# Failure of Transformers Due to Harmonic Loads

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**Abstract: Transformers are the backbone of electricity transmission. Due to presence of non-linear loads the transformers which are normally designed and built for use at rated frequency and perfect sinusoidal load current. A non-linear load across the transformer causes a reactive power loss which causes heating in power system components. It leads to higher losses, early breakdown in insulation, and reduction of useful lifetime of transformer. It reduces reliability on transformers as experience has shown us the increasing number of transformer explosions both in industrial as well as in domestic conditions. A study on this losses is conducted which causes hundreds of transformer meltdowns and estimate the approximate life of transformers.**

**Keywords: Transformer losses, Stray losses, Derating of Transformers, Harmonic Loads, Transformer Capacity, Transformer failures.**

## I. INTRODUCTION:

Transformers are one of the component and usually the interface between the supply and most non-linear loads. They are usually manufactured for operating at the linear load under rated frequency. Nowadays the presence of nonlinear load results in production harmonic current. Increasing in harmonic currents causes extra loss in transformer winding and thus, leads to increase in temperature, reduction in insulation life, increase to higher losses and finally reduction of the useful life of transformer. Harmonic voltage increase losses in its magnetic core while harmonic currents increased losses in its winding and structure.

In general, harmonics losses occur from increased heat dissipation in the windings and skin effect both are a function of the square of the rms current, as well as from eddy currents and core losses. This extra heat can have a significant impact in reducing the operating life of the transformer insulation the increased of eddy current losses that produced by a non-sinusoidal load current can cause abnormal temperature rise and hence excessive winding losses. Therefore the influence of the current harmonics is more important. A detailed work has been shown to describe effect of harmonics on loss of life of distribution transformer.

## II. TRANSFORMER LOSSES IN HARMONIC LOADS:

Transformer manufacturers usually try to design transformers in a way that their minimum losses occur in rated voltage, rated frequency and sinusoidal current. However, by increasing the number of non-linear loads in recent years, the load current is no longer sinusoidal. This non-sinusoidal current causes extra loss and temperature in transformer. Transformer loss is divided into two major groups, no load and load loss as shown in (1).

$$P_T = P_{NL} + P_{LL} \qquad (1)$$

Where $P_{NL}$ is No load loss, $P_{LL}$ is Load loss, and $P_T$ is total loss.

A brief description of transformer losses and harmonic effects on them is presented in following:

(A) **No Load Loss:** No load loss or core loss appears because of time variable nature of electromagnetic flux passing through the core and its arrangement is affected the amount of this loss. Since distribution transformers are always under service, considering the number of this type of transformer in network, the amount of no load loss is high but constant this type of loss is caused by hysteresis phenomenon and eddy currents into the core. These losses are proportional to frequency and maximum flux density of the core and are separated from load currents. Many experiments have shown that core temperature increase is not a limiting parameter in determination of transformers permissible current in the non-sinusoidal currents.

Furthermore, considering that the value of voltage harmonic component is less than 5%, only the main component of the voltage is considered to calculate no load loss, the error of ignoring the harmonic component is negligible. So, IEEE C57 .110 standards has not considered the core loss increase due to non-linear loads and has supposed this loss constant, under non-sinusoidal currents .

(B) **Load Loss:** Load loss includes dc or ohmic loss, eddy loss in windings and other stray loss and it can be obtained from short circuit test [4]:

$$P_{LL} = P_{DC} + P_{EC} + P_{OSL} \qquad (2)$$

Here, $P_{DC}$ is Loss due to resistance of windings, losses in structural parts of transformer such as tank, clamps. The sum of $P_{EC}$ and $P_{OSL}$ its value from the difference of load loss and ohmic loss:

$$P_{TSL} = P_{EC} + P_{OSL} = P_{LL} - P_{DC} \quad (3)$$

It should be mentioned that there is no practical or experimental process to separate windings eddy loss and other stray loss yet [1].

(C) **Ohmic Loss:** This loss can be calculated by measuring winding of load current increases due to harmonic component, this loss will increase by of load current. The winding ohmic loss under harmonic condition is shown in Eq. 4:

$$P_{DC} = R_{DC} \times I^2 = R_{DC} \times \sum_{h=1}^{h=h_{max}} I_{h_{max}}^2 \quad (4)$$

(D) **Eddy Current Loss in Windings:** This loss is caused by time variable electromagnetic flux that covers windings. Skin effect and proximity effect are the most important phenomenon in comparison to external windings, internal loss. The reason is the high electromagnetic flux intensity near the core that covers these windings. Also, the most amount of loss is in the last layer of conductors in wind to high radial flux density in this region [2]:

$$P_{EC} = \frac{\pi \tau^2 \mu^2}{3\rho} f^2 \times H^2 \propto f^2 I^2 \quad (5)$$

Here:

$\tau$ = A conductor width perpendicular to field line.

$\rho$ = Conductor's resistance.

$$P_{EC} \propto I^2 \times f^2 \quad (6)$$

The impact of lower-order harmonics on the skin effect is negligible in the transformer windings. Equation shown below can be used for calculating the eddy current loss too:

$$P_{EC} = P_{LL-R} - [(R_1 I_{1-R}^2 - R_2 I_{2-R}^2)] \quad (7)$$

According to IEEE C57 .110 standards about 33% of total stray loss for oil-filled transformers:

$$P_{EC-R} = 0.33 P_{TSL} \quad (8)$$

(E) **Other Stray Loss:** Due to the linkage between electromagnetic flux and conductor, a voltage induces in the conductor and this will lead to producing eddy current Eddy current produces loss and increases temperature. A part of eddy current loss which is produced in structural parts of transformers (except in the windings) is called other stray loss [5, 6]. Many factors such as size of core, class of voltage of transformer and construction of materials used to build tank and clamps [7]. To determine the effect of frequency on the value of other stray loss, different tests have been fulfilled. Results shown that the ac resistance of other stray loss in low frequency (0-360Hz) is equal to [3]:

$$R_{AC}^{if} = 0.00129 (\frac{f_h}{f_1})^{0.8} \quad (9)$$

The frequencies in the range of (420-1200 Hz), resistance will be calculated by:

$$R_{AC}^{hf} = 0.33358 (\frac{f_h}{f_1})^{-1.87} \quad (10)$$

Thus this loss is proportional to the square of the load current and the frequency to the power of 0.8

$$P_{EC} \propto I^2 \propto f^{0.8} \quad (11)$$

Below equation can be used for calculating the other stray loss

$$P_{OSL} = P_{TSL} - P_{EC} \quad (12)$$

**Effect of Harmonics on No-Load Losses:**

According to Faraday's law the terminal voltage determines the transformer flux level, i.e.:

$$N \frac{d\emptyset}{dt} = v(t) \quad (13)$$

Transferring this equation into the frequency domain shows the relation between the voltage harmonics and the flux components:

$$Nj\,(h\,\omega) = V_h \quad (14)$$

This equation shows that flux magnitude is directly proportional to the harmonic voltage and inversely proportional to the harmonic order h. Furthermore, within most power systems, the harmonic distortion of the system voltage THD is well below 5% and the magnitudes of the voltage harmonic components are small compared to fundamental component. Hence neglecting the effect of harmonic voltage will only give rise to an insignificant error. Nevertheless, if THDv is not negligible, losses under distorted voltages can be calculated based on ANSI-C.27-1920 standard with [8].

$$P = P_M \left[ P_h + P_{ec} \left( \frac{V_{hrms}}{V_{rms}} \right)^2 \right] \quad (15)$$

Where, $V_{hrms}$ and $V_{rms}$ are the RMS values of distorted and sinusoidal voltages, $P_M$ and P are no-load losses under distorted and sinusoidal voltages, $P_h$ and $P_{EC}$ are hysteresis and eddy current losses, respectively.

## III. EFFECT OF HARMONICS ON LOAD LOSSES:

As per in most power systems, current harmonics are of more significance. It causes increase losses in the windings and other structural parts of the distribution transformer.

(A) **Effect of Harmonics on DC Losses:** If the rms value of the load current is increased due to harmonic components, and then these losses will increase by square of RMS of load current. The windings ohmic loss under harmonic condition is shown by:

$$P_{DC} = R_{DC} \times I^2 = R_{DC} \times \sum_{h=1}^{h=h_{max}} I_{h_{max}}^2 \quad (16)$$

(B) **Effect of Harmonics on Eddy Current Losses:** As mentioned above, eddy current loss of windings is proportional to square of current and square of harmonic frequency in harmonic condition. In following equation, this loss is calculated:

$$P_{EC} = P_{EC-R} \times \sum_{h=1}^{h=h_{max}} h^2 \left[\frac{I_h}{I_R}\right]^2 \quad (17)$$

Where, $P_{EC-R}$ is Rated eddy current loss of windings, $I_h$ is the current related $h^{th}$ harmonics $I_R$ is rated load current, h is the order of harmonics. Also, the harmonic loss factor for eddy current loss of winding can be defined according to [2]:

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} h^2 I_h^2}{\sum_{h=1}^{h=h_{max}} I_h^2} = \frac{\sum_{h=1}^{h=h_{max}} h^2 \left[\frac{I_h}{I_R}\right]^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_R}\right]^2} \quad (18)$$

(C) **Effects of Harmonics on Other Stray Losses:** The other stray losses are assumed to vary with the square of the rms current and the harmonic frequency to the power of 0.8:

$$P_{OSL} = P_{OSL-R} \times \sum_{h=1}^{h=h_{max}} h^{0.8} \left[\frac{I_h}{I_R}\right]^2 \quad (19)$$

Harmonic loss factor for other stray losses is expressed in a similar form as for the winding eddy currents.

$$F_{HL-STR} = \frac{P_{OSL}}{P_{OSL-R}} = \frac{\sum_{h=1}^{h=h_{max}} h^{0.8} \left[\frac{I_h}{I_R}\right]^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_R}\right]^2} \quad (20)$$

So under non-sinusoidal currents it is only necessary to multiply the rated other stray loss by harmonic loss factor, $F_{HL-STR}$ .

## IV. EVALUATION OF LOSSES AND CAPACITY OF TRANSFORMER IN HARMONIC LOADS:

When a transformer is utilized under non-sinusoidal voltages and currents, due to loss increase results, increase of temperature, and its rated power must decrease. This action will be possible by limiting total transformer loss under non-sinusoidal current to the amount of loss in sinusoidal voltage and load current. In other word, maximum permissible current of transformer in harmonic load must be determined as its loss would be equal to the loss in hot spot and under sinusoidal current condition. The equation that applies to linear load conditions is [8]:

$$P_{LL-R}(pu) = 1 + P_{EC-R}(pu) + P_{OSL-R}(pu) \quad (21)$$

Where, $P_{LL-R}$is Rated load losses, 1 is per unit amount of dc losses ,$P_{EC-R}$is Eddy current loss, $P_{OSL-R}$is other stray loss in rated current. As the effect of harmonic on losses of transformer evaluated in previous sections, a general equation for calculating of losses when transformer supplying a harmonic load can be defined as follows:

$$P_{LL-R}(pu) = I^2(pu) \times [1 + F_{HL} P_{EC-R}(pu) + F_{HL-STR} P_{OSL-R}(pu)] \quad (22)$$

So, maximum permissible load current to determine the capacity reduction of transformer is expressed as:

$$I_{max}(pu) = \sqrt{\frac{P_{LL-R}(pu)}{1 + [F_{HL} P_{EC-R}(pu)] + [F_{HL-STR} P_{OSL-R}(pu)]}} \quad (23)$$

From above equation, we can determine the maximum permissible load current oftransformer and also we can evaluate its capacity reduction under the effects of non-sinusoidal current of transformer.

## V. TRANSFORMER CAPACITY AND LIFE WITH HARMONIC LOADS:

In recent years, non-linear loads (computers, electronic power supplies, discharge lamps, rectifiers, motor controllers, and induction furnaces...) are increasingly into electrical networks. increasing use of such devices is created concern for power grid Number of non-linear loads that injected non-sinusoidal current into the network are increased, they has very growing trend. Nonlinear loads considerably causing disturbance, which can create harmonics and reduce the network capacity. In transformers, harmonic currents cause increase of Foucault flow and disorganization of leaking fields. More losses create more heat in transformers and transformer temperature increases that made damage or extreme burnout of insulation and reduce the useful life transformers or transformer work under rated capacity (de-rate). One of the ways to overcome this problem is that the transformer design so strong and large to bear this kind of loss.

Therefore the maximum allowed current for decreasing rated power and capacity of transformers with harmonic load can be determined that this action be called derating for estimate reduced transformer life, degradation rate of insulation material must considered 50% reduction of transformer life is due by thermal stress is caused by harmonic currents. Most important factor in reducing the life of transformers is $\theta_{HS}$ point temperature. Reduction of life and real life of a transformer can be calculated from the following relations:

$$Life(pu) = 9.8 \times 10^{-18} \exp\left(\frac{15000}{\theta_{HS} + 273}\right) \quad (24)$$

Real Life =Life (pu) ×Normal insulation life (25)

## VI. CALCULATION IN HARMONIC LOADS:

Two transformers of the same specifications as are connected back to back was used in the experiment, this circuit fed by an autotransformer and in the output a harmonic load is placed amount of losses on both sides is measured and recorded by data logger.

Table -1: Characteristic Table of Two back to back Transformers with a Harmonic Load in its Output

| Characteristic | Value | Characteristic | Value |
|---|---|---|---|
| Rated Power | 15KVA | Primary Winding Resistance | 435.12Ohm |
| Rated Frequency | 50Hz | Secondary Winding Resistance | 0.0412Ohm |
| Primary Voltage | 20000Volt | No Load Loss | 120.12Watt |
| Secondary Voltage | 231 Volt | Full Load Loss | 550.82Watt |
| Rated Primary Current | 0.75Amp | Average Environment Temperature | 35 C |
| Rated Secondary Current | 65.2Amp | Permissible Winding Temperature Rise | 65 C |

The differences of measurement data that measured, transformers losses are achieved. The following table shows the result of measurement and calculation values for transformer losses.

Table -2: Final Table of Measurement and Calculation Values for Transformer Losses

| Difference Calculations With Test Results(percent) | Calculation Result | Measured Losses Result(test result) | | |
|---|---|---|---|---|
| | Harmonic Losses | Loss Increase(percent) | Losses With Harmonic Load | Losses With Sinusoidal Load |
| 1.86% | 152.9w | 7% | 150.1w | 141.4w |
| 0.60% | 167.9w | 1% | 166.9w | 165.2w |
| 1.56% | 188.3w | 21% | 185.4w | 153.5w |

The above table shows the percentage difference between the calculations with test results is less than 2% and the losses due to harmonic load is more than compared with sinusoidal loads.

To calculate the reduction of transformer life $\theta_a$=35cand $\theta_{TO-R}$=60C and Reference temperature 110C.

Be considered:

$$\theta_{TO} = 60 \times \left(\frac{758}{670.94}\right)^{0.8} = 66.15^{\circ C}$$

$$\theta_g = 10 \times \left(\frac{637.9}{550.82}\right)^{0.8} = 11.25^{\circ C}$$

$$Life(pu) = 9.8 \times 10^{-18} \exp\left(\frac{15000}{112.4 + 273}\right) = 0.784$$

Real Life=0.784×30=23.5 years

The following graph shows the different harmonic values specified at different harmonic orders.

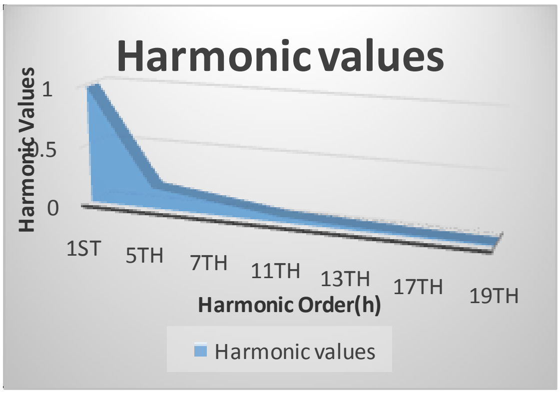


**Fig-1:** Graph between Harmonic values vs. Harmonic orders

## VII. LOSSES RELATING TO TRANSFORMERS FAILURES:

In recent years, there has been an increased concern about the effects of nonlinear loads on the electric power system. Nonlinear loads are any loads which draw current which is not sinusoidal and include such equipment as fluorescent lamp, gas discharge lighting, solid state motor drives, diodes, transistors and the increasingly common electronic power supply causes generation of harmonics. Harmonics are voltages and currents which appear on the electrical system at frequencies that are integral multiples of the generated frequency. It results to a significant increase in level of harmonics and distortion in power system. Presence of harmonics may or may not affect the power system present but increase in harmonics gives problem to transformers working which may conclude to a failure.

Application of non-sinusoidal excitation voltages to transformers increases the iron losses in the magnetic core of the transformer in much the same way as in a motor. A more serious effect of harmonic loads served by transformers is due to an increase in winding eddy current losses. Eddy currents are circulating currents in the conductors induced by the sweeping action of the leakage magnetic field on the conductors.

Eddy current concentrations are higher at the ends of the transformer windings due to the crowding effect of the leakage magnetic fields at the coil extremities. The eddy current losses increase as the square of the current in the conductor and the square of its frequency. The increase in transformer eddy current loss due to harmonics has a significant effect on the operating temperature of the transformer. Transformers that are required to supply power to nonlinear loads must be derated based on the percentages of harmonic components in the load current and the rated winding eddy current loss. Also, the presence of harmonics causes saturation of core which causes the magnetic field flux(Ø) remaining constant even by increasing magnetic field force(mmf).As the ferromagnetic materials cannot support infinite magnetic flux densities they tend to saturate at a certain level. The increase in harmonics causes distortions in voltage levels, to nullify this effect primary voltage is increased. After increasing the primary voltage to a certain level the core's flux will saturate. The saturation produces undesirable effects like noise and overheating.

The following are the common reasons of transformer failures due to losses:

(A)**High Ambient Temperature:** The ambient temperature of the installation site should always be specified when ordering a transformer, failure to do so could result in the overheating of the transformer coils leading to deterioration in the coil insulation and resulting in a complete failure of the transformer coil. But the loss gradually increases the temperature gradually damaging the insulation and overheating the core hence causing the failure.

(B) **Inadequate Airflow & Cooling:** Transformers will dissipate two types of losses, No load losses which are iron (Fe) losses and Full load losses which are Copper (Cu) and iron losses combined, in larger transformers these can be substantial, it is therefore essential that adequate space around the transformer/enclosure is left, to allow a natural free flow of air. Sufficient ventilation should also be supplied to allow for a constant change of air in and around the transformer/enclosure. Failure to do so can result in the ambient air temperature dramatically increasing and consequent result in transformer failure.

(C) **Overloading:** Transformers are designed to work at a given load to exceed that rating and due to harmonic loads will result in an increase in temperature. This increase in temperature will cause a rapid deterioration in the coil insulation and cause a complete failure of the transformer coil.

## VIII. CONCLUSION:

There is a wide spread utilization of electronic devices which has significantly increased the number of harmonics generated in the power systems. The harmonics causes distortions in voltage and current waveforms that have adverse effects on electrical equipment’s. This effect of harmonics has effects like increased losses of devices, equipment heating, loss of life and economic losses.

In this paper, impacts of harmonics on transformers has been reviewed and verified. Effects of non-linear loads on transformer losses based on the conventional method have been studied for derating purpose. Increased transformer loss caused by non-linear loads leads to an increase in transformer temperature, fatigue and premature failure of insulator and transformer life reduction. Therefore under harmonic load currents, to prevent the described problems, the capacity of transformer must be supposed smaller. The losses measured in the conventional and from the data logger showed nearly the same result but the calculated result was more. The total losses measured due to harmonic loads were higher than compared with the perfect sinusoidal waves showing the overloading characteristics of the harmonics on the transformers. So for power system with transformer, it is better to carry out monitoring on voltage and current, to reach to useful capacity of transformer based on available standards and the proposed model, if harmonic components exist.

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