A Method for Additional Losses Determination in Distribution Transformer Supplying Nonlinear Load

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***Abstract* – A method for additional core and winding losses calculation, is presented. It is intended for studying the steady-state mode of operation of a three-phase distribution transformer with non-linear loads. The method is applied to certain transformer and the results are compared to the measured values and values, obtained by another analytical methods. The comparison proves the new method's propriety and appliety.**

Keywords: Harmonics, distribution transformer, core losses, winding losses

I. INTRODUCTION

There are a lot of electrical power loads and electromechanical devices, which deform the three-phase voltage and current waveforms. So the "nonlinear loads" generate higher harmonics [8]. The harmonics distribute into the supply grid and cause power equipment losses increasing [2,4,8].

The aim of this paper is to study the influence of the harmonics, generated by the non-linear loads on the core and winding losses of the distribution transformer.

The method is derived supposing that three-phase symmetrical sinusoidal voltage supplies the transformer. It is assumed also that it is possible to measure the secondary winding voltage and current, and their harmonics spectra are known.

II. ADDITIONAL LOSSES DETERMINATION

Then the transformer supplies consumers with linear VA characteristics, efficiency coefficient is determined as:

$$\eta = P_2 / P_1 \qquad (1)$$

where P_2 is the output power measured on the transformer secondary side;

P_1 – the input power, supplying the transformer, determined as:

$$P_1 = P_2 + P_{nl} + P_{sc}.\beta^2$$

where P_{nl},P_{sc} are rated no-load and short-circuit losses respectively

β - load coefficient $\beta = I_2 / I_{2,nom}$;

$I_{2,nom}$,I_2 - rated secondary winding current and secondary winding current at the studied operation mode respectively.

In the case of the non-linear loads:

$$P_1 = P_2 + \left(P_{nl} + P_{a,SPF}\right) + \left(P_{sc} + P_{w,SPF}\right).\beta^2 \qquad (2)$$

where $P_{a,SPF}$, $P_{w,SPF}$ are additional core losses and winding losses due to the secondary power flow (SPF) existing in low voltage grid [6,7]

After entering the symbols:

$\overline{p}_a$ -relative iron losses increasing due to the secondary power flow:

$$\overline{p}_a = P_{a,SPF} / P_{nl} \ ;$$

$\overline{p}_w$ -relative winding losses increasing due to the secondary power flow:

$$\overline{p}_w = P_{w,SPF} / P_{sc} \ ,$$

the transformer efficiency coefficient can be reexpressed as:

$$\eta = \frac{P_2}{P_2 + P_{nl}\left(1 + \overline{p}_a\right) + P_{sc}\left(1 + \overline{p}_w\right).\beta^2}\ , \qquad (3)$$

The two terms $-\overline{p}_a$ and $\overline{p}_w$, are integral measures for transformer additional core and winding losses magnitudes, which occurred if the secondary power flow exist. They depend on:

a/ distribution transformer type and design;

b/ values of total harmonic voltage distortion (THD_U) and total harmonic current distortion (THD_I) [8];

в/ magnitudes of each of current and voltage harmonics measured on the secondary winding outputs.

A. Relative core losses increasing

The main construction dimensions are determined so that it is realized optimal relation between iron core masse G_a, winding masse G_w and flux density B. In reference [3] is given a relationship between two iron masse values and respective flux density values. It is based on the constant no-load losses condition

$$G_2 = G_1.\left(K_2 + K_1.\sqrt{\frac{B_1}{B_2}}\right).\left(\frac{B_1}{B_2}\right), \qquad (4)$$

where K_1, K_2 are coefficients, which values depend on the transformer's main dimensions [6].

As the transformer iron losses are $p_a = P_{nl} / G_a$, the equation (4) could be written as:

$$p_{a,1} = p_{a,2}.\left(K_2 + K_1.\sqrt{\frac{B_1}{B_2}}\right).\left(\frac{B_1}{B_2}\right) \qquad (5)$$

When the transformer supplies non-linear load and the secondary power flow exists:

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$$\frac{P_{nl}}{G_a}=\frac{P_{nl}+P_{a,SPF}}{G_a}.\left(K_2+K_1.\sqrt{\frac{B}{B+\overline{B}}}\right)\left(\frac{B}{B+\overline{B}}\right) \qquad (6)$$

where $\overline{B}$ is flux density, due to the secondary power flow. It can be defined as sum of partial flux densities, created from the secondary power flow for one period of the supply voltage, which are transferred to basic frequency [6,7];

G_a – transformer iron masse.

The relative core losses, due to the secondary power flow, are:

$$\overline{p}_a=\frac{1+\overline{B}/B}{\left(K_1+K_2.\sqrt{1+\overline{B}/B}\right)}-1 \qquad (7)$$

Substitute: $B=\dfrac{U_{1(1)}}{4{,}44w_1 f.S}$

and respectively $B_{(k)}=\dfrac{U_{2(k)}}{4{,}44w_2 kf.S}$,

for main flux density creating for secondary power flow can be reexpressed as:

$$\overline{B}=\sum_{k=1}^{\infty}\hat{B}_{(k)}=\sum_{k=1}^{\infty}B_{(k)}k_{B(k)}=\sum_{k=1}^{\infty}\frac{U_{2(k)}}{4{,}44w_2 fS}\frac{\sqrt{k^{1,3}}}{k} \qquad (8)$$

where $U_{2,(k)}$ is voltage with frequency kf;

- S - cross-section area of the core;
- $k_{B,(k)}$ - flux density transforming coefficient. It is determined in [6,7] and it is equal to $k^{-0,65}$;
- w_1,w_2 - primary and secondary winding turns respectively.

Assuming that:

$$K_{KU}=\sum_{k=1}^{\infty}\left(\frac{U_{2(k)}}{U_{2(1)}}k^{-0,35}\right), \qquad (9)$$

the equation (7) can be expressed as follow:

$$\overline{p}_a=\frac{(1+K_{KU})^{3/2}}{\left(K_1+K_2.\sqrt{1+K_{KU}}\right)}-1 \qquad (10)$$

B. Relative winding losses increasing

For determination of the relative winding losses increasing it is necessary to separate the short-circuit transformer losses [1]:

$$P_{sc}=P_{dc}+P_{wt}+P_t+P_{se}$$

where P_{dc} are direct current winding losses;

- P_{wt} - winding taps losses;
- P_t - transformer tank losses;
- P_{se} - losses which are caused from skin-effect and windings transposition.

The different transformer short-circuit losses portions depend mostly on the transformer rated power. Applying the coefficients k_t and k_{sc} [1,5] the tank losses P_t and the skin-effect losses P_{se} can be determine.

$$k_t=\frac{P_t}{S_{nom}}=0{,}578+0{,}325.10^{-3}.S_{nom},$$

$$k_{se}=\frac{P_{se}}{S_{nom}}=0{,}111+0{,}0264.\sqrt{S_{nom}},$$

In upper expressions the rated transformer power S_{nom} is measured in kVA [1]:

The additional winding losses causing from secondary power flow can be expressed as follow [5]:

$$P_{w,SPF}=(P_{dc}+P_{wt}).\left[\sum_{k=2}^{\infty}\left(\frac{I_{2(k)}}{I_{2,nom(1)}}\right)^2\right]+$$

$$+(P_t+P_{se}).\left[\sum_{k=2}^{\infty}\left(\frac{k.I_{2(k)}}{I_{2,nom(1)}}\right)^2\right] \qquad (11)$$

Transformer winding losses increasing $\overline{p}_w$, due to the secondary power flow is equal [5]:

$$\overline{p}_w=THD_I^2+\frac{S_{nom}}{P_{sc}}(k_{se}+k_t).\left(K_{KI}^2-THD_I^2\right) \qquad (12)$$

where K_{KI} is coefficient, defined as:

$$K_{KI}=\sqrt{\sum_{k=2}^{\infty}\left(\frac{k.I_{(k)}}{I_{(1)}}\right)^2} \qquad (13)$$

This coefficient K_{KI} is analogue to K-factor [8].

By reason of non-sinusoidal secondary current waveform, the load coefficient:

$$\beta^2=\left(\frac{I_2}{I_{2,nom}}\right)^2=\left(\frac{1}{I_{2,nom}}\sum_{k=1}^{\infty}I_{2(k)}\right)^2=\left(\frac{I_{2(1)}}{I_{2,nom}}\right)^2.\left[1+\sum_{k=2}^{\infty}\left(\frac{I_{2(k)}}{I_{2,nom}}\right)^2\right]$$

consequently:

$$\beta=\beta_{(1)}\sqrt{1+THD_I^2}$$

where $\beta_{(1)}$ is load coefficient giving by:

$$\beta_{(1)}=I_{2(1)}/I_{2,nom}$$

So, the efficient coefficient of transformer supplying non-liner consumer is:

$$\eta_{SPF}=\frac{P_2}{P_2+P_{nl}.(1+\overline{p}_a)+P_{cs}.(1+\overline{p}_w).\left(1+THD_I^2\right)\beta_{(1)}^2},$$

The general additional transformer losses increasing is:

$$\overline{p}_o=\frac{P_{nl}.(1+\overline{p}_a)+P_{cs}.(1+\overline{p}_w).\left(1+THD_I^2\right)\beta_{(1)}^2}{P_{nl}+P_{cs}.\beta_{(1)}^2}-1 \qquad (14)$$

III. Results and Analysis

The experiments with three phase transformer type TT16002 manufacturing №88480 with parameters: S_{nom}=1200VA, U_1=380V, I_1=1,8A, U_2=110V, I_2=6,3A, and winding connected as Y/Δ. This transformer supplied three-phase bridge diode rectifier. The currents and voltages waveforms of phase A are given on fig.1 There are two case:

a/ if the rectifier supplies active-inductive load;

b/ if the rectifier supplies active-capacitive load.

For reliability verification of this developed method for transformer additional losses determining is made comparison between its results and the experimental results. In this calculation the coefficients K_1 and K_2 values are determined for flux density varying from 1.2T to 1.8T [2]. The experiments was made as the rectifier loads are change such as transformer active output power are varying from 10% to 99% in comparison with nominal power S_{nom}.

For secondary voltage and current harmonics spectrum measuring in used power quality analyzer type MI 2192, №12091431, manufactured by METREL, Slovenia. The results are created the possibility the additional transformer losses calculating (see table 1). The measured values of THD_U, THD_I and input transformer power P_1 and the calculated values are approximately equals. This is the base to affirm that the proposed method usage cause to reliable results receiving

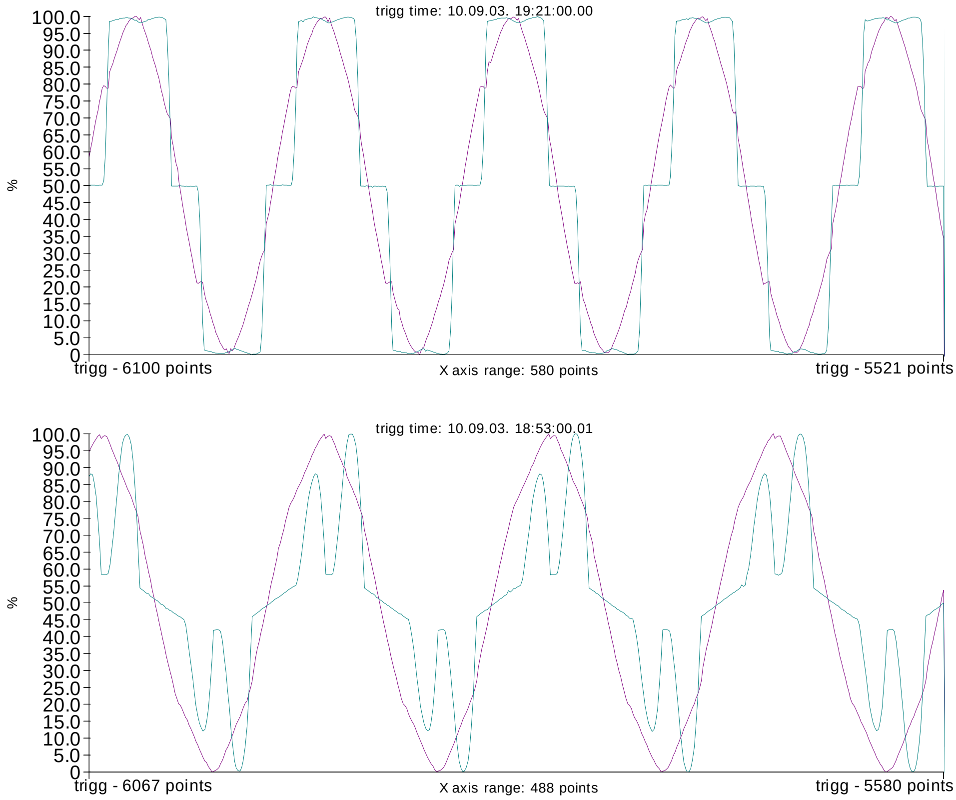

Fig.1. Voltage and current waveforms in phase A, if transformer supplied three-phase diode bridge rectifier with active-inductive load (a) and active-capacitive load (b) and with DC power P_{dc}=333W

TABLE 1.
HIGH HARMONICS CAUSED LOSSES.
AS THE NONLINEAR LOAD, GENERATING HIGH HARMONICS IS USED TRHEE PHASE DIODE BRIDGE RECTIFIER WITH ACTIVE-INDUCTIVE LOAD

№		P_2,W	$\beta_{(1)}$	THD_I,%	THD_U,%	K_{KI}	K_{KU},%	$\bar{p}_a$,%	$\bar{p}_w$,%	$\bar{p}_o$,%	P_1,W
1	M	126	-	29,43	3,27	-	-	-	-	-	149
	C	-	0,163	28,20	3	2,321	4,3	5,7	10,9	11,0	166
2	M	218	-	29,33	3,3	-	-	-	-	-	249
	C	-	0,164	28,10	3,1	2,31	4,4	5,8	10,8	11,2	259
3	M	333	-	28,83	3,43	-	-	-	-	-	368
	C	-	0,238	28,00	3,3	2,297	4,7	6,1	10,7	11,4	376
4	M	753	-	27,70	3,9	-	-	-	-	-	815
	C	-	0,604	27,20	3,7	2,176	5,0	6,6	9,9	13,0	818
5	M	1186	-	26,53	5	-	-	-	-	-	1290
	C	-	0,903	25,30	4,6	2,041	6,3	8,3	9,4	14,0	1282

Remarks: With M are signed measured values, with C – calculated values.

Comparison with another analytical methods for additional losses determining was made [2,4].

In [2] was proposed the relationship:

$$\Delta P_{R2} = P_{nl}\sum_{k=2}^{\infty} U_{(k)}^2 + 0{,}607.\frac{P_{sc}}{u_k^2}.\sum_{k=2}^{\infty}\frac{1+0{,}05.k^2}{k.\sqrt{k}}U_{(k)}^2 , \quad (15)$$

and in [4]:

$$\Delta P_{R4} = 3\sum_{k=2}^{\infty} I_{(k)}^2 R_2 \sqrt{k} \ . \qquad (16)$$

The relative additional transformer losses increasing due to the secondary power flow, is:

$$\overline{p}_{o,R2} = \frac{\Delta P_{R5}}{P_{nl} + P_{sc}.\beta_{(1)}^2} \qquad (15a)$$

and respectively:

$$\overline{p}_{o,R4} = \frac{\Delta P_{R7}}{P_{nl} + P_{sc}.\beta_{(1)}^2} \qquad (16a)$$

The relationship between relative transformer losses versus to total distortion factor of voltage is given in fig.2. The secondary current harmonics spectrum influence to relative additional transformer losses is given in table 2. All values presented in fig.2 and table 2 are received by applying the proposed method and expressions (15a) and (16a).

Comparing the presented results, could make the following conclusions:

1. The core losses transformer increasing is due to the voltage harmonics (table 1). The increasing DC power cause the transformer influence increasing to the alternative current waveform. Increasing the overlap angle values cause to current harmonics spectrum improving (THD_I is changed from 28.2% to 25.3%) and the additional winding losses are decreasing – from 10.9 % to 9.4 %.

2. The equation (15) render an account of output transformer voltage harmonics. Of course, the harmonics exert main influence on additional core losses. The additional winding losses due to the skin-effect are determined by current harmonics. It is indirect rended an account of the second term of equation (15).

3. The term (16) render an account of skin-effect losses increasing but not the core losses increasing

4. After analysis of the proposed in fig.2, table 1 and table 2 results could make the conclusion that disregarding of each one of the additional losses parts could cause a big mistake.

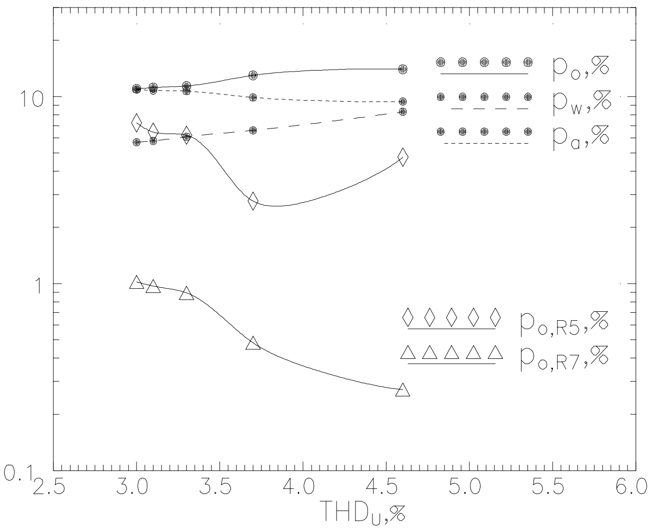

Fig.2. Distribution transformer losses increasing. Transformer is connected with three-phase diode bridge rectifier with active-inductive load

TABLE.2. RELATIVE TRANSFORMER LOSSES INCREASING VERSUS DIFFERENT TYPE OF RECTIFIERS DC LOAD (SEE FIG.1)

Load	RC		RL	
	M	C	M	C
P_2,W	333,6	-	333	-
β_1	-	23,8	-	12,8
THD_U,%	3,8	4,8	3,43	3,3
THD_I,%	57,8	58,3	28,83	28,00
K_{KU},%	-	8,2	-	4,7
K_{KI}	-	3,451	-	2,297
$\overline{p}_a$,%	-	10,8	-	6,1
$\overline{p}_w$,%	-	33,9	-	10,7
$\overline{p}_o$,%	-	37,2	-	11,4
P_1,W	365	357,3	368	376
$\overline{p}_{o,R2}$,%	-	43,501	-	6,213
$\overline{p}_{o,R4}$,%	-	7,473	-	0,891

Remarks: With M are signed measured values, with C – calculated values.

IV. CONCLUSION

The method for additional distribution transformer losses determining is presented. This method render an account of increasing frequency of nonlinear load generate harmonics. The additional winding and core losses are determining with secondary current and secondary voltages harmonic spectrum measuring.

V. REFERENCES

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