

ANALYSIS OF THE EFFECT OF CURRENT HARMONIC INDUCED HEATING ON TRANSFORMER AGEING

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Abstract

Due to advanced control and increased efficiency, the concentration of power electronics-based equipment is increasing rapidly in recent times causing higher injection of nonlinear current to the system, affecting various equipment in the power system. The ageing of a transformer depends primarily on the hotspot temperature. However, the hotspot temperature is influenced by the loading condition of the transformer and the nature of the current drawn by the loads connected to it. In this study, the loss of life of transformers due to non-linear current is assessed. For the analysis, the non-linear current with different THD (4.48%, 10.55%, 15.22%, 24.09%, and 30.79%) is created in the laboratory and the transformer life under varying loading level (80%, 90%, 100%, and 110%) with these currents is evaluated. The parameters of a 3000 kVA transformer are used for analysis, and nonlinear current is generated by connecting a rectifier load to a small UPS transformer. The analysis is performed by estimating the temperature of the hotspot and calculating the acceleration factor of ageing (F_{AA}) and the percentage of loss of life (LoL). It is found from the study that a higher harmonic content in the system's current leads to larger loss of life of the transformer, and degradation in the transformer's life occurs even if the THD of the current signal is within the standard limit.

Keywords: Hotspot temperature, Ageing acceleration factor, Transformer's loss of life, Current harmonics

1. Introduction

Recent trends show a growing shift towards non-linear load from linear load, increased electrification and digitization, growing penetration of inverter based renewable energy, and higher concentration of electronics per industry due to their improved efficiency and control (Dhameliya, 2022). These technologies employ power electronics devices which introduce harmonics in the system (Wagner et al., 1993). The electrical equipment's such as transformers, generators, motors, capacitor banks, electronic equipment's and relays, and circuit breakers of the power system are vulnerable to the harmonics, especially current harmonics. Transformers, one of the major component of power system gets heavily influenced by current harmonics regarding its life. Traditional

transformers in use are not designed to accommodate such non-linear loads. Hence under harmonics condition, the loss of these transformers increases reducing efficiency (Elmoudi et al., 2006). The increased loss causes winding temperature of the transformer to rise. Frequent presence of such current harmonics could result in creation of local hotspot in the core or winding of the transformer. If the temperature of such hotspot increases beyond the limit of thermal insulation of the transformer, the life of transformer may degrade rapidly, or its winding may get destroyed completely. So, it's crucial to assess and monitor the life of transformers under harmonics condition i.e. non-linear load for maintaining system reliability and avoiding premature failures (Pejovski et al., 2017).

The high penetration of power electronic devices in power system has led to significant harmonic injection in power system networks today (IEEE, 2018). The thermal stress on transformers caused by harmonic current accelerates the degradation of insulation materials, ultimately leading to dielectric failures and reduced

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transformer lifespan (Cazacu et al., 2017). The eddy current loss and other stray loss of transformers increases due to harmonic current. Assessing transformer life and diagnosing failures are crucial for electric utility companies for system security and reliability. The ageing of transformer insulation, and thus overall lifespan of the transformer, is primarily influenced by temperature and load profile (Majzoobi et al., 2017). Various techniques such as active power filters, passive filters, demand side management methods, and advanced cooling techniques can be employed to reduce the effects of harmonics on transformers eventually improving efficiency, dependability, and the reliability of the transformer system (Gouda et al., 2012). One of the common bases for determining a transformer's ageing is the estimation of ageing acceleration factor, F_{aa} (George et al., 2017). The most widely applied techniques for evaluating the condition of the transformer insulation are, dissolved gas analysis (DGA), degree of polymerization (DP), and Furan analysis employing time domain techniques and frequency domain spectroscopy (Chakravorti et al., 2013). Which allows early fault detection enabling early maintenance to prevent transformer failures. Shareghi et al. (2012) analyzed the impact of current and voltage harmonics on transformer's core loss by conducting short circuit and open circuit test of distribution transformer. The calculation of transformer's losses and evaluation of its capacity under the effect of non-sinusoidal currents is studied in (Gupta and Singh, 2011). Prediction of life expectancy of transformers under certain non-linear loads (variable frequency drive, adjustable speed drive, and office equipments) connected to it includes in study (Cazacu et al., 2017). However, the effect of varying harmonics condition with different levels of loading is also necessary to analyze the effect of harmonics content on transformer ageing.

This study aims to assess the ageing of oil immersed transformer's life under harmonics conditions with varying loading level by estimating the hotspot temperature of transformer based on IEEEstdC57.110-2018 (IEEE, 2018). For this hotspot temperature rise and top oil temperature rise model is employed in MATLAB script for five different non-linear current with varying THD (4.48%, 10.55%, 15.22%, 24.09% and 30.79%). Hotspot temperature of the 3000kVA transformer is estimated at four different levels of loading: 80%, 90%, 100% and 110% at particular harmonics condition. With the help of estimated hotspot temperature, the ageing acceleration factor (F_{aa}) followed by loss of life of transformer is calculated.

The literature is organized as; Section 2 presents the methodology of the study followed by results and discussion in Section 3, finally the study is concluded in Section 4 with the concluding remarks.

2. Methodology

The estimation of hotspot temperature is based on IEEEstdC57.110-2018 (IEEE, 2018). It involves estimation of losses (eddy current loss, other stray loss, and copper loss), top oil temperature rise, and finally hotspot temperature rise as mentioned in different sections below.

2.1. Transformer Loss Under Harmonics Condition

2.1.1 Eddy Current Loss

Eddy current loss is caused by exposing conductors into time varying leakage magnetic fields due to skin effect and proximity effect. Winding eddy current loss of the transformer under harmonics condition is heavily dependent upon the frequency of the harmonics order.

$$P_{ech} = \frac{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 \cdot h^2}{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2} \cdot P_{ec} \quad (1)$$

where, P_{ec} = Rated Eddy Current Loss

P_{ech} = Eddy current loss under harmonic conditions

h = Harmonic Order

I_h = Corresponding Harmonic Current

I_1 = Fundamental Current

2.1.2 Other Stray Loss

It is a part of the load loss that occurs in the metallic structural part of the transformer due to induced eddy currents and circulating currents caused by leakage flux.

$$P_{oslh} = \frac{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 \cdot h^{0.8}}{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2} \cdot P_{osl} \quad (2)$$

where, F_{osl} = Rated other stray loss factor

F_{oslh} = Other stray loss factor under harmonic condition

2.1.3 I^2R Loss

I^2R loss, also called copper loss, is power loss due to the resistance of the transformer winding. The copper loss of the transformer depends on the amount of current flowing through the transformer, i.e. the loading level.

$$P_{cuh} = x^2 \cdot P_{cu} \quad (3)$$

where, P_{cu} = Rated Copper Loss

P_{cuh} = Copper loss under harmonic conditions

$x = \frac{\sum_{h=1}^{h_{max}} \sqrt{I_h^2}}{I_1}$, loading level

2.2. Hotspot Temperature

The hotspot temperature (HST) is the highest temperature inside the transformer found in the winding or core of the transformer. Due to increased loss under harmonics conditions, the hotspot temperature of the transformer increases. This influences the lifetime, insulation ageing, and overload capability of the transformer.

$$\theta_{HST} = \theta_{amb} + \Delta\theta_{ToT} + \Delta\theta_{HST} \quad (4)$$

where, θ_{HST} = Hotspot Temperature,
 θ_{amb} = Ambient Temperature
 $\Delta\theta_{ToT}$ = Top oil temperature rise above ambient temperature,
 $\Delta\theta_{HST}$ = Hotspot temperature rises above top oil temperature.

2.2.1 Top Oil Temperature Rise

It is the temperature rise of the top oil above ambient temperature. The rise in the top oil temperature above the ambient temperature under harmonic conditions is given as

$$\Delta\theta_{ToT} = \theta_{ToTr} \cdot \left(\frac{P_{cuh} + P_{ech} + P_{oslh} + P_{NL}}{P_{cu} + P_{ec} + P_{osl} + P_{NL}} \right)^{0.8} \quad (5)$$

where, $\Delta\theta_{ToT}$ = Top oil temperature rise above ambient temperature
 θ_{ToTr} = Rated top oil temperature rise above ambient temperature
 P_{NL} = Rated no-load Loss

2.2.2 Hotspot Temperature Rise

It is the temperature rise of hottest spot with respect to the top oil temperature of transformers.

$$\Delta\theta_{HST} = \theta_{HSTr} \cdot \left(\frac{I_{pu}^2 \cdot (1 + F_{ec} \cdot P_{ec}(pu))}{1 + P_{ec}(pu)} \right)^{0.8} \quad (6)$$

where, $\Delta\theta_{HST}$ = Hotspot temperature rise above top oil temperature
 θ_{HSTr} = Rated hotspot temperature rise above top oil temperature
 I_{pu} = Per unit current

2.3. Loss of Life of Transformer

Rise in hotspot temperature is the main cause of the ageing of transformers. The IEEE loading guide (IEEE, 1995) includes a coefficient, often referred to as the ageing acceleration factor (F_{aa}), that quantifies the impact of the

hotspot temperature on the lifespan of a transformer as shown in Equation (5). This factor is used to model how increased temperatures can accelerate the ageing process of the transformer's insulation, thereby reducing its overall life expectancy (Rad et al., 2012).

$$F_{AA} = e^{\frac{15000}{\theta_{ref}} - \frac{15000}{\theta_{HST} + 273}} \quad (7)$$

where, θ_{ref} = Reference Hotspot temperature

F_{AA} = Aging Acceleration Factor

θ_{ref} is 110°C for a 65°C average winding temperature rise transformer and 95°C for a 55°C average winding temperature rise in a transformer (IEEE, 1995).

The ageing acceleration factor provides the rate at which the transformer's insulation is degrading under non-linear load with reference to hotspot temperature θ_{HST} . Mathematically, percentage loss of the transformer's life (LOL) is associated with the ageing acceleration factor (F_{AA}) as below.

$$\%LOL = \frac{F_{AA}}{NIL} \cdot t \cdot 100 \quad (8)$$

where, NIL = Normal Insulation Life in years

t = Time up to which a non-linear load is connected to a transformer in years.

Normal insulation life (NIL) is the life of transformer if its hotspot temperature always equals to reference temperature specified by the manufacturer. Hence the loss of life in hours,

$$LOL = F_{AA} \cdot t \cdot 100 \quad (9)$$

where LOL represents transformer's life that has been degraded by connecting particular non-linear load for t hours of duration.

2.4. Generation of Non-linear Current

The non-linear current with different levels of harmonics content is generated in laboratory by connecting diode rectifier with RL (Resistor and inductor) load as presented in the single line diagram in Figure 1. The varying nature of non-linear current is obtained by varying value of R and L connected to the rectifier. The rectifier load is connected to the secondary of 12/220V UPS transformer and non-linear current is sensed in primary side of the transformer with the help of ACS712 current sensor. Thus, sensed current is fed to top oil temperature rise model and hotspot temperature rise model where harmonics content of the sensed current signal is extracted through Fast Fourier Transform (FFT). The temperature rise models are implemented for the 3000 kVA transformer with the parameters as presented in Table 1. Hence the hotspot temperature and the loss of life for this transformer under different harmonics condition with varying loading level is assessed as discussed in Result and Discussion section. Five different current signals with

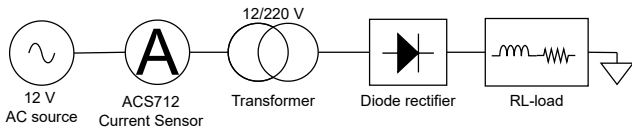


Figure 1. Single line representation of setup for non-linear current generation

Table 1. Rating of Transformer

S.N.	Parameter	Description
1	Ambient Temperature	40 °C
2	Top Oil Temperature Rise	10 °C
3	Hotspot Temperature Rise	5 °C
4	Load Loss	28500 W
5	No-load Loss	3700 W
6	Normal Insulation Life	20.55, (IEEE, 1995)

different harmonics content are created by varying value of R and L. The higher THD (i.e. 24.09% and 30.79%) is obtained with half wave diode rectifier and lower THD (i.e. 10.55% and 15.22%) is obtained by replacing half wave diode rectifier with full wave diode rectifier.

3. Results and Discussion

The harmonics order and its corresponding per unit magnitude for different current signals generated in the laboratory is presented in Table 2. Out of these five different current signals, the current signal and its harmonic spectrum at 10.55% and 15.55% THD is presented in Figure 2 and Figure 3 respectively.

Table 2. Harmonic order and corresponding per-unit magnitude of current signals

Harmonics order	4.48%	10.55%	15.22%	24.08%	30.79%
1	1	1	1	1	1
2	-	-	-	0.1861	0.248
3	0.042	0.0783	0.1354	0.1212	0.1530
4	-	-	-	0.0824	0.0920
5	0.017	0.0372	0.0606	0.0359	0.0291
6	-	-	-	0.0242	0.0166
7	-	0.04	0.0271	-	-
8	-	-	-	-	0.0178
9	-	0.0338	-	-	-
10	-	-	-	-	-
11	-	0.0289	0.0213	-	-
12	-	-	-	-	-
13	-	0.0189	-	-	-

3.1. Hotspot Temperature and Ageing Acceleration Factor

The hotspot temperature and its corresponding ageing acceleration factor at different THD and varying loading levels are presented in Figure 4 and Figure 5 respectively. From these two graphs it's clear that the transformer's ageing increases exponentially with increase in hotspot

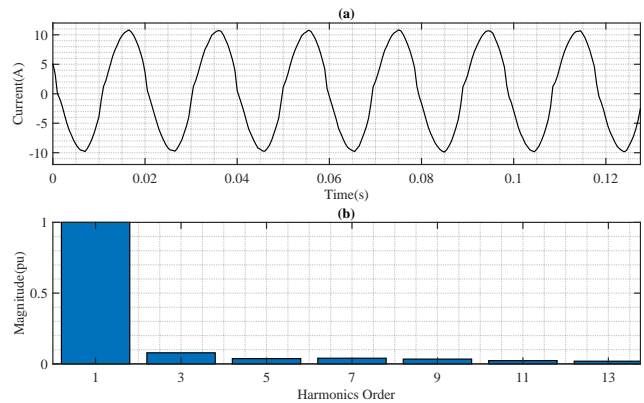


Figure 2. Current signal of 10.55% THD

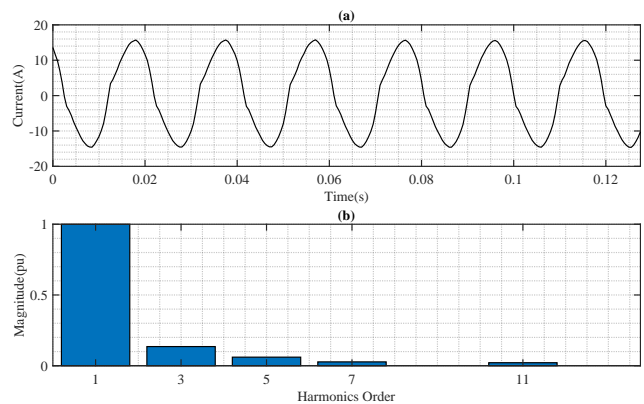


Figure 3. Current signal of 15.22% THD

temperature. In general, the hotspot temperature is found to be increasing with increase in harmonics content in the current signal under particular loading level of transformers. However, a contrasting result is found in the scenario of 10.55% and 15.22% THD condition of current signal. Here the rise in hotspot temperature and corresponding ageing acceleration factor while increasing harmonics content of current signal from 10.55% to 15.22% THD is found to be slightly different from the rise in another scenario as seen in the graph. The harmonic orders of current signals with 10.55% THD is more and have few higher order harmonics. Hence it can be said that the higher order of harmonics order with smaller magnitude has large influence on hotspot temperature than the lower order harmonics with larger magnitude i.e. even if the THD of current signal is within the limit, it has great influence on transformer's ageing if it contains higher order harmonics.

3.2. Loss of Life

Loss of life of transformers under harmonics conditions is directly related to the duration of loading i.e. longer the non-linear load is connected to the transformer, higher will be the loss of life. Assuming 10.55% THD condition as the base case scenario the, the loss of life of transformer for

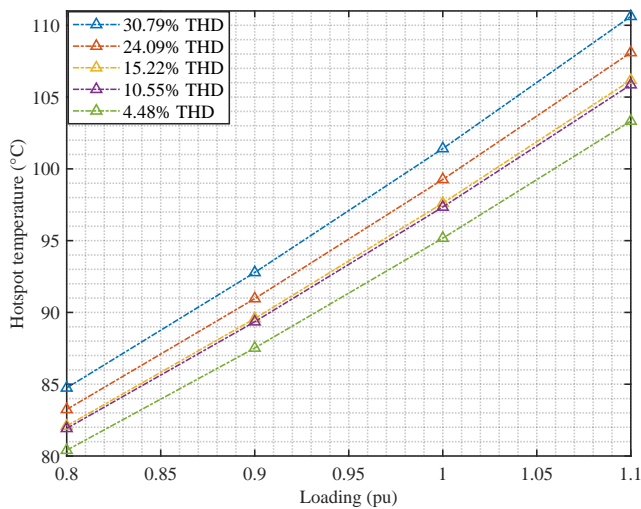


Figure 4. Hotspot temperature at different loading conditions

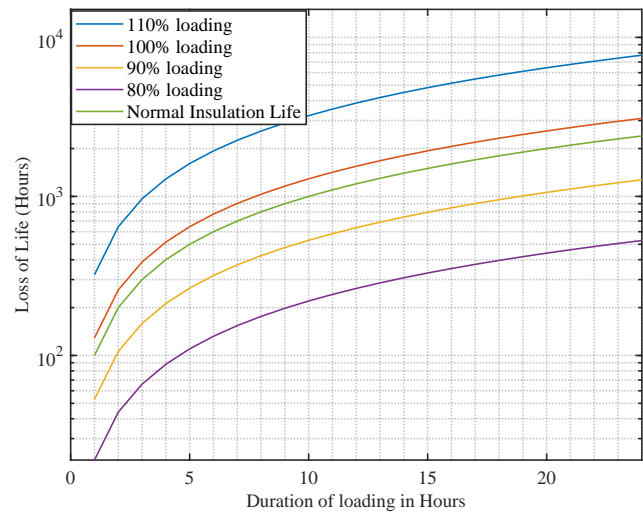


Figure 6. Loss of life of transformers at 10.55% THD

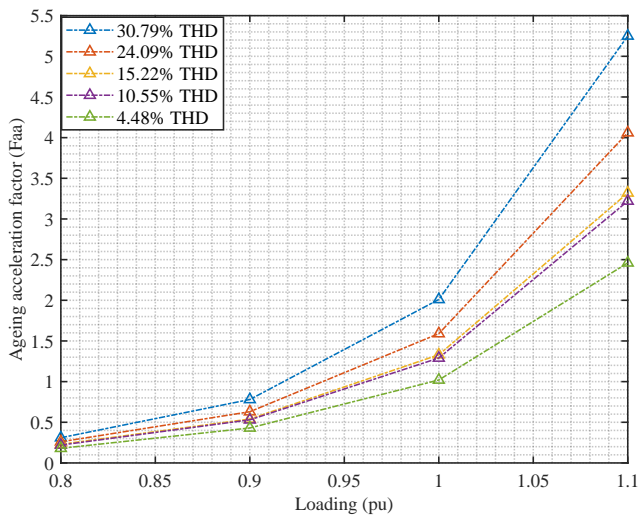


Figure 5. Ageing acceleration factor at different harmonic conditions

24 hours of duration is presented in Figure 6. Considering 10 hours of duration as the reference loading duration, transformers will lose its life by 2.2 hours, 5.3 hours, 12.9 hours, and 32.2 hours at 80%, 90%, 100% and 110% loading level respectively. In this scenario, the hotspot temperature at 80% and 90% loading is well below its reference temperature, hence it won't affect thermal life of the transformer. However natural ageing of insulation may be greater than the estimated loss of life due to hotspot temperature. Hence, transformers might loss its life by great extent than the loss of life calculated above but will be less than the 10 hours i.e. loading duration.

In the scenario where harmonics content is within the standard limit i.e. at 4.48% THD condition, the ageing acceleration factor is greater than 1 during 100% and 110% loading condition. The power transformers may operate

above 100% loading during certain periods of the day, hence the presence of harmonics content even if it's within the standard limit may accelerate ageing of power transformers. Therefore, the k-rated transformer or transfer with advanced cooling system should be employed to absorb such extra heat generated in the harmonics prone area.

4. Conclusion

The study finds that the presence of harmonics increases the overall loss of the system, eventually increasing the hotspot temperature of the transformer. An increase in hotspot temperature degrades the life of the transformer. From the scenario of conditions 2nd and 3rd, i.e., current signal with 10.55% and 15.22% THD, it can be concluded that if two signals have same THD, one of them has higher order of harmonics order. The current signal with higher order of harmonics results in a higher hotspot temperature because of a higher eddy current loss and other stray loss. On the other hand, even if the THD of current flowing through the system is within the standard limits, it could result in rapid degradation of life of transformers, especially power transformers as they get subjected to more than 100% load during a certain period of the day.

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