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Development of conductive parts power losses calculation method in case of interharmonics

Abstract*.This paper presents the algorithm for computing supplementary losses in conductive parts under interharmonics formed with side frequencies generated by variable-frequency drives. The algorithm is based on a signal frequency decomposition with wavelet packet transform (WPT). This algorithm makes the calculation of losses for each frequency more accurate and this allows the decisions on production of certain frequency filters to be made.*

Streszczeni. *W niniejszej pracy jest zaproponowany algorytm do obliczenia strat dodatkowych w przewodzących prąd elementach w przypadku istnienia składowych interharmonicznych (wytwarzanych przez częstotliwości boczne), generowanych przez napędy regulowane częstotliwościowo. U podstaw algorytmu leży dekompozycja częstotliwościowa sygnału z zastosowaniem pakietowej transformaty falkowej. Zaproponowany algorytm pozwala bardziej precyzyjnie obliczać straty na każdej częstotliwości, co z kolei pozwoli podejmować decyzje o zastosowaniu filtrów poszczególnych częstotliwości.* ***Algorytm do obliczenia strat dodatkowych w przewodzących prąd elementach w przypadku istnienia składowych interharmonicznych***

Keywords:.Wavelet transform, interharmonics, higher harmonics, losses.
Słowakluczowe: transformata falkowa, składowe interharmoniczne, wyższe harmoniczne, straty.

Introduction

The in force guideline defining the proper quality requirements for electrical energy in a number of European countries (France, Germany, Great Britain, Poland etc.) is Standard EN 50160:2010 «Voltage characteristics of electricity supplied by public distribution networks». This standard high lights one of the possible types of excessive voltage waveform distortion, that is interharmonics. Interharmonicis «a sinusoidal voltage with frequency between the harmonics, i.e. the frequency is not an integer multiple of the fundamental» [1]. If to consider the effective standards throughout the world, the absence of any common approaches and considerable differences is obvious. In the European Union standards process in the field of interharmonics is currently at the stage of knowledge accretion and discussion. For instance, according to Standard IEC 61000-4-7:2002 [2] interharmonic voltage is limited to 0.2%. Standard EE Std 519 [3], being applicable in the USA, defines threshold values of interharmonics in low voltage (up to 1kV), medium voltage (69-161 kV) and high voltage (more than 161 KV) systems.

One of the factors for the occurrence of interharmonics is «the asynchronous switching (i.e. not synchronized with the power system frequency) of semiconductor devices in static converters» [4]. Rapid changes of current in the equipment can also result in voltage fluctuations. The sources of interharmonics in power supply systems are arc furnaces, variable frequency drives, frequency converters, etc. [4].

Interharmonics have a negative effect on power supply systems operation. Depending on the interharmonics current amplitude the voltage distortions occur in the load buses at a given frequency. Depending on the interharmonics frequency bandwidth the probability of resonance increases leading to even more significant voltage distortion, to conductive parts overload and complete disturbance for electric users. One of the substantial effects of interharmonics on power supply systems is the effective voltage change and voltage flicker occurrence. Interharmonics cause low frequency fluctuations of electromechanical systems, create interferencein relay protection and automation systems, negatively affect luminous sources [4].

The aim of this work is to develop the algorithm for computing supplementary losses in conductive parts under harmonics generated by a wavelet transform variable-frequency drive.

Interharmonics theory and modeling

Interharmonics are one of the reasons of a spectral leakage effect in analyzing operation modes of electric power systems. To eliminate this effect a short-time Fourier transform (STFT) with various types of window functions is applied. In paper [5] the authors presented a detailed analysis of using a Hanning Window and its advantages if to compare with a rectangular window provided that frequencies are grouped as required by standard [2].

The authors in paper [6] examined the current spectral composition of industrial frequency converters and illustrated the advantages of high-resolution methods, namely a Prony`s method and a min-norm harmonic retrieval method.

The conclusion is drawn in this paper that "both high-resolution methods do not show the disadvantages of the traditional tools and allow exact estimation of the interharmonics frequencies" [6]. Paper [7] represents the technique of harmonics and interharmonics spectral analysis based on Hilbert transform.

The authors present an approach to defining an envelope and harmonic components by a window shift method and an interpolation, this approach resulting in a number of advantages. One of them is that the approach is "not affected by the spectral leakage caused from the harmonics" [7].

A detailed analysis of current and voltage spectral composition in the electric power system with converter equipment, such as double conversion systems, cycloconverters, etc. is given in paper [8]. Thus, the harmonic composition of voltage (current) can be defined by technical specifications of converters [8]:

(1) $$f_i = (p_1 m \pm 1) f \pm p_2 n f_0$$

where: p_1– pulse number of rectifier section, p_2– pulse number of output section, m, n– integers.

Depending on the output frequency of the cycloconverter f_0 the current (voltage) spectral composition can vary. Generally, the frequency spectrum can be represented in the form of a fundamental harmonic and two side frequencies:

(2) $$i(t) = I_m \cdot \sin(\omega t) + I_m \cdot m \cdot \sin((\omega \mp \Omega)t)$$

where I_m - fundamental frequency amplitude, $I_m \cdot m$ -side frequency amplitude, ω – electricity network angular frequency, rad/s, Ω – envelopeangular frequency, rad/s.

The presence of side frequencies causes the effect of voltage fluctuation. In paper [9] an analysis of interharmonics interconnection generated by a variable frequency drive and voltage fluctuation in power supply systems is given.

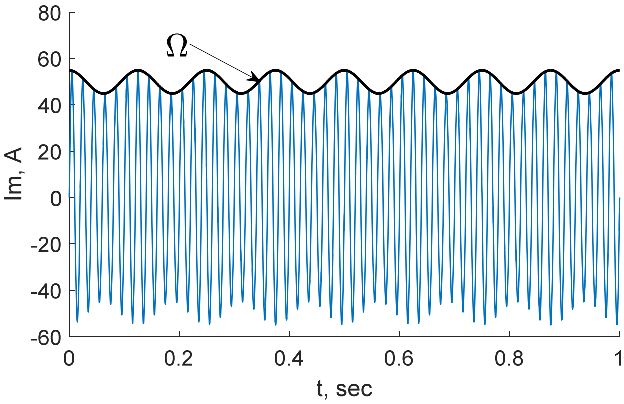

Fig. 1 – Side frequency formation

A definite difficulty of harmonics analysis occurs under the low frequency of an envelope Ω << ω, in this case the interharmonics can enter the so called harmonic group [2]. The interval of the examined spectral lines is 5 Hz. The harmonic groups are the fundamental harmonic frequency and two adjoining frequencies. The interharmonic group makes an interval between two harmonic groups.

The extraction of harmonic and interharmonic groups is aimed at minimizing the effect of spectrum spreading, but in this case the adding of an interharmonic generated by converter equipment to the harmonic group leads to an error in mode calculation and in the analysis of losses in conductive parts. An application of a traditional low-pass and high-pass filter approach does not allow extracting the interharmonic component.

To solve this problem frequency decomposition of voltage (current) signal based on wavelet packet transform is proposed. The review of wavelet transform application for calculation of steady-states and transients in electric power systems is introduced in [10]. A major role in implementing wavelet packet transform plays a scaling function and a corresponding wavelet function. Wavelets are the class of functions obtained from one function by means of its time axis shifting and tension. These functions are bases used for signal decomposition and recovery. The fast wavelet transform on Mallat algorithm allows computing coefficients without integration based on convolution:

(3) $$\varphi(t) = \sum_k h_0(k)\sqrt{2}\varphi(2t-k)$$
$$\psi(t) = \sum_k h_1(k)\sqrt{2}\varphi(2t-k)$$

where, h_0, h_1 – filter coefficients defined for each type of wavelet. In accordance with (3) the matrix of instantaneous current values can be represented in the form of arrays of approximation i_j^A and detail i_j^D coefficients:

(4) $$\begin{cases} i_j^A = \sum_k h_0(2t-k) i_{j-1}^A \\ i_j^D = \sum_k h_1(2t-k) i_{j-1}^A \end{cases}$$

The result of the wavelet packet transform is signal frequency decomposition allowing to extract specific frequency bands (Fig. 2).

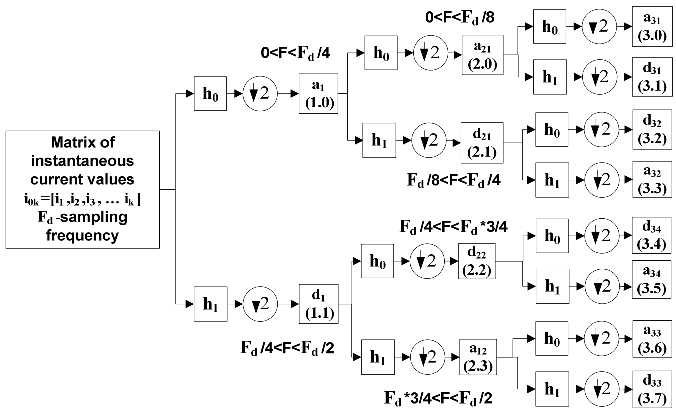

Fig. 2 – Wavelet packet transform tree

In each case specific frequency ranges are defined by signal f_d sampling frequency to be chosen in accordance with Nyquist theorem and the depth of the signal wavelet decomposition.

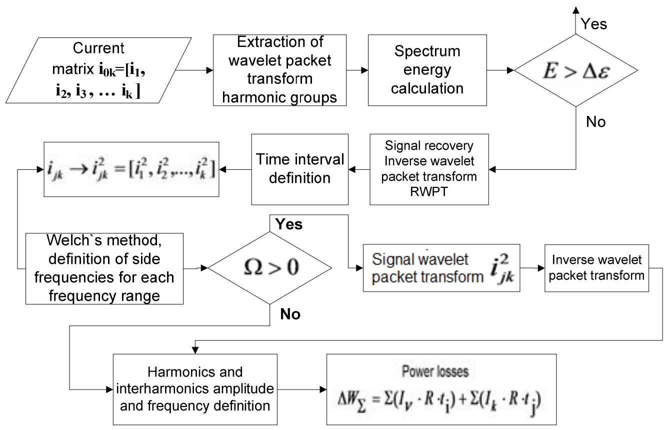

Fig. 3 –Proposed algorithm

Algorithm design

To calculate losses in conductive parts under non-sinusoidal modes (interharmonics including) it is necessary to know the spectral composition of current and the time (length) of high-frequency components. To solve this problem the following algorithm is introduced (Fig. 3).

Step 1. The digital current signal of a measuring device forms the matrix of instantaneous values. The frequency decomposition of the current matrix with the wavelet packet transform (WPT) is performed. The decomposition is performed so that the band pass interval centered in the area of a specific harmonic group matches each set of wavelet coefficients [2]. In accordance with the wavelet decomposition tree (Fig. 2) the original signal is decomposed into frequency bands when both higher harmonic with frequency kωand side frequencies produced by interharmonics kω±Ω are present. The matrix size of wavelet coefficients relative to the original matrix of the current signal is lowered by a factor of 2*j*, this being defined by the depth of wavelet decomposition *j*.

Step 2. The spectral energy of wavelet coefficients on each frequency range is defined. If the spectral energy is less than the assigned threshold level of error Δε, these coefficients can be neglected, since this means the absence of frequency components within the given range.

Step 3. The inverse wavelet transform is carried out by wavelet coefficients with the spectrum energy being higher than the assigned level Δε. Thus, the current signal for a particular circuit-wise frequency range is restored (Fig.2), and the matrix size of the extracted frequency range is equal to the matrix size of the original signal.

Step 4. The time of mode variation, that is time intervals Δt with signal interharmonics is defined by extended wavelet coefficients d1. The necessity to define time intervals is caused by the problem of estimating energy losses in conductive parts. At the same time the power consumption behavior of electric load buses can be of random nature. A bus operation mode change can be accurately determined by specific excursions (short amplitude increase)of extended coefficients (Fig. 5).

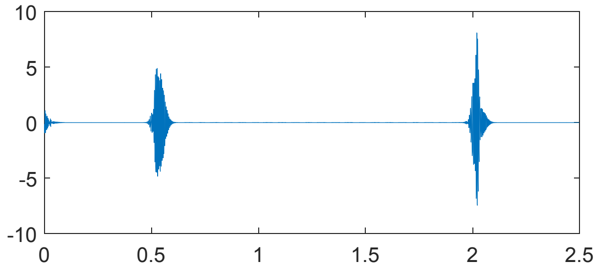

Fig. 4 – Diagram of extended coefficient d 1

Step 5. The matrix of the recovered signal is element-wise squared.

(5) $$i_{jk}^2 = [i_1^2, i_2^2, ..., i_k^2]$$

Thus, if the extracted signal is defined by the formula (1), the result of squaring is:

$$\begin{aligned} i^2(t) &= I_m^2 \cdot \sin^2(\omega t) + I_m^2 \cdot m^2 \cdot \sin^2((\omega \mp \Omega)t) = \\ &= I_m^2 \cdot \left(\frac{1}{2} + m^2\right) + 2I_m^2 \cdot m \cdot \cos\Omega \cdot t + I_m^2 \cdot m^2 \cdot \cos 2\Omega t + \\ &+ I_m^2 \cdot \left(m^2 - \frac{1}{2}\right) \cdot \cos 2\omega t - I_m^2 \cdot m \cdot \cos(\omega - \Omega) - \\ &- I_m^2 \cdot m \cdot \cos(\omega + \Omega) - \frac{I_m^2 \cdot m}{2} \cdot \cos 2 \cdot (\omega - \Omega) - \\ &- \frac{I_m^2 \cdot m}{2} \cdot \cos 2 \cdot (\omega + \Omega). \end{aligned} \quad (6)$$

It is clear from expression (5) that squaring the examined function brings to the direct current component and frequency component Ω, 2Ω, 2ω, $(\omega \mp \Omega)$, $2 \cdot (\omega \mp \Omega)$ in the signal. Envelope frequency Ω is of practical interest since it allows defining interharmonic frequency.

Step 6. Welch`s method is used to fix side frequencies Ω for each frequency range defined from the previous step. Absence of a side frequency allows calculation of effective current to be made without changes in frequency band pass of wavelet filter, and to move to step 7.If a side frequency is fixed, the necessity to alter the filter frequency band pass originates. Then we find the optimal frequency band pass from condition $\Delta\omega < \Omega$.

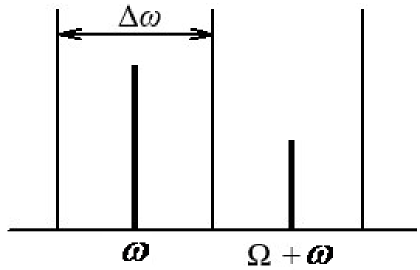

Fig. 5 – Filter frequency band pass

Step 7. Taking in to account an optimal band pass of wavelet filter $\Delta\omega$, frequency signal decomposition is carried out. Harmonic and interharmonic frequencies and their effective values are defined then. The effect of spectral leakage does not occur as far as signal recovery is realized with in the time ranges defined in step 4merely. That permits this signal to be considered as a steady-state one.

Step 8. Based on the algorithm data, the calculation of energy losses in conductive parts is performed in the closing stage.

(7) $$\Delta W_\Sigma = \Sigma(I_v \cdot R \cdot t_i) + \Sigma(I_k \cdot R \cdot t_j),$$

where I_v, I_k - current value of harmonic and interharmonic components respectively, R - resistance of an electric conductor, t_i - time interval with v harmonic component, t_j - time interval with k interharmonic component.

Theproposedalgorithmallowstheaccuracyofelectricalsupplymodescalculationtobeimprovedundernon-sinusoidalunsteady modes. This approach also allows the calculation of additional losses due to conductive parts interharmonics to be made.

Numerical experiment results

As a numerical experiment we propose the current signal with harmonics and interharmonics generated by the 6 pulse rectifier and inverter frequency convertor:

(8) $$i(t) = \begin{cases} i(t) = I_m \sin(2\pi t \cdot f), & 0 < t < 0{,}5; \\ i(t) = i_{50}(t) + i_{58}(t) + i_{158}(t) + i_{242}(t) + i_{250}(t) + i_{350}(t), & 0.5 < t < 2; \\ i(t) = I_m \sin(2\pi t \cdot f), & 2 < t < 2{,}5; \end{cases}$$

where $I_m = 10\sqrt{2}$, $f = 50\text{Hz}$, $\Omega = 8Hz$,

$$i_{50}(t) = 5I_m \cdot \sin(2\pi \cdot t \cdot f) + I_m \cdot \sin(2\pi \cdot t \cdot f),$$

$$i_{58}(t) = \frac{I_m}{2} \cdot \sin(2\pi \cdot t \cdot (f + \Omega)),$$

$$i_{158}(t) = \frac{I_m}{2} \cdot \sin(2\pi \cdot t \cdot (3f + \Omega)),$$

$$i_{242}(t) = \frac{I_m}{2} \cdot \sin(2\pi \cdot t \cdot (5f - \Omega)),$$

$$i_{250}(t) = \frac{I_m}{2} \cdot \sin(2\pi \cdot t \cdot (5f)),$$

$$i_{350}(t) = \frac{I_m}{2} \cdot \sin(2\pi \cdot t \cdot (7f)).$$

The examined current signal is shown in figure 6.

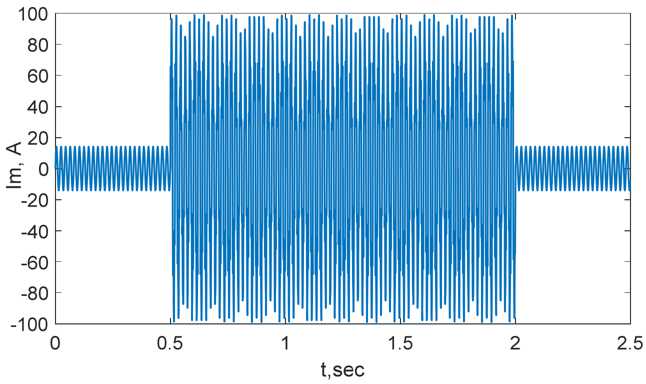

Fig. 6 – Examined current signal

WPT is applied to the original signal to be divided it into harmonic groups. We use Daubechies wavelet "db42" for making analysis. Decomposition is performed up to the 3[d] level, and as the result we obtain 8 harmonic groups or frequency ranges.

We calculate the spectrum energy of each frequency range $\Delta\omega$.

Table 1. Frequency ranges spectrum energy

E1	E2	E3	E4	E5	E6	E7	E8
94,88	0,6	1,21	3,23	0,0016	0,0016	0,050	*0,0024*

The inverse WPT of segments $E > \varepsilon$ is carried out, $E < \varepsilon$ segments are dropped. Other frequency ranges are squared. Then we use Welch`s method for each frequency range.

In figure 7 the result of Welch`s method is presented for the first segment. It is obvious that this segment contains side frequency Ω. It follows that it is necessary toad just filter frequency band pass. From the condition $\Delta\omega < \Omega$ the optimal frequency band pass of the filter is deducted.

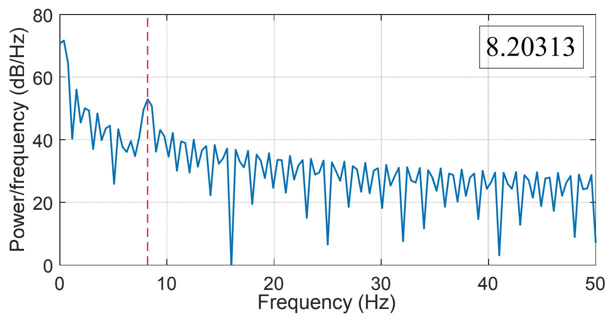

Fig. 7 – Result of Welch`s method for the first frequency range

Taking into account the optimal selected band pass of wavelet filter $\Delta\omega$, we carry out signal frequency decomposition. Then, we find out the values of frequencies and an effective value of harmonic and interharmonics components within this range.

Table 2. Experiment results

f, Hz	50	58	158	242	250	350
Im, A	49.26	4.786	4.839	4.851	9.855	6.859
ε, %	1.48	4.28	3.22	2.97	1.45	2
ΔW, Watts	738.89	6.975	7.13	7.166	29.573	14.325

Next, we calculate the energy losses due to these frequency components.

In table 2 the values of frequencies, effective values, calculation error of effective values and energy losses of each frequency component are represented.

Conclusion

In the paper the algorithm losses calculation due to harmonics and interharmonics in conductive parts is proposed. The introduced method is based on frequency decomposition of current signal with WPT The advantage of mathematical apparatus for the wavelet transformis the possibility to analyse signals not only in the field of frequency, but in the field of time, and this is aconstitutive condition for calculation of losses in the elements of electrical power supply systems. The difference between the proposed technique and the familiar ones is in the possibility of separate definition of losses at higher harmonics (multiple frequency) and losses at interharmonics (formed by side frequencies). The proposed technique allows the calculation of losses for each frequency to be refined in order to promote filters ofcertain frequencies for the reasons of economic effect.

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REFERENCES

[1] EN 50160:2010 «Voltage characteristics of electricity supplied by public distribution networks».

[2] IEC 61000-4-7:2002 Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto

[3] 519-2014 - IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. DOI: 10.1109/IEEESTD.2014.6826459

[4] Z. Hanzelka and A. Bien, "Power Quality Application Guide: Harmonics & Interharmonics," A guide material by Leonardo Power Quality Initiative, Copper Development Association, 2004.

[5] A. Tesla, D. Gallo and R. Langella, "On the Processing of harmonics and interharmonics: using Hanning window in standard framework,"IEEE Trans. PowerDelivery, vol. 19, pp. 28–34, 2004.DOI: 10.1109/TPWRD.2003.820437.

[6] Z. Leonowicz, T. Lobos and J.Rezmer, "Advanced spectrum estimation methods for signal analysis in power electronics,"IEEE Trans. Industrial Electronics, vol. 50, pp. 514–519, 2003.DOI: 10.1109/TIE.2003.812361.

[7] J. Xiong, B. Wang "Measuring power system harmonics and interharmonics by envelope spectrum analysis,"Przegląd Elektrotechniczny, vol. 12, pp. 319–324, 2010.

[8] A. Tesla "Interharmonics: Theory and modeling," IEEE Trans. Power Del., vol. 22, no. 4, pp. 2335–2348, Oct. 2007.DOI: 10.1109/TPWRD.2007.905505.

[9] T. Tayjasanant, W. Wang, C. Li, W. Xu"Interharmonic - flicker curves," IEEE Trans. Power Del., vol. 20, no. 2, pp. 1017–1024, 2005.DOI: 0.1109/TPWRD.2004.838639.

[10] D. Osipov"Applications of wavelet transform for analysis of electrical transients in power systems: the review,"Przegląd Elektrotechniczny, vol. 4, pp. 162–165, 2016.