Analysis of the Increase of Transformer Power Losses due to the Operation of Unbalanced Nonlinier Loads

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Abstract - Non-linear loads are the source of harmonic current for electric utilities. The high level of harmonics greatly affects the increase of losses of electrical power (losses). The quality of electric power is determined by the parameters of power losses that occur in the transformer due to harmonic distortion. In this research will be analyzed THD from result of measurement and simulation in accordance with IEEE 519-2014 standard, power loss analysis on transformer before and after. Harmonics, the impact is increased due to unbalanced linear currents.

Index Terms — Trafo, Losses, nollinier load, unbalanced, harmonic

I. INTRODUCTION

The power system is designed to work at a frequency of 50 Hz. Non-linear loads can result in the formation of waves at high frequencies which are multiples of their fundamental frequencies and are known as harmonics. [1] [5] [6] [7]. This can disrupt the electrical system in its fundamental frequency, so that the current waveform or voltage which ideally is pure sinusoidal will become defective due to harmonic distortion that occurs.

The operation of power electronics equipment at Udayana University Faculty of Engineering can cause distortion in its electric current waveform. The transformer is designed to supply electrical power with minimum losses at its fundamental frequency. The high level of harmonics is very influential on the transformer, so that there will be an increase in losses [2]

IEEE 519 Standards 2014 is the standard used as a limitation for analyzing THD (Total Harmonic Distortion). From the results of the short-circuit ratio, according to IEEE 519 Standards 2014 standard, the maximum allowable threshold of the transformer feeder in the Udayana University Faculty of Engineering is 8.0%, while the maximum THD limit is 5.0%. The measurement data on the transformer feeder at the Udayana University Faculty of Engineering shows the current THD content is still over the standard of more than 8%. While the THD content of the voltage has met the standard, the value is less than 5%.

The current THD content of the transformer feeder at the Udayana University Faculty of Engineering is currently incompatible with the IEEE 519 standard 2014, causing higher power losses. In this research, the analysis of electrical power losses caused by the emergence of harmonic current in 200 kVA power transformer.

II. LITERATURE REVIEW

2.1. Harmonics On Electric Power System

Harmonics is a phenomenon arising from the operation of non-linear electric load, which is the source of the formation of high frequency waves (multiples of fundamental frequencies, eg 100Hz, 150Hz, 200Hz, 300Hz, and so on). The harmonic voltage or current measured by the magnitude of each harmonic component of its component is expressed in the prosen. To obtain a parameter used to assess the harmonics is used THD [5]. THD is expressed by the following equation, [5]:

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} M_h{}^2}}{M_1} \qquad (1)$$

Where M_h is the rms value of the harmonic component h in the sum of M.

2.2. Linear and non-linear load

a. Linear load

Linear load is a load whose current component is proportional to its voltage. There is a linear relationship between the current and the voltage so that the current waveform will be the same as the voltage waveform, as shown in Figure 1. Linear loads absorb sinusoidal currents when supplied by sinusoidal voltages. Examples of linear loads include electric motors, heating, incandescent, and others [6].
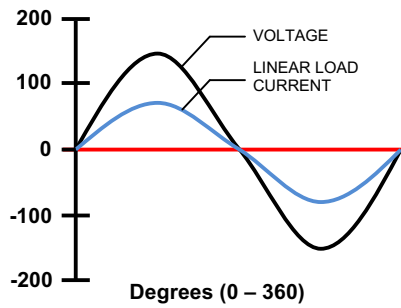
Fig. 1. Current and voltage waves on
linear load [6]

b. Non-linear load

The load whose current component is not proportional to the voltage component, so the current waveform is not the same as the voltage waveform. There is no linear relationship between current and voltage. Non-linear loads absorb non sinusoidal currents as well as harmonic currents, although they are supplied by sinusoidal voltages, as shown in Figure 2. Examples of non-linear loads include rectifiers (power supply, UPS, computer, motor speed setting, release lamps), ferromagnetic devices, DC motors, and fire arc furnaces, and others [6].
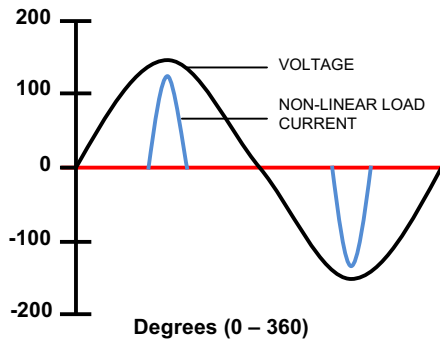

Fig. 2. Current and voltage waves
on non-linear load [6]

2.3. Standard THD voltage & THD currents
a. THD voltage

Table 1 of the IEEE standard 519-2014, suggests the following values as the recommended maximum limit for voltage correction.

TABLE 1
MAXIMUM VOLTAGE LIMIT CONFORMS TO IEEE STANDARD
519-2014 [4]

BusVoltage at PCC	Individual Voltage Distortion (%)	Total harmonic distortion THD (%)
V ≤ 1,0 kV	5,0	8,0
1 kV < V < 69 kV	3,0	5,0
69 kV < V ≤ 161 kV	1,5	2,5
161 kV < V	1,0	1,5

b. THD current

Table 2 of the IEEE standard 519-2014, suggests the following values as the recommended maximum limit for current distortion.

TABLE 2
MAXIMUM VOLTAGE LIMITS CONFORM TO IEEE STANDARD
519-2014 [4]

I_{SC}/I_L	$3 \leq h \leq 11$	$11 \leq h \leq 17$	$17 \leq h \leq 23$	$23 \leq h \leq 35$	$35 \leq h \leq 50$	THD
< 20	4,0	2,0	1,5	0,6	0,3	5,0
20 - 50	7,0	3,5	2,5	1,0	0,5	8,0
50 - 100	10,0	4,5	4,0	1,5	0,7	12,
100 - 1000	12,0	5,5	5,0	2,0	1,0	15
>1000	15,0	7,0	6,0	2,5	1,4	20,0

2.4. Losses Calculation On Transformer Effects
 Harmonics

Load loss (PLL) transformer in per unit, can be searched with the following formula;

$$P_{LL} = \sum I_h{}^2 + (\sum I_h{}^2 \, x \, h^2) . P_{EC-R} \quad (p.u) \qquad (2)$$

Where PEC-R is eddy current loss factor, h is the harmonic number and I_h is the harmonic current. $I_h{}^2 \times h^2$) PEC-R is an eddy current loss factor under basic conditions in p.u.Σ $I_h{}^2$ is an I^2R loss component in p.u, whereas (Σ The eddy current loss factor is shown in Table 3 [5].

TABLE 3
VALUES OF PEC-R [5]

Type	MVA	Voltage	%P_{EC-R}
Dry	≤ 1		3 - 8
	≥ 1.5	5 kV HV	12 - 20
	≤ 1.5	15 kV HV	9 - 15
Oil - filled	≤ 2.5	480 V LV	1
	2.5 - 5	481 V LV	1 - 5
	> 5	482 V LV	9 -15

III. METHODOLOGY

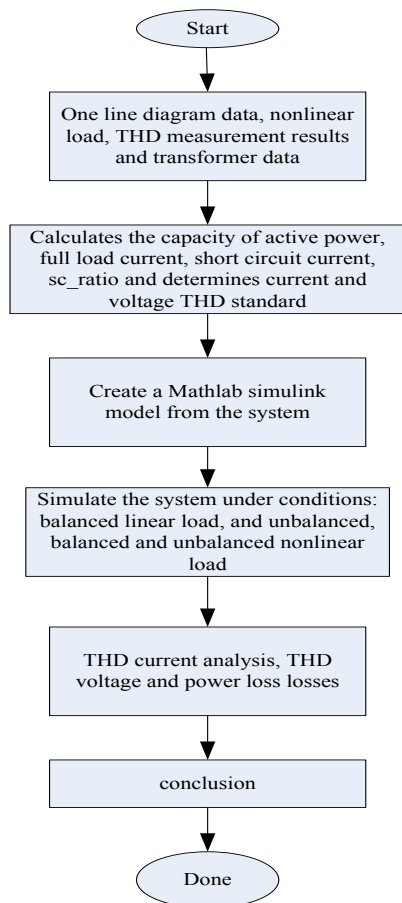The analysis in this research is done in several stages like figure 3.

Fig. 3   Step analysis

IV. RESULTS AND DISCUSSION

4.1. THD$_{i\&v}$ simulation

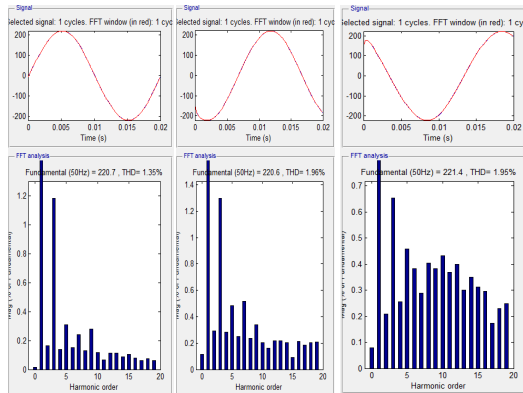The simulation on the transformer feeder at Udayana University Faculty of Engineering requires parameters

Fig. 4 Wave and spectrum THD voltage:
(a) THDVPhasa R, (b) THDV Phase S, (c) THDV Phasa

R   =   1.36   Ohm   and   L   =   0.0241   Henry
The result of voltage harmonic simulation and voltage harmonic spectrum is shown in figure 4. While the result of

THDi simulation by using FFT obtained result as shown in figure5. The source of three phases is equivalent to the transformer secondary to the feeder. Vtrafo = 400/231 V; Z = 4%; f = 50%; X / R = 3,638; Rs = 0.0085 Ω and Ls = 9,84e-5 H. Nonlinear load of 35442 Watt / phase. R_L = 1.36 Ohm and L_{Load} = 0.0241 Henry.

The result of voltage harmonic simulation and voltage harmonic spectrum is shown in figure 4.
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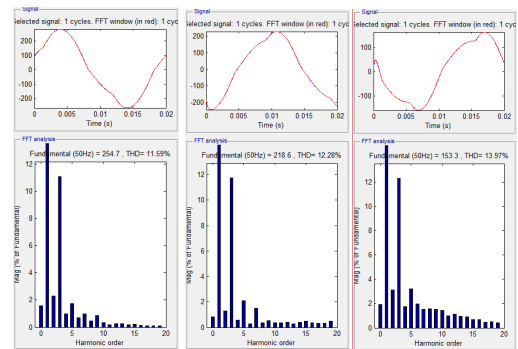

Fig. 5 Wave and THD current spectrum:
(a) THDi Phase R, (b) THDi Phase S, (c) THDi Phase T transformer.

The average THDv is 1.75%, while the average THDi is 12.61% as table 4. The voltage and current values of the simulation results for the harmonic order of the odd multiple of phases R, S, and T can be seen in table 5.

TABLE 4
AVERAGE THD SIMULATION RESULTS.

Phase	THD$_v$ (%)	THD$_i$ (%)
R	1,35	11,59
S	1,96	12,28
T	1,95	13,97
Average	1,75	12,61

TABLE 5
FLOW VALUES IN EACH ORDER OF ODD HARMONICS PHASA R.

Order of Harmonics	Phase R		Phase S		Phase T	
	Current (%)	Current (A)	Current (%)	Current (A)	Current (%)	Current (A)
1	100,0	157,6	100,0	206,7	100,0	189,0
3	8,0	12,6	4,6	9,4	6,3	11,8
5	4,1	6,6	6,6	13,6	3,8	7,3
7	5,0	7,8	2,6	5,4	4,6	8,7
9	2,9	4,5	1,7	3,4	2,3	4,2
11	1,3	2,0	1,0	2,1	1,3	2,4
13	1,0	1,5	0,7	1,4	0,9	1,6
15	0,8	1,2	0,5	1,0	0,7	1,4
17	0,4	0,6	0,4	0,8	0,6	1,1
19	0,5	0,7	0,3	0,7	0,6	1,1

4.2. Losses Transformer Analysis

Factors that can cause the loss of transformer is THDi on the transformer. The analysis is done in two ways:
  i. Analysis of losses without harmonic influence.
  ii. Analysis of losses due to the influence of harmonics.

The purpose of the analysis is to find out how much increase in losses due to the influence of transformer harmonics.

I. Trafo Losses Analysis Without Effect of Harmonics.

There are two losses that need to be known to calculate total transformer losses:
  i. No-load losses
  ii. Load Losses

Based on SPLN 50: 1997 on distribution transformer specifications, for distribution transformers with a power capacity of 200 kVA has iron losses of 480 Watt and copper losses of 2500 Watt. Once the value is known and then the total loss value can be calculated as follows:

$$Total\ Losses = P_i + P_{cu}$$
$$= 480 + 2500$$
$$= 2980\,W = 2,98\,kW$$

II. Losses Trafo Analysis Due Effect Harmonics.

Losses of a transformer can technically be referred to as loadloss. In units per unit (p.u), loadloss can be calculated using the equation:

$$P_{LL} = \sum I_h^2 + \left(\sum I_h^2 \times h^2\right) \times P_{EC-R}(p.u)$$

where :

$$P_{EC-R} = Eddy\ CurrentLossFactor(\%)$$
$$h = Harmonics\ (\%)$$
$$I_h = Current\ Harmonics\ (A).$$

P_{EC-R} value is known at 1%. Based on the measurement results, it is known that:

S   = 200 kVA
$Cos\,\varphi$ = 0,8

So the value can be calculated by the equation below:

$$P_{Base\,1\phi} = \frac{S \times \cos\varphi}{\sqrt{3}}$$
$$= \frac{200 \times 0,8}{\sqrt{3}}$$
$$= 92,376\,kW$$

Furthermore, the calculation of losses can be done due to the influence of harmonics for each phase .

a. Phasa R Losses

To calculate the losses of the transformer in phase R need to know the harmonic current of each odd order in units per unit with the following calculation:

$$I_{h1}(p.u) = \frac{I_{h1}}{I_1} = \frac{157,6}{157,6} = 1,000\,(p.u)$$

$$I_{h3}(p.u) = \frac{I_{h3}}{I_1} = \frac{12,6}{157,6} = 0,08\,(p.u)$$

$$I_{h5}(p.u) = \frac{I_{h5}}{I_1} = \frac{6,6}{157,6} = 0,042\,(p.u)$$

In the same way, the harmonic currents in phase R in pu can be determined, the order of harmonics is shown in table 6.

TABLE 6
ANALYSIS OF PHASE HARMONIC FLOW R

Order of Harmonics	I_h (%)	I_h (A)	I_h (p.u)	I_h^2 (p.u)	$I_h^2 \times h^2$ (p.u)
1	100,0	157,6	1,000	1,0000000	1,0000000
3	8,0	12,6	0,080	0,0063919	0,0575269
5	4,1	6,6	0,041	0,0017538	0,0438445
7	5,0	7,8	0,050	0,0024495	0,1200253
9	2,9	4,5	0,029	0,0008153	0,0660386
11	1,3	2,0	0,013	0,0001610	0,0194865
13	1,0	1,5	0,010	0,0000906	0,0153094
15	0,8	1,2	0,008	0,0000580	0,0130447
17	0,4	0,6	0,004	0,0000145	0,0041888
19	0,5	0,7	0,005	0,0000197	0,0071218
Total				1,0117543	1,3465864

From the calculation of harmonic order of 1 to 19, it can be calculated loadloss in phase R:

$$P_{LL\_PhaseR} = 1.0117543 + 1,3465864 \times 0,01 = 1,0252201\ p.u$$

From the calculation of known copper loss has increased by 0.0117543 p.u. The R-phase losses in kW are:

$$P_{cu}\,(kW) = P_{cu}\,(p.u) \times P_{base\,1\phi}$$
$$P_{cu}\,(kW) = 0.0117543\ p.u \times 92,376\,kW$$
$$P_{cu}\,(kW) = 1,086\,kW$$

Eddy-Current Loss has increased by 0,003465864 p.u. Eddy-Current Loss in kW are:

$$P_e\,(kW) = P_e\,(p.u) \times P_{base\,1\phi}$$
$$P_e\,(kW) = 0,003465864\ p.u \times 92,376\,kW$$
$$P_e\,(kW) = 0,32\,kW$$

Hysterisis Loss can be calculated by:

$$P_h = K_h \times \sum_{h=1}^{\infty} i_h \times h$$
$$P_{h1} = 0,26 \times 157,6 \times 1 = 40,976\,W$$
$$P_{h3} = 0,26 \times 12,6 \times 3 = 9,828\,W$$

In the same way, the total hysteresis losses in Table 7.

TABLE 7
HYSTERESIS LOSSES PHASA R.

Order of Harmonics	I_h (A)	P_h (Watt)
1	157,6	40.976
3	12,6	9.828
5	6,6	8.580
7	7,8	14.196
9	4,5	10.530
11	2	5.720
13	1,5	5.070
15	1,2	4.680
17	0,6	2.652
19	0,7	3.458
Total		105,69

The total addition of losses in phase R due to the influence of harmonic distortion are:

$$Losses_{Phasa\,R} = P_{cu} + P_i$$
$$Losses_{Phasa\,R} = Pcu + (P_e + P_h)$$
$$Losses_{Phasa\,R} = 1,086 + (0,32 + 0,106)$$
$$Losses_{Phasa\,R} = 1,512\ kW$$

b. Phasa S Losses

The calculation of the transformer losses in phase S is the same as that done in phase R. In the same way the harmonic current obtained in phase S in units p.u, from the order of harmonics 1-19 in table 8.

TABLE 8
ANALYSIS OF PHASE HARMONIC FLOW

Order of Harmonics	I_h (%)	I_h (A)	I_h (p.u)	I_h^2 (p.u)	$I_h^2 \times h^2$ (p.u)
1	100,0	157,6	1,000000	1,0000000	1,0000000
3	8,0	12,6	0,045477	0,0020681	0,0186130
5	4,1	6,6	0,065796	0,0043291	0,1082273
7	5,0	7,8	0,026125	0,0006825	0,0334428
9	2,9	4,5	0,016449	0,0002706	0,0219160
11	1,3	2	0,010160	0,0001032	0,0124894
13	1,0	1,5	0,006773	0,0000459	0,0077529
15	0,8	1,2	0,004838	0,0000234	0,0052663
17	0,4	0,6	0,003870	0,0000150	0,0043291
19	0,5	0,7	0,003387	0,0000115	0,0041402
Total				1,0075492	1,2161770

Loadloss (P_{LL}) in phase S obtained from the calculation of harmonic order 1-19.

$$P_{LL\_PhasaS} = 1.0075492 + 1,2161770 \times 0,01 = 1,0197110\ p.u$$

From the calculation of PLLs it is known that the copper loss has increased by 0.0075492 p.u.

$$P_{cu}\,(kW) = P_{cu}\,(p.u) \times P_{base\,1\phi}$$
$$P_{cu}\,(kW) = 0.0075492\ p.u \times 92,376\ kW$$
$$P_{cu}\,(kW) = 0,697\ kW$$

While Eddy-Current Loss has increased by 0,002161770 p.u

$$P_e\,(kW) = P_e\,(p.u) \times P_{base\,1\phi}$$
$$P_e\,(kW) = 0,002161770\ p.u \times 92,376\ kW$$
$$P_e\,(kW) = 0,2\ kW$$

To calculate the hysterisis loss S phase can be calculated by:

$$P_{h1} = 0,26 \times 206,7 \times 1 = 53,742\ W$$
$$P_{h3} = 0,26 \times 9,4 \times 3 = 7,332\ W$$

In the same way, m, hysteresis loss until the harmonic order of 19 can be seen as table 9.

TABLE 9
THE HYSTERESIS LOSSES PHASE S.

Order of Harmonics	I_h (A)	P_h (Watt)
1	206,7	53,7420
3	9,4	7,3320
5	13,6	17,6800
7	5,4	9,8280
9	3,4	7,9560
11	2,1	6,0060
13	1,4	4,7320
15	1	3,9000
17	0,8	3,5360
19	0,7	3,4580
Total		118,17

Total addition of losses in phase S due to the influence of harmonics can be calculated:

$$Losses_{Phasa\,S} = 0,697 + (0,2 + 0,118)$$
$$Losses_{Phasa\,S} = 1,015\ kW$$

c. Phasa T Losses

The calculation of the transformer losses in phase T is the same as that done in phase R & S. In the same way the harmonic current obtained in phase T in units p.u, from the order of harmonics 1-19 in table 10.

TABLE 10
THE HYSTERESIS LOSSES PHASE S.

Order of Harmonics	I_h (%)	I_h (A)	I_h (p.u)	I_h^2 (p.u)	$I_h^2 \times h^2$ (p.u)
1	100	189	1,000000	1,0000000	1,0000000
3	6,3	11,8	0,062434	0,0038980	0,0350819
5	3,8	7,3	0,038624	0,0014918	0,0372960
7	4,6	8,7	0,046032	0,0021189	0,1038272
9	2,3	4,2	0,022222	0,0004938	0,0400000
11	1,3	2,4	0,012698	0,0001612	0,0195112
13	0,9	1,6	0,008466	0,0000717	0,0121116
15	0,7	1,4	0,007407	0,0000549	0,0123457
17	0,6	1,1	0,005820	0,0000339	0,0097895
19	0,6	1,1	0,005820	0,0000339	0,0122284
Total				1.0083581	1.2821914

Loadloss (P_{LL}) in phase T obtained from the calculation of harmonic order 1-19.

$$P_{LL\_PhasaT} = 1.0083581 + 1,2821914 \times 0,01 = 1,02118\ p.u$$

From the calculation of PLLs it is known that the copper loss has increased by 0,0083581 p.u.

$$P_{cu}\,(kW) = 0.0083581\ p.u \times 92,376\ kW$$
$$P_{cu}\,(kW) = 0,772\ kW$$

While Eddy-Current Loss has increased by 0,002821914 p.u

$$P_e\,(kW) = 0,002821914\ p.u \times 92,376\ kW$$
$$P_e\,(kW) = 0,261\ kW$$

To calculate the hysterisis loss T phase can be calculated by:

$$P_{h1} = 0,26 \times 2 = 189 \times 1 = 49,14\,W$$

$$P_{h3} = 0,26 \times 11,8 \times 3 = 9,204\,W$$

In the same way, m, hysteresis loss until the harmonic order of 19 can be seen as table 11.

TABLE 11
THE HYSTERESIS LOSSES PHASE S.

Order of Harmonics	I_h (A)	P_h (Watt)
1	189	49,1400
3	11,8	9,2040
5	7,3	9,4900
7	8,7	15,8340
9	4,2	9,8280
11	2,4	6,8640
13	1,6	5,4080
15	1,4	5,4600
17	1,1	4,8620
19	1,1	5,4340
Total		121,524

Total addition of losses in phase S due to the influence of harmonics can be calculated:

$$Losses_{Phasa\,T} = 0,772 + (0,261 + 0,122)$$

$$Losses_{Phasa\,T} = 1,154\ kW$$

The total losses of the transformer due to the influence of harmonics can be calculated from the losses of each phasa as in table 12.

TABLE 12
ADDITION OF LOSSES TRANSFORMATOR DUE EFFECT OF HARMONICS

Phasa	P_{cu}(kW)	P_e (kW)	P_h(kW)	Losses (kW)
Phasa R	1,086	0,32	0,106	1,512
Phasa S	0,692	0,2	0,118	1,015
Phasa T	0,772	0,261	0,122	1,154
Total Losses Trafo				3,681

Table 12 shows that the transformer has increased losses due to harmonic effect of 3,681 kW, so that the overall transformer losses are:

$$Total\ Losses_{trafo} = Losses_{tanpa\,harmonisa} + Losses_{akibat\ harmonisa}$$
$$= 2,98 + 3,681 = 6,661\,kW$$

IV. CONCLUSION

From the results of simulations and analysis conducted it can be concluded losses transformer without the influence of non-linear load unbalanced by 2.98 kW.

The result of Losses analysis by using unbalanced nonlinear load for each phases is: Phasa R losses 1,512 Kw, Phasa S losses 1,015 Kw, Phasa T losses 1,154 Kw. Operation of unbalanced nonlinear loads can increase the transformer losses by 3,681 Kw

From the results of the analysis of losses that have been done, it can be concluded that the operation of non-linear unbalanced load at Faculty of Engineering Unud Bukit Jimbaran will be able to increase the Losses of the transformer operated.

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