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Evaluation of the Fast Synchrophasors Estimation Algorithm Based on Physical Signals

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Abstract: The goal of this study is to evaluate the performance of the fast algorithm for synchrophasor estimation proposed on the basis of a physical system. The test system is represented by a physical model of a power system with four synchronous generators (15 and 5 kVA). Three synchronous machines represent steam turbine generators, while the fourth machine represents a hydro generator. The proposed method of accuracy assessment is based on comparison of the original and the recovered signals, using values of amplitude and phase angle. The experiments conducted in the study include three-phase faults, two-phase faults and single-phase faults at various buses of the test model. Functional dependencies of initial signal standard deviation from the recovered signal are obtained, as well as those for sampling rate and window width. Based on the results, the following requirements for measurement system and window width are formulated: sampling rate of analog-to-digital converter should be 10 kHz; and window width should start from 5 ms. In addition, the fast algorithm of synchrophasor estimation was tested on event recorder signals. The sampling rate of these signals was 2 kHz. Acceptable window width for event recorder signals is 8 ms. The algorithm was implemented using programming language Python 3 for the testing purposes. The proposed fast algorithm of synchrophasor estimation can be applied in methods for emergency control and equipment state monitoring with short time response.

Keywords: phasor measurement unit; power system modeling; digital signal processing; signal analysis

MSC: 28-08

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1. Introduction

Phasor measurement units (PMU) are important in control and modelling of modern power systems. Creation of the PMU had become possible due to launch of the global positioning system (GPS), increased computational capabilities, and development of digital processing algorithms, namely those for current and voltage [1]. The first prototype was built and tested at the Virginia Polytechnic Institute and State University in 1980s [1], with support from the US government and the National Science Foundation. Synchrophasors estimation was carried out using the discrete Fourier transform (DFT).

PMUs attracted a widespread interest in terms of solving practical problems of power system control, as well as in academic studies due to their high accuracy of measurements synchronization and high sampling rate of synchrophasors estimation. The main applications of PMUs include:

- Monitoring of power system operation [2];
- State estimation [3];
- Dynamic state estimation [4];
- Estimation of power system parameters [5];
- Low frequency oscillation analysis [6];

- Emergency control [7];
- Estimation of inertia constant [8];
- Event detection [9];
- Stability analysis [10];
- Signal selection and design of Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS) [11];
- Control and operation of isolate power systems [12].

Modern PMUs are one of the primary tools of dynamic analysis of low-inertia power systems with integrated renewable energy sources (RES). Decommissioning of conventional fossil fuel generation results in decreased inertia of a power system, which in turn is caused by a decrease in the total amount of rotating masses represented by rotor of synchronous machines. At the same time, a significant amount of zero-inertia RES-based generation is being incorporated. As a result, the time of electromechanical transients decreases and leads to inaccurate operation of traditional protection and control devices. The problem of decreased inertia of a power system is solved by means of synthetic inertia [13]. Updates in dynamic behavior of modern power systems promote development of new PMU-based algorithms and provide both numerical values of estimation accuracy and minimal time response [14].

The purpose of this study is to evaluate the fast algorithm of synchrophasor estimation proposed in [15]. The evaluation is based on a real-life physical model of a power system, and those from event recorders installed on a substation in a Russian power system. As a result, the optimal settings of the synchrophasors estimation algorithm and sampling rate of instantaneous currents and voltages are found.

The paper is organized as follows. In Section 1, we introduce and describe the study. Section 2 is devoted to a review of modern literature on PMU-based algorithms. Section 3 describes the proposed modification of the algorithm in [15]. The evaluation on a physical model is presented in Section 4. Section 5 contains results of the testing based on event recorder data. The program implementation of the fast algorithm of synchrophasor estimation is described in Section 6. A concluding summary of the study and further research prospects are presented in Section 7.

This paper extends the results established in [15] as follows:

- A novel algorithm for correction of the basic angular velocity is proposed;
- A new method for estimating the accuracy of determining the synchrophasor in the absence of reference values is proposed;
- Testing was performed on a physical model of the power system;
- Algorithms for estimating synchrophasors are implemented in Python 3 programming language.

The main scientific contribution of the study is to determine the optimal width of the window of the algorithm for accelerated identification of synchrophasors proposed in [15]. In particular, the optimal window is derived for currents and voltages of physical signals that are obtained in the electrodynamic model of the power system. Determining the value of the calculation window on physical signals allows us to demonstrate the applicability of the algorithm [15] in the conditions of noise, outliers and asymmetry of the original data. Moreover, an enhancement of the algorithm [15] for operation under conditions of a significant deviation of the frequency of alternating current is provided.

2. Literature Review

Algorithms of synchrophasor estimation are key elements of modern PMUs. Accuracy and adequacy of power system control actions depend on parameters and mathematical basis of an algorithm. Hence, the algorithm used by a PMU should provide fast time response, rated accuracy of synchrophasors estimation and reliability, i.e., ability to avoid estimates when the algorithm is not stable enough.

The majority of existing algorithms of synchrophasors estimation can be divided into two types:

1. Static mode algorithms: synchrophasors estimation is possible in steady state only (constant frequency);
2. Dynamic mode algorithms: synchrophasors estimation is possible in both steady state and transient states (variable frequency).

The first type of the algorithms include: DFT, interpolated discrete Fourier transform (IpDFT) and fast Fourier transform (FFT).

The second type of the algorithms are the following: least squares (LS), weighted least squares (WLS), Taylor–Fourier transform (TFT), Hilbert transform (HT), Prony method (MP), digital filtering and discrete wavelet transform (DWT).

The classification of synchrophasor estimation algorithms is shown on Figure 1.

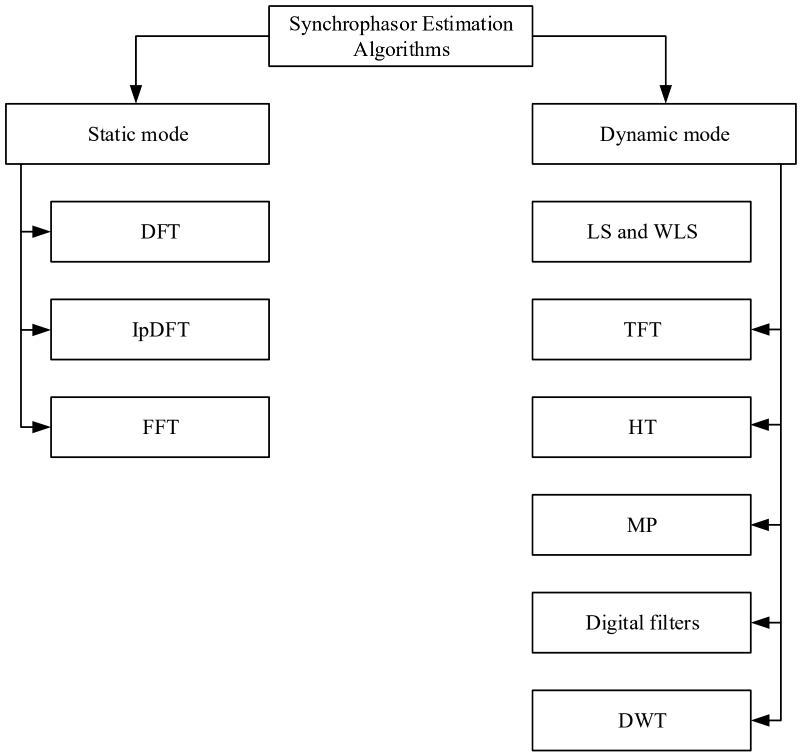


Figure 1. Classification of synchrophasor estimation algorithms.

DFT, IpDFT and FFT were some of the first algorithms applied in PMUs [16–24]. DFT-based algorithms are simple, fast and reliable. Most often the sliding window with width of full cycle (50 or 60 Hz) is used in DFT. Frequency deviation from the nominal value leads to spectrum shifting and rapid drop of synchrophasor estimation accuracy. IpDFT was developed in order to overcome this obstacle. Spectral leakage is compensated by interpolation of the DFT results using fundamental frequency of a signal. There exist several forms of FDT in literature. However, the most effective are those based on the half-cycle [25], although even these types of algorithms are highly sensitive to noise and higher harmonics.

The need to estimate synchrophasors in dynamic conditions of power system operations has facilitated the development of algorithms that are not based on the assumption that parameters of the signal under analysis are constant. LS and WLS were two of the first algorithms to estimate dynamically changing synchrophasors [26,27]. These algorithms are simple and reliable. However, requirement to choose a model of signal variation and existence of higher harmonics can make these algorithms more difficult to use. The TFT algorithm has been widely used in synchrophasors estimation [28]. Time-domain based estimation and high accuracy in dynamic conditions can be achieved using this algorithm. However, the major drawback is its high computational costs. The HT can also be used to estimate synchrophasors in dynamic modes of operation [29]. This algorithm is based on orthogonal decomposition of a signal with further calculation of amplitude and phase. The sliding window of significant width (starting from several cycles) is needed for effective operation of the HT. The MP is used to estimate synchrophasors in [30]. A great number of algorithms aimed at estimation of synchrophasors in dynamic conditions are based on digital filters [31]. Moreover, the Kalman filter is observed to be used [32]. In [15] the fast algorithm of synchrophasors estimation was used in dynamic conditions of power system operation. It was shown in [14] that the required accuracy can be ensured with window width starting from 3 ms and sampling rate starting from 5 kHz.

Table 1 shows the comparison of the considered algorithms for synchrophasors estimation.

Table 1. Comparison of synchrophasors estimation algorithms.

Algorithm	Advantages	Disadvantages
DFT, IpDFT, FFT	Simplicity.	For static conditions only. Spectral leakage occurs when frequency changes.
LS, WLS	Low noise-sensitivity, high reliability.	Higher harmonics cause substantial accuracy drop.
TFT	High accuracy in dynamic conditions.	High computational costs.
HT	Low computational costs.	If window is smaller than frequency cycle, then required accuracy cannot be ensured.
MP	Low computational costs.	Limited frequency resolution on short time periods.
Digital Filters	Harmonic composition can be estimated.	High sampling rate is necessary.
KF	Small number of measurements is used to estimate a synchrophasor.	Nonlinear filter can be unstable.
DWT	Wavelet bases have many different base functions that can be used to solve different problems.	Ambiguous selection of the mother wavelet.
Fast estimation algorithm [15]	Short time response, high accuracy and reliability.	Testing is required.

The above methods for synchrophasor estimation have several advantages and disadvantages. In dynamic conditions, the main drawback of these algorithms is related to the use of window width from one to several cycles. It can be negated by means of using the fast algorithm of synchrophasor estimation [15].

3. The Algorithm for Synchrophasor Estimation in Dynamic Conditions

The algorithm for synchrophasor estimation, which was proposed in [15], is based on the orthogonal decomposition using sliding windows. Dynamic model of a signal is given by the equation:

$$x(t) = a_0(t) + a(t) \cdot \sin(w \cdot t) + b(t) \cdot \cos(w \cdot t), \tag{1}$$

where $x(t)$ is signal value, $a_0(t)$ is constant component of a signal, $a(t)$ is sine factor, $b(t)$ is cosine factor, w is the basic angular velocity of the signal.

The factors of the model (1) are found by using the LS approximation. Amplitude and phase of the signal are estimated using the factor values obtained in (1):

$$A(t) = a_0(t) + \sqrt{a(t)^2 + b(t)^2}, \tag{2}$$

$$\varphi(t) = arcsin\frac{a(t)}{\sqrt{a(t)^2 + b(t)^2}}, \tag{3}$$

where $A(t)$ is amplitude, $\varphi(t)$ is phase. The frequency is found by numerical differentiation of the phase signal.

The procedure of angular velocity correction is used in order to prevent an increase in the synchrophasor estimation error in dynamic conditions (Figure 2). The correction of angular velocity boils down to replacement of basic angular velocity value in (1) by the value that was obtained in the previous cycle as a result of synchrophasor estimation.

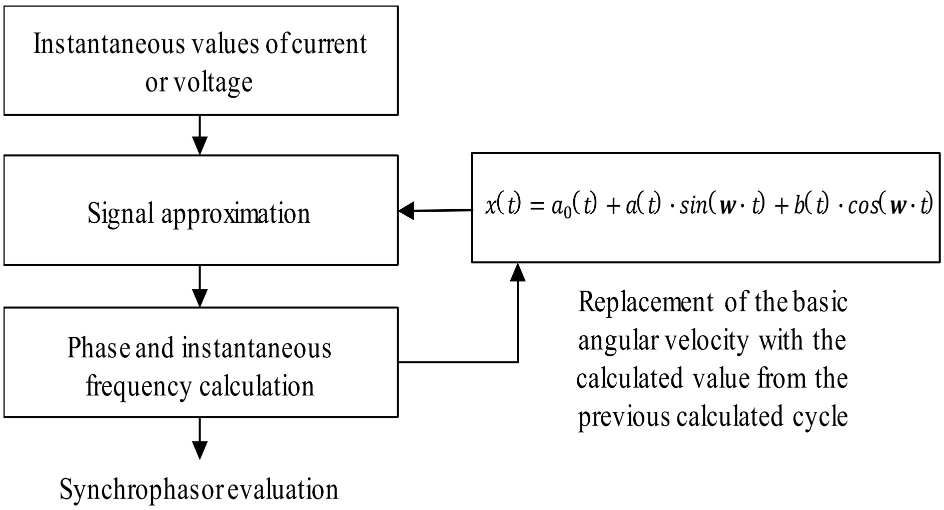


Figure 2. The correction of the basic angular velocity in (1).

The algorithm for the correction of the value of w is as follows:

- The initial value for w is set according to the value of the AC frequency at 50 Hz;
- For a given value of the calculation window, the coefficients of the expression (1) are calculated;
- The calculated values of expression (1) are used to find the amplitude, phase and frequency of the signal;
- In the next calculation cycle, the value of w is calculated based on the frequency value obtained in the previous cycle.

Comparison of the frequency values obtained by using the constant basis for the fundamental frequency of 50 Hz and using the adaptive basis in (1), respectively, are shown in Figure 3. The signal with incremental frequency increase from 47.5 Hz to 51.5 Hz and frequency increase rate of 1 Hz/s was used as the test frequency.

The use of constant basic angular velocity results in oscillations of phase, amplitude and instantaneous frequency. Oscillation magnitudes increase along with an increase in frequency deviation from the fundamental value (50 Hz). Accuracy of synchrophasor estimation is evaluated without available benchmark signal values (when it is impossible to calculate total vector error). For this purpose, a new approach is proposed based on the static analysis of deviation of the original signal using the following equation:

$$x_{rec}(t) = x_0(t) + A(t)\cdot \sin(\varphi(t)), \tag{4}$$

where $x_{rec}(t)$ is the value of the recovered signal at time t.

An example of the current signal recovery is shown in Figure 4. The signal is obtained as a result of transient simulation on the physical model of power system. The difference between the initial and the recovered signals is denoted by «Δ», while the instantaneous current signal is denoted by «i».

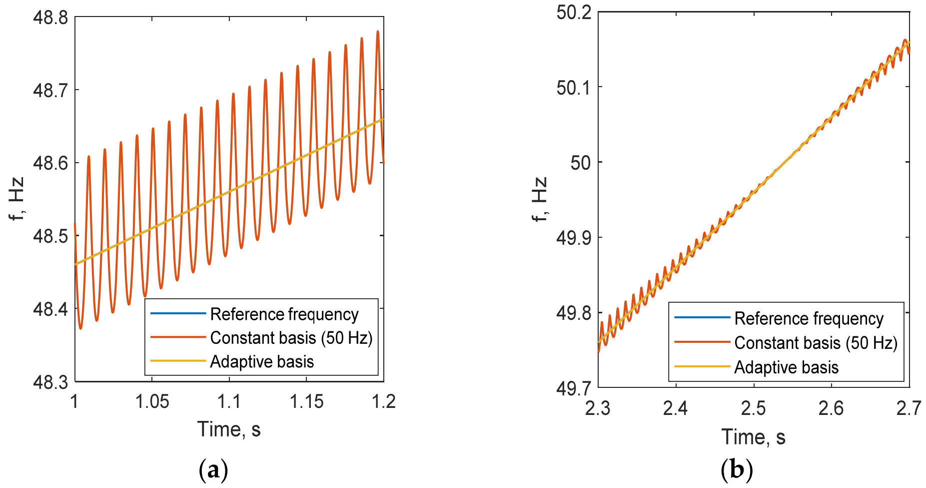


Figure 3. Comparison of the frequency values obtained by using the constant basis for the fundamental frequency of 50 Hz and using the adaptive basis in (1), respectively: (**a**) time period 1–1.2 s; (**b**) time period 2.3–2.7 s.

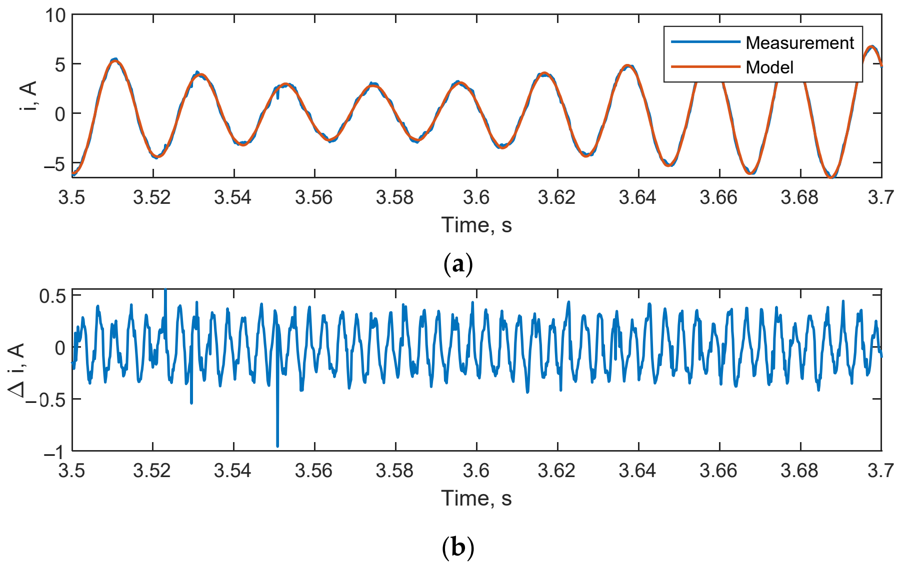


Figure 4. An example of the current signal recovery: (**a**) the original signal and the recovered signal; (**b**) the difference between the original and the recovered signals.

It is observed that the difference «Δ» does not exceed 1 A for the signal under consideration. The proposed signal recovery procedure allows us to evaluate the accuracy of calculating synchrophasors of physical signals for which there are no reference values. This procedure allows us to configure the algorithm for estimating the synchrophasor and evaluate the effect of distortions in the shape of the curve of the source data.

4. Results of Testing on a Real-Life Physical Model of a Power System

The fast algorithm of synchrophasors estimation was tested using signals of current and voltage from stator windings of synchronous machines. These signals were obtained during transient tests on a physical model of a power system. The analog-to-digital converter (ADC) with sampling rate of 60 kHz was used to obtain data sets with different sampling rates. After applying multiple decimation, the range of sampling rate values was expanded to 5, 10, 15, 20, 30, and 60 kHz.

4.1. Description of the Real-Life Physical Model of a Power System

The physical model of a power system [33] includes synchronous machines, loads, transmission lines, power electronics units and control devices. Photos of the model are presented on Figure 5. A detailed description of the experimental setup and the measurement system is given in [34].

The evaluation of the fast algorithm for synchrophasor estimation [15] was carried out using the prepared 4-machine model of power system including infinite bus (IB) (Figure 6). The parameters of synchronous generators (SG) are shown in Table 2.

(**a**) (**b**)

Figure 5. Photos of the physical model of power system: (**a**) general view; (**b**) generators.

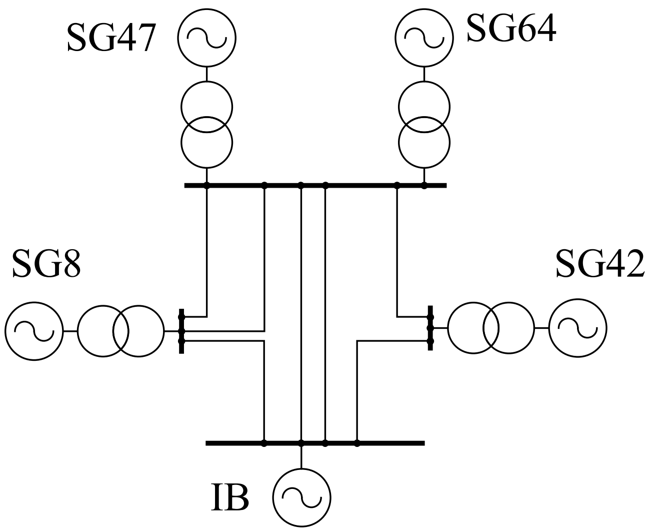


Figure 6. Single-line diagram of the physical model of the power system.

Table 2. Parameters of the synchronous generators.

SG	S_{rated}, kVA	$cos(\varphi_{rated})$	U_{rated}, V	I_{rated}, A	Z_{base}, Ω
8	15	0.8	230	37.5	3.52
42	5	0.8	230	12.5	10.58
47	5	0.8	230	12.5	10.58
64	5	0.8	230	12.5	10.58

The following notation is used in the tables:

- S_{rated}—Rated apparent power capacity of a machine;
- $cos(\varphi_{rated})$—Power factor;
- U_{rated}—Rated voltage;
- I_{rated}—Rated stator winding current;
- Z_{base}—Base impedance.

Total harmonic distortion (THD) was used to evaluate the distortions of a signal in steady state. The derived values of THD and non-symmetry factor for negative (K_{2U}) and zero sequences (K_{0U}), respectively, are shown in Table 3.

Table 3. The found values of THD and non-symmetry factors.

Phase Voltages		**Line-to-Line Voltages**	
Signal	THD, %	Signal	THD, %
Phase A	2.431	AB	0.117
Phase B	2.447	BC	0.127
Phase C	2.466	CA	0.121
Mean	2.448	Mean	0.121
K_{0U}, %		K_{0U}, %	
4.031		0.001	
K_{2U}, %		K_{2U}, %	
0.586		0.011	

Examples of phase and line-to-line voltages combined with approximation sine wave are shown in Figure 7.

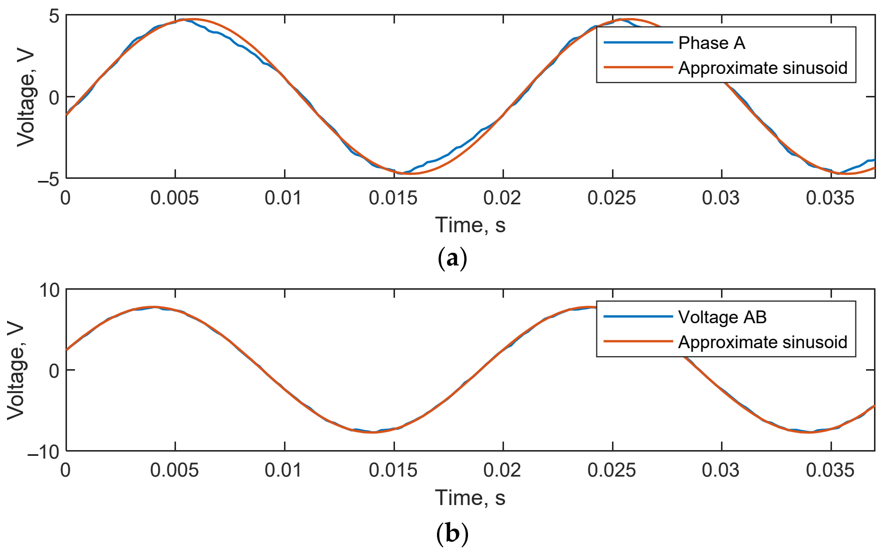


Figure 7. Examples of phase and line-to-line voltages combined with approximation sine wave: (**a**) phase A voltage; (**b**) AB voltage.

It can be seen from Table 3 and Figure 7 that distortion of phase voltage is almost 20 times lower than that of line-to-line voltage. Therefore, it is recommended to use line-to-line voltages to estimate instantaneous frequency values.

4.2. The Results of Testing the Fast Algorithm for Synchrophasors Estimation

Figure 8 shows the distribution of root mean square (RMS) value for the difference between the original and recovered signals. It was done in relation to window width and sampling rate of initial data for the post-emergency state for the SG 42 after close three-phase fault.

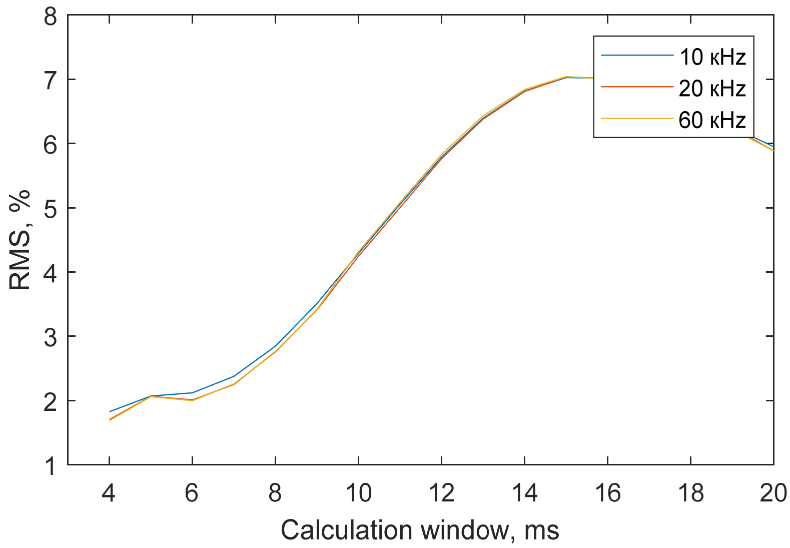


Figure 8. Functional dependency of RMS on the window width and data sampling rate.

It is observed that using a sampling rate of 10 kHz and higher, the impact of the difference between the original and restored signals on RMS is not essential for all conducted experiments. As a result, application of the proposed algorithm for fast synchrophasor estimation is possible with a data sampling rate of 10 kHz or higher.

Figure 9 describes the results of signal processing that were obtained from testing a two-phase fault near SG 42. The minimum SD value of difference between the original and the restored signals for simulated events related to SG 42 is equal to window width of 3 ms. The «i» is the instantaneous current value, «u» is the instantaneous voltage value.

Table 4 shows the results of signal processing for several experiments that were conducted on the physical model of the power system. The following designations are used in Table 4: NS is Normal state; ES is Emergency state; PES is Post emergency state; K(3) is three-phase fault; K(2) is two-phase fault; and K(1) is single-phase fault.

Table 4. Results of experiments on the physical model of power system.

SG	Experiment	Sampling Rate, kHz	Window Width for SD 5%	Window Width for SD 10%
64	K(3), phase voltage, NS	10	4 ms	3 ms
	K(3), phase voltage, ES	10	–	–
	K(3), phase voltage, PES	10	12 ms	7 ms
	K(3), phase current, PES	10	4 ms	3 ms
47	K(3), phase voltage, PES	10	12 ms	10 ms
	K(3), phase current, PES	10	5 ms	3 ms
	K(2), phase voltage, PES	10	12 ms	8 ms
	K(2), phase current, PES	10	3 ms	–
	K(1), phase voltage, PES	10	11 ms	10 ms
	K(1), phase current, PES	10	3 ms	–
42	K(2), phase voltage, PES	10	14 ms	8 ms
	K(2), phase current, PES	10	2 ms	–
8	K(1), phase voltage, PES	10	12 ms	8 ms
	K(1), phase current, PES	10	4 ms	2 ms
	K(1), phase voltage, NS	10	6 ms	4 ms
	K(1), phase current, NS	10	4 ms	3 ms

Values of window width and sampling rate that provide SD equal to 10% and 5% are calculated. In case the required accuracy is not obtainable, the table cell is indicated with «–». The calculated value of SD is shown in brackets. It is found that the acceptable sampling rate is 10 kHz in all conducted experiments for SG 64, 47, 42 and 8. In addition, acceptable window width depends on the requirements of signal recovery. This value is in the range from 2 to 12 ms when SD = 5%, and in the range from 2 to 10 ms when SD = 10%.

The requirements for the window width parameter estimation method and sampling rate of primary analog measurements are set based on the results of experiments. Moreover, it was observed that the window width should change in line with the parameters of SG operation states.

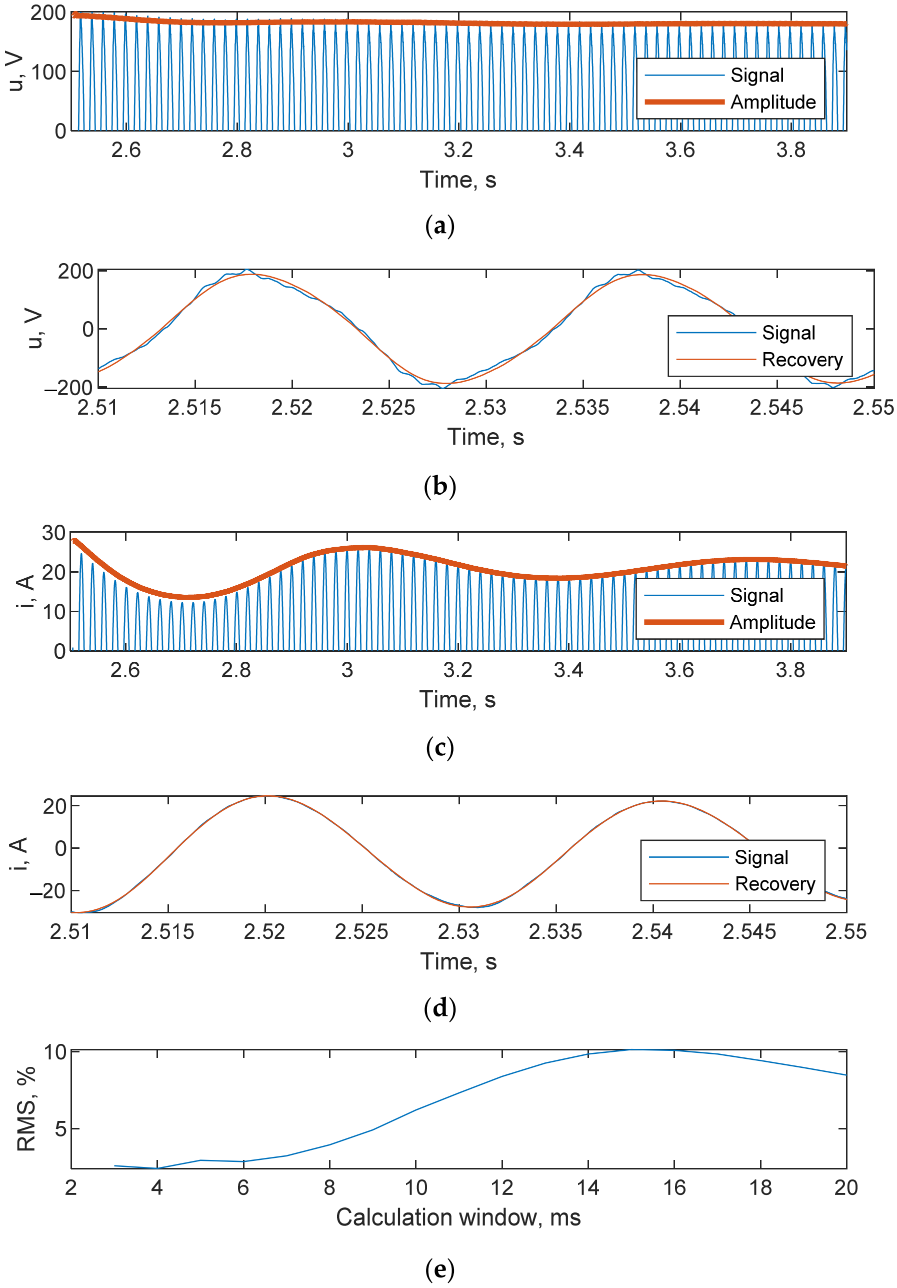
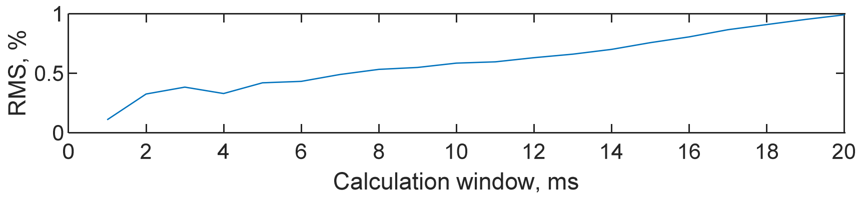


Figure 9. *Cont.*



(**f**)

Figure 9. Results of SG42 estimation for post-emergency state of three-phase fault, where the sampling rate is 10 kHz: (**a**) instantaneous voltage of phase A and its amplitude; (**b**) recovered signal of instantaneous voltage of phase A; (**c**) instantaneous current of phase A and its amplitude; (**d**) recovered signal of instantaneous current of phase A; (**e**) functional dependency of SD on window width for voltage of phase A; (**f**) functional dependency of SD on window width for current of phase A.

5. The Results of the Experiments Based on the Signals Obtained from Event Recorders

The fast algorithm for estimating the synchrophasors of current and voltage [15] was tested using the data from event recorders. The sampling rate for initial data was 2 kHz. Table 5 shows the test results with values of window width providing minimum difference between the original and the restored signals. Figure 10 describes the results of voltage synchrophasor estimation, where «u» denotes the signal of instantaneous voltage and «p.u.» denotes the per unit.

Table 5. The results of processing of event recorder signals.

Event	Minimal SD, %	Calculation Window Width, ms
1	1.08	8
2	0.50	8
3	0.86	10
4	2.70	10
5	1.02	8
6	2.78	10
7	1.05	8
8	4.86	10
9	1.25	8
10	5.51	15
11	4.29	8
12	3.08	10
13	5.76	10
14	1.04	8
15	0.84	8
16	0.84	8
17	1.28	8
18	1.09	8

Next, the sampling rate is set at 2 kHz. This particular value was chosen to analyze the accuracy of synchrophasors estimation using event recorder signals. The event recorder data show that the acceptable window width starts from 8 ms.

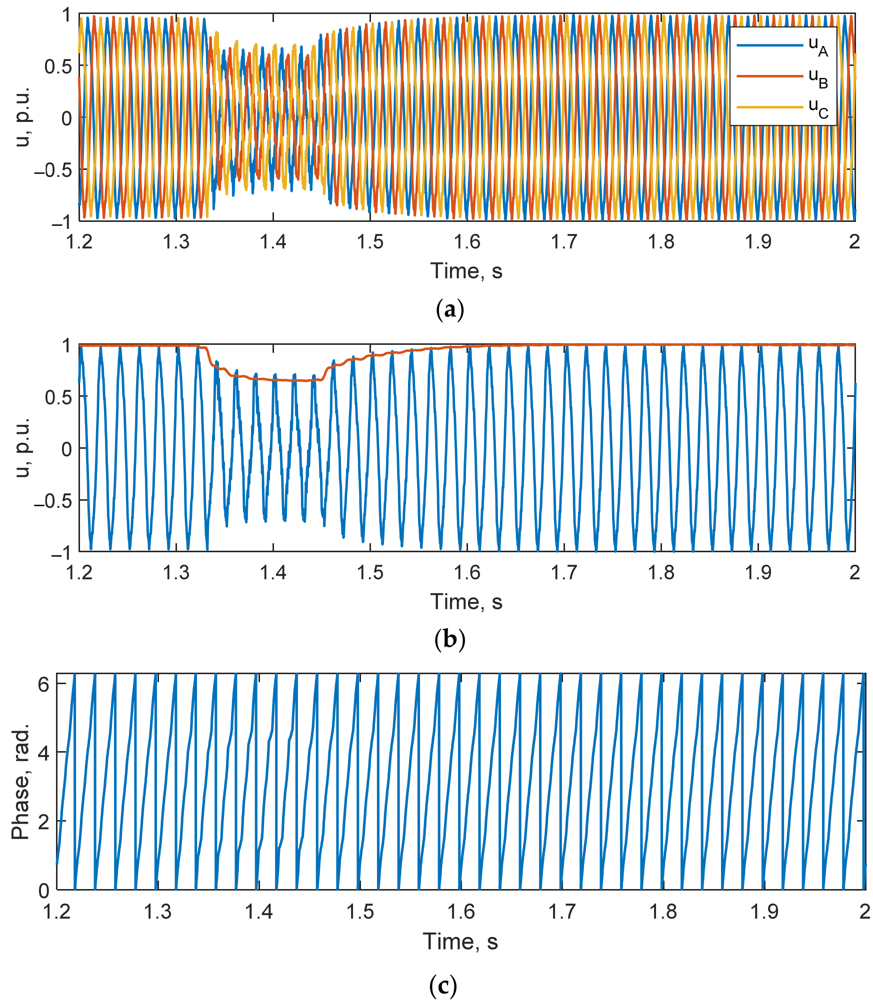


Figure 10. The results of processing measurements from the event recorder: (**a**) original signals of voltage; (**b**) phase A voltage (blue line) and amplitude of the signal (orange line); (**c**) phase A angle.

6. Implementation of the Synchrophasor Estimation Algorithm

The fast algorithm for synchrophasor estimation of currents and voltages was implemented using Python 3 programming language with the following libraries:

- PyQt5—graphical user interface;
- Matplotlib—visualization and plots;
- Requests—database exchange via Rest API;
- Xlwt—export to Microsoft Excel;
- Pandas, scipy—algorithms and calculations.

A snapshot of the main window of the developed program is shown in Figure 11, along with the results of the voltage synchrophasor estimation.

The following functions were implemented:

- Removal of outliers in original signals using the model filter;
- Estimation of inception and ending of an electromagnetic transient [35];
- Estimation of synchrophasors of currents and voltages;
- Calculation of instantaneous frequency;
- Calculation of active and reactive power values;
- Calculation of load angle of a synchronous machine.

The software implementation requires the following minimum criteria: Processor Intel (R) Core (TM) i5-4670K CPU @ 2.90 GHz or better. In case of availability of multiple processing cores, the computing times can be improved using parallel processing.

Comparison of computational delays of one calculation iteration is shown in Figure 12. A computer with the following parameters is used: processor Intel (R) Core (TM) i7-7700T 2.90 GHz and 16.0 Gb RAM.

Figure 11. Snapshot of Python implementation of the algorithm for estimating the voltage and current synchrophasors.

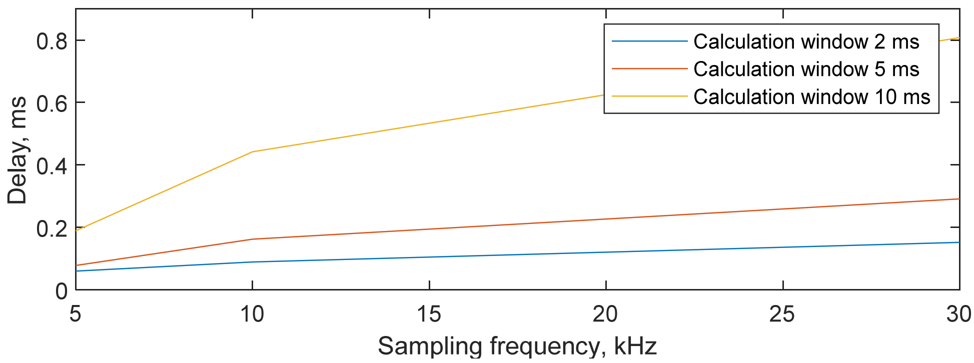


Figure 12. Comparison of computational delays to calculate signal parameters.

Calculation of non-filter signal parameters was done for the purpose of comparison. It can be seen that computer parameters have a huge impact on the computational delay. Note that computational delays on more capable computers are 3–10 times less than those of less effective computers.

7. Conclusions

This study presents the results of testing the fast algorithm for synchrophasor estimation using a real-life power system and the corresponding event recorders. It was shown that a sampling rate of 10 kHz is enough to ensure acceptable accuracy of synchrophasors estimation. In addition, the acceptable window width is less than 10 ms for all conducted experiments with SD value limited to 10%. The results of the experiments can be used to develop promising devices of power system protection and control, such as adaptive protection devices, and closed-loop emergency control devices with real time detection capabilities. In addition, fast estimation of synchrophasors of current and voltage can be used to ensure highly accurate estimation of equivalent circuit parameters for equipment state monitoring, as well as the automation of technological processes and actions.

Based on the results of this study, the following set of recommendations is formulated for the application of the accelerated synchrophasor estimation algorithm:

- The optimal sampling rate is 10 kHz;
- The value of the calculation window depends on the degree of signal distortion and starts from 8 ms;
- The computational delay of the synchrophasor estimation algorithm depends directly on the performance of the processor.

The next step in research is the development of a PMU based on the above fast estimation algorithm. This prototype is planned to be tested both on the Real-Time Digital Simulator and the physical model of power system. The proposed algorithm for estimating synchrophasors of currents and voltages is planned to be used for an adaptive algorithm for emergency control of power system modes [36–38].

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviation	Meaning
ADC	Analog-to-digital converter
AVR	Automatic voltage regulator
DFT	Discrete Fourier transform
DWT	Discrete wavelet transform
ES	Emergency state
FFT	Fast Fourier transform
GPS	Global positioning system
HT	Hilbert transform
IB	Infinite bus
IpDFT	Interpolated discrete Fourier transform
LS	Least squares
MP	Prony method
NS	Normal state
PES	Post-emergency state
PMU	Phasor measurement unit
PSS	Power system stabilizer
RES	Renewable energy sources
RMS	Root mean square
SD	Standard deviation
SG	Synchronous generator
TFT	Taylor–Fourier transform
THD	Total harmonic distortion
WLS	Weighted least squares

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