The Accelerate Estimation Method of Power System Parameters in Static and Dynamic Processes

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ABSTRACT Current trends in power system development and the issues they pose have increased the urgency of automatic and emergency control alongside transient electromechanical processes. Such control devices place high demands on mode-parameter estimation algorithms in terms of their speed, accuracy, and transient sensitivity. This paper proposes a rapid estimation algorithm for power system parameters to investigate its optimal settings and applicability in both static and dynamic states. The proposed algorithm is based on signal approximation on a sliding window using a multiparameter model, which is highly stable and reliable. The signals modeled in MATLAB/Simulink were used as initial data. From the experimental results, it became clear that the rapid estimation algorithm of the power system parameters showed high accuracy in steady-state mode as well as during transients, and its optimal parameters were identified. The developed algorithm can be used in relay protection, automatic and emergency control devices, and synchronous machine state-monitoring systems.

INDEX TERMS Digital signal processing, phasor measurement units, power systems, power system simulation, signal analysis.

I. INTRODUCTION

Modern development trends are increasingly penetrating power systems worldwide and involving significant changes. In recent decades, power industry digitization, demand response integration, low-carbon energy source transition, advanced methods of power equipment monitoring development and implementation, changes in operation, and the structure of energy markets have played a major role in the development of power systems around the world. These transformations in the electric power industry are aimed at improving economic efficiency, reducing carbon emissions, increasing observability, and improving control systems.

However, there are several issues associated with these changes, such as the increased uncertainty of power system states and the decreased stability of bulk power systems. Another crucial issue related to the growing number of renewable energy sources is the total inertia of the rotating masses reduction.

The problem at hand is the increasing probability of inaccurate control actions of automatic and emergency control. Furthermore, the reduced inertia leads to the increasing transient rate that requires the improvement of automatic and emergency control algorithms based on the “post-disturbance” principle [1]. The accuracy of such algorithms depends on the appropriate estimation of the electromechanical transient parameters. In this situation, a phasor measurement unit (PMU) can potentially be utilized to resolve this issue.

The first studies aimed at developing the PMU were carried out at the Virginia Polytechnic Institute and State University in the 1980-s [2] with the support of the USA government and the National Science Foundation. The modern definition of phasor measurements describes it as a set of power system parameters (RMS and phase values of voltage and current, frequency, rate of change of frequency (ROCOF)) are to be measured with a certain sample rate.
These values are synchronized using GPS [1].

PMU allows the current and voltage identification as a phasor by determining the amplitude and phase of a signal. The PMU can be used in solving several problems unattainable for conventional measurements such as [1]:

1) Phase shift evaluating for power system objects with installed PMUs;
2) Analysing the synchronous generators with low frequency oscillations (LFO);
3) Assessing the power system stability;
4) Monitoring the equipment condition;
5) Monitoring the bus voltage level and equipment thermal current loading;
6) Monitoring the operation accuracy of the automatic voltage regulator (AVR);
7) Clarifying the power equipment mathematical models;
8) Performing the power systems automatic and emergency control.

It is an accepted practice to conduct the compliance tests with prepared test signals, where time curves and set error margins are known for all PMUs. The digital real-time simulation systems and mathematical power system model are used in these tests [1].

Therefore, PMU is a powerful tool for estimation of the power system parameters, and there are many calculation algorithms that vary in mathematical implementation, accuracy, time delay, and application areas. Despite the accuracy and wide application of these algorithms, there are several issues associated with them such as considerable time delays, increasing errors during transients, and insufficient adaptability to transients with significant frequency change.

The purpose of this paper is to demonstrate a rapid estimation algorithm of the power system parameters leading to an investigation of its optimal settings and applicability both in static and dynamic states. The validity of a proposed method is based on the numerical experiment presenting the obtained estimation results.

This paper is organized as follows: Next Section provides a review of the existing assessment methods. Section III focuses on the proposed rapid estimation of the power system parameters. Section IV presents the examined system. Section V discusses the obtained results of the numerical experiment. Conclusions are drawn in Section VI.

II. REVIEW ON POWER SYSTEM ESTIMATION METHODS

Currently, PMUs are one of the main tools for monitoring, assessment, and control [2] both in large power systems and islanded ones [3]. PMUs find their use in high voltage (HV) and extra-high voltage (EHV) transmission networks of China (more than 2500 units [4]), the USA (more than two thousand units [5]), the Russian Federation (more than seven hundred units). The purpose of their installation is digital processing of instantaneous values of current and voltage signals, which are performed by the representation of a signal as a phasor (extraction of amplitude and phase angle), identifying a frequency and its derivative by time.

Existing estimation algorithms of power system parameters are divided into two groups: frequency-based and time-based algorithms. The former is based on the Discrete Fourier Transform (DFT) [6-13]. Their main disadvantages are related to the inability of DFT to accurately estimate the parameters of a power system in dynamic conditions, followed by the modulation of signal frequency and amplitude. Therefore, dynamic [14,15] and interpolation [16] algorithms were developed for such conditions.

Time-based algorithms include the weighted least squares method (WLS) [17, 18], the Kalman filter [19], recursive algorithms [20], and signal models of amplitude and phase modulation [21]. These methods use static or dynamic initial signal representation. Other research works have focused on the wavelet transform-based algorithm, which is time-frequency based for the estimation of power system parameters [22].

It is an accepted practice to use DFT-based algorithms in commercial PMUs, in which processing delay exceeds the period of commercial frequency. Considerations should be given to the Kalman filter, which is also widely used for evaluation of the power system parameters, but its drawbacks make it more difficult to be used in real-time assessment [23].

Table I shows the list of estimation algorithms of power system parameters depending on the process type.

| Algorithm             | Static process                              | Dynamic process                   |
|-----------------------|---------------------------------------------|------------------------------------|
| Frequency             | DFT                                         | Interpolation DFT                 |
| Time                  | WLS, Kalman filter, recursive algorithms,   | Prony’s method                     |
| Frequency-time        | Wavelet transform                            |                                    |

Despite the efficiency and wide application of the mentioned algorithms, there are the following issues associated with them: considerable time delays which are few periods of commercial frequency, lack of error consideration during a disturbance, and insufficient adaptability to states with significant frequency change. In this regard, there is a need for an estimation algorithm that results in a rapid evaluation of the power system parameters considering optimal settings, and its utilization in both static and dynamic states.

III. THE PROPOSED RAPID ESTIMATION OF PARAMETERS

The method of rapid estimation [24] is based on the approximation of a signal using first Fourier components with sliding windows and the multi-parameter model [25]:

\[ x(t) = a_0(t) + a(t)\sin(wt) + b(t)\cos(wt), \]

where \( x(t) \) is the value of current or voltage at the time moment \( t \); \( w \) is the angular frequency of a signal, \( a_0 \) is the constant
component of a signal; \( a, b \) are coefficients of the first Fourier components.

The diagram to present the proposed approach is shown in Fig. 1.

The first stage of the proposed algorithm is to pre-process the source data by removing outliers using a modal filter. Next, the search for the beginning of the transition process is performed by analyzing the initial signal prediction error at a pre-selected interval of the preemption. When determining the beginning of the transition process, the calculation window is shifted by a pre-selected value and its width is reduced.

This procedure ensures that there are no outliers in the amplitude and phase signals in the presence of two processes: stationary and transient within the boundaries of one calculation window. After the calculation window is moved, its sequential increase is performed. Next, the signal is approximated by expression (1), and the amplitude and phase are determined. The instantaneous frequency calculation is performed using numerical differentiation of the phase signal.

The rapid estimation method of power system parameters makes it possible to find the aperiodic component of a signal by calculating the constant component \( a_0 \) in (1). The coefficients of approximation polynomial (1) can be found using the multi-parameter model, with the probabilistic behaviour of a power system. The latter allows for improving the reliability of the proposed method, considering the examined signal has some degree of noise. The adaptive correction of angular frequency (1) is applied under conditions of alternating frequency of an input signal. The correction algorithm uses the forecast value of angular frequency obtained because of the approximation of the preceding angular frequency change vector by the second-degree polynomial.

The values of amplitude \( A \) and phase angle \( \phi \) are found using coefficients in (1) according to extracting orthogonal components of a signal classic methods:

\[
A(t) = a_n(t) + \sqrt{a(t)^2 + b(t)^2}. \quad (2)
\]

\[
\phi(t) = \arcsin \frac{a(t)}{\sqrt{a(t)^2 + b(t)^2}}. \quad (3)
\]

The instantaneous value of frequency is found using numerical differentiation of a phase signal with a sliding window by the second-degree polynomial.

The complex approach of analyzing the deviation of a signal from the recovered one was developed to assess the estimation accuracy of power system parameters without reference values of a signal:

\[
x_{rec}(t) = A(t)\sin(\phi(t)), \quad (4)
\]

where \( x_{rec}(t) \) is the value of the recovered signal at time \( t \); \( A(t) \) is the amplitude of a signal at time \( t \); \( \phi(t) \) is the phase angle of a signal at time \( t \).

The margin of error (ME) of the recovered signal is:

\[
ME = \frac{1}{N} \sum_{t=0}^{N} \frac{|x(t) - x_{rec}(t)|}{\max|x(t)|} \cdot 100%, \quad (5)
\]

where \( x(t) \) is the value of the initial signal at time \( t \), \( N \) is a number of measurements.
IV. A DESCRIPTION OF THE TEST SYSTEM

The single-machine power system was modeled in MATLAB/Simulink. The transient was simulated with the arbitrary trajectory of parameters changes. The test system includes models of a turbine, AVR, and governor control and is modeled relatively excessively to use in further studies.

The topology of the system is shown in Fig. 2, whereas parameters can be found in Table II. It should be noted that the parameters of real equipment were used in the current study.

![Test System Diagram](image)

**FIGURE 2. The test system.**

The temporary three-phase fault with a duration of 0.2 s was used as a disturbance. The red arrow indicates the fault location (Fig. 2).

The following assumptions are used (Table II):

1. $\sigma$ is droop of the governor’s control, \%;
2. $X_d$, $X_a$, $X'_d$ are steady state-axis synchronous reactances, transient $d$-axis reactance and sub-transient $d$-reactance of a synchronous machine respectively.
3. $T_i$ is the inertia time coefficient of the generator, s;
4. $P_{nom}$ is the nominal power of the generator, MW;
5. $x$ is the reactance of the transformer, $\Omega$;
6. $k_U$ is the ratio of voltage transformer;
7. $r$ is the series impedance of the transmission line, $\Omega$;
8. $x_0$ is zero sequence reactance of transmission line, $\Omega$;
9. $b$ is the conductance of the transmission line, $\mu$S;
10. $T_g$ is the time constant of the governor, s;
11. $P_{SGMin}$ is the upper power boundary of the synchronous generator in relation to its rated capacity, \%;
12. $P_{SGMax}$ is the lower power boundary of the synchronous generator in relation to its rated capacity, \%;
13. $K_1$, $K_2$, $K_3$ are components of turbine power output for high, middle, and low pressure respectively;
14. $T_1$, $T_2$, $T_3$ are turbine time constants for high, middle, and low pressure respectively, s.

![Diagram of System Parameters](image)

**TABLE II

PARAMETERS OF THE TEST SYSTEM**

| Model                  | Parameters            |
|------------------------|-----------------------|
| Generator (G)          | $P_{nom} = 300$ MW; $x_d = 610 \Omega$; $x_f = 186 \Omega$; $x_0 = 75 \Omega$; $T_0 = 4$ s; $K_1 = 0.3$; $K_2 = 0.4$; $K_3 = 0.3$; $T_1 = 0.2$ s; $T_2 = 7.0$ s; $T_3 = 0.4$ s; $\sigma = 4$ %; $T_g = 0.3$ s; $P_{SGMax} = 1.05$; $P_{SGMin} = 0.4$ |
| Turbine (T)            | $x = 28.3 \Omega$; $k_U = 11.5$ kV /330 kV; $x_0 = 118.06 \Omega$; $b = 444.3 \mu$S; $T_1 = 0.2$ s; $T_2 = 7.0$ s; $T_3 = 0.4$ s; $\sigma = 4$ %; $T_g = 0.3$ s; $P_{SGMax} = 1.05$; $P_{SGMin} = 0.4$ |
| Governor control       | $x = 28.3 \Omega$; $k_U = 11.5$ kV /330 kV; $x_0 = 118.06 \Omega$; $b = 444.3 \mu$S; $T_1 = 0.2$ s; $T_2 = 7.0$ s; $T_3 = 0.4$ s; $\sigma = 4$ %; $T_g = 0.3$ s; $P_{SGMax} = 1.05$; $P_{SGMin} = 0.4$ |
| Transformer (Tr.)      | $r = 2.75 + j 43.23 \Omega$; $k_U = 11.5$ kV /330 kV; $x_0 = 118.06 \Omega$; $b = 444.3 \mu$S; $T_1 = 0.2$ s; $T_2 = 7.0$ s; $T_3 = 0.4$ s; $\sigma = 4$ %; $T_g = 0.3$ s; $P_{SGMax} = 1.05$; $P_{SGMin} = 0.4$ |
| Slack bus (SB)         | $P = 330$ kV |

The results of testing the rapid estimation algorithm of power system parameters estimation according to the standard [26] are demonstrated in the next chapter.

V. OBTAINED RESULTS OF NUMERICAL EXPERIMENT

The numerical experiment was conducted to identify the validity of the developed estimation method using signals described in the standard [26], including signals of the transient. The applied software is MATLAB/Simulink. The test system is presented by the single-machine mathematical model of a power system.

The accuracy of the considered method is assessed according to [26] by means of calculating the total vector error (TVE) in the following way:

$$TVE = \sqrt{\left(\frac{x_r - x_i}{x_r + x_i}\right)^2 + \left(\frac{x_i - x_r}{x_r + x_i}\right)^2 \cdot 100\%},$$

where $x_r$ is the real component of the measured vector; $x_i$ is the real component of the true vector; $x_i$ is the imaginary component of the measured vector; $x_i$ is the imaginary component of the true vector.

A. CASE OF THE STATIC PROCESS

The initial signal and results of TVE calculation are given in Fig. 3. The following designations are used in Fig. 3-5: Window – the minimal window size, TVEmax – the maximum value of TVE.

![TVE Calculation Results](image)

**FIGURE 3. Results for case of the static process.**

The sinusoidal signal with sampling rates within the ranges from 1 to 60 kHz and oscillations frequency of 50 Hz was used.
as the signal of the static process. The curves $TVE$-window size and $TVE$-sampling rate were obtained using (6). The margin value for $TVE$ is 1\% [26].

The requirements of [26] were met for the considered signal for all values of the sampling rate. There is almost no influence on the value of $TVE$ starting from window size 4 ms and the sampling rate of the initial signal higher than 10 kHz.

**B. CASE OF THE DYNAMIC PROCESS WITH AMPLITUDE MODULATION**

The set of signals with sampling rates within the range from 1 to 60 kHz and known modulation law with a modulation frequency of 1.9 Hz was used as the input data as follows:

$$x(t) = X_m [1 + 0.1 \cos(2f_m \pi t)] \cdot \cos[100\pi t],$$

(7)

where $x(t)$ is the test signal, $X_m = 57.73$, $f_m$ is modulation frequency ($f_m = 1.9$ Hz).

The marginal value of $TVE$ for a case of the dynamic process is 3\% [26]. The initial signal and results of $TVE$ calculation are provided in Fig. 4.

![Initial signal](image1)

*FIGURE 4. Results for the case of the dynamic process include amplitude modulation.*

The requirements of [26] can be met for the considered signal starting from a window size of 4 ms and for all values of the sampling rate. With the sampling rate of the initial signal being higher than 10 kHz there is almost no influence on the $TVE$ value.

**C. CASE OF THE DYNAMIC PROCESS WITH LINEAR FREQUENCY CHANGE**

The set of signals with sampling rates within the range from 1 to 60 kHz, linear change of frequency from 46 to 52 Hz, and ROCOF of 1 Hz/s were used as the input data. The curves $TVE$-window size and $TVE$-sampling rate were obtained using (6).

The marginal value of $TVE$ for a case of the dynamic process is 1\% [26]. Fig. 5 shows the initial signal and results of $TVE$ calculation for the sampling rate of 10 kHz.

![TVE calculation results](image2)

*FIGURE 5. Results for the case of the dynamic process considering linear frequency change.*

The requirements of [26] can be met for the considered signal starting from a window size of 4 ms and for all values of the sampling rate. With the sampling rate of the initial signal being higher than 10 kHz there is almost no influence on the $TVE$ value.

**D. CASE OF THE DYNAMIC PROCESS WITH APERIODIC COMPONENT**

The signal with a sampling rate of 10 kHz was considered for finding the aperiodic component (Fig. 7). The curve aperiodic component – window size is shown in Fig. 6.

The rapid estimation method makes it possible to find aperiodic component starting from a window size of 1 ms and less than 1\% error. The acceptable value of window size (10 ms) for the signal under consideration was found at the moment of reaching the steady-state value of $TVE$. $TVE$ is not shown in Fig. 6. since in [26] there is no dynamic test provided for the case of aperiodic component of the considered signal.
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**FIGURE 6.** Values of the aperiodic component.

**FIGURE 7.** Results for the case of the dynamic process with the aperiodic component.

**E. THE CASE OF DYNAMIC PROCESS USING MATLAB/SIMULINK**

The test system (Fig. 2) was used to simulate the signal of the transient. The initial signal of transient and ME are shown in Fig. 8.

The results of calculating the values of TVE and ME for both the initial and the recovered signal were compared. It was done to verify the method of assessing the accuracy of the rapid estimation of power system parameters. The case under consideration is one of a dynamic process with amplitude modulation. The results of this comparison, as well as the distribution of the difference between the initial signal and the recovered, standard deviation (STD), and the mean is shown in Fig. 9, the window size is 5 ms.

The curves ME – window size and ME – sampling rate were obtained for part of the signal after the fault using (5). The value of ME is set within the range of 1% with sampling rates and window size starting from 10 kHz and 7 ms respectively.

**FIGURE 8.** Results for the arbitrary transient.

**FIGURE 9.** Comparison of TVE and ME, the window size is 5 ms.
The values of TVE and ME for the case of the static process are qualitatively similar (almost constant). The same results can be obtained for the case of a dynamic process.

VI. OBTAINED RESULTS OF REAL DATA EXPERIMENT

The developed accelerate estimation algorithm was compared with the algorithm proposed in [27], which is based on the Taylor-Fourier model. The results of amplitude and instantaneous frequency calculation for the physical power system model signal are shown in Figure 10.

![Comparison of the proposed algorithm with the existing one](image)

The average error of the amplitude calculation using the proposed algorithm relative to the algorithm from [27] is less than 0.8%, and the error of the instantaneous frequency estimation is less than 0.5%. The large amplitude and instantaneous frequency noise level obtained using the proposed algorithm are associated with the use of a calculation window with a width of 10 ms.

VII. CONCLUSIONS

The method of rapid estimation of the power system parameters was proposed in this paper. It was carried out based on the data simulated in MATLAB/Simulink.

The method of rapid estimation allows evaluating the parameters of a dynamic process with a time delay of 3-5 ms, with the sampling rate of the initial signal being 10kHz and higher. The efficiency of the suggested approach is demonstrated for signals with unknown reference dynamic values. ME of the difference between the initial signal and the recovered one is found using (4).

The method of rapid estimation can be used for calculating a signal aperiodic component. It can be found for window sizes larger than 1 ms and error less than 1%. The suggested method can be used in automatic and emergency control devices, systems of state monitoring of synchronous machines, and transient recording systems. Further studies are aimed at testing this method of rapid estimation on physical data from the electro-dynamic model.

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