Proceedings of 12th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: October Volume: 12

Impact in Substation Power Transformer Due to Injection of Non-linear Load

Sujit Tiwari [a], Mahammad Badrudoza [b]

[a] *Department of Mechanical and Aerospace Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[b] *Department of Electrical Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[a] tiwari.sujit88@gmail.com, [b] mbadrudoza@ioe.edu.np

Abstract
In electrical power system transformer is consider as one of the mostly used major component. The thermal condition of transformer is considered as a critical case while operating in abnormal conditions such as harmonic loading. In this paper, transformer thermal behavior analysis is carried out due to influence of nonlinear load and impact on its life is simulated and analyzed. As, additional heat is generated due to core loss in transformer caused by harmonic load which will increase in hot spot temperature and decrease in transformer loading capacity. For this purposed, IEEE standard C57.91 modelling is used to identify the hot spot temperature of transformer by using MATLAB simulation at different nonlinear loading conditions. The measured hot spot temperature of 22.5 MVA, 66/11 kV, ONAF cooling temperature at different loading conditions are compared with the model. It is concluded that the temperature of transformer rises with the percentage increase in non-linear loading of the transformer. There is significant loss of life of transformer is noticed when non-linear loading insertion is greater than 15 percent of total transformer rating. So, awareness of the effect on increasing non-linear load must be considered while inserting large number of non-linear loads in feeder and designing the next generation of transformer.

Keywords
Transformer, Non-linear Load, Harmonics, Hot spot temperature, Loss of life

1. Introduction

Transformer is also considered as expensive and major component of power system networks. As, it is always in continues operation so, the attempts are always made to prevent from failure. Normally, insulation breakdown is the common cause for transformer failure. The hot spot temperature of transformer winding is important factor for aging of transformer. The main problem of non-sinusoidal waves of current experienced in the modern electric devices are from nonlinear loads as electronic and electrical equipment have built-in feature with electronic components that is used for control mechanism and to make efficient use of energy [1, 2]. These days there is increase of the harmonic loads which adds stresses on the electrical transformers by increasing their built-in losses and consequently the devices have to go through premature aging or even failure [3].

Aging of transformer insulation is in close relationship with humidity level, temperature and the percentage of oxygen level contain in the air. These days, change in design and construction of transformer has terminated the impact of oxygen and moisture level on the oil of transformer. Therefore, the dominance of these factors can be ignored due to which transformer life is reduced. The unsettled factor is temperature due to which the transformer life is affected severely [3, 4]. The temperature distribution of transformer in overall surface is not uniform so in order to identify the prominent temperature in transformer part which adds in the transformer loss of life i.e., highest temperature part called as hotspot of the transformer is used. There are lots of factors which affect temperature so that the reduction in service life of transformer cannot be identified correctly even if it is considered under constant and controlled or uncontrolled and conditions [3, 5]. Hence, to determine the most accurate prediction of the remaining life and loss of life of the transformer the internationally defined standard, namely the IEEE standards is essential to use.

The paper deals with the analysis of the losses under nonlinear loading condition uses IEEE guide to determine the transformer hot spot temperature[6]. Also, awareness from failures and to determine the operational life of transformers in order to avoid blackouts of distribution system, approach used for predicting the loss of life of transformers based on hotspot temperature is convenient. Evaluating the insulation life of the transformer by calculating hot spot temperature which is based on Arrhenius theorem and the aging factor of winding insulation described in IEEE C57.91[7] procedure use maximum value of hot spot temperature by 110 °C [8]. The execution of the prediction strategies can make the transformer perform with higher efficiency at the appropriate non-linear loading conditions before any serious damage happen to transformers and results in blackouts.

The transformer has crucial role and it is considered as the major part of the electrical system network because of many reasons such as, it is so costly and it has direct effect on operation of network. So, it must be protected from failure otherwise will affect the electrical network and result into blackout condition. The oil temperature rise is considered as main reason for transformer failure. The rating of transformer is determined by winding temperature which limits the transformer loading therefore, the oil of transformer must remain in its standards as per manufacture. The whole winding temperature of the transformer is not uniform. Therefore, the standard value is identified by the highest temperature of the transformer winding section. This temperature of the winding insulation represents the major factor for aging of transformer. The rise in ambient temperature and the temperature increases due to loading experience the greater loss of life percentage in transformer[9, 10]. As, non-linear loads are being increased continuously which will supplement hot spot temperature rise of transformer[10]. It is important to understand behavior of temperature rise in the transformer with the changes in harmonic loading, and how these changes have effect in the transformer lifespan. So, a designed model is expected to calculate the winding hot spot temperature of transformer on different non-linear loading, ambient temperature and the impact in sizing of the transformer.

In this paper a model is designed and is expected to analyze the hot spot temperature of transformer on different percentage of non-linear loading, ambient temperature and the impact in sizing of the transformer. The main objective of this thesis is to determine the impact in transformer life due to operating with non-linear load injection, ambient temperature change due to seasonal variations and the impact in sizing of the transformer.

2. Methodology

All the electrical equipment has its nominal life from its installation to the operation of devices. The aging of devices is influenced by the deterioration of insulation of the equipment. This process of degradation involves the numerous factor such as mechanical stress, moisture content, ambient temperature and the working temperature of the equipment. Among all the working temperature is considered as the most dominant factor that determines the life span of devices. Since, the temperature in most of the equipment is not uniformly distributed, so the devices will experience larger deterioration at the part where highest temperature has occurred. Hence, in loss of life studies, it is useful to consider the highest temperature known as hot spot temperature.

MATLAB program has been used to simulate the input loading, non-linear loading, ambient temperature and transformers data to obtain the hot spot temperature and top-oil temperature of transformer. These temperatures were carried out by use of IEEE Std C57.91 model. The calculated output is being utilized to calculate the sizing of transformer, aging acceleration factor and the loss of life of transformer.

The figure 1 shows all the step-to-step procedure to calculate the loss of life of transformer by insertion of non-linear load to existing load of Lainchaur substation transformer. Real time data has been taken form lainchaur substation transformer of 22.5 MVA, 66/11 kV system to acquire the daily load of winter and summer seasons in the time interval of hourly loading. In this study the transformer used has a 20 year of life time based on the IEEE standards where average ambient temperature for winter season was 6°C and for summer it was 24°C. The other required parameter of transformer for IEEE standards simulation was taken from name plate of transformer. The pu_1 loading of 22.5 MVA transformer in summer and winter seasons with ambient temperature is taken. The non-linear load pu_2 containing THD is inserted into the model in order to calculate total load pu_3 including eddy current losses. Therefore, overall load the sum of pu_1 and pu_3 is taken for top oil and hot spot model to calculate final hot spot temperature. Loss of life factor is calculated by the using aging acceleration factor F_AA(t) at every hour which is the function of hot spot model.

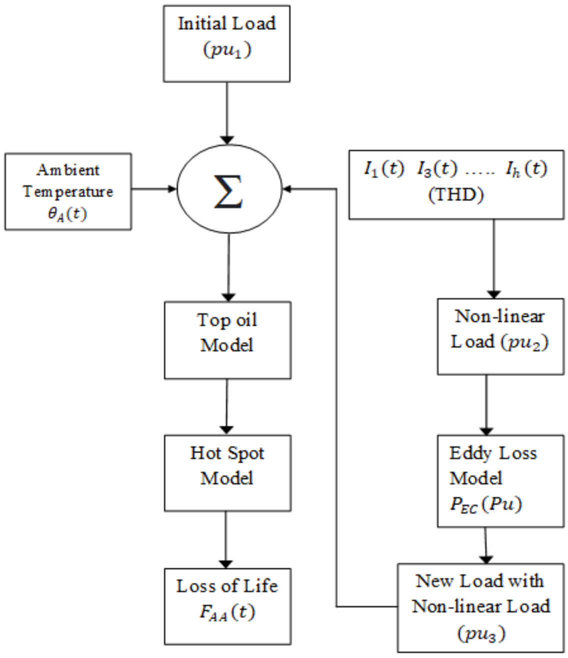

Figure 1: Simplified diagram for HST with loss of life

2.1 Top oil transformer temperature model

The model for overall increase in the temperature is due to temperature rise of top oil over the ambient temperature which shows that an increase in the losses of transformer is due to its loading current of the device. The change in temperature of transformer depends on the overall thermal time constant. The mass of core, coils, and oil are the factors that depends on the heat capacity of transformer and the rate at which heat is transferred out of transformer. So, temperature change is a function of time which has been modelled as a first-order exponential response that change from the initial temperature state to its final temperature state is in the equation (1)[11].

$$\Delta\Theta_T oil = [\Delta\Theta_{TO,u} - \Delta\Theta_{TO,i}][1 - e^{-t/T_{TO}}] + \Delta\Theta_{TO,i} \quad (1)$$

Where, $\Delta\Theta_{TO,i}$ represents initial temperature rise, $\Delta\Theta_{TO,u}$ represents final temperature rise, T_{TO} represents top oil time constant, t is time refers to the time of change in loading and $\Delta\Theta_{TOil}$ gives top oil temperature rise over ambient temperature variable. Equation (1) is the solution of the first-order differential equation (2).

$$T_{TO}\frac{d\Theta_{Toil}}{dt} + \Theta_{TO,u} = \Theta_{TO,i} \quad (2)$$

From IEEE standards model, the final temperature rise is dependent on the existing load of transformer and obtained by the equation (3)[7].

$$\Delta\Theta_{TO,u} = \Delta\Theta_{TO,R}[\frac{K_u^2R+1}{R+1}]^n \quad (3)$$

Where, $\Delta\Theta_{TO,u}$ gives rated load top oil temperature rise over ambient temperature. R is the ratio of full load loss to no-load loss. K represents ratio of the particular load to full load where, $K = \frac{I}{I_{rated}}$ and n is an exponent value which depends on method of cooling. It is recommended to use n = 0.8 for natural air convection and n = 0.9 to 1.0 for air forced cooling of transformer. Equations (1) and (3) are thermal model for the IEEE top oil temperature rise. The time constant of top-oil at the particular load is given by equation (4)[7].

$$T_{TO,u} = \frac{C_{th-oil}X\Delta\Theta_{TO,R}}{q_{tot,rated}} \quad (4)$$

Where, T_{TO} represents rated top-oil time constant taken in hours, $\Delta\Theta_{TO,R}$ gives rated top-oil temperature rise, $q_{tot,rated}$ gives the total losses in watts (W), which is at the rated load and the equivalent thermal capacitance represented as C_{th-oil} of the transformer oil (Watthours / °C). Finally, the thermal capacitance for the transformer oil is obtain by the equations (5)[11].

$$C_{th-oil} = 0.48XM_{oil} \quad (5)$$

M_{oil} is the weight of oil in transformer measured in kilograms (kg). This equation is based on heat run tests which is intrinsically taken into consideration with the effect of the metallic parts also which is recommended to use when only the information of transformer fluid mass is known.

2.2 Hot spot temperature model

The increase in transformer losses due to loading is the effect of current increase which will increase the temperature of oil and the winding of transformer[7]. The transformer temperature state change from initial state to final state of the hot spot rise is a first order exponential response, calculated as equation (6).

$$\Delta\Theta_H = [\Delta\Theta_{Hu} - \Delta\Theta_{Hi}][1 - e^{-t/T_H}] + \Delta\Theta_{Hi} \quad (6)$$

Where, $\Delta\Theta_{Hi}$ represents initial temperature rise, $\Delta\Theta_{Hu}$ represents final temperature rise, T_H represents hot spot time constant, t is time refers to the time of change in loading of transformer and $\Delta\Theta_H$ gives hot spot temperature rise. The first-order differential equation solution represents equation (6).

$$T_h \frac{d\Theta_h}{dt} + \Theta_h = \Theta_{hu} \quad (7)$$

$$\Delta\Theta_{Hu} = \Delta\Theta_{H,R}[K_u]^{2m} \quad (8)$$

Where, $\Delta\Theta_{H,R}$ gives rated hot spot temperature rise and m is an exponent value depending on the methods of cooling. The hot spot time constant of transformer winding, is calculated as in equation (9)[7].

$$T_H = 2.75X \frac{\Delta\Theta_{H,R}}{(1+P_e)XS^2} \quad (9)$$

Where, T_H is the time constant of winding at the rated load measured in minutes; Pe gives relative winding eddy losses of transformer; S gives current density measured in A/mm^2 at rated loading of transformer. Finally, by adding the ambient temperature with top oil temperature rise and the hot spot temperature rise, the hot spot temperature of transformer is calculated in equation (10).

$$\Theta_H = \Theta_A + \Delta\Theta_H + \Delta\Theta_{Toil} \quad (10)$$

Where, Θ_A represents ambient temperature and Θ_H represents hot spot temperature.

2.3 Power (Loss) due to non-linear load model

For the transformer having rated current greater than 1000A, the eddy current losses (power) in pu are given by equations[12](11) and (12) which is required equivalent power of transformer under non-linear loads.

$$P_{EC}(Pu) = \frac{2.8P_{EC-R}}{3I_2^2R_L} \quad (11)$$

Where, P_{EC-R} is pu eddy losses at rated load and hot spot location. The I^2R loss at the rated load is 1 pu in the assumption that all of the stray losses equal to eddy current losses of transformer windings.

$$I_{max}(Pu) = [\frac{1+P_{EC-R}(pu)}{1+KP_{EC-R}(pu)}]^{\frac{1}{2}} \quad (12)$$

Where, factor K value is one, when rms current of loading equals to transformer rated current.

2.4 Simulation of Transformer Loss of life model

At each instant of time the hot spot temperature is the result of sum of three components ambient θ_A, top oil rise $\Delta\Theta_{Toil}$ and hot spot rise temperature $\Delta\Theta_H$ represented by equation (10). Additional heat generated $P_{EC}(Pu)$ by harmonics loads is given by equation (11) and (12). Finally, loss of life factor is calculated by the using aging acceleration factor $F_{AA}(t)$ at every hour which is the function of hot spot model and given by equation (13).

$$F_{AA} = exp[\frac{15000}{383} - \frac{15000}{\Theta_H + 273}] \quad (13)$$

The model equations are being solved by the use of MATLAB Simulink for top oil and hot spot model along with equation (13) is used to determine loss of life of transformer by harmonic loading.

3. Results and Discussion

In the study it is considered that for load factor equals to one the maximum loading will be 540MWh per day of energy. So, percentage of loading per day is considered in the analysis of result in both winter and summer seasons respectively. For the worst case, loading of peak hour has been consider in calculation of hot spot temperature and loss of life of transformer. Non-linear loading has been added on the simulation model in order to determine the effect of harmonic loading on winding hot spot temperature and transformer loss of life from its normal life.

3.1 Analysis of the Effects of Loading on Loss of Life

In this study, the daily load and the ambient temperature of substation transformer has been taken at the interval of every hour. Then, the peak load is determined from the daily load cure. Also, the percentage of non-linear loads were inserted in the simulation model to calculate hot spot temperature and the aging acceleration factor. In figure 2 daily load curve reached peak demand at 11 AM which is 0.65 pu loading of transformer. At, the time ambient temperature has been 6°C recorded. For, average loading it has been around 258 MWh per day of energy. The average loading is near about 0.47 pu. In this case, at peak load the hot spot temperature of the transformer is 39.2°C given by IEEE standards model.

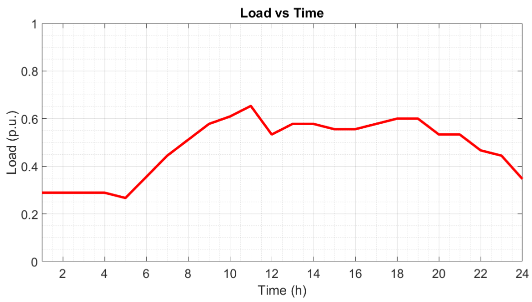

Figure 2: Daily Load Cure for Winter Season

The figure 3 shows the hot spot temperature of transformer at base load condition at recorded ambient temperature.

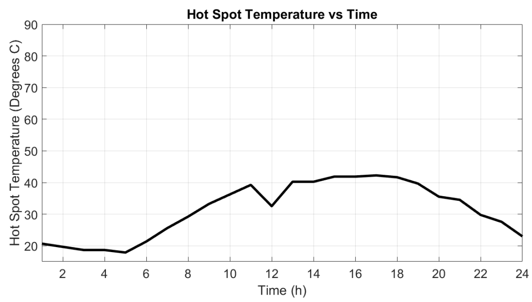

Figure 3: Hot spot Temperature as per Base Load Condition

In hot spot temperature vs time graph the hot spot temperature is rising after 12 PM sharply because of rise in ambient temperature from 7°C to 12°C even if pu loading is decreased. This shows that hot spot temperature is dependent on ambient temperature too.

The figure 4 shows the exponential pattern for loss of life of transformer by insertion of non-linear load in the distribution system. The non-linear load is being inserted in simulation model by certain percentage of the transformer capacity. The hot spot temperature at the time of peak load is used in different percentage loading to calculate the aging acceleration factor of transformer. So, the factor for aging acceleration is used to calculate loss of life per day if loading will be 24 hours for a day. It came to know that after 15% of non-linear loading the loss of life will sharply increase. When the non-linear loads increase above 15% the harmonic current will also rise. This will add up eddy current loss to generated additional heat. Hence, hot spot temperature increases with increase in aging acceleration factor and consequently the loss of life of transformer is significantly increases.

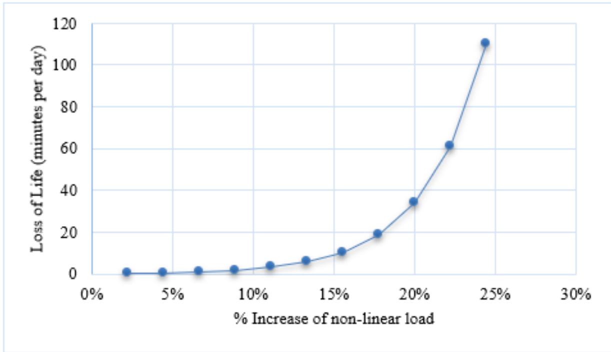

Figure 4: Effect of Non-linear Loading on Transformer Life (Winter)

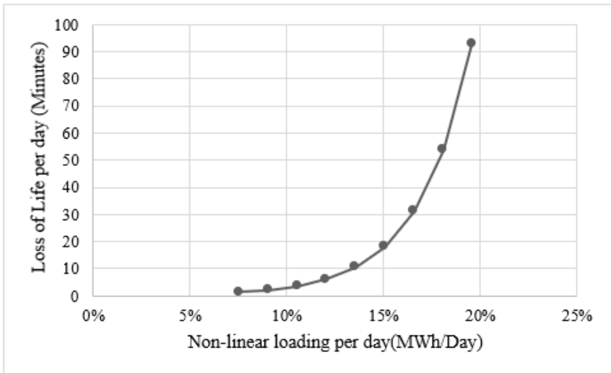

Figure 5: Effect of Non-linear Average Loading on Transformer Life (winter)

As, the ambient temperature is changed frequently and hot spot temperature is also the function of the ambient temperature. The transformer life is dependent on the hot spot temperature. For better understanding of loss of life of transformer, the cumulative aging acceleration factor for 24 hour is taken in model. This will give the aging acceleration factor for every hour. Finally, the cumulative factor will provide the better information about loss of life of transformer.

The figure 5 shows the significant loss of life of transformer when loading of non-linear load exceed 15% of rated capacity of transformer. The transformer is initially loaded at 47% of average loading per day. When there is non-linear loading up to 10% the effect of loss of life is negligible. But when the loading increases above 15% the loss of life is being noted to be 20 minutes per day. After that if the loading percentage increases the loss of life of transformer will increase exponentially.

3.2 Analysis of Hot spot Temperature Towards Non-linear Load Increase

When transformer is at 65% loading the hot spot temperature is 39.4°C at ambient temperature of 6°C. It shows that hot spot temperature rises by less than 1°C for every 1% load increase. But in case of harmonic loading the pattern is different from linear loads.

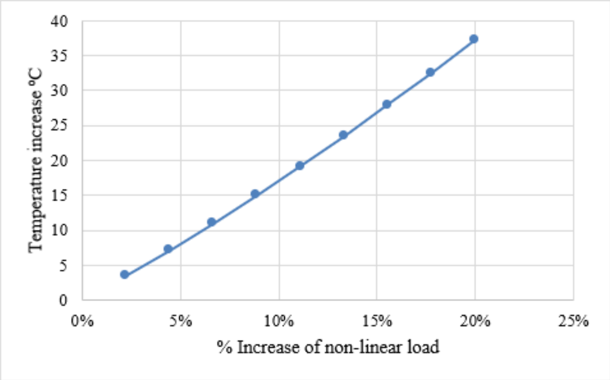

Figure 6: Effect on hot spot temperature rise due to harmonic loads (Winter)

The figure 6 shows the increase in hot spot temperature with the increase in percentage loading of non-linear load. It shows for every 1% increase in non-linear load the hot spot temperature rises by 2°C. As we know that the hot spot temperature can go up to 110°C maximum after that the winding insulation of transformer will degrade sharply and leads to failure.

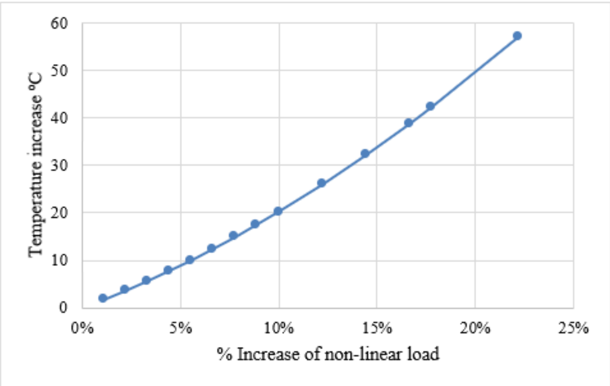

Figure 7: Effect on hot spot temperature rise due to harmonic loads (Summer)

The figure 7 also shows the effect on hot spot temperature rise due to harmonic loads in case of summer. In this case up to 10% of harmonic loading for every percentage rise in non-linear load the hot spot temperature rises by 2°C maximum. But when the harmonic loading is increased above 13%, for every percentage loading of non-linear load the hot spot temperature will rise greater than 2°C. In this case ambient temperature was already at 24°C. So, that increasing the harmonic loading the effect of ambient temperature also come into play.

3.3 Analysis of Non-Linear Loading Towards Sizing of Transformer

The rated capacity of transformer is limited by the hot spot temperature of the transformer at rated load. As, per design consideration and IEEE standards normally the maximum hot spot temperature of transformer is 110°C. If the loading of transformer is increased then the heat is generated inside transformer due to currents flowing through windings along with eddy current loss. This will cause to increase in hot spot temperature.

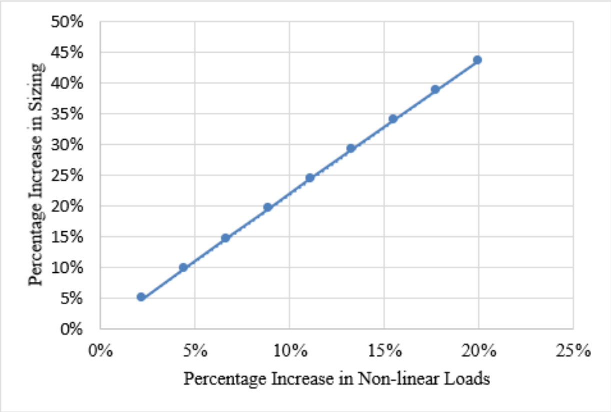

Figure 8: Effect on sizing of transformer in different non-linear loading condition (winter)

The figure 8 shows the linear relationship for percentage increase of size of transformer as per percentage increase in harmonic loading. For, every 1% increase in harmonic loading the size of transformer increases by 2 percentage. This is because the company standards transformer had already declared the value for rise in hot spot temperature for specific loading condition in case of linear load. But due to harmonic loading there will be extra losses in transformer due to eddy current loss which will increase the hot spot temperature before actual loading conditions. Finally, transformer will be in more loading than it was actually loaded.

The ambient temperature come in to play when hot spot temperature is determined so, in sizing of transformer ambient temperature will affect. The figure 9 shows the effect of ambient temperature in sizing of transformer when non-linear load is inserted. It makes clear that for every 1% increase in harmonic loading the sizing of transformer will increase by 3%.

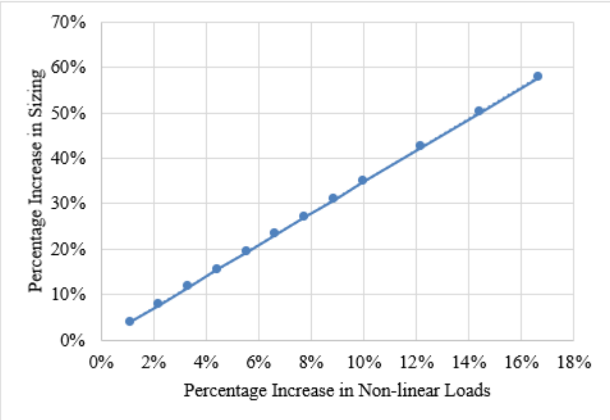

Figure 9: Effect on sizing of transformer in different non-linear loading condition (Summer)

The ambient temperature will come in to play in order to increase hot spot temperature along with eddy current losses. Ambient temperature added into the transformer results in temperature increase in the transformer. This increase in temperature of transformer is accelerated by heating due to continuous loading of the transformer.

From figure 5 at 18% of non-linear load insertion the transformer has load factor of around 0.65 pu and where aging acceleration factor becomes 1 for per day cycle as loss of life of transformer shows 60 minutes per day. Similarly, for validation paper[13] demonstrated the aging acceleration factor of 1 at load factor of pu 0.646 by operating 250 kVA oil type transformer under nonlinear loads condition.

4. Conclusion and Recommendation

The consequence of non-linear loading with loss in nominal life of the transformer relationship is exponential in nature, that indicates higher the harmonic load of the transformer, nominal life will sharply decrease such that the transformer will be failure abruptly. The transformer considered in the study shows the significant life reduction while non-linear loads is injected above 15% of the transformer rating. It concluded that the higher the harmonic load current there will be greater additional of losses in the transformer windings and core which cause raise in temperature of transformer higher than the standard operating temperature. This indicates that hot spot temperature increases by 2°C for every 1% increase of non-linear loading of rated capacity of transformer along with 2% increase in size of transformer. Therefore, manufacturers along with users of transformers should address the impact of non-linear load behavior and its vulnerability to acquire a procedure in order to prevent premature failure of transformer by improving the power system reliability. By derating of transformer loading capacity, we can achieve the recent solution for the addressed problem.

Acknowledgments

The authors are thankful to Nepal Electricity Authority of Lainchaur substation for providing necessary data.

References

[1] Kerry D McBee, P Rudraraju, and J Chong. Transformer rating due to high penetrations of pv, ev charging, and energy storage. In *2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, pages 1–5. IEEE, 2019.

[2] Amin Mohsenzadeh, Mohammad Heidari Kapourchali, Chengzong Pang, and Visvakumar Aravinthan. Impact of smart home management strategies on expected lifetime of transformer. In *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, pages 1–5. IEEE, 2016.

[3] Emil Cazacu, Lucian Petrescu, and Valentin Ionita. Derating of power distribution transformers serving nonlinear industrial loads. In *2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP)*, pages 90–95. IEEE, 2017.

[4] Ewald F Fuchs, Dingsheng Lin, and Jonas Martynaitis. Measurement of three-phase transformer derating and reactive power demand under nonlinear loading conditions. *IEEE Transactions on Power Delivery*, 21(2):665–672, 2006.

[5] Deniz Yildirim and Ewald F Fuchs. Measured transformer derating and comparison with harmonic loss factor (f/sub hl/) approach. *IEEE Transactions on Power Delivery*, 15(1):186–191, 2000.

[6] Shamsodin Taheri, Hamed Taheri, Issouf Fofana, Hossein Hemmatjou, and Ahmad Gholami. Effect of power system harmonics on transformer loading capability and hot spot temperature. In *2012 25th IEEE Canadian Conference on Electrical and*

Computer Engineering (CCECE), pages 1–4. IEEE, 2012.

[7] Ieee guide for loading mineral-oil-immersed transformers and step-voltage regulators. *IEEE Std C57.91-2011 (Revision of IEEE Std C57.91-1995)*, pages 1–123, 2012.

[8] Dai Wan, Miao Zhao, Xujin Duan, Hengyi Zhou, Liuming Mao, and Kai You. Life assessment study on distribution electric power transmission equipment based on harmonic modified hot spot temperature calculating model. In *2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2)*, pages 138–141. IEEE, 2019.

[9] Sarah Afifah, Jannus Maurits Nainggolan, Gunawan Wibisono, and Chairul Hudaya. Prediction of power transformers lifetime using thermal modeling analysis. In *2019 IEEE International Conference on Innovative Research and Development (ICIRD)*, pages 1–6. IEEE, 2019.

[10] Olus Sönmez and Guven Komurgoz. Determination of hot-spot temperature for onan distribution transformers with dynamic thermal modelling. In *2018 Condition Monitoring and Diagnosis (CMD)*, pages 1–9. IEEE, 2018.

[11] OE Gouda, GM Amer, and WAA Salem. Predicting transformer temperature rise and loss of life in the presence of harmonic load currents. *Ain Shams Engineering Journal*, 3(2):113–121, 2012.

[12] Mohammad Bagher Bannae Sharifian, Jawad Faiz, SA Fakheri, and A Zraatparvar. Derating of distribution transformers for non-sinusoidal load currents using finite element method. In *10th IEEE International Conference on Electronics, Circuits and Systems, 2003. ICECS 2003. Proceedings of the 2003*, volume 2, pages 754–757. IEEE, 2003.

[13] Emil Cazacu, Valentin Ionita, and Lucian Petrescu. Thermal aging of power distribution transformers operating under nonlinear and balanced load conditions. *Advances in Electrical and Electronic Engineering*, 16(1):92–100, 2018.