POWER ANALYSIS OF TRACTION TRANSFORMER UNDER NON-SINUSOIDAL CONDITIONS

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Summary Article deals with power analysis of traction transformer 110/27 kV, S_n =10 MVA under non-sinusoidal conditions. The power analysis is evaluated by means of IEEE Trial Use Standard Definitions of the Measurement of Electric Power Quantities Under Non-Sinusoidal Conditions, Document Number: IEEE 1459-2000.

Abstrakt V článku je prezentována výkonová analýza trakčního transformátoru 110/27 kV, S_n =10 MVA s neharmonickými průběhy veličin. Výkonová analýza je posuzována v souladu s doporučením standardu IEEE 1459-2000.

1. INTRODUCTION

Measured voltage and current waveforms (Fig. 1, Fig. 2) of primary and secondary windings of single-phase transformer are alternating non-harmonic periodic functions, whose can be expressed by means of Fourier series as the sum of harmonic functions

$$v(t) = \sum_{k=1}^{\infty} V_{m(k)} \sin(k\omega t \pm \psi_{(k)}).$$

Waveform distortion $v_z(t)$ is defined by difference between measured waveform $v(t)$ and its first harmonic function $v_1(t)$

$$v_z(t) = v(t) - v_{(1)}(t).$$

The waveform distortion is unambiguously represented by its root mean square value

$$V_z = \sqrt{V^2 - V_{(1)}^2}\,.$$

Quotient of rms distortion waveform V_z and rms first harmonic function is called total harmonic distortion (THD)

$$\text{THD V} = 100\frac{V_z}{V_{(1)}} = 100\sqrt{\frac{V^2 - V_{(1)}^2}{V_{(1)}^2}} = 100\sqrt{\frac{V^2}{V_{(1)}^2} - 1}\,.$$

The total harmonic distortion THD is a suitable tool for monitoring, whereas waveform distortion and harmonic analysis are commonly used at full analysis of the periodic signals.

When we divide rms distortion waveform of the primary winding $V_{z\,I}$ by rms distortion waveform of the secondary winding $V_{z\,II}$ we obtain

$$\frac{V_{z\,I}}{V_{z\,II}} = \frac{V_{(1)\,I}\cdot \text{THD V}_I}{V_{(1)\,II}\cdot \text{THD V}_{II}} \Rightarrow \frac{V_{z\,I}}{V_{z\,II}}\cdot\frac{\text{THD V}_{II}}{\text{THD V}_I} = \frac{V_{(1)\,I}}{V_{(1)\,II}}\,.$$

2. POWER ANALYSIS

The unambiguous information about a change of the state any mass indicates power waveform (Fig. 1c, 2c) – product of voltage and current waveform

$$p = ui\,.$$

Power waveform is defined by equation [1,2]

$$p = ui = (u_1 + u_z)(i_1 + i_z) = u_1 i_1 + u_1 i_z + u_z i_1 + u_z i_z = \\ = u_1 i_1 + p_z = p_1 + p_z \quad ,$$

one is algebraic sum of first harmonic power waveform p_1 and power waveform distortion p_z. The average value of the power waveform over period T is called active power

$$P = \frac{1}{T}\int_0^T p\cdot dt = \\ = \frac{1}{T}\left[\int_0^T u_1 i_1 \cdot dt + \int_0^T u_1 i_z \cdot dt + \int_0^T u_z i_z \cdot dt + \int_0^T u_z i_z \cdot dt\right] = \\ = P_1 + 0 + 0 + P_z \quad ,$$

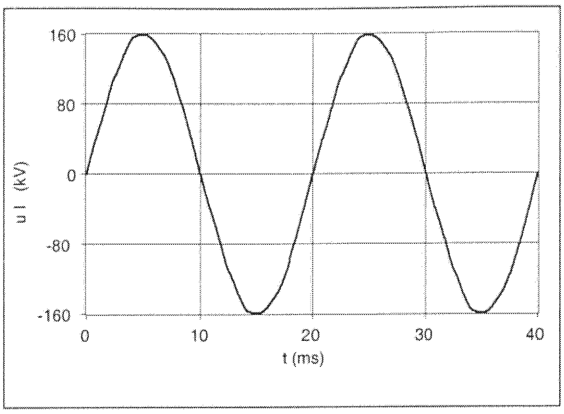
because scalar product of instantaneous values distortion and first harmonic quantity over period is orthogonal [3].

The active power P is the algebraic sum of the active power of first harmonic voltage and first harmonic current P_1 and active power of distortion voltage and distortion current P_z, whereas apparent power S is the geometric sum of the apparent power of first harmonic voltage and first harmonic current S_1 and apparent power distortion S_z

$$S = UI = \sqrt{(U_1^2 + U_z^2)(I_1^2 + I_z^2)} = \sqrt{S_1^2 + S_z^2} = \\ = \sqrt{U_1^2 I_1^2 + U_1^2 I_z^2 + U_z^2 I_1^2 + U_z^2 I_z^2} = \sqrt{U_1^2 I_1^2 + S_z^2}\,.$$

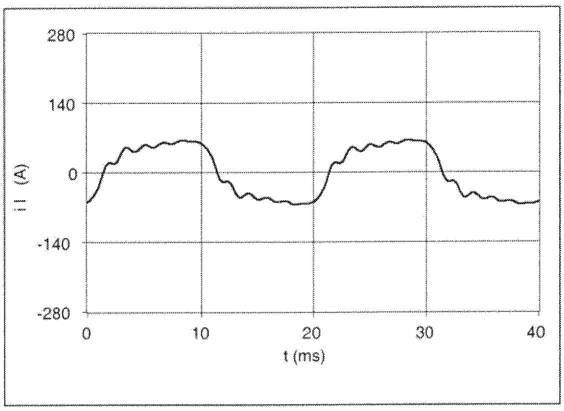
Total harmonic distortion of the power is defined by equation

$$\text{THD S} = 100\frac{S_z}{S_1} = 100\sqrt{\frac{S^2 - S_1^2}{S_1^2}} = 100\sqrt{\frac{S^2}{S_1^2} - 1}\,.$$



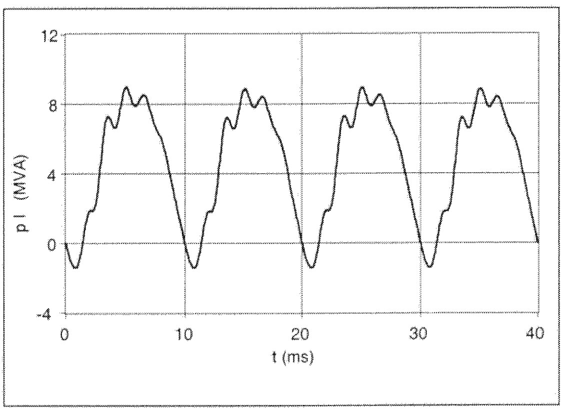
a) voltage waveform

$U_{\mathrm{I}} = 113{,}7$ kV ; THD $\mathrm{U}_{\mathrm{I}} = 0{,}5\,\%$



b) current waveform

$I_{\mathrm{I}} = 50{,}23$ A ; THD $\mathrm{I}_{\mathrm{I}} = 24{,}6\ \%$

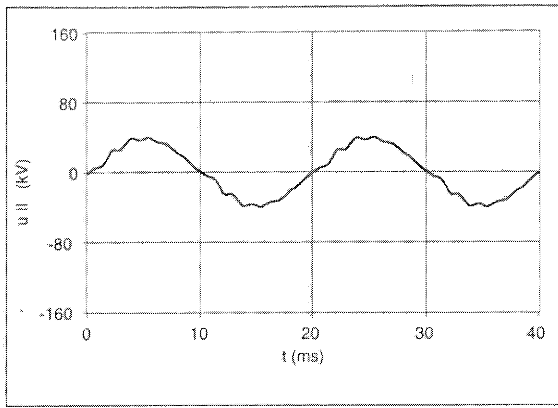


c) power waveform

$S_{\mathrm{I}} = 5{,}712$ MVA ; THD $\mathrm{S}_{\mathrm{I}} = 24{,}6\ \%$

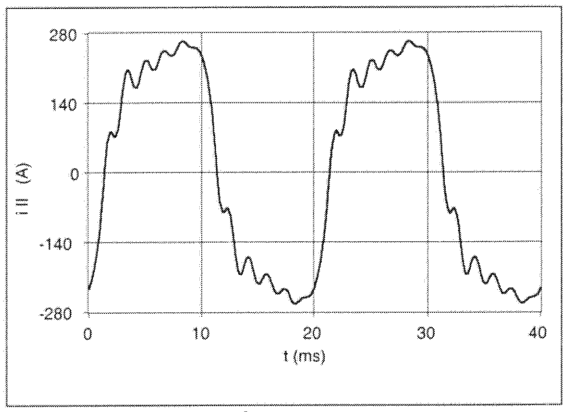
$\lambda_{P\,\mathrm{I}} = 0{,}807$.

Fig. 1. The waveforms of the primary winding.



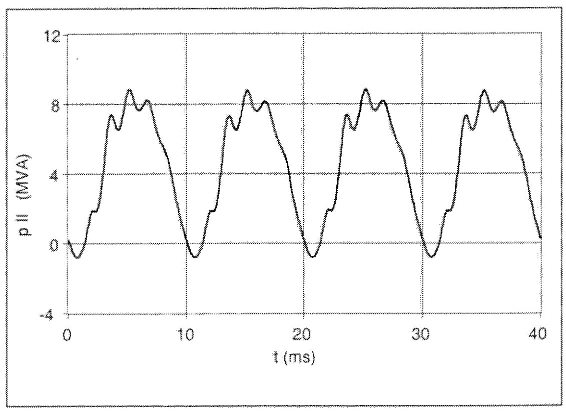
a) voltage waveform

$U_{\mathrm{II}} = 26{,}81$ kV ; THD $\mathrm{U}_{\mathrm{II}} = 7{,}4\,\%$



b) current waveform

$I_{\mathrm{II}} = 203{,}2$ A ; THD $\mathrm{I}_{\mathrm{II}} = 23{,}6\ \%$

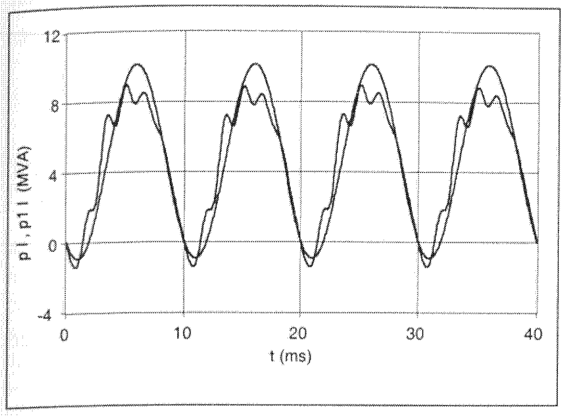


c) power waveform

$S_{\mathrm{II}} = 5{,}448$ MVA ; THD $\mathrm{S}_{\mathrm{II}} = 25{,}4\ \%$

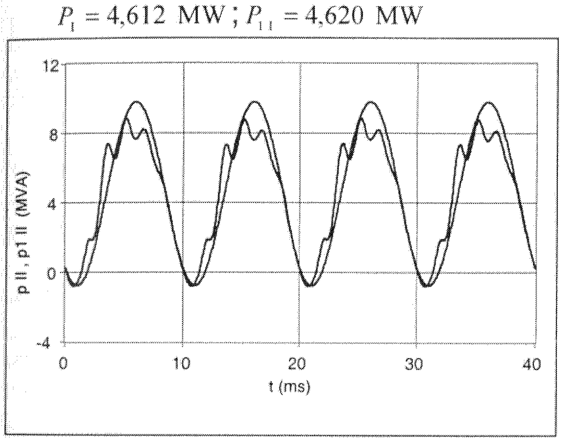
$\lambda_{P\,\mathrm{II}} = 0{,}828$.

Fig. 2. The waveforms of the secondary winding.



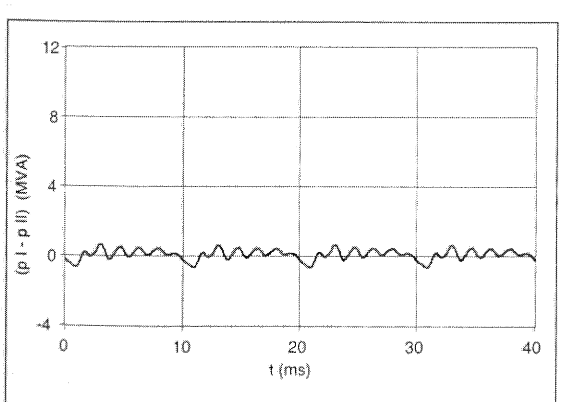
a) power waveform and product of first harmonic voltage and current of primary winding

$P_{I} = 4{,}612\ \text{MW}$; $P_{1\,I} = 4{,}620\ \text{MW}$



b) power waveform and product of first harmonic voltage and current of secondary winding

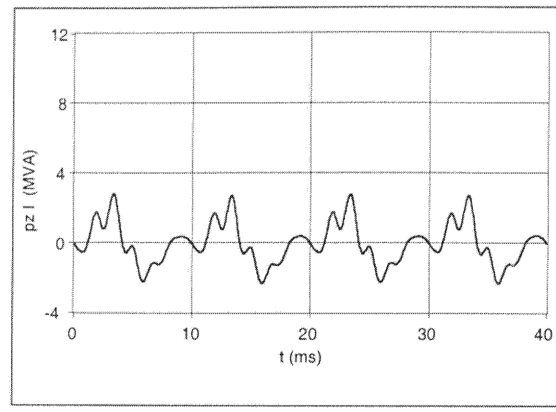
$P_{II} = 4{,}511\ \text{MW}$; $P_{1\,II} = 4{,}525\ \text{MW}$



c) difference between power waveform of primary and secondary winding

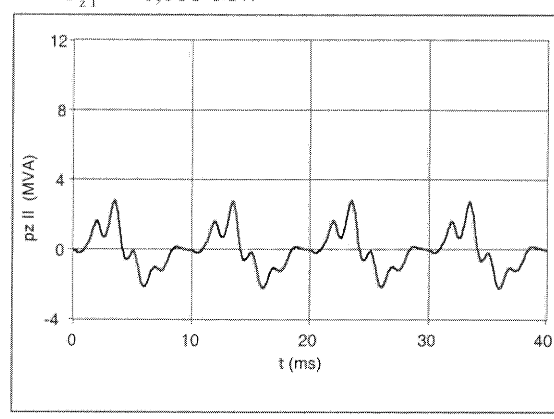
$P_{\Delta} = 0{,}101\ \text{MW}$; $P_{1\,\Delta} = 0{,}095\ \text{MW}$

Fig. 3. Power waveforms.



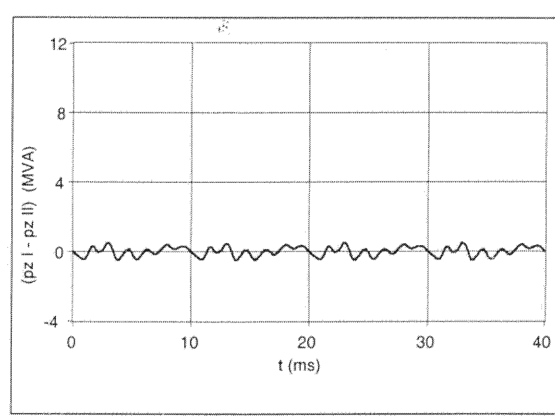
a) power waveform distortion of primary winding

$P_{z\,I} = -0{,}008\ \text{MW}$



b) power waveform distortion of secondary winding

$P_{z\,II} = -0{,}014\ \text{MW}$



c) difference between power waveform distortion of primary and secondary winding

$P_{z\Delta} = 0{,}006\ \text{MW}$

Fig. 4. Power waveform distortions.

Instantaneous power loss p_Δ (Fig. 3c) is defined as algebraic difference between instantaneous power of the primary winding p_I and instantaneous power of the secondary winding p_{II}

$$p_\Delta = p_I - p_{II},$$

their average values are called active power losses

$$P_\Delta = \frac{1}{T}\int_0^T p_\Delta \cdot dt = \frac{1}{T}\int_0^T (p_I - p_{II}) \cdot dt = P_I - P_{II}.$$

For the full power analysis in accordance with [1,4] we express the instantaneous powers as the algebraic sum of first harmonic power waveform and power waveform distortion by means of equations.

$$p_\Delta = p_I - p_{II} = (p_{1\,I} + p_{z\,I}) - (p_{1\,II} + p_{z\,II}) =$$
$$= p_{1\,I} - p_{1\,II} + p_{z\,I} - p_{z\,II} = p_{1\Delta} + p_{z\Delta} \quad ,$$
$$p_{1\Delta} = p_{1\,I} - p_{1\,II},$$
$$p_{z\Delta} = p_{z\,I} - p_{z\,II}$$

and active powers analogously

$$P_\Delta = P_I - P_{II} = P_{1\Delta} + P_{z\Delta}$$
$$P_{1\Delta} = P_{1\,I} - P_{1\,II},$$
$$P_{z\Delta} = P_{z\,I} - P_{z\,II}.$$

Figured voltage, current, power time courses (Fig. 1, Fig. 2, Fig. 3, Fig. 4) are characterized by their parameters. Power factor is given by the formula

$$\lambda = \frac{P}{S}.$$

3. SIGNIFICANT RESULTS OF POWER ANALYSIS

a) In this case, the active power loss of the traction transformer $P_\Delta = 101\,\text{kW}$ that is 2,2 % from active power $P_I = 4{,}612\,\text{MW}$.

b) The active power loss of the traction transformer $P_\Delta = 101\,\text{kW}$ is the algebraic sum of the active power loss of the first harmonic voltage and current waveform $P_{1\Delta} = 95\,\text{kW}$ and active power loss distortion waveform $P_{z\Delta} = 6\,\text{kW}$.

c) The values of active powers $P_I = 4{,}612\,\text{MW}$, $P_{II} = 4{,}511\,\text{MW}$ are less than the values of active powers $P_{1I} = 4{,}620\,\text{MW}$, $P_{1II} = 4{,}525\,\text{MW}$ of the first harmonic voltage and current waveform both windings.

d) Active power distortion waveform of the secondary windings $P_{zII} = -14\,\text{kW}$ and active power distortion waveform of the primary windings $P_{zI} = -8\,\text{kW}$ reversal operate, because both possess minus sign.

e) Total harmonic distortion of the primary apparent power $\text{THD}\,S_I = 24{,}6\,\%$ is less then total harmonic distortion of the secondary apparent power $\text{THD}\,S_{II} = 25{,}4\,\%$.

4. CONCLUSION

In this article is developed the powerful technique that enable us evaluated electromagnetic phenomena under non-sinusoidal conditions.

Acknowledgement

The research described in this publication is supported by the Grant Agency of the Czech Republic, grant No. 102/02/1059/A.

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