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Improvement of Transients' Parameters Evaluation Algorithms for Relay Protection and Automation with Use of Modern Methods of Digital Signal Processing

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KEYWORDS

Transients in electrical power systems, short-time Fourier transform, wavelet transform, complex wavelets, wave spectrum, scalogram, frequency evaluation, phases and amplitudes of sinusoidal oscillations, evaluation accuracy and processing time.

1 INTRODUCTION

In view of power engineering industry growth namely growth of power consumption and development of generating powers the problem of system transient stability ensuring is becoming more and more important. This problem supposes increase of relay protection speed, sensitivity and reliability. Fulfillment of these requirements to relay protection devices depends mainly on parameters of input signals from instrument current and voltage transformers. That is why a major part is assigned to digital signal processing algorithms.

The subject of investigation is means of increase of non-steady processes parameters evaluation accuracy under limited observation time.

At present short-time Fourier transform (STFT) is mainly used to evaluate parameters of a transient. This way of analysis does not present clearly the composition of transient and has limited accuracy of system frequency parameters under limited observation time.

A new way of digital signal processing (wavelet transform (WT)) is considered in this report which is aimed at non-stationary processes analysis, possibilities of WT are shown to increase information clearness concerning transient composition and increase of its components evaluation accuracy.

2 MAIN PART

As known transients in power engineering are of a non-stationary nature, i.e. frequency composition of the signal changes in time spontaneously, components of the signal appear and disappear with the course of time. Algorithms of transient parameters evaluation, built on the basis of normal STFT, used in such conditions do not provide required speed and accuracy. The main problem is that limited time causes big errors in frequency composition evaluation. According to indeterminacy principle attempt to increase resolution in frequency domain leads to transform time increase and vice versa.

2.1 Information representation

As was mentioned in [3] for transients analysis in power engineering it's reasonable to use wavelet transform, which has substantial advantages compared to ways of digital signal processing used in modern relay protection terminals. Also in [1, 2] it is shown that accuracy of parameters

evaluation depends mainly on similarity of analyzed signals and wavelets used. Calculations have shown that to evaluate parameters of transients the most convenient and accurate is well time- and space-allocated Morlet wavelet which is described by function:

$$\psi(t) = \exp(-t^2/\alpha^2) \cdot [\exp(ik_0 t) - \exp(-k_0^2 \alpha^2/4)],$$

where α and k_0 define duration and frequency of wavelet filling.

When a complex wavelet is used a matrix of wave spectrum complex values is formed showing composition of analyzed signal. For obvious representation of the wave spectrum in three dimensional space magnitude, argument, real and imaginary part are used depending on the problem set.

Application of WT is demonstrated in an example of real transient analysis $u_0(t)$, which was registered at one of substations in Nizhny Novgorod (fig.1). The figure derived by Retom (Russian multi-functional analyzer) shows the process under consideration $u_0(t)$ (fig. 1 a) and harmonic spectrum of the process (fig. 1 b) in the observation window set off by rectangle (width of rectangle is 0.02 s). STFT defines at least eight harmonic components multiple of 50 Hz.

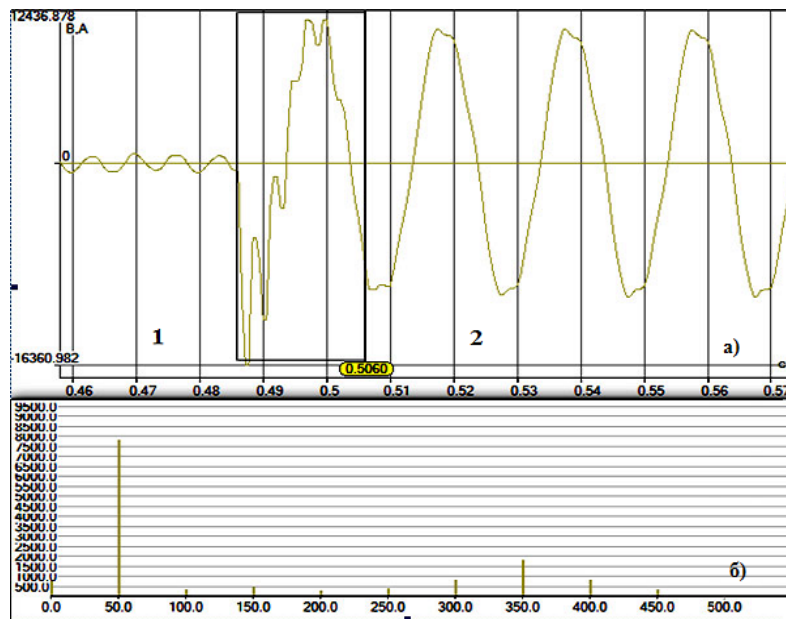


Fig. 1: Transient $u_0(t)$ under consideration

In this example real part of complex spectrum, derived in the result of WT, gives more visual division of the signal into frequency components than magnitude. For definiteness process under consideration is divided into two parts – «before disturbance» (1) and «after disturbance» (2). Real part of wave spectrum $u_0(t)$ is shown in fig.2. It is seen that before disturbance unbalance voltage existed and after disturbance as opposed to STFT data (fig.1, b) only two components exist: component of system frequency and decaying oscillating component of a frequency significantly exceeding system frequency.

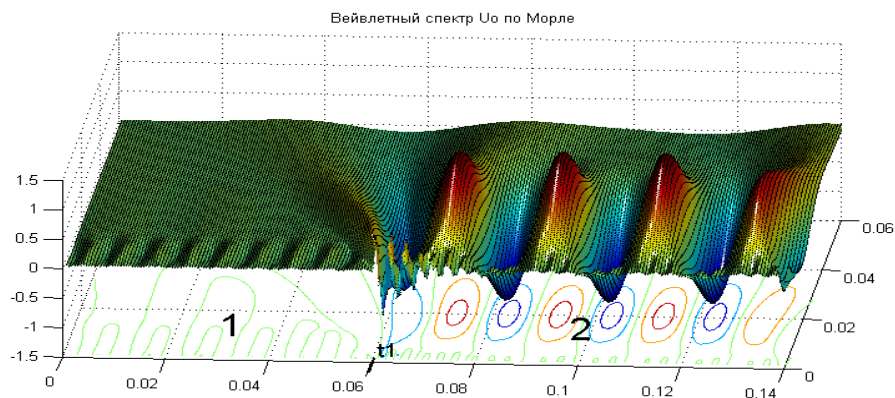


Fig. 2: Real part of wave spectrum of the process $u_0(t)$.

The main interest is in transient parameters evaluation during data acquisition time of 0.02 s. The process of transient parameters evaluation on a time segment defined by a rectangle set off in fig.1.a) is shown in fig.3.

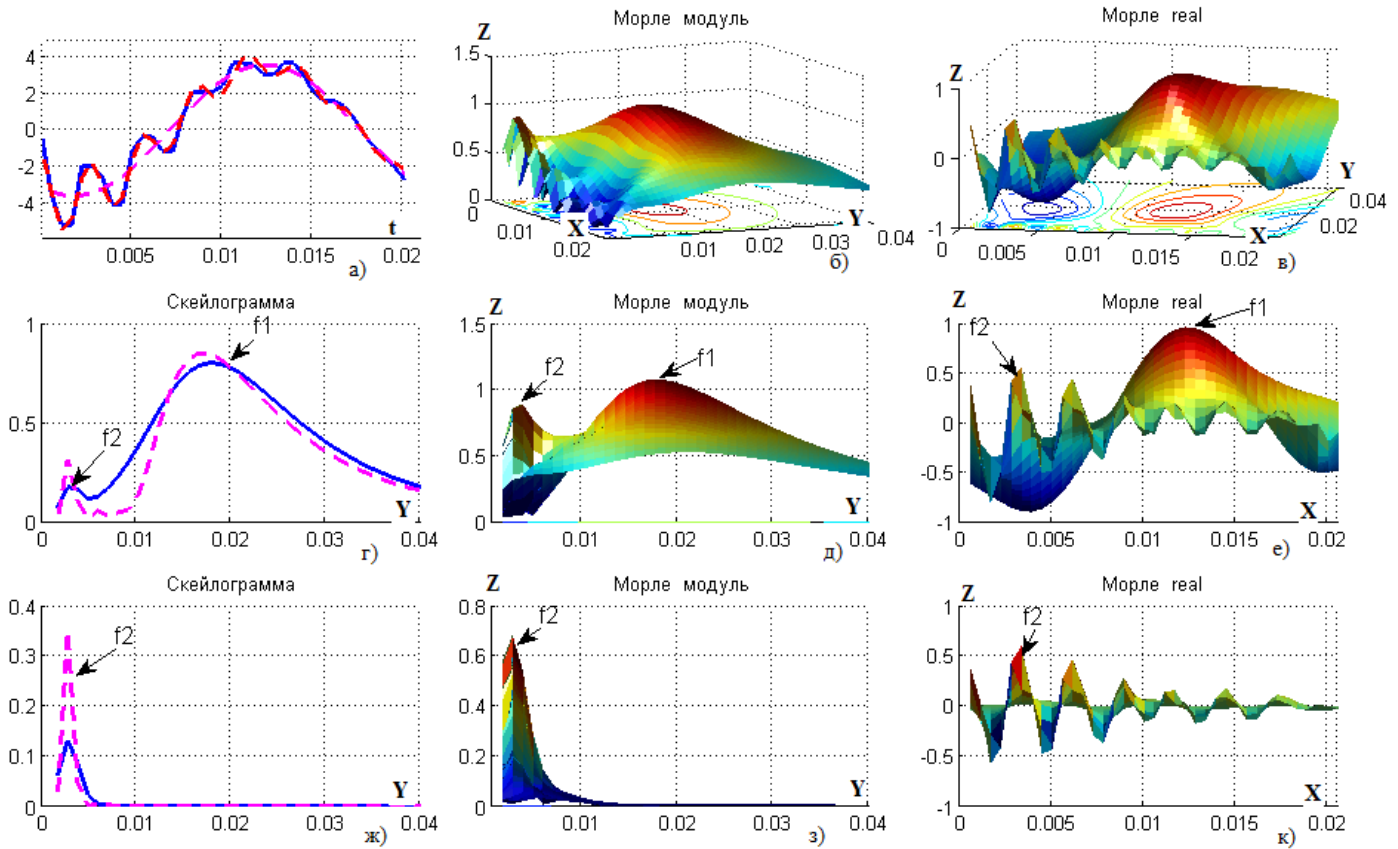


Fig. 3: Transient parameters' evaluation.

In fig. 3 a) continuous blue line shows a part of a transient selected for parameters evaluation. Red dotted line – regenerated transient in the basis of signal processing results. Violet dotted line – regenerated system frequency component. Blue and red lines practically match each other what indicates parameters evaluation quality.

In fig. 3 b) magnitude of wave spectrum of WT is shown, while fig. 3 c) shows its real part. Division of transient into components is clearly seen in both figures. Z axis is for calculated values of wave spectrum, X axis is for time shift (b), Y axis – time scale (a), inverse to frequency.

To evaluate quantitative composition a scalogram is used as a rule (fig. 3 d, g). It is the sum of squared wave spectrum by time shift parameter (b). Scalogram in fig. 3 d) calculated in two ways shows presence of two wave components in the transient. The maximal values on the scalogram allow to approximately evaluate frequency of these components. Similar representation is given by Z-Y projection Z-Y (fig. 3 e). Less clearly amount of harmonic components can be defined by Z-X projection (fig. 3 f), but this projection shows phase correlations of sinusoidal processes relatively origin.

After main frequency parameters evaluation its regenerated value is subtracted from time representation of the process under consideration (fig. 3 a). Scalogram of remaining process is shown in fig. 3 g). Point 0.02 on the Y axis refers to 50 Hz frequency. In the neighborhood of this frequency a zero value of scalogram is obtained which means absence of system frequency in the remaining signal and consequently parameters of the main frequency are calculated with high accuracy. Same result is seen in Z-Y projection of the wave spectrum (fig. 3 h). Z-X projection (fig. 3 j) also shows inhibition of the first harmonic. This projection can be used to visual evaluation of remaining signal. In this example it shows presence of undetermined interference.

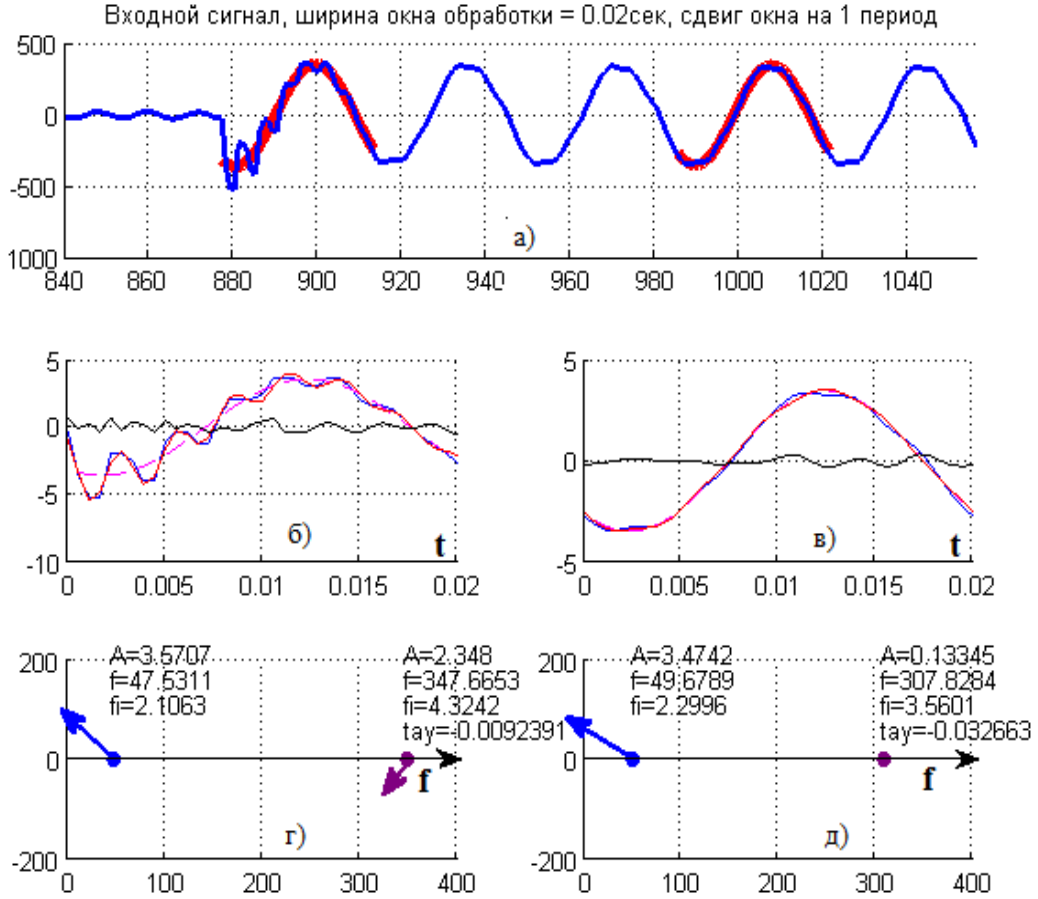


Fig. 4: Transient composition visualization.

Detailed consideration of transient parameters evaluation is given to show accuracy of this evaluation. Under routine transient parameters evaluation it is sufficient to implement the main algorithm for all oscillating components evaluation. Use of this evaluation enables representation of a transient composition (fig. 4 d, e). Fig. 4 a) shows a long fragment of the transient under analysis. Red line shows two windows of 0.02 ss duration where transient parameters evaluation is carried out and vector representation of transient composition is also given. First window gives parameters evaluation in the beginning of the transient, the s window – after several periods. Fig. 4 b, c) shows parts of the transient under consideration, its evaluation and their difference bearing undetermined nature.

It is reasonable to present the composition of a transient as a set of vectors (fig. 4 d, e). Vector tail is placed on the frequency axis in the point of evaluated frequency. Vector length is proportional to magnitude evaluation and phase is counted out from positive frequency axis direction towards positive direction. During smooth movement of the parameters evaluation window towards positive direction the vectors rotate in positive direction and vector lengths change according to appropriate component's fading.

2.2 Transient parameters evaluation for wide-area measurement systems (WAMS)

Phasor Measurements unit (PMU) must provide data transmission speed of one, two and five periods [4] of system frequency and at the same time it should provide predefined data acquisition error which is evaluated by total vector error (TVE):

$$TVE = \sqrt{\frac{(X_r(n) - X_r)^2 + (X_i(n) - X_i)^2}{X_r^2 + X_i^2}} \quad (3)$$

where $X_r(n)$ and $X_i(n)$ – measured values sent by PMU, and X_r and X_i – theoretical values of input signal under known X_m , ω and ϕ conditions.

Algorithms of PMU based on least-squares method (LSM), short-time Fourier transform and wavelet transform are considered. LSM uses non-linear approximation of observed sinusoidal function i.e. observed process is approximated by chosen non-linear function with minimal residual method (residual – difference of measurements and chosen function values). The routine algorithm is based on STFT. Algorithm based on WT is developed for the first time. Verification of the algorithms is performed in steady-state and dynamical modes.

To verify algorithms in steady-state mode it's essential to evaluate TVE of parameters evaluation under frequency variation of ± 0.5 Hz of the rated value, magnitude of harmonic distortion of 1% and presence of white noise bearing standard deviation of 1% (which corresponds to maximum deviation of 3% and dispersion of 0.0001). Allowed error is up to 1%.

STFT-based algorithm requires at least 2 periods for parameters evaluation while LSM- and WT-based methods use two time intervals (1 and 2 periods), sampling interval equals to maximum allowed, one hundred samples per period.

Fig. 5 shows the result of parameters evaluation using three algorithms under input signal frequency of 50.5 Hz and above mentioned requirements. Fig. 5 a - e) parameters evaluation is performed by a 0.04 s width window shifted by 0.02 s. X axis shows the number of evaluation performed. Real values and evaluations of magnitude (fig. 5 a) and frequency (fig. 5 b), errors in magnitude (in percent, fig. 5 c) and frequency (fig. 5 d) evaluation are calculated. Phase evaluation is not shown but its accuracy significantly influences TVE evaluation. TVE (fig. 5 e) is referred to evaluations obtained using window of 2 periods. Fig. 5 f) shows general error for LSM- and WT-based algorithms with 0.02 s evaluation window.

Calculations show that the most precise evaluation during least processing time is obtained using WT-based algorithm. Drawbacks of LSM-based algorithm are defined by large evaluation acquisition time and problems of convergence to predefined function at undetermined initial conditions, the moment of unpredictable convergence is marked with an oval in fig. 5 f). Error reaches a hundred percent.

Verification of algorithms in dynamical mode is performed during evaluation of modulated signals

$$X = X_m[1 + k_x \cos(\omega t)] \cdot \cos[\omega_0 t + k_a \cos(\omega t - \pi)] \quad (4)$$

Under normal frequency and predefined modulation parameters: modulation frequency $f_m = \omega/2\pi$ varies between 1 and 3 Hz (1 Hz is used for visualization), magnitude modulation depth $k_x = 0.1$ and frequency modulation depth $k_a = 0.1$. General evaluation error allowed is up to 3%.

LSM-, STFT- and WT-based algorithms are considered. LSM- and WT-based algorithms use 1 and 2 periods of system frequency are used for parameters evaluation, while STFT-based algorithm uses only two periods. Fig. 6 shows the results of parameters evaluation using three algorithms. In fig. 6 a - e) parameters evaluation is performed with a window of 0.04 s shifted by 0.02 s. X axis shows the number of evaluation performed. Fig. 6 a - d) show variations of magnitude and frequency, their evaluations and evaluation errors correspondingly. TVE under 0.04 s signal processing interval is shown in fig. 6 e). Fig. 6 f) shows TVE for LSM- and WT-based algorithms with 0.02 s evaluation window.

Frequency variation during processing time is $-k_a \cdot f_m \cdot \sin(2\pi \cdot f_m \cdot t - \pi)$. In the example shown with $f_m = 1$ Hz and processing time 0.02 ms frequency changes by $0.1 \cdot 1 \cdot \sin(2\pi \cdot 1 \cdot 0.02) = 0.0125$ Hz while with processing time 0.04 ms frequency changes by $0.1 \cdot 1 \cdot \sin(2\pi \cdot 1 \cdot 0.04) = 0.0249$ Hz. WT and LSM give frequency evaluation corresponding to average frequency value over calculation time, comparison of frequency and magnitude evaluation with true values is performed in the middle of evaluation period. The main reason of errors in parameters evaluation – variation of values of parameters during evaluation time. Evaluations are averaged in this case.

Calculations show that the most precise evaluation during shorter signal processing window time is given by algorithm based on WT.

2.3 Main frequency parameters evaluation during less than a period time interval.

When evaluating parameters on a limited time interval a major error is caused by edge effect [3]. Author's technology of edge effect correction allows depressing its influence and obtaining high accuracy of evaluation under short evaluation times. Fig.7 shows orthogonal components obtained with STFT which requires processing time longer than one period and with Morlet wavelet at

observation time of 0.01 s. Comparison of orthogonal components of the same name shows identity of the results.

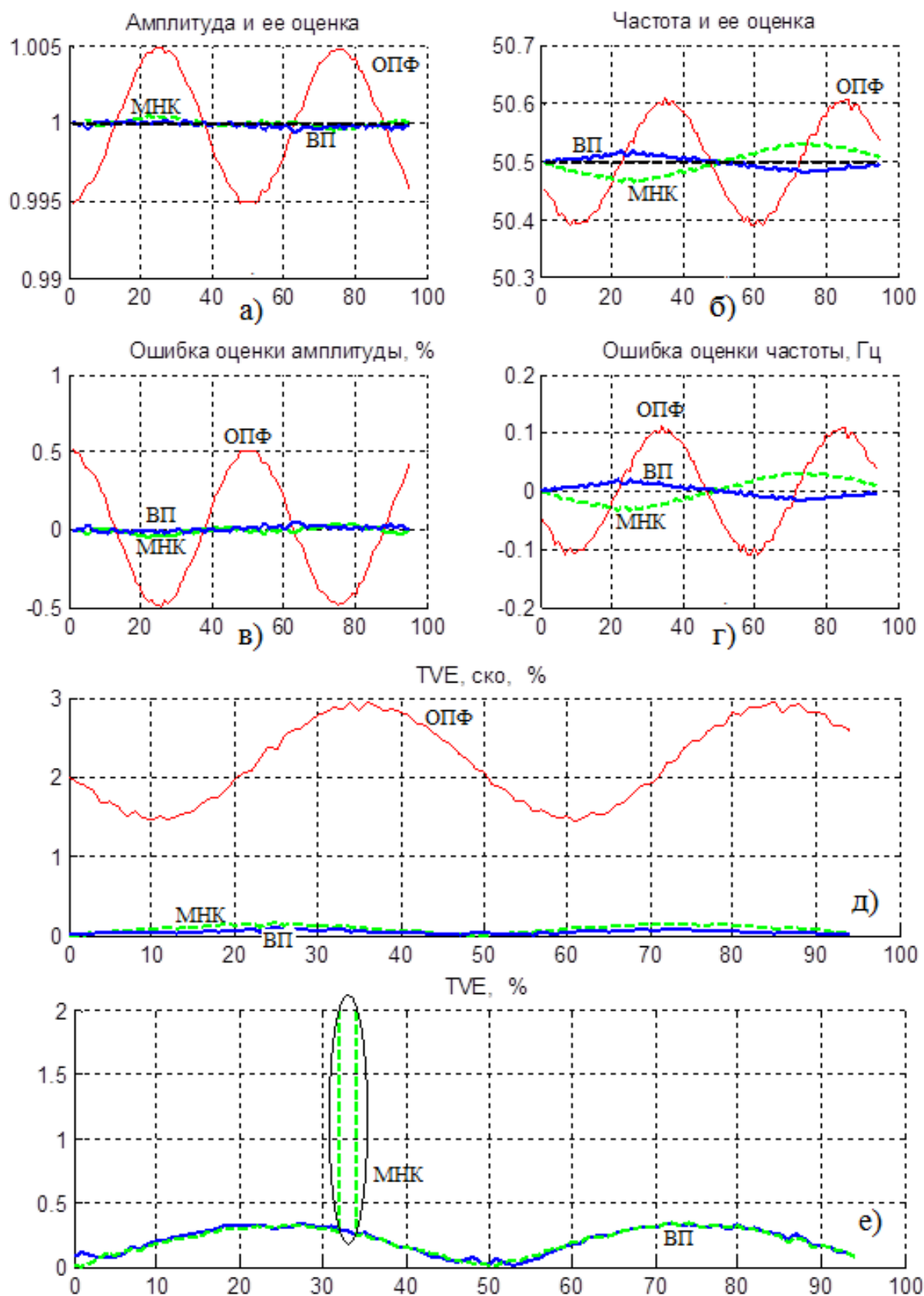


Fig. 5: Verification of PMU algorithms in steady-state mode.

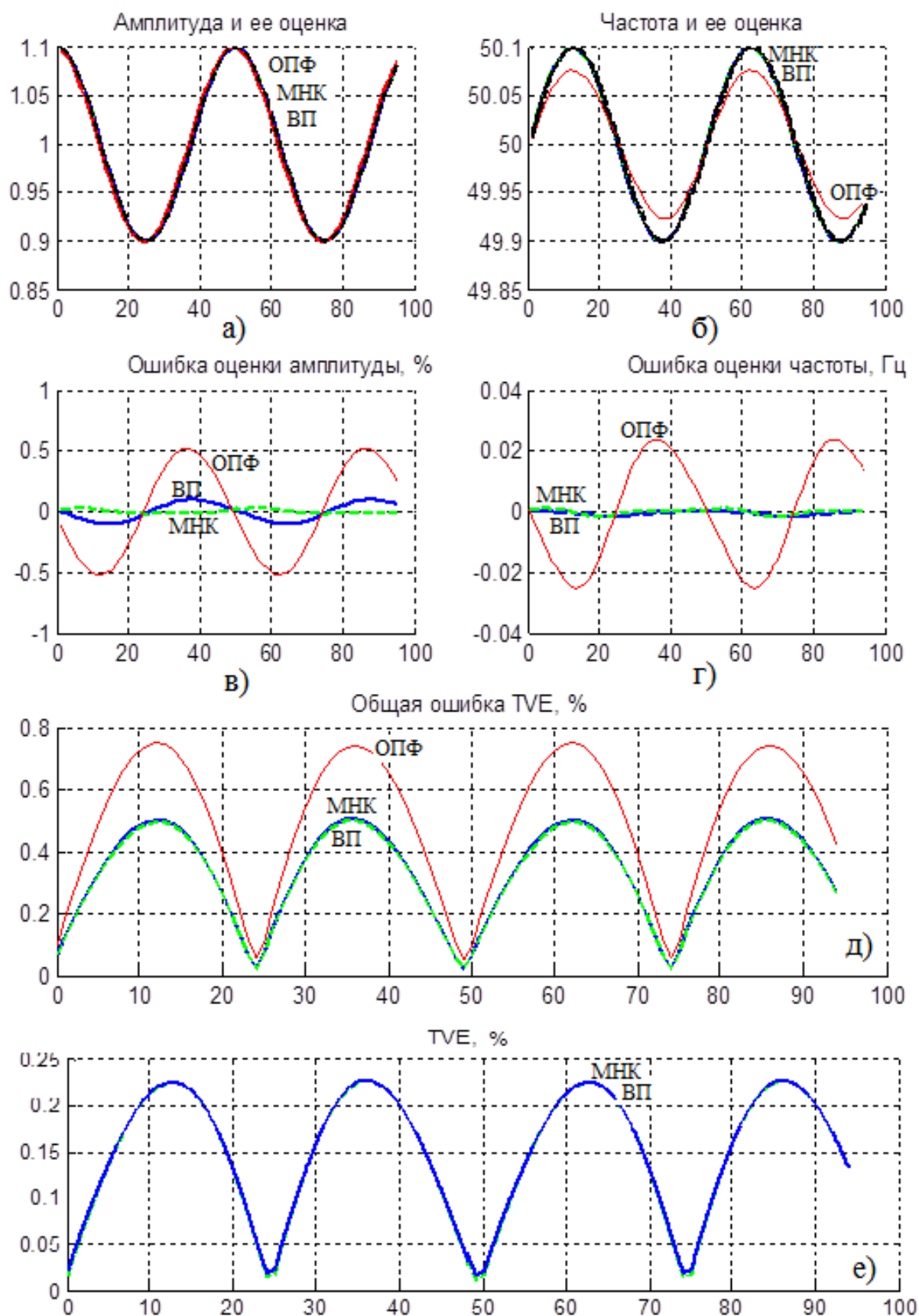


Fig. 6: Verification of controllers' algorithms in dynamic mode

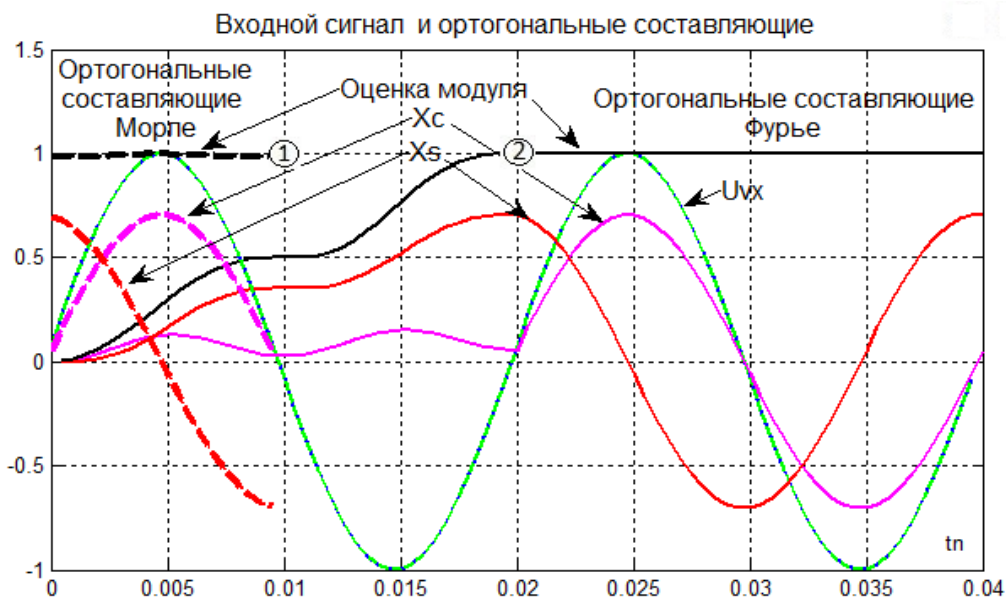


Fig. 7: Forming of orthogonal components with STFT and WT

3 RESOLUTION

Developed algorithms allow to define quantitative composition of transients and to evaluate parameters of its components (frequency, phase and magnitude of all oscillations as well as fading of aperiodic and higher quasiharmonic components), visually represent a transient. Depending on requirements these algorithms can be used in online mode (for relay protection and starting elements of system automation) and offline mode (transient analysis). Influence of different window durations of signal processing over accuracy of evaluation is examined. Possibility of main frequency parameters evaluation during less than a period time interval is shown.

4 CONCLUSION

1. Wavelet transform is a visual way of transients analysis;
2. Correct choice of wavelet and its parameters enables transient parameters evaluation of accuracy by a factor of ten higher than that of calculated using STFT.

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