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Synchrophasor Evaluation Based on Point-on-Wave Measurements

Pavel Y. Kovalenko
Automated electrical systems department
Ural Federal University
Yekaterinburg, Russia
pkovalenko@urfu.ru

Mihail D. Senyuk
Automated electrical systems department
Ural Federal University
Yekaterinburg, Russia
mdsenuk@gmail.com

Valentin I. Mukhin
Automated electrical systems department
Ural Federal University
Yekaterinburg, Russia
valentinmukhin@yandex.ru

Diana D. Kornilova
Automated electrical systems department
Ural Federal University
Yekaterinburg, Russia
diana.98214@gmail.com

***Abstract* – The accelerated synchrophasor measurements algorithm is presented. The algorithm allows to evaluate synchrophasors with less than one basic frequency cycle time delay. The reference points method was suggested to determine the synchronous frequency, with magnitude and phase being calculated by means of extrema interpolation. Tests were carried out using the simulation data and the real data of the 110 kV, 220 kV, and 500 kV grids steady states and transients. Requirements for time delay of the suggested algorithm and sampling rate of the initial measurements data were formulated. The total vector error minimum was selected as the optimality criterion. Since the algorithm was tested on the real data without actual reference values, the alternative method of defining the total vector error was proposed. The suggested algorithm can be applied to protection & control systems based on the reactive action (the so-called "1-After" concept, when the set values of protection & control systems are calculated after a disturbance), development of dynamic power system models and generators technical state assessment.**

Keywords – phasor measurement unit, synchronous frequency, signal parameters, total vector error, synchrophasor algorithm, digital signal processing

I. Introduction

Modern power systems development witnesses extensive deployment of renewable energy sources (RES) [1], energy storage systems (ESS) [2], intelligent monitoring and control systems, introducing Smart Grid paradigm [3]. This drives inevitable changes in system static and dynamic response, transient properties and, consequently, in system operational control techniques.

However, along with the advantages delivered with the utilization of new active and reactive power sources and intelligent steady-state and transient analysis solutions, there are also drawbacks brought by the following:

- Power system inertia drop due to the massive introduction of low-inertia generation units. To date it is partially countervailed by simulating "artificial inertia" [4]. However, RES deployment is growing steadily and is going to follow this trend in the future [5], which will still lead to the system dynamic properties change, and to transients speeding up with the corresponding tightening of emergency control requirements.
- Steady-state and transient analysis are both based on the computational models (equivalent circuits), the parameters of which are mostly set according to the reference data or, much rarely, according to the periodical testing results.

One of the ways to address these challenges is utilizing the innovative devices designed for power system dynamics monitoring bases on synchrophasors – phasor measurement units (PMU). They provide high sampling rate GPS time synchronized measurements of voltage and current phasors. This capability enables significant increase in accuracy of power system analysis, specifically, stability and reliability problems.

PMU data processing algorithms and testing procedures were summarized in standard [6], and further refined in [7]. Both standards highlight two classes of PMUs: Class M – for higher-accuracy measurements intended for power systems analysis, and Class P – for protection applications, especially under transient conditions. Nevertheless, for both Class M and Class P PMUs a synchrophasor is evaluated during a period equal to one basic frequency cycle. However, authors of [8] show, that such a period might appear to be insufficient for the purposes of emergency control in power systems with lowered inertia.

Hence, fast refinement of power systems equivalent circuit parameters for emergency control tasks requires accelerated synchrophasor evaluation algorithm with as-low-as-possible computation delay, obviously less than one basic frequency cycle.

II. Synchrophasor Definition: State-of-the-art

Development of standards [6] and [7] led to creation of a group of methods, the delay of which equals basic frequency cycle [9–22].

One of the first methods to be applied to the synchrophasors calculation was the discrete Fourier transform (DFT) [9–14]. For example, a comparison of the canonical DFT, the Taylor-Fourier transform (TFT), the interpolated DFT (IDFT) and the extended IDFT was made in the study [15]. The distinctive advantage of the IDFT is noise and high-order harmonics influence minimization by means of DFT values interpolation using the rated sine wave frequency. The comparison revealed that under the condition

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of high noise level the method requires a significant time delay of 3 basic frequency cycles. However, the common drawback of DFT is the necessity to pre-define the transform basis, which matches the existing basis during steady-state operation and differs during transients.

Another approach to evaluate synchrophasors is Prony's method [16–17], enabling low evaluation error during transients. On the other hand, computational complexity of this method is relatively high, which is a clear disadvantage.

Hybrid methods have been utilized for the purpose of synchrophasors evaluation as well. For example, the distinctive feature of the method proposed in [18] is the analysis of two signals, one of which is a measured one, while the other is the reference sine wave. Approximation and detail coefficients can be defined as a result of these two signals DFT with the same basis function and scaling function. Per unit magnitude is obtained using the angle between approximation coefficients vectors of the reference signal and the measured one.

Kalman filter application for synchrophasor evaluation is described in [19-21]. The synchrophasor evaluation algorithm based on the signal convolution and autocorrelation was presented in [22].

Summarizing the analysis, one can see numerous synchrophasor evaluation methods with time delay equal to the basic frequency cycle. Thus, the primary aim of present research is the development of an algorithm for synchrophasor evaluation with time delay less than a basic frequency cycle, allowing to define power system synchronous frequency for the purposes of automatic emergency control.

III. Fast Synchrophasor Definition Algorithm

Fig. 1 shows the synchrophasor evaluation algorithm flowchart. The initial input data is instantaneous values of currents and voltages. Three-phase instantaneous values are used for the synchronous frequency evaluation by means of reference points method. The magnitude of currents and voltages is considered to correspond to the signals extrema envelope, formed using cubic splines. Treating the envelope as the magnitude is explained by the power system signals narrow-band nature, i.e. their spectral density is different from zero only around the vicinities of rated frequency, which is equal to 50 or 60 Hz. Then signal phase can be derived from its magnitude.

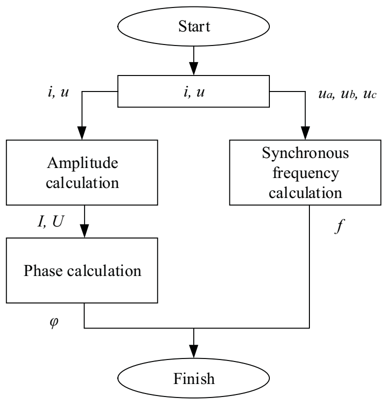

Fig. 1. The synchrophasor evaluation algorithm flowchart.

Fig.1 notation adopted: *i, u* – instantaneous current and voltage values; *I, U* – current and voltage magnitudes; *ua, ub, uc* – instantaneous a, b and c phases voltage; *f* – synchronous frequency; φ – current or voltage phase.

A. Synchronous frequency background and calculation

Based on the synchronous frequency definition, its following properties can be derived:

- Frequency is the same for all three voltage phases (this property describes the process of energy conversion by a generator with rigid stator windings).
- Impossibility of step-like frequency change.

The algorithm for synchronous frequency evaluation is based on its properties. The initial data includes three phases voltage signals and time marks vector. The algorithm is based on calculating time between two reference points in a three-phase system, with reference points being: signals zero-crossings, signals extrema and phases intersections. Sliding parabolas [23] and sliding linear sections methods are utilized in order to locate the reference points. The method of moving least squares uses the opportunity to replace a multimodal optimization procedure (locating multiple extrema) with unimodal optimization on the function interval. Since step size is usually set less than a window width, multiple extrema near the true solution will be detected as a result of using the moving least squares method. The extremum choice is made by means of averaging coordinates of the obtained extrema set [24].

B. The alternative method of total vector error estimation

The standard [6] describes the approach to the estimation of synchrophasor evaluation accuracy using the reference values on the time interval equal to the basic frequency cycle. In this connection, the following accuracy estimation algorithm was developed:

- The signal is reconstructed based on the obtained synchrophasors using the equation:

$$y(t) = A(t)\sin(\varphi(t_0) + 2\pi f(t)t), \tag{1}$$

where *y(t)* is the value of the reconstructed signal at *t* time instant, *A(t)* – is the signal magnitudes at *t* time instant, *f(t)* – is the synchronous frequency value at *t* time instant, t_0 – is the starting point of the frame in question.

Using (2) for the purpose of accuracy estimation is possible under the condition that the discrete functions for *A(t)* and *f(t)* are obtained by means of using the methods described above.

- The difference between the initial signal and the reconstructed one is calculated;
- The standard deviation (SD) of the reconstructed signal to the initial one , mean total vector error (TVE), is found.

Therefore, the proposed TVE estimation method allows to select the optimum calculation window width in order to minimize the difference between the reconstructed and the calculated signals.

IV. Determining the Requirements For the Proposed Method Parameters and the Initial Measurements Sampling Rate

The key parameter of the proposed synchrophasor evaluation algorithm is the computation window width (i.e. the computation delay), which defines its both speed of operation and accuracy. It's also important to define the reference points set in order to evaluate synchronous frequency. It was shown in [24], that zero-crossings and phase intersections should be adopted as reference points. To define the optimum computation window width and initial data sampling rate a series of calculations was carried out using the following data sets:

- Simulated transient with dynamic frequency oscillations from 50 to 49 Hz.
- Short-circuit fault recording obtained from the physical electrodynamic simulator operated by Joint Stock Company "Scientific and Technical Center of Unified Power System".
- Steady state recordings obtained from 110 to 500 kV substations in the UPS of Russia.

The initial data sampling rate was 10 kHz, it was changed through cubic spline interpolation and decimation. The computation window width and sampling rate were varied in the ranges of 0.5 ms to 40 ms and 5 kHz to 30 kHz, respectively, in order to define the optimum window width and sampling rate. Synchrophasor evaluation on windows from 1.5 ms to 40 ms was achieved by averaging the values derived for 1.5 ms approximation interval.

A. Simulated Signal

Simulated electromechanical transient with dynamic frequency oscillations from 50 to 49 Hz was considered. Fig. 2 shows the initial data, Fig. 3 shows the TVE dependence upon the algorithm computation delay and the initial data sampling rate. Fig. 4 demonstrates the synchronous frequency evaluated at the optimum algorithm parameters.

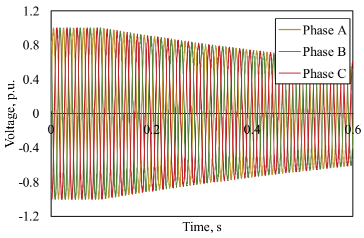

Fig. 2. The synchrophasor evaluation algorithm flowchart.

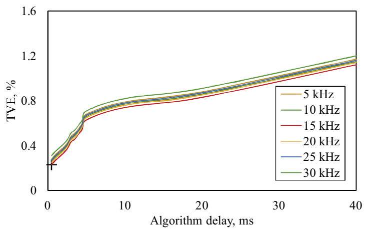

Fig. 3. Dependence of TVE on the time delay value of the algorithm and on the source data sampling rate.

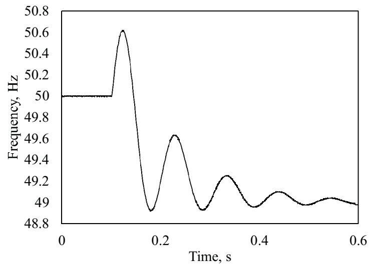

Fig. 4. The calculated value of the frequency of the signal under study.

B. The electrodynamic simulator signal

The physical electrodynamic simulator operated by JSC "STC UPS" comprises over 1000 units of generator models of 30 to 1,5 kVA rated power, motors, transformers, transmission lines, HVDC lines, etc. The whole complex allows to simulate disturbances and automatic control systems actions.

Two-phase (B and C) short-circuit was considered. The initial data recordings are shown in Fig. 5, while Fig. 6 demonstrates the dependence of TVE upon the sampling rate and computation delay.

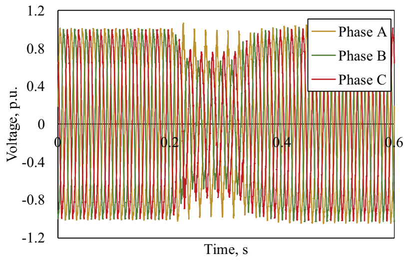

Fig. 5. The electromechanical model signal under study.

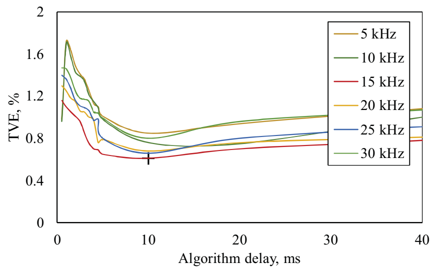

Fig. 6. Dependence of TVE on the time delay value of the algorithm and on the source data sampling rate.

C. Steady state recordings from the UPS of Russia operational substations.

Steady-state recordings obtained from 110, 220, and 500 kV substations were considered as the initial data. All signals apparently follow the trend of TVE growth with the approximation window width increase, which can be explained by the signal reconstruction error in case of its parameters averaging.

D. *Requirements for the proposed method parameters and the initial measurements sampling rate.*

Table I shows certain requirements for the computational delay of the proposed method and for the initial measurements sampling rate.

TABLE I. REQUIREMENTS FOR THE COMPUTATIONAL DELAY OF THE PROPOSED METHOD AND FOR THE INITIAL MEASUREMENTS SAMPLING RATE

Source of signals	System state	Time delay, ms	Sampling rate, kHz
500 kV grid	Steady-state	1.5	15
220 kV grid	Steady-state	1.5	15
110 kV grid	Steady-state	1.5	15
Electrodynamic simulator	Transient	10	15

It can be seen from Table I that for all considered signals the optimum sampling rate is 15 kHz. One can also see that the electrodynamic simulator signal computational delay is 6.6 times higher than the one for the real data, which can be accounted for by the electrodynamic simulator poor data quality.

V. CONCLUSION

The research proposes the detailed description of the development and implementation of the synchrophasor evaluation algorithm with the delay less than a basic frequency cycle. The algorithm comprises three component blocks implementing signals synchronous frequency evaluation, magnitude and phase. The synchronous frequency is evaluated using the proposed reference points method – signal zero-crossings and phase intersections. For the purpose of the proposed method accuracy assessment the alternative TVE computation method was proposed, based on the comparison of the initial signal to the one reconstructed through the evaluated synchrophasor. Three kinds of signals were considered with the aim of testing the proposed algorithm: mathematically simulated signal, the one obtained from the physical electrodynamic simulator and three signals recorded at the 110 to 500 kV UPS of Russia operational substations. The optimum initial data sampling rate and algorithm computation delay were established for the considered data set. It was demonstrated that the TVE ramps up with the computation window width increase, which is driven by the signal reconstruction error under the condition of the synchrophasor averaging. As a result, it was outlined that the optimum sampling rate is 15 kHz.

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