Developing the calculation methods of effective values of current and voltage for nonsinusoidal transient modes in electric power systems based wavelet transform

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Abstract. The necessity to develop analysis and calculation methods of nonsinusoidal modes in electric power networks is conditioned by the increasing number of electrical receivers parental to non-linear distortions (variable-frequency electric drive, LED-based lightning and so on). Higher harmonic components increase power and efficiency loss in current carrying parts, result in overheating of conductors and intense insulation deterioration, can cause resonance overvoltage and automation equipment malfunctions. Due to digitalization of the electric power industry it is necessary to develop methods of receiving, processing and digital communication on system state variables (currents, voltage, power), including nonsinusoidal modes. Wavelet transform is wider applied to analyze complex harmonic processes in electric power industry in conditions of transient modes. The paper introduces calculation methods of integrated indexes of electric power system modes – currents, voltage and power in the presence of electrical receivers with non-linear current-voltage characteristics. The method is based on Parseval equality and allows calculating via wavelet coefficients received by transformation of the initial stream of transient values of currents and voltages. Herewith the issue of data compressing is solved when transmitting digital information. The method allows determining the variables of every frequency component, interpreting the data in the three-dimensional scale (peak values, frequency and time) which will be used in choosing activities for higher harmonics filtration to reduce the loss in current carrying parts.

1. Introduction

Fourier processing is conventionally used to harmonically analyze nonsinusoidal processes in electrical power industry. Fourier processing is applied for the spectral analysis of resonance oscillations with the limiting amplitude in a mechanical system of vibration electromagnetic activators [1]. This method had a restriction; it was applicable only to sinus wave oscillations of the system with relatively low damping, which is why works [2, 3] suggest improvements to the method. When analyzing transient modes a negative effect of the spectrum flow appears, which can be reduced by Short Time Fourier Transformation. Nevertheless, due to Heisenberg equivocating, it is impossible to achieve good frequency and time resolution. To reduce the effect of the spectrum flow, the work [4] introduces a “pseudowavelets” method. To analyze complex harmonic transient processes in electric
power supply industry a mathematical apparatus of wavelet transform is more often used. This kind of transform is widely used to analyze the parameters of electric power quality, including harmonic and interharmonic analysis [5, 6], transient simulation, short circuits and ground faults [7], electric equipment diagnostics and others. Decomposition of the data rows, received as a result of physical tests (measurements), applying the wavelet transform theory allows determining frequency ranges of the required width in the signal (depending on the sampling rate of the initial signal and decomposition depth), allows determining time and occurrence of some harmonic component.

2. Basic theorems of wavelet transform theory

There are continuous and discrete wavelet transforms in scientific and technical literature. When solving practical tasks connected with data digital processing, continuous wavelet transform is excessive. In its turn, discrete wavelet transform due to its peculiarity, when further wavelet decomposition is done only by approximate wavelet coefficients, is also restricted in its application. A variety of discrete wavelet transformation is a batch transformation, done according to the scheme in figure 1.

Batch wavelet transform allows more evenly localization of frequency ranges of a signal, which is convenient for analyzing nonsinusoidal transient modes of electric power systems. Nowadays, there are fairly enough wavelet functions, which have different gain-frequency characteristics. For effective application of wavelet transform for calculating integral characteristics of a nonsinusoidal mode it is necessary to formulate a choice criterion for an optimal wavelet function. Two conditions can be used as a criterion: 1) minimum error when desampling by the wavelet coefficients; 2) uppermost energy of the spectrum for upper harmonic, corresponding to the pass band of wavelet function (wavelet filter). In this case, the choice criterion of the wavelet function can be written as an equation (1).
A choice of the optimal wavelet function according to (1) allows increasing determination accuracy of the effective value of current and voltage of individual harmonic.

3. Methods for determining the effective value of current and voltage of individual harmonic by wavelet coefficients

Determining higher harmonic for loss analysis and elaborating measures on filtration is a relevant task [8]. Increase of LED-based lighting results in overload of current-carrying parts with higher harmonic [9] and onset of voltage oscillations and a flicker [10]. Wavelet transform allows calculating integrated indexes of the electric power system mode for every frequency component. According to the theory of wavelet transform, instantaneous value of voltage and current, recorded by digital instruments can be represented by wavelet coefficients according to the formulas:

\[
i(t) = \sum_{j=n}^{2^{-1} n^{(m+1)-1}} i_{j,m}(k) \cdot \psi(t)
\]  

\[
u(t) = \sum_{j=n}^{2^{-1} n^{(m+1)-1}} u_{j,m}(k) \cdot \varphi(k)
\]

Active power can be determined for every frequency range via wavelet coefficients according to the scheme of decomposition (figure 1):

\[
\begin{align*}
P_{j,m} & = \frac{1}{n} \left( \sum_{j=n}^{2^{-1} n^{(m+1)-1}} i_{j,m}(k) u_{j,m}(k) \right) \\
g & = \frac{P_{j,m}}{(U_{j,m})^2} = \frac{1}{n} \left( \sum_{j=n}^{2^{-1} n^{(m+1)-1}} i_{j,m}(k) u_{j,m}(k) \right) \\
1 & = \sum_{j=n}^{2^{-1} n^{(m+1)-1}} u_{j,m}^2(k)
\end{align*}
\]

According to the theory of Frise reactive power, active current recorded via wavelet coefficients

\[
i_a = gu_{j,m} = \frac{1}{n} \left( \sum_{j=n}^{2^{-1} n^{(m+1)-1}} i_{j,m}(k) u_{j,m}(k) \right) \cdot \frac{1}{n} \sum_{j=n}^{2^{-1} n^{(m+1)-1}} u_{j,m}^2(k)
\]

Effective value of the active current in this case will be determined by the formula:
This method allows determining effective value of current and voltages of individual harmonic. At the same time wavelet coefficients allow determining time (occurrence length) of every harmonic component.

4. Simulation modeling. Numerical experiment

A simulation model of the electric power system 110/35/6 kv was developed to test this method in Matlab Simulink software (figure 2). A control station for immersible pumps was determined as a node for non-linear load. A spectral composition of non-linear load was determined with certified equipment (Metrel MI 2792A).

![Simulation model to analyze a mode of the electric power system.](image)

As a result of wavelet transform of the bus voltage in substation 6 kv (figure 3) a set of wavelet coefficients was received (figure 4).

![Voltage signal, subject to batch wavelet transform.](image)

The analogous procedure of wavelet transform, according to the scheme (figure 1) was conducted for a range of instantaneous current.
Figure 4. Result of batch wavelet transform of the voltage signal.

With this method active, reactive and distortion power have been determined for every harmonic recorded with the measuring instrument (table 1).

Table 1. Calculation of mode parameters by wavelet coefficients.

| Frequency, Hz | Symbol, measurement unit | True value | Value, calculated via wavelet coefficients |
|---------------|--------------------------|------------|-------------------------------------------|
| Active current component | $I_{a1}$, A | 523 | 523 |
| 250 | $I_{a5}$, A | 89 | 90 |
| 350 | $I_{a7}$, A | 55 | 56 |
| Actual power | $P_1$, kW | 5 701 | 5 694 |
| 250 | $P_5$, kW | 970 | 978 |
| 350 | $P_7$, kW | 597 | 602 |
| Reactive power and distortion power | $Q_1 + N_1$, kVar | 4 103 | 4 105 |
| 250 | $Q_5 + N_5$, kVar | 728 | 727 |
| 350 | $Q_7 + N_7$, kVar | 471 | 468 |

This method can be applied to calculate interharmonic components, if the scheme of decomposition will correspond to accentuation of this frequency band with application of additional algorithms of interharmonic localization [11].

5. Conclusion

Applying mathematical apparatus of wavelet transform to calculate transitional nonsinusoidal modes of electric power systems allows eliminating a negative effect of the spectrum flow. Here a researcher doesn’t face the issue of the bandwidth selection (as in Short Time Fourier Transform). Wavelet transform allows data flow contraction, which characterizes the mode of the electric power system. This method allows determining effective value of current and voltage during a nonsinusoidal mode.
Basing on the received wavelet coefficients after transformation we can receive active and distortion power for individual harmonic, which allows précising technical and economic calculations when choosing measures for harmonic filtering.

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