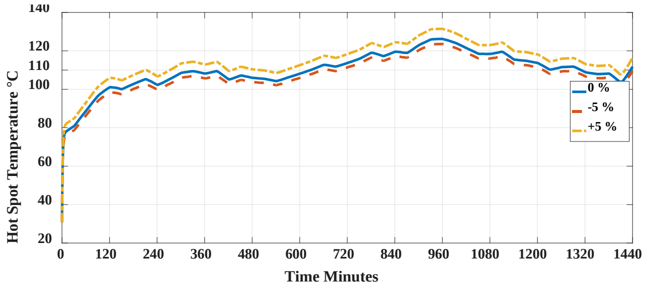

Figure 5. HST for the different TC positions.

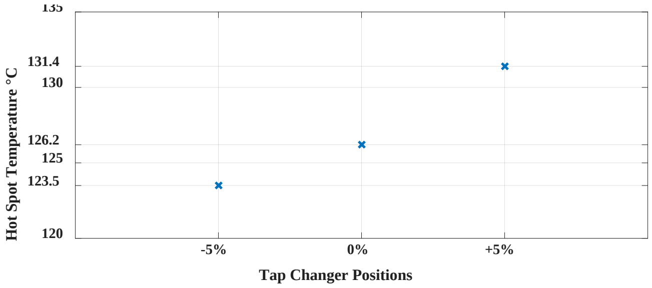

Figure 6. Maximum winding HST for the different TC positions.

4. Aging model

The loading of the transformer may exceed the rated loading with few amperes but without reducing the transformer life time. Because the surrounding average ambient temperature is lower than 30°C. Hence, the winding HST at 110°C represents the limit of the transformer aging. The winding HST represents the input for the transformer aging model. An allusion factor called aging acceleration factor (F_{AA}) is used for modeling the transformer aging. If HST increased by 6.9 °C, this factor will be doubled causing the real life to be half of the normal life. During period of time dt, the transformer loss of life (L_f) is expressed as in (12) [19].

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H+273}\right]} \quad (10)$$

$$dL = F_{AA} dt \quad (11)$$

$$L_f = \frac{1}{T}\int_0^T F_{AA}\, dt \quad (12)$$

$$L_f\% = \frac{\text{Accumulative age (hours)}*100}{180000} \quad (13)$$

Eq. (13) is used for the simulation of the loss of life percentage through the whole day for the three scenarios of TC positions as shown in Fig. 7. The results show the daily loss of life in case of -5%

tap is the lowest one achieving 0.01434%, at 0% tap achieves 0.01825%, and at +5% tap achieves 0.02908%. The results show the aging at +5% tap is higher than double of that at -5% tap. This reduction in the aging of the transformer is due to the lower winding resistance at -5% tap which led to the reduction of losses and the internal heat generation.

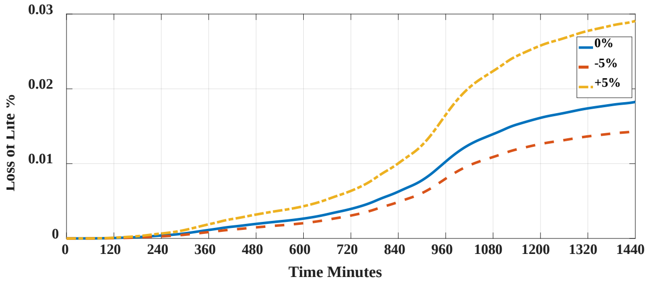

Figure 7. Daily loss of life for the different TC positions.

5. Transformer energy losses

Due to modifying the TC positions, the resistance of the windings will vary causing variation of the transformer energy losses. If the winding resistance is increased due to increasing the number of winding turns, the transformer energy losses will be increased. Hence, the consumed energy from the utility will be increased causing increasing into the cost of energy consumption. The cost-effectiveness of the transformer relies on total energy losses cost and the bid price of the transformer. In this paper, the transformer bid price is constant as the same transformer is considered. Hence, the TC positions play an important role to determine the cost effectiveness of the transformer based on the cost of the total energy losses. The transformer energy losses can be calculated by determining the area under the curve of the transformer energy losses through the whole day. The cost of them will be obtained by multiplied the energy losses by the energy tarrif which is 1.05 LE/kWh.

As shown in Fig. 8, the transformer monthly energy losses in case of -5% tap is lower than that at 0% tap by 465 kWh. But in case of +5% tap is higher than that at 0% tap by 615 kWh. This means the transformer monthly energy losses in case of -5% tap is lower than that at +5% tap by 1080 kWh. The results show -5% tap caused the transformer is more cost effective than that at 0% tap or +5% tap.

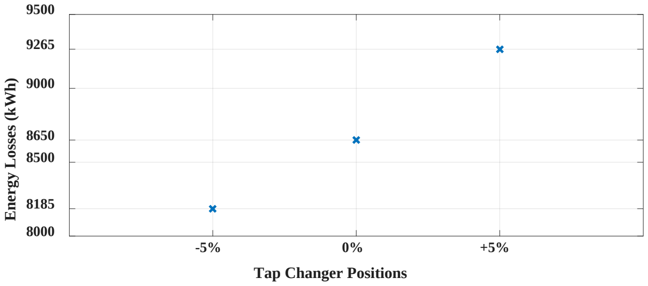

Figure 8. Monthly energy losses of the transformer for the different TC positions.

6. Transformer loading capability

The results of the winding HST model show -5% tap led to the lowest HST and +5% tap led to the highest HST. Hence it is mandatory to show to what extent the tap changer positions affect the transformer loading. The transformer loading is based on the winding HST which will be affected by the transformer total losses, ambient temperature, and the thermal characteristics of the oil. Hence, it's recommended to use materials for the core, conductors, and the structural parts of the transformer with minimum losses.

Eq. (4, 8) are used to simulate the winding HST under ambient temperature of 30℃ with varying the transformer loading starting from 0.1 P.U to 1.1 P.U as shown in Table 3. The results show the transformer loading capability under -5% tap shall not exceed 98.4%, under 0% tap shall not exceed 96.12%, and under +5% tap shall not exceed 91.9% to avoid exceeding HST of 110℃ as shown in Fig. 9.

Table 3. Winding HST (℃) versus the transformer loading

Loading(P.U)	Winding HST ℃ under different positions of TC		
	-5% tap	0% tap	+5% tap
0.1	40.9	40.9	41.08
0.2	44.67	44.86	45.33
0.3	50.14	50.48	51.36
0.4	56.79	57.41	58.77
0.5	64.42	65.34	67.24
0.6	72.86	74.06	76.52
0.7	81.89	83.41	86.45
0.8	91.4	93.26	96.91
0.9	101.4	103.5	107.8
1	111.6	114.1	119.1
1.1	122.1	125.1	130.6

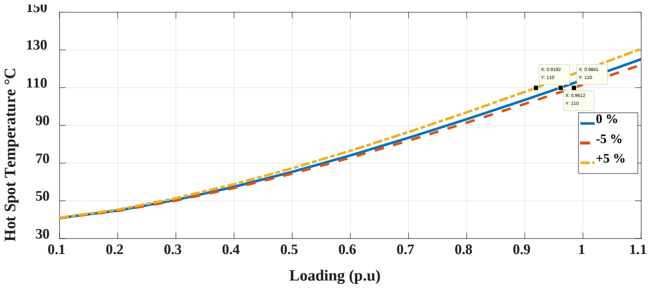

Figure 9. The transformer loading capability considering the tap changer positions.

7. Conclusion

This paper shows the impact of the TC positions on the aging and the cost-effectiveness of the oil-immersed transformer. A 630 kVA, ONAN cooling type, ±5% voltage tap at the low voltage winding transformer is considered. The results show the winding HST at -5% tap is lower than that at +5% tap by 7.9℃ and this will lead to more transformer loading capacity. Also the aging at +5% tap is higher than double of that at -5% tap. The transformer monthly energy losses in case of -5% tap is lower than that at +5% tap by 1080 kWh. Hence, the transformer at -5% tap is more cost-effectiveness than that at +5% tap. The transformer loading capability under -5% tap is higher than that under +5% tap with 6.5%. Hence, the impact of the tap position of the transformer should be considered in the planning stage of the electrical network.

References

1. M. Todorovski, Transformer voltage regulation – compact expression dependent on tap position and primary/secondary voltage, IEEE Trans. on Power Delivery, vol. 29, no. 3, (2014) pp. 1516-1517.
2. S. Jothibasu, M. K. Mishra, An Improved Direct AC–AC Converter for Voltage Sag Mitigation, IEEE Trans. on Industrial Electronics, vol. 62, no.1, (2015) pp. 21-29.
3. Josemar de Oliveira Quevedo, Fabricio Emmanuel Cazakevicius, Rafael Concatto Beltrame, Tiago Bandeira Marchesan, Leandro Michels, Cassiano Rech, and Luciano Schuch, Analysis and Design of an Electronic On-Load Tap Changer Distribution Transformer for Automatic Voltage Regulation, IEEE Trans. on Industrial Electronics, vol. 64, no.1, (2017) pp. 883-894.
4. Pavlos S. Georgilakis, Spotlight on Modern Transformer Design, Technical University of Crete, 2009.
5. Martin J. Heathcote, The J & P Transformer Book, Elsevier Ltd, 2007.
6. Kalle Rauma, Florent Cadoux, Guillaume Roupioz, Adrien Dufournet, and Nouredine Hadj-Said, Optimal Location of Voltage Sensors in Low Voltage Networks for on-load Tap Changer Application, IET Gener. Transm. Distrib., Vol. 11, (2017) pp. 3756–3764.
7. Mohamed M. M. Salama, Diaa-Eldin A. Mansour, Samir Mohamed Abdelkasoud, and Ahmed Abbas, Impact of Long-Term Climatic

Conditions on the Ageing and Cost Effectiveness of the Oil-Filled Transformer, 2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo University, Egypt, (2018) pp. 494-499.

8. Momen Bahadornejad and Nirmal-Kumar C. Nair, Intelligent Control of On-Load Tap Changing Transformer, IEEE Transactions on Smart Grid, Vol. 5, (2014) pp. 2255-2263.
9. Tariq Aziz and Nipon Ketjoy, Enhancing PV Penetration in LV Networks Using Reactive Power Control and On Load Tap Changer With Existing Transformers, IEEE Access, Vol. 6, (2017) pp. 2683-2691.
10. Guishu Liang, Litong Wang, Fei Gao, and Xin Liu, A New Maximum Step Voltage Calculation Method of On-Load Tap-Changer for Symmetrical Two-Core Phase Shifting Transformer, IEEE Transactions on Power Delivery, Vol. 33, (2018) pp. 2718-2725.
11. Zhenhua Li, Qiuhui Li, Zhengtian Wu, Jie Yu, and Ronghao Zheng, A Fault Diagnosis Method for On Load Tap Changer of Aerospace Power Grid Based on the Current Detection, IEEE Access, Vol. 6, (2018) pp. 24148 - 24156.
12. Martin J. Heathcote, Transformer Design Principles with Applications to Core-Form Power Transformers, CRC Press LLC, 2002.
13. Colin Bayliss and Brian Hardy, Transmission and Distribution Electrical Engineering, Elsevier Ltd, 2012.
14. Ahmed Abbas, Essam Abou Elzahab, and Ahmed Elbendary, Thermal Modeling and Ageing of Transformer under Harmonic Currents, 23rd International Conference on Electricity Distribution, lyon, 2015.
15. James H. Harlow, Electric Power Transformer Engineering, CRC Press LLC, 2004.
16. Dejan Susa and Hasse Nordman, A Simple Model for Calculating Transformer Hot-Spot Temperature, IEEE Transactions on Power Delivery, Vol. 24, (2009) pp. 1257-1265.
17. Yi Cui, Hui Ma, Tapan Saha, Chandima Ekanayake, and Daniel Martin, Moisture-Dependent Thermal Modelling of Power Transformer, IEEE Transactions on Power Delivery, Vol. 31, No. 5, (2016) pp. 2140-2150.
18. Dejan Susa and Matti Lehtonen, Dynamic Thermal Modeling of Power Transformers: Further Development—Part I, IEEE Transactions on Power Delivery, Vol. 21, No. 4, (2006) pp. 1961-1970.
19. Nikolaos G. Paterakis, Iliana N. Pappi, Ozan Erdinç, Radu Godina, Eduardo M. G. Rodrigues, and João P. S. Catalão, Consideration of the Impacts of a Smart Neighborhood Load on Transformer Aging, IEEE Transactions on Smart Grid, Vol. 7, (2016) pp. 2793-2802.