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# Engineering Methods of Evaluation of Additional Power Losses in Electric Power Networks at Non-Sinusoidal Conditions

***Abstract**. Engineering methods of evaluation of additional power losses in electric power networks at non-sinusoidal conditions were proposed in the paper, by the known value of total harmonic distortions (THD). In exploitation practice such coefficient can be both measured and calculated in specific grid nodes of the power supply systems. The peculiarity of the method proposed is an obligatory of considering interharmonics in the presence of the corresponding sources.*

***Streszczenie.** W artykule zaproponowano metodę techniczną oceny dodatkowych strat energii w sieciach elektroenergetycznych na podstawie znanej wartości całkowitego współczynnika odkształcenia napięcia harmonicznymi (THD). W praktyce eksploatacyjnej wartości tych współczynników mogą być mierzone lub obliczane w poszczególnych węzłach systemów zasilania. Szczególną własnością proponowanej metody jest konieczność uwzględniania obecności źródeł interharmonicznych (**Metoda oceny dodatkowych strat mocy w sieciach elektroenergetycznych w warunkach odkształcenia napięcia**).*

**Keywords**: Power losses, higher harmonics, interharmonics, losses coefficient
**Słowa kluczowe**: Straty mocy, wyższe harmoniczne, interharmoniczne, współczynnik strat

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## Introduction

The values of electric power loses at its transmission from the power sources to the consumers are one of the most important technical and economic indices. Electric power being a specific kind of product so its losses at transmission are inevitable. Hence, economically substantiated losses level should be evaluated.

The value of power losses at transmission and distribution in power networks in many countries does not exceed 5-8 %, which is considered to be satisfactory. In Ukraine, nowadays, overall power losses amount to the value of 15 % (in some regions, like Zakarpatye, Kiev, or Donetsk) the losses reach 22-25 %. Such value requires development of a complex of measures, aimed at their diminishing. Such complex of measure should comprise both corresponding state programmes and solution of particular problems, aimed at reducing separate technical and commercial components of power losses. To solve these problems it is required to find out concrete values of the structural components of these losses.

Non-sinusoidal conditions in electric supply networks are known to cause additional losses in electric power equipment [1]. The problem of evaluating such losses is poorly explored, mainly due to the difficulties in calculating the losses at harmonics frequencies in separate components of power supply systems, especially if interharmonics are present [1, 2, 3]. Therefore, it is reasonable to develop an engineering method for evaluation of additional loses at non-sinusoidal conditions.

## Development of an engineering method of evaluation of additional losses

The equations for evaluation of relative power losses in electric equipment in the presence of higher harmonics (HH), in most cases, possess the following structure [4]

$$\Delta P_{\Sigma n*} = \frac{\Delta P_{\Sigma n}}{\Delta P_{nom}} = q \sum_n \frac{U_{n*}^2}{n\sqrt{n}} \qquad (1)$$

where: $n$ – being the number of the HH; $\Delta P_{\Sigma n}$ – overall additional losses at harmonics frequencies; $\Delta P_{nom}$ – nominal electric losses; $q$ – coefficient, depending on the type of electrical equipment; $U_{n*}$ – relative values (in fractions of the nominal voltage) of the $n$-th harmonics components.

Thus, for evaluation of additional losses in the elements of power supply systems it is necessary to know both parameters of electric equipment and the values of voltages of separate harmonics components in the attached units. Such procedure seems to be quite complicated [5].

In case interharmonics (IH) are present in the power supply systems, having similar to HH negative influence and consequently, being the source of additional power losses, the equation (1) can be written in the following form

$$\Delta P_{\Sigma \nu_k *} = q \sum_{\substack{k=1, \\ \nu_k \neq 1}}^{N} \frac{U_{\nu_k *}^2}{m\sqrt{m}} \qquad (2)$$

where: $k$ – is the number of harmonic component; $\nu_k$ – relative frequency of $k$-th harmonic component (the value of $\nu_k$ at which $k$ will coincide with relative frequency of HH); $U_{\nu_k *}$ – the relative value of voltage of $\nu_k$-th harmonic; $N$ – the number of the last harmonic, taken into account; $m$ – coefficient, taking into account the phenomenon of the surface effect [6],

$$m = \begin{cases} 1 & \text{ï ðè} \;\; \nu_k < 1; \\ \nu_k & \text{ï ðè} \;\; \nu_k > 1. \end{cases} \qquad (3)$$

According to [7] for evaluation of the total harmonic distortion of the voltage ($THD_U$), one should take into consideration the harmonics up to the 40-th inclusive. Then $N$ in equation (2) must be such, so that $\nu_N$ could be close or equal to 40. Equation (2) can be used for the case of discreet IH spectrum, which, primarily, several frequency converters have. If IH spectrum is solid, then it can be made discrete.

Equations for evaluation of additional power losses at harmonics frequencies have the following form.

For asynchronous motors

$$\Delta P_{a.m\nu_k} = 2\Delta P_{nom} k_S^2 \sum_{\substack{k=1, \\ \nu_k \neq 1}}^{N} \frac{U_{\nu_k *}^2}{m\sqrt{m}}. \qquad (4)$$

For synchronous machines

$$\Delta P_{s.m\nu_k} = k_{s.m} P_{nom} \sum_{\substack{k=1, \\ \nu_k \neq 1}}^{N} \frac{U_{\nu_k *}^2}{m\sqrt{m}}. \qquad (5)$$

For transformers

(6) $$\Delta P_{T\nu_k} = 0,6\frac{\Delta P_{s.c}}{u_s^2}\sum_{\substack{k=1,\\ \nu_k\neq 1}}^{N}\frac{\left(1+0,05m^2\right)U_{\nu_k *}^2}{m\sqrt{m}}.$$

For capacitors banks

(7) $$\Delta P_{CB\nu_k} = Q_{CB}\,\mathrm{tg}\delta\sum_{\substack{k=1,\\ \nu_k\neq 1}}^{N} mU_{\nu_k}^2 .$$

For LC-filters

(8) $$\Delta P_{f\,\nu_k} = 3I_{\nu_k}^2 X_r\left(m\,\mathrm{tg}\delta+\sqrt{m}\,\mathrm{ctg}\varphi_r\right).$$

For overhead transmission and cable lines

(9) $$\Delta P_l = 1,41R\sum_{\substack{k=1,\\ \nu_k\neq 1}}^{N} I_{\nu_k}^2\sqrt{m}.$$

The additional power losses in the design model (Fig. 1) are being calculated for the following variants:

– Variant 1 refers to 6-pulse converter, generating amplitude spectrum, pictured in Fig. 2.

– Variant 2 corresponds to three phase 6-pulse cycloconverter with amplitude spectrum, pictured in Fig. 3.

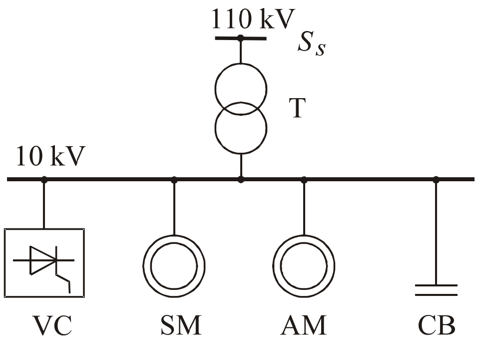


Fig. 1. Design model

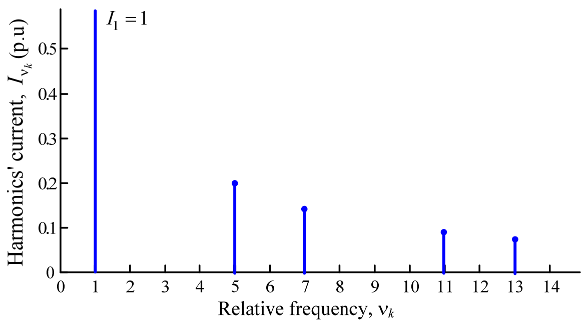


Fig. 2. Amplitude spectrum of the input current of 6-pulse frequency converter

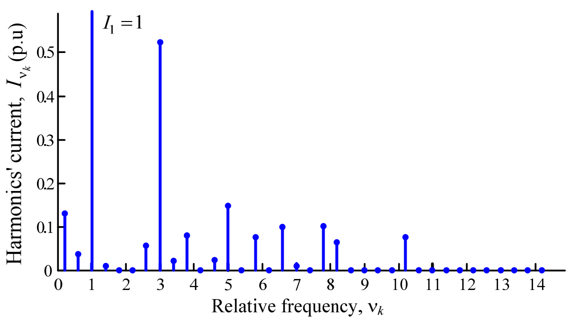


Fig. 3. Amplitude spectrum of the input current of three phase bridge 6-pulse cycloconverter with sinusoidal control law; $f_{out}$ = 20 Hz

The model's parameters are as follows:

– the short circuit power on the buses 110 kV: $S_s$ = 2000 MV·A,

– transformer (T): $S_{nom}$ = 25 MV·A; $\Delta P_{s.c}$ = 120 kW; $u_s$ = 10.5 %,

– a synchronous motor (SM): $P_{nom}$ = 6 MW; $\cos\varphi$ = 0.9; $I_s/I_{nom}$ = 6.5; $\eta_{nom}$ = 97.5 %,

– an asynchronous motor (AM): $P_{nom}$ = 8.4 MW; $\cos\varphi$ =0.8; $I_s/I_{nom}$ = 5.5; $\eta_{nom}$ = 97.7%.

– capacitor bank (CB): $Q_{CB}$ = 2.2 Mvar; $\mathrm{tg}\delta$ = 0.0025.

The determined values of $THD_U$ on 10 kV buses and additional power losses at different values of nominal power of converter $S_{nom}$ are given for Variants 1 and 2 in Tables 1 and 2, respectively. Nominal powers of converters were taken so that in both variants there are comparable levels of distortion.

Table 1. $THD_U$ values and the values of additional power losses in networks' elements in dependence of the power of non-sinusoidal source for Variant 1

| Converter's nominal power, $S_{nom}$ [MV·A] | $THD_U$ [%] | Losses in network's elements [kW] | | | | |
|---|---|---|---|---|---|---|
| | | T | AM | SM | CB | The sum |
| 1.80 | 5.07 | 3.31 | 0.72 | 0.46 | 0.17 | 4.65 |
| 2.00 | 5.64 | 4.09 | 0.88 | 0.57 | 0.20 | 5.74 |
| 2.20 | 6.20 | 4.95 | 1.06 | 0.69 | 0.25 | 6.95 |
| 2.40 | 6.76 | 5.89 | 1.28 | 0.82 | 0.29 | 8.28 |
| 2.60 | 7.33 | 6.91 | 1.50 | 0.97 | 0.35 | 9.73 |
| 2.80 | 7.89 | 8.02 | 1.72 | 1.12 | 0.40 | 11.26 |
| 3.00 | 8.45 | 9.20 | 2.00 | 1.29 | 0.46 | 12.95 |

Table 2. The values of $THD_U$ and additional power losses in network's elements, in dependence of the power of non-sinusoidal source for Variant 2

| Cycloconverter's nominal power, $S_{nom}$ [MV·A] | $THD_U$ [%] | Losses in network's elements [kW] | | | | |
|---|---|---|---|---|---|---|
| | | T | AM | SM | CB | The sum |
| 0.60 | 5.01 | 3.22 | 0.68 | 0.44 | 0.16 | 4.50 |
| 0.67 | 5.59 | 4.02 | 0.86 | 0.55 | 0.20 | 5.63 |
| 0.74 | 6.18 | 4.90 | 1.04 | 0.68 | 0.25 | 6.87 |
| 0.81 | 6.76 | 5.88 | 1.24 | 0.81 | 0.29 | 8.22 |
| 0.88 | 7.34 | 6.93 | 1.48 | 0.95 | 0.35 | 9.71 |
| 0.95 | 7.93 | 8.08 | 1.72 | 1.11 | 0.40 | 11.31 |
| 1.02 | 8.51 | 9.32 | 1.98 | 1.28 | 0.47 | 13.05 |

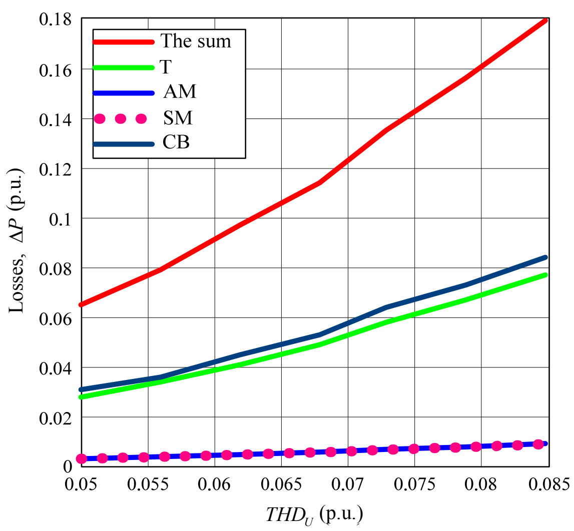


Fig. 4. The diagram of dependences of relative additional power losses in network's components upon $THD_U$, when a 6-pulse converter is the source of distortion

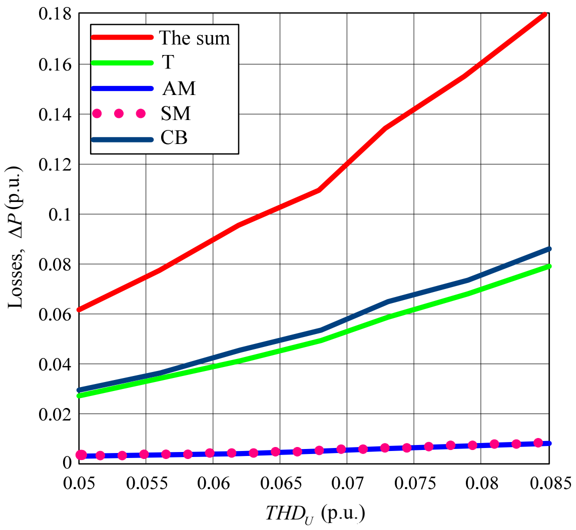


Fig. 5. The diagram of dependences of relative additional power losses in network's components upon $THD_U$, if three phase-three phase 6-pulse cycloconverter is the source of distortion

In order to preserve clarity, the diagrams of dependences of overall relative additional power loses in network's components upon the corresponding relative values of $THD_U$ for variants 1 and 2 are pictured in Fig. 4 and 5.

The analysis of Fig. 4 and Fig. 5 and numerous conducted investigations show that irrespective of the sources of distortion, at equal $THD_U$ in power network components, the values of overall additional power losses are practically equal. With due regard to this fact and taking into consideration the evident quadratic dependence between the values of overall additional losses and the corresponding $THD_U$ it is proposed to evaluate the value of the overall additional losses in relative units according to the following equation:

(10) $$\Delta P_{\Sigma *} = k_{los} THD_{U*}^2,$$

where: $k_{los}$ – is the losses coefficient; $THD_{U*}$ – $THD$ (in p.u.) of the voltage curve in the analyzed component of electrical power network.

For the diagram in Fig. 1 it was obtained, that the value of the losses coefficient was $k_{los} \approx 25$. It should be noted that in case the configuration of the diagram or the content of equipment is changed, the losses coefficient will be changed too.

Thus, for engineering evaluation of additional power losses, due to non-sinusoidal conditions, it is possible to apply coefficients of losses for various typical electrical layout schemes with typical equipment content. In order to determine the corresponding losses coefficients, it is necessary to perform a series of additional investigations, including measurements at exploitation conditions.

## An example of computation

In order to confirm the possibility of application of the method proposed for evaluation of additional power loses one should consider an example for the diagram, pictured in Fig.1 with the following initial data:

Diagram's parameters:

– The short circuit power on the buses 110 kV: $S_s$ = 3200 MV·A,
– T: $S_{nom}$ = 16 MV·A; $\Delta P_{s.c}$ = 85 kW; $u_s$ = 10.5 %,
– SM: $P_{nom}$ = 2 MW; $\cos\varphi$ = 0.8; $I_s/I_{nom}$ = 6.5; $\eta_{nom}$ = 98 %,
– AM: $P_{nom}$ = 2.5 MW; $\cos\varphi$ = 0.8; $I_s/I_{nom}$ = 5.5; $\eta_{nom}$ = 98 %,
– CB: $Q_{CB}$ = 1.25 Mvar; $\mathrm{tg}\delta$ = 0.0025.

The results of evaluation of the overall relative losses, obtained by two methods and the values of the corresponding errors are summarized in tables 3 and 4. The method No. 1 was used in evaluation of relative losses, according to equations (2)-(7) and method No. 2 – in evaluation of relative losses in accordance with (10).

Table 3. The results of error evaluation at determination of additional losses, according to (10), when 6-pulse converter is the source of distortion

| Converter's nominal power, $S_{nom}$ [MV·A] | $THD_U$ [p.u.] | Overall losses in network's elements [p.u.] | | Error value [%] |
|---|---|---|---|---|
| | | No 1 method | No 2 method | |
| 1.00 | 0.049 | 0.062 | 0.061 | 2.31 |
| 1.20 | 0.059 | 0.090 | 0.088 | 2.42 |
| 1.40 | 0.069 | 0.124 | 0.119 | 3.51 |
| 1.60 | 0.079 | 0.160 | 0.156 | 2.27 |
| 1.80 | 0.089 | 0.202 | 0.198 | 2.07 |
| 2.00 | 0.099 | 0.249 | 0.244 | 2.36 |
| 2.20 | 0.109 | 0.300 | 0.295 | 1.80 |

Table 4. The results of error evaluation at determination of additional losses, according to (10), when cycloconverter is the source of distortion

| Cycloconverter's nominal power, $S_{nom}$ [MV·A] | $THD_U$ [p.u.] | Overall losses in network's elements [p.u.] | | Error value [%] |
|---|---|---|---|---|
| | | No1 method | No2 method | |
| 0.38 | 0.051 | 0.069 | 0.065 | 5.53 |
| 0.45 | 0.060 | 0.093 | 0.091 | 2.36 |
| 0.52 | 0.070 | 0.127 | 0.122 | 3.81 |
| 0.59 | 0.079 | 0.162 | 0.156 | 3.58 |
| 0.66 | 0.089 | 0.204 | 0.196 | 4.16 |
| 0.73 | 0.098 | 0.248 | 0.240 | 3.44 |
| 0.80 | 0.107 | 0.298 | 0.288 | 3.31 |

The given computation confirms the correctness of application of the developed engineering methods of evaluation of the relative values of additional losses, due to the presence of HH and IH, according to the value of $THD_U$, which can be obtained either by calculating, or by means of measurements.

## Conclusions

The value of the total additional power loses in electric power network can be evaluated knowing the $THD_U$ in accordance to equation (10). In this case, the distortion coefficient can be obtained both by calculating and by making necessary measurements. In both cases for a correct evaluation of additional losses one must take into account the interharmonics. The error of the proposed method of evaluation of additional losses, due to distortion of voltage does not exceed 10 %.

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