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Non-Sinusoidal Loading Effect on Oil Immersed Power Transformers

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Abstract

Transformers are usually designed for nominal frequency and sinusoidal load current. Nowadays, usage of non-linear loads such as power electronics loads has extremely increased. These loads produce harmonic currents, which induce additional losses in transformer windings and other transformer parts and cause temperature rise, and ultimately can cause insulation deterioration, ageing and finally fast failing. The purpose of this paper effort to quantify the increasing in transformer losses due to harmonic load current and the corresponding temperature rise in transformer and study the effect of harmonics on loss of insulation life, total ownership cost of transformer, capacity of transformer and oil viscosity. An eddy current harmonic loss factor for transformer windings and harmonic loss factor for other stray loss are presented and used to calculate the transformer losses under harmonic load currents. The impact of transformer winding conductor size on winding eddy current harmonic loss factor is presented. Three loads with different amount of harmonic content of load current are proposed in this paper.

Keywords: Transformer losses, nonlinear load, eddy current, transformer temperature rise

تأثير الاحمال الغير جيبية على محولالت القدرة المغطسة بالزيت

الخلاصة

تصمم المحولات عادة للعمل بالتردد الاسمي والتيار الخالي من التشويه. في الوقت الحاضريتزايد استخدام الاحمال اللاخطية بشكل كبير كاحمال الكترونيات القدرة حيث ان هذه الاحمال ستولد تيارات توافقية وتؤدي الى خسائر اضافية في ملفات المحولة و اجزائها الاخرى وبالتالي زيادة حرارة المحولة, والتي قد تؤدي الى تقادم العوازل وسرعة انهيارها .الغرض من هذا البحث هو حساب الزيادة في خسائر المحولة نتيجة وجود التوافقيات وما يقابلها من زيادة في الحرارة وكذلك دراسة تأثير التوافقيات على عمر العوازل و الكلفة الاجمالية للمحولة و سعة المحولة و لزوجة الزيت. تم تمثيل و انجازعامل خسائر تيارات التوافقيات الدوامة لملفات المحولة واجزائها الاخرى وذلك لحساب الخسائرفي المحولة نتيجة وجود التوافقيات في تيار الحمل. كذلك دراسة تاثير حجم موصلات ملفات المحولة على عامل خسائر تيارات التوافقيات الدوامة لملفات المحولة. في البحث الحالي تم اقتراح ثلاثة احمال ذات قيم تيارات توافقية مختلفة .

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1. Introduction

Transformers are the most important component of power system and are interfaces between consumers and supplies. With increasing of electrical energy demand, the number of installed transmission transformers and especially distribution transformers are increasing. However, considering the point that the efficiency of these components is 97-99%, there was not enough attention to the amount of loss of and performance of transformers. By increasing the large number of transformers in transmission and distribution networks, it can be seen that the total power loss of these components is high .So, any reduction in loss of transformers would considerably reduce the total loss of electrical network and this will lead to optimum utilization of energy resources and helps environmental preservation [1].

Increasing in harmonic distortion component can cause excessive transformer winding losses and hence abnormal temperature rise which will decrease the expected lifetime and reduction of transformer capacity and lack of system performance of the plant. Such conditions require either transformer de-rating to return to the normal life expectancy or upgrading with a larger and more economical unit. Therefore the need for investigating the harmonic problems is obvious [2].

2. Transformer Losses

Transformer losses are categorized as no-load loss (excitation loss), load loss (impedance loss), and total loss (the sum of no-load loss and load loss).This can be expressed by the equation below [1, 3]:

$$P_T=P_{NL}+P_{LL} \quad \ldots\ldots. \ (1)$$

P_{NL}=No load loss, Watt
P_{LL}=Load loss, Watt
P_T=Total loss of transformer, Watt

$$P_{LL}=P_{dc}+P_{EC}+P_{OSL} \quad \ldots.. \ (2)$$

Where, P_{dc} is loss due to resistance of winding, P_{EC} is winding eddy loss, P_{OSL} is other stray losses in structural parts of transformer such as tank, clamps [4, 5].

3. Harmonic effect on transformer losses

Transformer manufactures usually try to design transformer in a way that their minimum losses occur in rated voltage and sinusoidal current. However, by increasing the number of non-linear load in recent years, the load current is no longer sinusoidal. This non-sinusoidal current causes extra loss and temperature in transformer [5]. The effects of harmonics on transformer losses are described below.

3.1 Harmonic Effect on P_{EC} loss

Winding eddy-current losses (P_{EC}) generated by the electromagnetic flux are assumed to vary with the square of the rms load current and the square of frequency (harmonics order) as in the following equation [6, 7].

$$P_{EC}=P_{EC-R}\sum_{h=1}^{h=max} h^2\left[\frac{I_h}{I_R}\right]^2 \ldots(3)$$

Where:

P_{EC-R} = Rated eddy current loss of winding.
I_h = The rms current at harmonic order.
h= Harmonic order.

I_R = Rated load current.

The harmonic loss factor for eddy current loss of winding for transformers which the dimension of their string of conductors are less than 3mm can be defined according to the following equation [7]:

$$F_{HL} = \frac{\sum_{h=1}^{h=max} h^2 \left[\frac{I_h}{I_R}\right]^2}{\sum_{h=1}^{h=max} \left[\frac{I_h}{I_R}\right]^2} \quad ..... (4)$$

Also, the transformer eddy current loss is calculated from the following equation:

$$P_{EC} = P_{EC-R} \times F_{HL} \quad ...... (5)$$

Due to skin effect in strings of conductor with dimensions more than 3 mm, electromagnetic flux cannot fully penetrate in string of winding conductor in high frequency .Therefore ,field permeability (δ) ,that depends on frequency ,can be defined as follows [4]:

$$\delta = \sqrt{\frac{\rho}{\mu\pi f h}} = \frac{\delta_R}{\sqrt{h}} \quad ...... (6)$$

Where:

δ_R = Penetration depth in rated frequency, which is about 10.2 mm for copper and about 13 mm. for aluminum in 50 Hz.

ρ = Conductor's resistance.

μ= Conductor permeability.

f = Fundamental frequency.

In mentioned condition, corrected harmonic loss factor, is calculated according to [8]:

$$F'_{HL} = \frac{\sum_{h=1}^{h=max} h^2 \left[\frac{F(\xi_h)}{F(\xi_R)}\right]\left[\frac{I_h}{I_R}\right]^2}{\sum_{h=1}^{h=max} \left[\frac{I_h}{I_R}\right]^2} ... (7)$$

Where

$$F(\xi_h) = \frac{1}{\xi_h} \times \frac{\sinh \xi_h - \sin \xi_h}{\cosh \xi_h - \cos \xi_h} ... (8)$$

$$\xi_h = \xi_R \times \sqrt{h} \quad .... (9)$$

$$\xi_R = \frac{\tau}{\delta_R} \quad .... (10)$$

Where

ξ_R = Relative skin depth compared to strand dimension.

τ = Conductor thickness.

According to the equation (7), the transformer eddy current loss under non-sinusoidal current is calculated from the following equation:

$$P_{EC} = P_{EC-R} \times F'_{HL} \quad (11)$$

3.2 Harmonic Effect on P_{OSL} Loss

This loss occurs due to the stray flux, which introduces losses in the core, clamps, tank and other iron parts. When transformers are subject to harmonic load currents these losses also increase. These losses may elevate the temperature of the structural parts. For oil filled transformers, these stray losses increase the oil temperature and thus the hot spot temperature [2]. 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 as shown in following equation [5, 9].

$$P_{OSL} = P_{OSL-R} \sum_{h=1}^{h=max} h^{0.8} \left[\frac{I_h}{I_R}\right]^2 \quad (12)$$

Where

P_{OSL-R}= other stray loss at rated load.

The harmonic loss factor for other stray loss is [9]:

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=max} h^{0.8} \left[\frac{I_h}{I_R}\right]^2}{\sum_{h=1}^{h=max} \left[\frac{I_h}{I_R}\right]^2} \quad (13)$$

So, under non-sinusoidal current, the other stray loss is calculated by the following equation.

$$P_{OSL} = P_{OSL-R} \times F_{HL-STR} \qquad (14)$$

4. Harmonic Effect on Transformer Capacity

To evaluate the transformer capacity under harmonic loading, it is convenient to consider transformer loss on a per unit basis. (Base current is rated current and base loss density is the P_{dc} (I^2R) loss). Load loss in linear load state and rated condition in per unit is equal to [10]:

$$P_{LL-R}(pu) = 1 + P_{EC-R}(pu) + P_{OSL-R}(pu) \qquad (15)$$

Where

P_{LL-R}=Rated load loss of transformer.

P_{EC-R}=Eddy current loss of winding at rated load

The number 1 in equation (15) is per unit amount of P_{dc} loss.

As the effect of harmonic on losses of transformer evaluated in previous section. A general equation for calculating of losses when transformer supplying a harmonic load in per unit can be defined as follow [1, 5]:

$$P_{LL}(pu) = I^2(pu) \times [1 + F_{HL} \times P_{EC-R}(pu) + F_{HL-STR} \times P_{OSL-R}(pu)] \qquad (16)$$

The maximum permissible load current of transformer is expressed as [5]:

$$I_{max}(pu) = \left[\frac{P_{LL-R}(pu)}{1 + F_{HL} \times P_{EC-R}(pu) + F_{HL-STR} \times P_{OSL-R}(pu)}\right]^{0.5} \qquad (17)$$

Base on equation (17), the transformer capacity under non-sinusoidal load can be calculated by the following equation [1]:

$$S_h = S \times I_{max}(pu) \qquad (18)$$

Where

S=Transformer rated capacity.

5. Harmonic Effect on Transformer Temperature

All effects of harmonic currents discussed so far will increase the transformer losses. These increased losses will obviously increase the temperature rise of the transformer from its sinusoidal value. The temperature rises are proportional to the losses according to the suggested standard exponents. The suggested exponents k and m define the non-linearity and depend on the transformer cooling method. The temperature rise can be calculated as follows [4, 11]:

The top oil temperatures rise over ambient, ^{o}C

$$\theta_{TO} = \theta_{TO-R} \times \left(\frac{P_{NL} + P_{LL}}{P_{NL-R} + P_{LL-R}}\right)^k \qquad (19)$$

Where

θ_{TO-R} = Top oil temperature rise over ambient under rated conditions ,^{o}C.

P_{NL} = No-load losses.

P_{LL} = Load losses, increased to account for harmonic load currents.

$$P_{LL} = P_{dc} + F_{HL} \times P_{EC-R} + F_{HL-STR} \times P_{OSL-R} \qquad (20)$$

P_{NL-R} = No load losses at rated load.

P_{LL-R} = Load losses at rated load.

The winding hot spot conductor temperature rise can be calculated as follows: [4, 11]:

$$\theta_W = \theta_{W-R} \times \left(\frac{P_W(pu)}{P_{W-R}(pu)}\right)^m \qquad (21)$$

Where

θ_{W-R} = The winding hot spot temperature at rated load.

P_W (pu) = The winding pu losses increases due to the harmonics.

P_{W-R} (pu) = The winding pu losses under rated load.

Equation (21) can be rewritten as:

$$\theta_W = \theta_{W-R} \times \left[\frac{I^2(pu) \times (1 + F_{HL} \times P_{EC-R}(pu))}{1 + P_{EC-R}(pu)}\right]^m \qquad (22)$$

The hottest spot temperature for a transformer under harmonic current load is equal to the sum of the ambient temperature, the top oil temperature rise over ambient and the hot spot temperature rise over top oil. This can be expressed by the equation below [12]:

$$\theta_H = \theta_A + \theta_{TO} + \theta_W \quad (23)$$

Where

θ_H = The hottest hot spot temperature at harmonic load current, °C.

θ_A = The ambient temperature, °C.

θ_{TO} = The top oil temperature rises over ambient at harmonic current spectrum load, °C.

θ_W = The winding hot spot temperature rise at harmonic current load ,°C.

6. Harmonic Effect on Oil Viscosity

The operating of transformer under harmonic load current is increase the transformer oil temperature. Oil viscosity is high temperature dependent. So, the oil viscosity can be calculated under harmonic load currents by the following equation [13]:

$$V_h = 0.0000013573 \times e^{\left[\frac{2797.3}{273+\theta_{oil}}\right]} \quad (24)$$

V_h=Oil viscosity at harmonic current, kg/ (ms).

θ_{oil} = The oil temperature at harmonic load current.

7. Harmonic Effect on Lossing of Insulation Life of Transformer

One factor in transformer over-temperature conditions is the loss of insulation life. The hottest temperature in the transformer determines the thermal ageing of transformer insulation. The relationship between the hottest spot transformer temperature and transformer life expectancy is given by the accelerating aging factor, FAA [12]. The accelerating ageing factor under harmonic load can be calculated by using following equation [4]:

$$FAA_h = e^{\left[\frac{15000}{383} - \frac{15000}{273+\theta_H}\right]} \quad (25)$$

For a transformer operated continuously at a specific temperature, the actual life expectancy is the normal life expectancy divided by the accelerating aging factor FAA. Transformers will not be operated at a constant over-temperature for a long period of time. Therefore, it is more practical to define a loss-of-life factor that is representative of the amount of insulation strength lost during an over-temperature event [12]. The loss of life factor under harmonic load can be defined as in following equation [12, 14]:

$$FEQA_h = \frac{\sum_{n=1}^{N} FAAn_h \times \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \quad (26)$$

Where

$FAAn_h$ = The accelerating aging factor at index n

n= Indix of time interval.

Δt_n = The time interval for transformer operation under harmonic load.

N= The total number of intervals.

According to above equation, the total loss of transformer life as percentage can be calculated under harmonic load by using following equation [12, 14]:

$$\%LOL = \frac{FEQA_h}{180000} \times 100 \quad (27)$$

8. Harmonic Effect on Total OwnershipCostof ransformer

The most widely used technique for the evaluation of transformers cost is the total ownership cost (TOC) method that is based on the following formula [15, 16]:

TOC =Purchase Price (PP) + Cost of No load loss + Cost of Load loss (28)
Cost of core loss=A×No load loss in watts.
Cost of load loss=B× load loss watts.
Where
A=Equivalent first cost of no load losses, Rs/watt

$$A = \frac{PW+EL+HYP}{1000} \quad \text{...........(29)}$$

PW= Present worth of future cash flows

$$PW = \frac{((1+i)^n - 1)}{i \times (1+i)^n} \quad \text{.........(30)}$$

i=per unit interest rate.
n=number of years.
EL= Cost of electricity, Rs/kWh.
HYP= Hours of operation per year.
B=Equivalent first cost of load losses.

$$B = \frac{(PW+EL+HYP)\times P^2 \times T}{1000} \quad (31)$$

P = per unit load on transformer.
T = Temperature correction factor. Details of its calculation are given in [15, 16].

Finally, the increase in transformer total owner cost due to harmonic load current can be determined by the following:
Increase transformer cost due to harmonic load $=B_h\times$ (load loss at harmonic load – rated load loss), watts.

$$B_h = \frac{(PW+EL+t_h)\times P^2 \times T}{1000} \quad (32)$$

t_h = Time of transformer operating under harmonic load per year (hours).

9. Case study

To illustrating the impact of the harmonic load on the power transformer, 30 MVA rated capacity, 115/6.3 kV, three phase oil- immersed transformer is considered. The transformer supplying harmonic load as shown in figure (1). The harmonic load is represented as harmonic current spectrum [1, 10, 11]. Three different loads with different amount of harmonic content of load current are used in this study. These harmonic loads spectrum are described in Tables (1), (2) and (3). The fundamental current is assumed to be equal to the rated current.

The data at rated load and fundamental frequency of transformer under study are given as follows [4, 11, 16]:

No load loss 16.1 kW
$P_{dc\text{-}R}$ 123.6 kW
$P_{EC\text{-}R}$ 11.4 kW
$P_{OSL\text{-}R}$ 11 kW
δ_R = 10.2 mm (copper conductor).
τ = 6mm, 9mm, and 12 mm
Top oil temperature rise (θ_{TO-R}) 50.7 ^{O}C
Hot spot temperature rise (θ_{W-R}) 25.6 ^{O}C
i (discounting factor)= 0.15
n (transformer life) = 20 year
EL (Cost of electricity) = 1.25 Rs per kWh
t_h =150 hour
Per unit transformer loading (P) = 0.75
V_R=0.0037 kg/ (ms)
k= 0.9
m=0.8

10- Algorithm of Harmonic Effect on power Transformer

Figure (2) illustrates the flow chart of the algorithm for Harmonic Effect on power Transformer. This algorithm consists of the following steps.
1-Input the rated and fundamental frequency data for transformer under study (No load loss, P_{dc}, p_{EC}, p_{OSL}, δ_R, τ, θ_{TO-R}, θ_{W-R}, S, i, n, EL, t_h, V_R, k and m.

2- Input the harmonic load current spectrum.
3- For $\tau < 3mm$
4-Compute F_{HL} from equation (4).
5-Compute p_{EC} from equation (5).
6- Compute F_{HL-STR} from equation (13).
7- Compute P_{OSL} from equation (14).
8- Compute S_h from equation (18).
9-Compute θ_{TO}, θ_W, θ_H from equations (19), (22), and (23) respectively.
10- Compute V_h from equation (24).
11- Compute % LOL from equation (25) to (27).
12- Compute TOC from equation (28) to (31).
13- For $\tau > 3mm$.
14- Compute F'_{HL} from equation (7).
15- Compute P_{EC} from equation (11).
16- Repeat steps from 6 to 12.

The above steps are repeated for each harmonic load current spectrum described in Tables (1), (2) and (3).

11. Results and Discussion

Operating the transformer under non sinusoidal load current is specified in Table 2.The harmonic loss factors F_{HL} and F_{HL-STR} are calculated by using equation (4) and (13) respectively as shown in Table (4).The corrected harmonic loss factor F'_{HL} for different values of conductor thickness (6, 9, 12) mm can be calculated by using equation (7) .The results are listed in Tables (5), (6) and (7) respectively. From these Tables, it can be seen that for a small conductor, skin effect is insignificant and only for large conductor dimension, the skin effect becomes significant, so F'_{HL} is minimum value for larger conductor thickness (τ =12) mm. As result, using F_{HL} predict losses accurately for small conductors while produces a certain degree of error for large conductor.

The results listed in Table (8) show the transformer parameters under harmonic load for the loads values listed in Tables (1), (2) and (3).The results listed in Table (8) are calculated by using the harmonic eddy loss factor F_{HL}. It can be seen from results listed in Table (8), that the load losses of transformer have been increased about (19%, 66%, 80%) for harmonic currents spectrums listed in Tables (1), (2) and (3) respectively.

The operating of transformer under non-sinusoidal load current increase the transformer hottest temperature with respect to rated load about (10.94%, 39.35%, 48.17%) for harmonic load current described in Tables (1), (2) and (3) respectively.

Due to non- sinusoidal load currents the transformer oil temperature is increased. The oil viscosity is dependent on oil temperature, so, the increase in oil temperature will decrease the oil viscosity with respect to rated load about (16.22%, 43.24%, and 48.17%) for harmonic load current described in Tables (1), (2) and (3) respectively.

The maximum permissible load current of transformer can be calculated according to the equation (17). Also, the capacity under non-sinusoidal load current can be determined by equation (18). It can be seen from result in Table(8) that the present of harmonic in load current reduces the transformer capacity with respect to rated load about (6.63%, 17.53%, 18.83%) for harmonic load current described in Tables (1), (2) and (3) respectively.

From Table(8), it can be seen that the transformer operating under harmonic load currents for 1 hour will, decrease the transformer insulation life about (0.0012 %, 0.0193%, 0.0418%) for harmonic currents spectrums listed in Tables (1), (2) and(3) respectively.

Operating the transformer under harmonic load currents for 150 hour in year will increase the TOC of transformer with values present in Table (8).

The data tabulated in Tables (9), (10) and (11) shows the parameters of transformer under harmonic load currents. In this cause the calculations are done using corrected harmonic loss factor F'_{HL} for different values of conductor thickness (6, 9, and 12) mm respectively. It can be seen from data listed in Tables (9), (10) and (11) that the conductor thickness effects only on P_{EC} loss .The value of P_{EC} loss decreases with the increase of conductor thickness and. Also, observed that the values in Tables (9), (10) and (11) is less than that in Table (8) because of the skin effect.

It can be seen from the whole obtained results, that all values of data listed in Tables (8), (9), (10) and (11) are dependent on values of harmonic content of load current. These values change with changes of harmonic component of load current, also the transformer supplying the load spectrum described in Table (3) is the worst case of loading on transformer parameters because it has high harmonic content of load current. From the results listed in Tables (8), (9), (10) and (11), one can observe that the values of results listed in Table (11) is less than the results listed in other Tables because of the skin effect.

12. Conclusion

One of the most issues in loss reduction of transformer under linear and non-linear loads is to determine the component of loss in different parts of transformer. The results have shown that the transformer losses increase when supplying harmonic loads. The effect of harmonic load on d.c loss and other stray loss is low, while its effect on winding eddy current loss is high. The increase in transformer losses due to harmonic loads lead to an increase in the transformer hot spot temperature, also reduce the transformer capacity. The transformer loss of life decreases when supplying harmonic loads. The total ownership cost of transformer increase due to harmonic loads.

Also, the results show that the transformer composed of thin conductors has winding eddy current losses smaller than transformer with largest conductors. Thus, transformers with small conductor dimension are less sensitive to harmonic. The harmonic loss factor dependents on the spectrum of harmonic current. So, every changing in content of harmonic current leads to change in harmonic losses factor and thus cause to change losses and all parameters of transformer.

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Table (1) Harmonic load current spectrum 1

Harmonic order (h)	(I_h/I_1)
1	1
5	0.1760
7	0.1100
11	0.0447
13	0.0264
17	0.0118
19	0.0106
23	0.0087
25	0.0086

Table (2) Harmonic load current spectrum 2

Harmonic order (h)	(I_h/I_1)
1	1
2	0.044
3	0.092
4	0.022
5	0.412
6	0.018
7	0.199
8	0.010
9	0.018
10	0.015
11	0.046
12	0.010
13	0.048

Table (3) Harmonic load current spectrum 3

Harmonic order (h)	(I_h/I_1)
1	1
3	0.453
5	0.267
7	0.186
9	0.0912
11	0.0712
13	0.0512
15	0.0425
17	0.0402
19	0.0387

Table (4) Computation table for (F_{HL},F_{HL-OSL}) of harmonic spectrum 3 .

h	I_h/I_1	$(I_h/I_1)^2$	h^2	$(I_h/I_1)^2 * h^2$	$h^{0.8}$	$(I_h/I_1)^2 * h^{0.8}$
1	1.0000	1.0000	1	1.0000	1.0000	1.0000
3	0.4530	0.2052	9	1.8469	2.4082	0.4942
5	0.2670	0.0713	25	1.7822	3.6239	0.2583
7	0.1860	0.0346	49	1.6952	4.7433	0.1641
9	0.0915	0.0084	81	0.6782	5.7995	0.0486
11	0.0712	0.0051	121	0.6134	6.8095	0.0345
13	0.0512	0.0026	169	0.4430	7.7831	0.0204
15	0.0425	0.0018	225	0.4064	8.7272	0.0158
17	0.0402	0.0016	289	0.4670	9.6463	0.0156
19	0.0387	0.0015	361	0.5407	10.5439	1.0000
$\sum$		1.3321		9.4730		2.0673
F_{HL}=7.1114						
F_{HL-OSL}=1.5519						

Table (5) Computation table for (F'_{HL}) of harmonic spectrum 3 with τ = 6mm.

h	I_h/I_1	$(I_h/I_1)^2$	h^2	$F(\zeta_h)/ F(\zeta_R)$	$h^2 *(I_h/I_1)^2 * F(\zeta_h)/ F(\zeta_R)$
1	1.0000	1.0000	1	1.0000	1.0000
3	0.4530	0.2052	9	0.9985	1.8441
5	0.2670	0.0713	25	0.9955	1.7742
7	0.1860	0.0346	49	0.9910	1.6800
9	0.0915	0.0084	81	0.9852	0.6681
11	0.0712	0.0051	121	0.9780	0.5999
13	0.0512	0.0026	169	0.9696	0.4296
15	0.0425	0.0018	225	0.9601	0.4414
17	0.0402	0.0016	289	0.9497	0.4435
19	0.0387	0.0015	361	0.9383	0.8880
$\sum$		1.3321			9.3368
F'_{HL}= 7.0092					

Table (6) Computation table for (F'_{HL}) of harmonic spectrum 3 with τ = 9 mm.

h	I_h/I_1	$(I_h/I_1)^2$	h^2	$F(\zeta_h)/F(\zeta_R)$	$h^2 *(I_h/I_1)^2 * F(\zeta_h)/F(\zeta_R)$
1	1.0000	1.0000	1	1.0000	1.0000
3	0.4530	0.2052	9	0.9924	1.8329
5	0.2670	0.0713	25	0.9778	1.7426
7	0.1860	0.0346	49	0.9571	1.6224
9	0.0915	0.0084	81	0.9315	0.6317
11	0.0712	0.0051	121	0.9026	0.5537
13	0.0512	0.0026	169	0.8716	0.3861
15	0.0425	0.0018	225	0.8396	0.3859
17	0.0402	0.0016	289	0.8076	0.3772
19	0.0387	0.0015	361	0.7764	0.7347
$\sum$		1.3321			8.9072
F'_{HL} = 6.6570					

Table (7) Computation table for (F'_{HL}) of harmonic spectrum 3 with τ = 12 mm.

h	I_h/I_1	$(I_h/I_1)^2$	h^2	$F(\zeta_h)/F(\zeta_R)$	$h^2 *(I_h/I_1)^2 * F(\zeta_h)/F(\zeta_R)$
1	1.0000	1.0000	1	1.0000	1.0000
3	0.4530	0.2052	9	0.9767	1.8039
5	0.2670	0.0713	25	0.9350	1.6664
7	0.1860	0.0346	49	0.8821	1.4954
9	0.0915	0.0084	81	0.8252	0.5596
11	0.0712	0.0051	121	0.7695	0.4720
13	0.0512	0.0026	169	0.7179	0.3181
15	0.0425	0.0018	225	0.6718	0.3088
17	0.0402	0.0016	289	0.6312	0.2948
19	0.0387	0.0015	361	0.5960	0.5640
$\sum$		1.3321			8.2054
F'_{HL} = 6.1559					

Table (8) Transformer data under non-sinusoidal load current

	Harmonic spectrum (1)	Harmonic spectrum (2)	Harmonic spectrum (3)
F_{HL}	2.7516	6.5287	7.1114
F_{HL-STR}	1.1399	1.5227	1.5519
P_{EC} (w)	31368	74427	81070
P_{OSL}(w)	12539	16750	17071
P_{dc} (w)	129610	151870	165040
P_{LL} (w)	173520	243040	263190
P_{NL} (w)	16100	16100	16100
P_T (w)	189620	259140	279290
$_{oil}$ (°C)	58.2866	77.2089	82.5894
$_{w}$(°C)	29.6408	40.9251	44.9105
$_{A}$(°C)	30	30	30
$_{H}$(°C))	117.9274	148.1340	157.4999
V_h (kg/ms)	0.0031	0.0021	0.0019
I_{max}(pu)	0.9337	0.8248	0.8117
$S_h = S \times I_{max}$	28.0116	24.7427	24.3515
Decrease of LOL%	0.0012	0.0193	0.0418
Increase of TOC(Rs)	20308	77438	95544

Table (9) Transformer data under non-sinusoidal load current for τ =6mm

	Harmonic spectrum (1)	Harmonic spectrum (2)	Harmonic spectrum (3)
F_{HL}	2.7231	6.4833	7.0092
F_{HL-STR}	1.1399	1.5227	1.5519
P_{EC} (w)	31043	73910	79905
P_{OSL}(w)	12539	16750	17071
P_{dc} (w)	129610	151870	165040
P_{LL} (w)	173190	242530	262020
P_{NL} (w)	16100	16100	16100
P_T (w)	189290	258630	278120
$_{oil}$ (°C)	58.1965	77.0703	82.2792
$_{w}$(°C)	29.5911	40.8398	44.7061
$_{A}$(°C)	30	30	30
$_{H}$(°C))	117.7876	147.9101	156.9853
V_h (kg/ms)	0.0031	0.0021	0.0019
I_{max}(pu)	0.9346	0.8257	0.8139
$S_h = S \times I_{max}$	28.0388	24.7725	24.4157
Decrease of LOL %	0.0012	0.0189	0.0401
Increase of TOC(Rs)	20059	76985	94483

Table (10) Transformer data under non-sinusoidal load current for τ =9mm

	Harmonic spectrum (1)	Harmonic spectrum (2)	Harmonic spectrum (3)
F_{HL}	2.6352	6.3171	6.6870
F_{HL-STR}	1.1399	1.5227	1.5519
P_{EC} (w)	30042	72015	76231
P_{OSL}(w)	12539	16750	17071
P_{dc} (w)	129610	151870	165040
P_{LL} (w)	172190	240630	258350
P_{NL} (w)	16100	16100	16100
P_T (w)	188290	256730	274450
$_{oil}$ (°C)	57.9194	76.5619	81.3004
$_{w}$(°C)	29.4380	40.5265	44.0602
$_{A}$(°C)	30	30	30
$_{H}$(°C))	117.3575	147.0884	155.3606
V_h (kg/ms)	0.0032	0.0022	0.0020
I_{max}(pu)	0.9374	0.8294	0.8207
$S_h= S \times I_{max}$	28.1230	24.8826	24.6213
Decrease of LOL %	0.0012	0.0176	0.0351
Increase of TOC(Rs)	19298	75329	91154

Table (11) Transformer data under non-sinusoidal load current for T =12mm

	Harmonic spectrum (1)	Harmonic spectrum (2)	Harmonic spectrum (3)
F_{HL}	2.4869	5.9654	6.1599
F_{HL-STR}	1.1399	1.5227	1.5519
P_{EC} (w)	28351	68006	70223
P_{OSL}(w)	12539	16750	17071
P_{dc} (w)	129610	151870	165040
P_{LL} (w)	170500	236620	252340
P_{NL} (w)	16100	16100	16100
P_T (w)	186600	252720	28440
$_{oil}$ (°C)	57.4511	75.4849	79.6966
$_{w}$(°C)	29.1790	39.8616	42.9987
$_{A}$(°C)	30	30	30
$_{H}$(°C))	116.6301	145.3466	152.6954
V_h (kg/ms)	0.0032	0.0022	0.0020
I_{max}(pu)	0.9422	0.8374	0.8323
$S_h= S \times I_{max}$	28.2669	25.1205	24.9691
Decrease of LOL %	0.0011	0.0152	0.0282

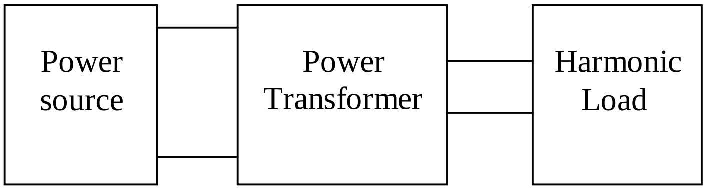

Figure (1) system under study

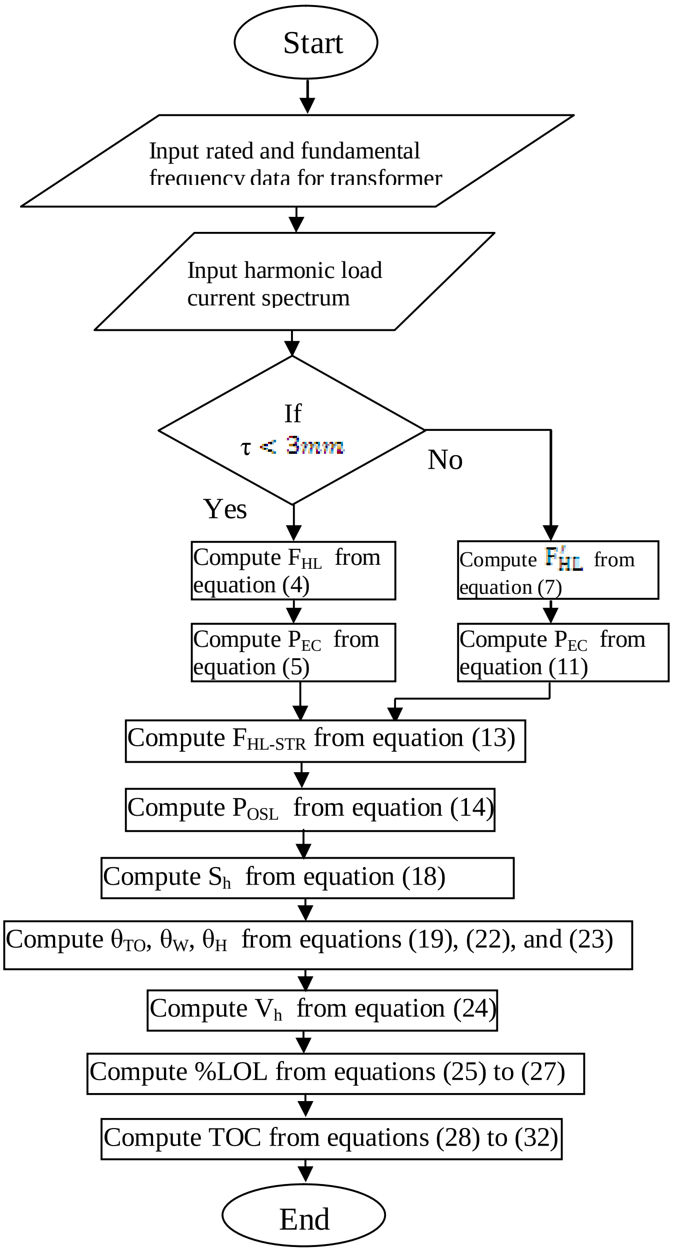

Figure (2) Flow chart of harmonic effect on power transformer algorithm