An impact of harmonic currents, load levels and ambient temperatures on transformer loss of life

Tirada Chegsakul* and Thavatchai Tayjasanant
Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand

Corresponding author: Mukk.tirada@hotmail.com

Abstract. This paper presents an analysis of thermal effect to transformer. The hottest-spot temperature of winding in transformer indicates the damage of thermal effect. The basic measured data, transformer parameters and ambient temperatures are used for estimating the hottest-spot temperature and transformer life when transformer supplies linear loads and nonlinear loads. The 50 MVA oil-immersed power transformer was investigated with field measurement data at Navanakorn4 substation in Pathum Thani. The results showed load level, harmonic current and ambient temperature are the factors which have impacts on transformer by increasing the hottest-spot temperature. The transformer life when increases the level of these factors is analyzed. When transformer supplies only linear loads, its life does not reduce from specification although load level and ambient temperature are increased. For the case of transformer supplies nonlinear load, harmonic current increases load level and transformer losses. Therefore, transformer life can be reduced when increasing the level of load, harmonic current and the ambient temperature.

1. Introduction
Transformer is an essential equipment which directly impacts on stability, safety and reliability therefore it requires the routine maintenance to prevent outage in the power system. There are many techniques for monitoring transformer in any condition, for example, dissolved gas analysis (DGA) for dissolved gases in oil, frequency response analysis (FRA) for winding movement, deformation and vibration analysis for wall and winding vibration and hottest-spot temperature for thermal analysis [1]. Presently, nonlinear loads are increasing, for example, electronic devices in households or factories and also power electronic equipment in the system. It causes harmonic current and harmonic voltage which impact on the system and equipment, especially transformer. [2] proposed impact of harmonic voltage on transformer due to increase no load loss of transformer, but it does not significant when compares with the damage of harmonic current. For harmonic current, it causes increasing load loss as presented in [3], and many works have been studied about impact of harmonic current as shown in [4-7]. Whereas increasing of linear loads and ambient temperature can also impact on transformer as presented in [8]-[12].

This paper proposed the method using the basic measured data in the system and transformer parameters to assess the life of oil immersed transformer by estimating the hottest-spot temperature. This method is developed by combining of IEEE Std. C57.91-2010 [13] and IEEE Std. C57.110-2018
3. Transformer Life

The insulation of oil-immersed transformer consists of oil insulation and paper insulation. The windings of transformer are covered by many layers of paper insulation and they are immersed in oil. The oil insulation and other parts of transformer can be changed when it deteriorates, but the paper insulation cannot be changed. Therefore, it can conclude that the transformer life can be same as the life of paper insulation. Normally, the life of paper insulation is 180,000 hours or 20.55 years [13]. Whereas it can be effected by many factors and its life may be reduced. The thermal is the most significant effect [15], therefore it is focused in this paper. The hottest-spot temperatures of winding in transformer are used to indicate the damage of thermal effect on transformer. So that the transformer life can be assessed by using it.

3.1 The hottest-spot temperature

The hottest-spot temperature is hardly to measure in directly, but it can be estimated as follow:

\[ \theta_h = \theta_A + \Delta \theta_{TO/A} + \Delta \theta_{H/TO} \]  
\[ \Delta \theta_{TO/A} = \Delta \theta_{TO,R} \left[ K^2 \left( P_{LL,RH} + P_{NL} \right)^n \right] \] \[ \Delta \theta_{H/TO} = (\Delta \theta_{W,R} - \Delta \theta_{TO,R}) \left[ \frac{K^2 P_{LL,RH}}{P_{LL,R}} \right]^m \]

Where, \( \theta_h \) is the hottest-spot temperature in °C, \( \theta_A \) is the ambient temperature in °C, \( \Delta \theta_{TO/A} \) is the top-oil rise over ambient temperature and \( \Delta \theta_{H/TO} \) is the winding hottest-spot rise over top-oil temperature. \( \Delta \theta_{TO,R} \) and \( \Delta \theta_{W,R} \) is the top-oil and the winding rise over ambient temperature at rated load. \( K \) is the ratio of load current and rated load current in per unit, \( P_{LL,R} \) is the load loss at rated load when harmonic is generated, \( m \) and \( n \) depend on type of cooling of transformer from [13]. For ONAN, \( m \) is 0.8 and \( n \) is 0.8 and \( m \) is 0.8 and \( n \) is 0.9 for ONAF, respectively.

The process of calculation is different in load level and load loss when transformer supplies linear load and nonlinear loads as in equation (5)-(8).

3.1.1 Linear loads

When transformer supplies linear loads, load loss and load level is calculated as in equation (5).

\[ P_{LL,R} = P_{LL,RH} = P_{DC} + P_{EC} + P_{OSL} \cdot K = \frac{1}{I_R} \]

Where, \( I_R \) and \( I_k \) are the load current and rated current in the secondary side of transformer in ampere.
3.1.2 Nonlinear loads
When transformer supplies nonlinear loads, harmonic is generated into the system. Harmonic current impacts on transformer by increasing load loss. The winding eddy current loss and other stray loss are multiplied by harmonic loss factor as in equation (6). The harmonic loss factors depend on harmonic current and its harmonic order as in equation (7). The load level is calculated by including harmonic current as in equation (8).

\[ P_{L-LH} = P_{DC,Dc} + F_{H-EC} P_{EC,Dc} + F_{H-OSL} P_{OSL,Dc} \]  
\[ F_{H-EC} = \sum_{h=1}^{\text{hmax}} \left( \frac{I_{h}}{I_{h1}} \right)^{2}, \quad F_{H-OSL} = \sum_{h=1}^{\text{hmax}} \left( \frac{I_{h}}{I_{h1}} \right)^{2} \]  
\[ K = \sqrt{\frac{\sum_{h=1}^{\text{hmax}} I_{h}^2}{I_{r} I_{h1}}} \]

Where, \( F_{H-EC} \) and \( F_{H-OSL} \) are the harmonic loss factor for winding eddy current loss and other stray loss, respectively. \( I_{h} \) is the harmonic current at any harmonic order, and \( I_{h1} \) is the fundamental harmonic current.

3.2 Estimation of transformer life
After the hottest-spot temperature of winding in transformer is calculated, then it is used to compare with its reference limit temperature which is 110 °C to calculate the aging factor [12]. The aging factor and its average indicate each factor impact on transformer as in equation (9). When the hottest-spot temperature is over its reference limit, transformer life will be reduced from its specification. Loss of life and remaining life of transformer can be estimated as in equation (10).

\[ F_{AA} = \exp \left[ -\frac{15000}{\theta_{H,ref} + 273} - \frac{15000}{\theta_{H} + 273} \right], \quad F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \]

\[ \text{LOL(\%)} = \frac{F_{EQA} \times T \times 100}{\text{NIL}}, \quad \text{RemainingLife} = \text{NIL} - \frac{\text{NIL} \times \text{LOL}}{100} \]

Where, \( F_{AA} \) and \( F_{EQA} \) is the aging factor and its average, \( \theta_{H,ref} \) is the hottest-spot temperature limit, \( \Delta t \) is the time interval, LOL is the transformer loss of life, T is the transformer usage time and NIL is the normal insulation life.

4. Case studies
4.1 Field measurement

\[ \text{Figure 1. Navanakorn4 substation} \]
The measured data in TP1 side as shown in Figure 1 such as load current profile and 1st - 16th harmonic current are used for case studies as shown in Figure 2. They are collected by power quality meter at Navanakorn4 substation in Pathum Thani for 30 days from 2/3/2018 to 3/3/2018 with interval of 10 minutes. The ambient temperature data are collected from https://www.wunderground.com at Khu Khot station as shown on the left side in Figure 3. The specification of investigated oil-immersed power transformer is shown in Table 1.

| Characteristic                          | Value   |
|----------------------------------------|---------|
| Rated Power (kVA)                      | 50000   |
| Primary Voltage (kV)                   | 115     |
| Secondary Voltage (kV)                 | 23.1    |
| Type of cooling                        | ONAF    |
| Ohmic loss at rated load (kW)          | 107.74  |
| Load loss at rated load (kW)           | 129.43  |
| No load loss (kW)                      | 16.657  |
| Total stray loss (kW)                  | 21.69   |
| Top oil rise over ambient temperature (°C) | 50      |
| Winding rise over ambient temperature (°C) | 55      |

The average of load level, total harmonic distortion in current and ambient temperature is 0.33 per unit, 4% and 27.7 °C, respectively. The hottest-spot temperature is calculated by using the proposed method under transformer supplies linear load, nonlinear load and nonlinear load when the average of total harmonic distortion in current increases up to 30% as shown on the right side in Figure 3.

Figure 2. Load current profile (left) and Total harmonic distortion in current (right)

Figure 3. Ambient temperature (left) and hottest-spot temperature which estimated by proposed method (right)
Firstly, the hottest-spot temperature is around 80 °C at peak load level around 0.7-0.8 per unit during 26th-27th day, but the other period is around 50 °C. Secondly, the hottest-spot temperature when transformer supplies linear loads is less than the hottest-spot temperature when transformer supply nonlinear load. And the last one, the hottest-spot temperature when the average of total harmonic distortion in current is 4% is less than the hottest-spot temperature when the average of total harmonic distortion increases up to 30%. These results above showed that the load level and harmonic current impact on transformer because the hottest-spot temperature increases upon them. From the measured data and parameters of this transformer in this substation, transformer life is same as life from specification due to the hottest-spot temperature is not over its reference limit and loss of life of this transformer is very low.

5. Analysis of thermal effect on transformer life
The thermal effect on transformer life is analyzed by increasing the level of load, harmonic current, and ambient temperature. For the case of transformer supplies linear load, the hottest-spot temperature will increase linearly when load levels and ambient temperatures are increased, but it is not over its reference limit so that it does not reduce transformer life. Whereas, transformer life is reduced in some cases of transformer supplies nonlinear load. Therefore, they were analyzed by using field measurement data and 50 MVA transformer. Transformer life under thermal effect throughout lifespan can be calculated as in equation (11).

\[
\text{RemainingLife} = \text{NIL} - \text{F}_{\text{EQA}} \times T , \quad T = \frac{\text{NIL}}{\text{F}_{\text{EQA}}}
\] (11)

5.1 Impact of harmonic current and load level on transformer
The load level without harmonic background and harmonic current are varied for estimating transformer life. The ambient temperature is fixed at 35 °C. It found the hottest-spot temperature is increased when harmonic current and load level are increased as shown on the left side in Figure 4. When load levels without harmonic background are 0.5, 0.7, and 0.9 per unit, the limits of total harmonic distortion in current that do not reduce this transformer life are 99.1%, 61.1%, and 35.1%, respectively. If it is over this limit, this transformer life will be decreased rapidly as shown on the right side in Figure 4. The detail of transformer life and load level which are increased by harmonic current are shown in Table 2. For example, when the total harmonic distortion in current is 40%, the load level is increased from 0.9 to 0.97 per unit and transformer life will be decreased from 20.55 to 11.52 years.

![Figure 4. The hottest-spot temperature (left) and transformer life (right) under impact of load level and harmonic current](image-url)
Table 2. The transformer life (year) and load levels (per unit) at 35°C under thermal effect

| THD (%) | 0.5 p.u. | 0.6 p.u. | 0.7 p.u. | 0.8 p.u. | 0.9 p.u. | 1.0 p.u. |
|---------|----------|----------|----------|----------|----------|----------|
|         | p.u. Year | p.u. Year | p.u. Year | p.u. Year | p.u. Year | p.u. Year |
| 20      | 0.51 6.2e-3 | 0.61 2.4e-3 | 0.71 841.3 | 0.82 274.4 | 0.92 85.1 | 1.02 25.5 |
| 30      | 0.52 4.3e-3 | 0.63 1.4e-3 | 0.73 452.2 | 0.84 130.2 | 0.94 35.8 | 1.04 9.5 |
| 40      | 0.54 2.6e-3 | 0.65 755.2 | 0.75 198.1 | 0.86 48.7 | 0.97 11.5 | 1.08 2.7 |
| 50      | 0.56 1.4e-3 | 0.67 336.3 | 0.78 73.2 | 0.89 15.1 | 1.01 3.0 | 1.12 0.6 |
| 60      | 0.58 685.4 | 0.70 132.7 | 0.82 23.6 | 0.93 4.0 | 1.05 0.7 | 1.17 0.1 |
| 70      | 0.61 306.2 | 0.73 47.5 | 0.85 6.9 | 0.98 1.0 | 1.10 0.1 | 1.22 - |
| 80      | 0.64 127.5 | 0.77 15.8 | 0.90 1.9 | 1.02 0.2 | 1.15 - | 1.28 - |
| 90      | 0.67 50.1 | 0.81 5.0 | 0.94 0.5 | 1.08 - | 1.21 - | 1.34 - |
| 100     | 0.71 18.9 | 0.85 1.5 | 0.99 - | 1.13 - | 1.27 - | 1.41 - |

*Normally, the specification of transformer life is 20.55 years.

5.2 Impact of ambient temperature on transformer

For the impact of ambient temperature on transformer, transformer life is estimated when the total harmonic distortion in current is 40% and load level without harmonic background are varied as shown in Figure 5. It found the ambient temperature does not reduce transformer life when the load levels less than 0.8 per unit. However, transformer will be reduced from its specification when the load levels are 0.8, 0.9 and 1.0 per unit and ambient temperature is over 43.2, 29.2 and 13.9°C, respectively. To compare this result with Table 2, when load level is 0.9 per unit and total harmonic distortion in current is 40%, the transformer life is reduced from 11.52 years to 10.43 year when the ambient temperature is increased from 35°C to 36°C. The ambient temperature increases the hottest-spot temperature, but it will impact on transformer life when level load and harmonic current are high enough.

Figure 5. The transformer life under impact of ambient temperature and load level when transformer supplies nonlinear load

6. Conclusion

Transformer life depends on its paper insulation condition which is effected by many factors. One of them that directly effective to paper insulation is thermal effect. Therefore, the hottest-spot temperature of winding can be used to estimate the life of transformer. When this temperature is more than its limit that is 110°C, the transformer life will be reduced from specification. This paper proposed the method using measured basic data and parameters of transformer to estimate the hottest-spot temperature and transformer life. The key factors impacted on transformer which are the load level, harmonic current and the ambient temperature have been analyzed when transformer supplies...
linear loads and nonlinear loads. The field measurement data and 50 MVA oil-immersed power transformer at Navanakorn4 substation are used for case studies. The results indicated the transformer life cannot be reduced when transformer supplies only linear load although the ambient temperature and load level are increased. However, when nonlinear loads are in the system, harmonic current will be generated and load level will be increased from harmonic current. It can occur overloading in transformer if harmonic problem is ignored. Increasing of load levels, harmonic current and ambient temperature can reduce transformer life. For the case of low load level and high harmonic current, transformer life cannot be reduced. Whereas, the case of high load level and low harmonic current, transformer life can be reduced. Therefore, the most sensitive factors form high to low are load level, harmonic current and the ambient temperature, respectively.

7. References
[1] Abu-Elanien A E and Salama M 2010 Asset management techniques for transformers Electric Power Systems Research 80 456–64
[2] Harold F M M, Andres P and Ivan C D 2017 Aging of distribution transformers due to voltage harmonics 2017 IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA)
[3] Bagheri P, Xu W and Shaloudegi K 2018 New indices to evaluate the impact of harmonic currents on power transformers 2018 18th International Conference on Harmonics and Quality of Power (ICHQP)
[4] Said D M, Nor K M and Majid M S 2010 Analysis of distribution transformer losses and life expectancy using measured harmonic data Proceedings of 14th International Conference on Harmonics and Quality of Power - ICHQP 2010
[5] Cazacu E, Petrescu L and Ionita V 2017 Losses and temperature rise within power transformers subjected to distorted currents 2017 15th International Conference on Electrical Machines, Drives and Power Systems (ELMA)
[6] Almohaimeed S A and Suryanarayanan S 2017 Steady-state analysis of the impact of temperature variations on a distribution transformer 2017 North American Power Symposium (NAPS)
[7] Rad M S, Kazerooni M, Ghorbany M J and Mokhtari H 2012 Analysis of the grid harmonics and their impacts on distribution transformers 2012 IEEE Power and Energy Conference at Illinois
[8] Majzoobi A, Mahoor M and Khodaei A 2017 Machine learning applications in estimating transformer loss of life 2017 IEEE Power & Energy Society General Meeting
[9] Stahlhut J W, Heydt G T and Selover N J 2008 A Preliminary Assessment of the Impact of Ambient Temperature Rise on Distribution Transformer Loss of Life IEEE Transactions on Power Delivery 23 2000–7
[10] Mahoor M, Majzoobi A, Hosseini Z S and Khodaei A 2017 Leveraging sensory data in estimating transformer lifetime 2017 North American Power Symposium (NAPS)
[11] Muthanna K T, Sarkar A, Das K and Waldner K 2006 Transformer Insulation Life Assessment IEEE Transaction on Power Delivery 21 150-56
[12] Sathyanarayana B R, Heydt G T and Dyer M L 2009 Distribution Transformer Life Assessment with Ambient Temperature Rise Projections Electric Power Components and Systems 37 1005–13
[13] IEEE Guide for Loading Mineral-oil-immersed Transformers and Step -Voltage Regulators, IEEE Std. C57.91-2011
[14] IEEE Recommend Practice for Establishing Liquid Immersed and Dry-Type Power and Distribution Transformer Capability when Supplying Nonsinusoidal Load Currents, IEEE Std C57-110-2018
[15] Yazdani-Asrami M, Mirzaie M and Akmal A A S 2010 Investigation on impact of current harmonic contents on the distribution transformer losses and remaining life 2010 IEEE International Conference on Power and Energy