Study of transient synchrophasors for the development of relay protection and control systems

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Abstract. The paper discusses issues of improving control and relay protection systems based on the study and analysis of voltage and current synchrophasors of electromechanical and electromagnetic transient processes. The authors consider methods for analyzing transient synchrophasors, the use of synchronized phasor measurement technology in control systems and for improving line distance protection. The paper provides examples of line impedance estimation using traditional protection algorithms and proposed algorithms based on phasor measurements.

1 Introduction

The development of control, protection and automation of power systems implies new requirements for indicators of the quality of their functioning. First, this concerns ensuring high performance of such systems and reliability of measurements.

The synchronized phasor measurement (SPM) technology is one of the promising areas for improving control and relay protection systems [1-2]. The development of protection and control algorithms based on SPM requires research into the equations of electromechanical transient processes in the values of voltage and current synchrophasors. Analysis of such equations makes it possible to justify the choice of certain components of transient synchrophasors for the implementation of signal processing algorithms in various control, protection and automation systems.

The paper presents the results of theoretical research, mathematical modeling of various electromechanical and electromagnetic transient processes, and an analysis of transient synchrophasors in order to improve control and relay protection systems.

2 Methods for analyzing transient synchrophasors

The most important advantage that SPM technology provides in protection and control devices is the accurate measurement of current and voltage synchrophasors during electromechanical transients [1-3]. The authors claim that the SPM, under certain conditions, also provides a reliable estimate of the power system equivalent circuit parameters during electromagnetic transients [4-7].

Effective use of SPM-enabled devices requires the study of equations in transient synchrophasors. However, existing methods and programs for calculating electromechanical and electromagnetic transient processes have solutions to differential equations in the form of instantaneous values of currents and voltages.

The authors have developed several methods for analyzing synchrophasors of transient processes in the power system (based on time-frequency representations, differential equation transformation and convolution integral) [8-9]. The development of special methods for analyzing transient synchrophasors, first, involves a more effective analysis of the functioning of IEDs with SPM support. The authors note that transient synchrophasors are often more complex functions than the synchrophasors assessed using PMU [9]. Therefore, it is important to establish which components of current and voltage synchrophasors need to be assessed using PMUs and other SPM-enabled devices [4-7].

Let us consider the application of a method for analyzing transient synchrophasors based on the transformation of differential equations. Below is an example of determining the line current and voltage synchrophasors for given power system and line parameters (Fig. 1). The line model is a simple RL equivalent circuit, and the power system EMF synchrophasors are functions of time.

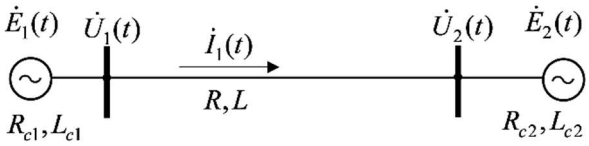

Fig. 1. Power system model № 1

Table 1 shows the solution of the line differential equation in transient synchrophasors. This solution involves a substitution $\Delta e_1(t) \to \Delta \dot{E}_1(t) e^{j\omega_0 t}$ and

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$i_1(t) \to \dot{I}_1(t)e^{j\omega_0 t}$ that is widely used in the complex amplitude method. Thus, we replace the original differential equation (Table 1, par. 1) in the instantaneous values with the differential equation in the transient synchrophasors (Table 1, par. 2).

Table 1. Calculation of current and voltage synchrophasors.

№	Name	Expression
1	Differential equation	$\Delta e(t) = R_\Sigma i_1(t) + L_\Sigma \frac{di_1(t)}{dt}$, $\Delta e(t) = e_1(t) - e_2(t)$, $R_\Sigma = R + R_{c1} + R_{c2}$, $L_\Sigma = L + L_{c1} + L_{c2}$
2	Synchrophasor expressions	$\Delta\dot{E}(t) = \underline{z}_\Sigma \dot{I}_1(t) + L_\Sigma \frac{d\dot{I}_1(t)}{dt}$, $\underline{z}_\Sigma = R_\Sigma + j\omega_0 L_\Sigma$
3	Current synchrophasor $\dot{I}_1(t)$	$\dot{I}_1(t) = \frac{1}{L_\Sigma}\int_0^t \Delta\dot{E}(\tau)e^{p_1(t-\tau)}d\tau$, $p_1 = \beta_1 + j\omega_0$, $\beta_1 = R_\Sigma / L_\Sigma$, $\omega_0 = 2\pi 50$ rad/s
4	Voltage synchrophasor $\dot{U}_1(t)$	$\dot{U}_1(t) = \dot{E}_1(t) - \underline{z}_{c1}\dot{I}_1(t) - L_{c1}\frac{d\dot{I}_1(t)}{dt}$
5	Voltage synchrophasor $\dot{U}_2(t)$	$\dot{U}_2(t) = \dot{U}_1(t) - \underline{z}\dot{I}_1(t) - L\frac{d\dot{I}_1(t)}{dt}$, $\underline{z} = R + j\omega_0 L$

The transient current synchrophasor (Table 1, par. 3) includes two components that determine the forced and free components of the transient process and is a compact description of the instantaneous transient current $i_1(t) = \mathrm{Re}\left[\dot{I}_1(t)e^{j\omega_0 t}\right]$. There are several methods for obtaining forced and free components from a complete synchrophasor, for example, based on the antiderivative integral, preliminary determination of the free component of the transient current synchrophasor and subsequent determination of the forced component [9].

Similar dependencies are present in the study of transient synchrophasors for relay protection. For example, to determine the current synchrophasor from the side of the first EMF source during a metal three-phase short circuit, it is necessary to make a replacement $\Delta\dot{E}(t) \to \dot{E}_1(t)$ and similar replacements in the expressions for resistances, inductances and impedances (Table 1).

The considered approach is valid for more complex models of lines and power systems. In this case, we will receive a set of differential equations in which synchrophasors of EMF, voltage and current are present. If it is necessary to take into account nonlinear elements in equivalent circuits, for example, nonlinear arc resistance, nonlinear inductance of the magnetic circuit of a transformer during a magnetizing inrush current (MIC), we obtain a set of differential equations, some of which will be nonlinear. In this case, current and voltage synchrophasors will contain many forced and free components [5-7]. The decision to use certain synchrophasor components for the development of new protection and control devices depends on the results of research.

3 SPM applications in control systems

The presented method for analyzing voltage and current transient synchrophasors provides dependencies for solving the following problems: estimating line parameters, verifying PMU data, implementing virtual PMU, increasing the efficiency of power system dynamic state estimation, searching for the source of low-frequency oscillations.

Let us consider solving the problem of estimating the parameters of a power transmission line (Fig. 1). The initial data are measurements of voltage synchrophasors at substations $\dot{U}_1(t)$ and $\dot{U}_2(t)$, as well as current synchrophasors in the line $\dot{I}_1(t)$. The task is to estimate line parameters using an *RL* equivalent circuit.

Using an approach similar to Table 1 we obtain the following differential equation:

$$\Delta\dot{U}(t) = \underline{z}\dot{I}_1(t) + L\frac{d\dot{I}_1(t)}{dt}. \qquad (1)$$

From equation (1) we obtain an expression for estimating the impedance of the power line:

$$\hat{\underline{z}}(t) = \frac{\Delta\dot{U}(t)}{\dot{I}_1(t) + \underline{k}_1\dot{I}_1'(t)}, \qquad (2)$$

where $\Delta\dot{U}(t) = \dot{U}_1(t) - \dot{U}_2(t)$, $\dot{I}_1'(t) = \frac{d\dot{I}_1'(t)}{dt}$, $\underline{k}_1 = \frac{L_\mu}{\underline{z}_\mu}$, $\underline{z}_\mu = R_\mu + j\omega_0 L_\mu$, R_μ, L_μ - line resistance and inductance, per km.

The additional component in the denominator of expression (2) provides a correct estimation of the line impedance during electromechanical and electromagnetic transient processes.

The authors emphasize that the error of the measuring current and voltage transformers, the error of the PMU and some other factors affect the accuracy of the line impedance estimation (2). Therefore, this expression represents the basis for the development of algorithms for identifying power line parameters. In turn, the practical implementation of the algorithm requires a transition from an analog model to a discrete one. Thus, we can improve the accuracy of line impedance estimation by using optimization techniques and using additional information about the current and voltage synchrophasors.

Estimation of power line parameters based on RL equivalent circuit (2) requires the use of current and voltage synchrophasors and the derivative of the current synchrophasor. A more complex *U*-shaped line equivalent circuit requires solving a set of differential equations in which current and voltage synchrophasors and their derivatives are present. We can obtain similar

models for other elements of the power system. The development of such models opens up opportunities for improving control, protection and monitoring systems, in particular, for power system dynamic state estimation and implementing virtual PMUs. The latter is a way to estimate the current and voltage synchrophasors at an adjacent substation based on the data from the synchrophasors at the substation where there is a PMU.

The practical implementation of algorithms based on expression (2) makes it difficult to calculate the discrete derivative of the current synchrophasor. The most preferable is to calculate this derivative in the PMU by analogy with the calculation of the instantaneous frequency as a derivative of the voltage synchrophasor. The second option involves increasing the transmission frequency of synchrophasors and calculating the derivative in another device. In this regard, additional requirements arise for protection devices, in particular, high transmission frequency of synchrophasors, high speed of operation. On the other hand, protection devices have lower requirements for the accuracy of synchrophasor measurements compared to PMUs.

In many cases, substations have PMU only at some bays. The presence of PMU at adjacent substations makes it possible to evaluate synchrophasors at bays without PMU. This problem arises in various applications, for example, when searching for the source of low-frequency oscillations in a power system.

To solve this problem, we use a discrete analogue of the integral expression to determine the current synchrophasor (Table 1, par.3):

$$\dot{I}_1(k) = \frac{1}{L}\sum_{m=0}^{k}\Delta\dot{U}(k)e^{p_0(k-m)T}, \qquad (3)$$

where $p_0 = \beta_0 + j\omega_0$, $\beta_0 = R/L$, $k \cdot T$ - discrete time.

The problem of calculating the current synchrophasor has a problem, which lies in the presence of a rapidly oscillating function in expression (3). To solve this problem, we need to increase the transmission frequency of the synchrophasors. At the same time, algorithms based on a simplified method for analyzing transient synchrophasors [3-9] provide satisfactory results for estimating the current synchrophasor for a standard transmission frequency.

There are other possibilities for increasing the efficiency of searching for the source of low-frequency oscillations using current and voltage synchrophasors, in particular, the use of additional signs of recognition of low-frequency oscillations based on the instantaneous frequencies of current synchrophasors, analysis of models of such oscillations using transient synchrophasors.

Thus, the use of transient synchrophasors makes it possible to solve various problems for improving control systems. The most promising areas are additional estimation of synchrophasors, virtual PMU, verification of PMU data, power system dynamic state estimation.

4 SPM applications in relay protection

4.1 Distance protection

Synchrophasor technology has several promising directions for relay protection; in particular, the authors argue that the use of current and voltage synchrophasors is promising for improving distance protection algorithms.

Let us consider the use of methods for one-sided and two-sided measurement of current and voltage synchrophasors in distance protection of a 110-220 kV line (Fig. 2).

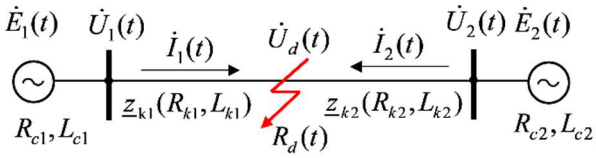

Fig. 2. Power system model № 2

Table 2 shows two line distance protection algorithms. The first algorithm involves one-sided synchrophasor measurements when we have data from only one protection device at the substation. The second algorithm uses two-sided measurements. This means that we have synchrophasor measurements from adjacent substations that the protected line connects.

Table 2. Estimation of short-circuit loop impedance.

№	Name	Expression
1	One-sided synchrophasor measurements	$\hat{\underline{z}}(t) = \frac{\dot{U}(t)}{\dot{I}(t) + \underline{k}\dot{I}'(t)}$, $\dot{I}'(t) = \frac{d\dot{I}(t)}{dt}$, $\underline{k} = L_\mu / \underline{z}_\mu$
2	Two-sided synchrophasor measurements	$\hat{\underline{z}}_1(t) = \frac{\Delta\dot{U}(t) + \underline{z}\dot{I}_2(t) + L\dot{I}_2'(t)}{\dot{I}(t) + \underline{k}\dot{I}'(t)}$, $\Delta\dot{U}(t) = \dot{U}_1(t) - \dot{U}_2(t)$, $\dot{I}(t) = \dot{I}_1(t) + \dot{I}_2(t)$, $\dot{I}'(t) = \dot{I}_1'(t) + \dot{I}_2'(t)$

We obtained the given algorithms (Table 2) based on the approach that this paper discusses in Section 3. These expressions have a more compact form compared to those previously published [4-6]. The one-sided line impedance estimation algorithm has disadvantages because it does not eliminate the influence of a nonlinear arc during a short circuit. The authors considered a more efficient one-sided measurement algorithm in [5, 7]. The algorithm for two-sided measurement of current and voltage synchrophasors eliminates the influence of a nonlinear arc [7] and ensures the correct operation of distance protection during electromechanical transient processes, including in asynchronous mode in the power system.

The proposed algorithms (Table 2) have a significant difference from traditional distance protection algorithms. This difference lies in the presence of

additional components with derivatives of current synchrophasors. These components can significantly improve the performance of the protection and ensure its correct operation during electromechanical and electromagnetic transients.

Distance protection depends on various factors that can have a negative impact on it [10-12]. One of these factors is the errors of current and voltage transformers. The saturation of the magnetic circuit of the current transformer has a particularly negative effect on distance protection. For this reason, the speed that the proposed algorithms (Table 2) can provide is an important tool for improving distance protection, since the time until saturation of current transformers is usually quite short.

Thus, the performance of distance protection algorithms may depend on the measurement system. The authors consider the use of digital optical current and voltage transformers [13] and digital current transformers based on a Rogowski coil [14] as a way to improve the efficiency of the proposed algorithms (Table 2). In this case, there is no saturation of the magnetic circuit of the current transformer, which ensures accurate current measurements (class 0.5) in the full range of its values. We propose the use of a combined digital current and voltage transformer ECIT for medium voltage switchgears (Engineering Center Energoservice LLC) [14]. ECIT has a Rogowski coil as a primary current converter and a capacitive voltage divider. Additionally, the ECIT has the function of measuring current and voltage synchrophasors. Thus, such a device provides more efficient operation of distance protection compared to electromagnetic current and voltage transformers.

4.2 Ground fault protection

Transient synchrophasors have promising applications for other types of protection, such as improving ground fault protection [15-16].

The zero sequence circuit of a three-phase network during a ground fault has distinctive features [17]. The authors analyzed differential equations for synchrophasors of zero sequence currents and voltages for various conditions of the occurrence of a ground fault. The results of the study allowed us to propose a new directional protection algorithm based on equivalent harmonic synchrophasors [7]. The advantage of such protection is the ability to work both locally and as part of centralized protection.

To improve ground fault protection, we can also use an approach based on line differential equation analysis similar to the short circuit mode (Section 4.1) [17-18]. However, for distance protection, it was sufficient to estimate the forced component of the current synchrophasor, and ground fault protection requires the estimation of synchrophasors taking into account the influence of free components. Therefore, this approach has a certain complexity of implementation.

The authors note that transient synchrophasors also have promise for other types of protection, for example, for differential protection of a power transformer [16]. The use of synchrophasors makes it possible to implement additional features for recognizing internal and external short circuit modes and the magnetizing current inrush mode.

5 Math modeling

We propose to consider several examples of mathematical modeling of the developed distance protection algorithms, which confirm their effectiveness.

Figure 3 shows a comparison of two distance protection options (Table 2). The power system model corresponds to Fig. 2. The upper graphs contain instantaneous values of currents and voltages, modules and phases of the corresponding synchrophasors. The lower graphs show the estimation of line impedance components based on the traditional (*t*) and proposed (*p*) algorithms. The graph with number 1 corresponds to the one-sided measurement algorithm (Table 2, par. 1). The graph with number 2 corresponds to two-sided measurements (Table 2, par. 2).

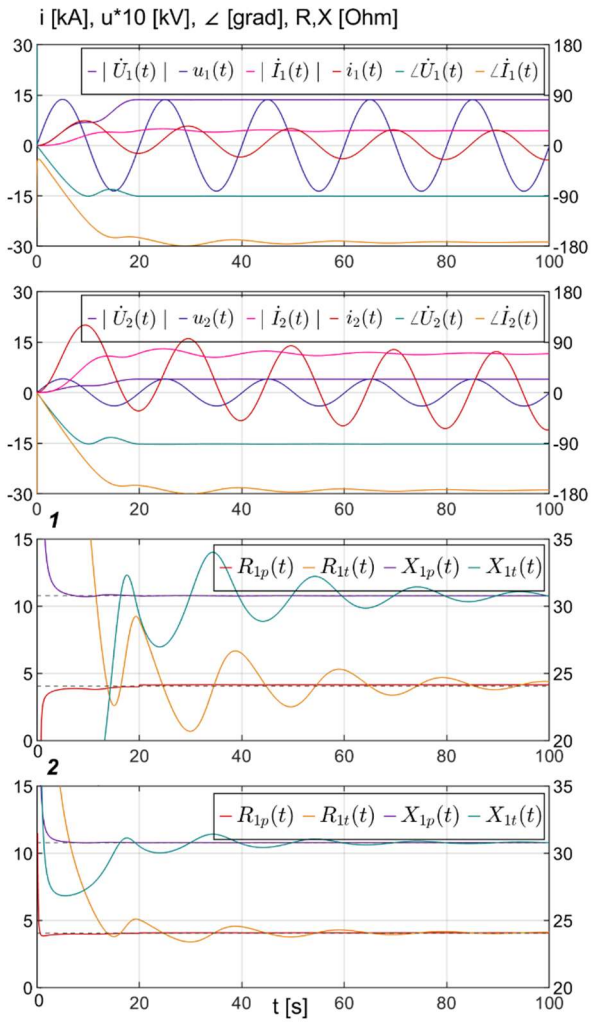

Fig. 3. One-sided (1) and two-sided (2) R, X estimation

The graphs (Fig. 3) confirm that the performance of distance protection based on the proposed algorithms (Table 2) significantly exceeds the performance of the traditional algorithm. The authors emphasize that the protection response time is a few milliseconds, despite

the fact that the evaluation of current and voltage synchrophasors takes about 20 ms. This is possible because the proposed expressions (Table 2) take into account the parameters of the line model.

If we compare the one-sided and two-sided measurement algorithms, we can confirm that the two-sided measurement algorithm has advantages over one-sided measurement. Distance protection with two-sided measurements can operate stably under various electromagnetic and electromechanical transient processes, in particular, in asynchronous mode in the power system.

Fig. 4 shows plots similar to Fig. 3, but taking into account the current transformer saturation model.

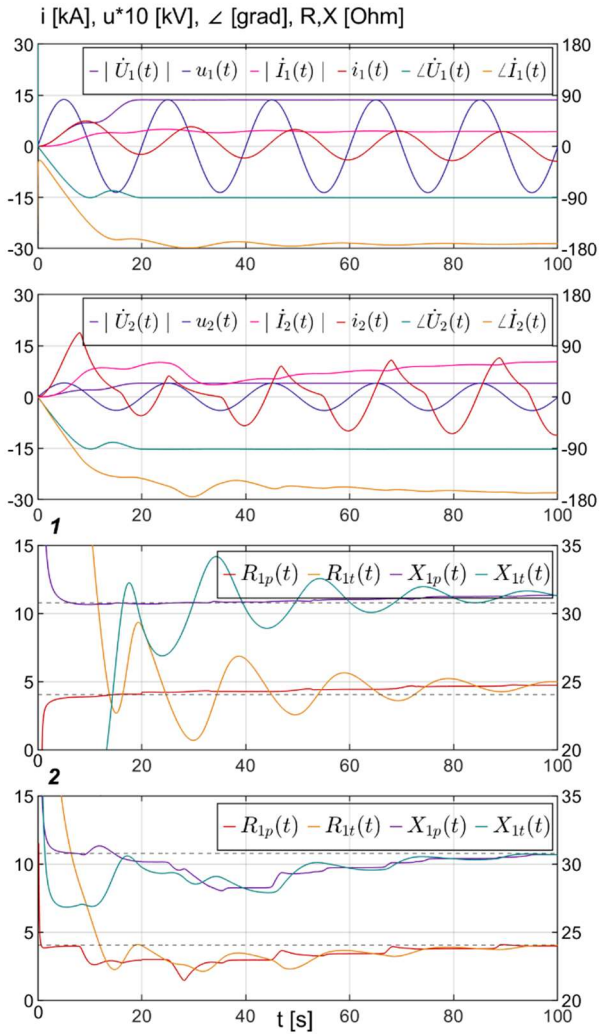

Fig. 4. R, X estimation in case of CT saturation

During a short circuit, rapid saturation of the current transformers occurs on the side of the second EMF source, which leads to a significant increase in the error in estimating the line impedance (Fig. 4). The authors note that the proposed distance protection algorithm (Table 2) provides high performance, so we obtain an accurate estimate of the line impedance before saturation of the current transformers (Fig. 4, plot 2).

Thus, the simulation results confirm that the use of transient synchrophasors is promising in relay protection systems.

6 Conclusion

The authors carried out a study concerning the use of current and voltage synchrophasors in protection and control systems. The paper examines several applications of transient synchrophasors. Analysis of voltage and current synchrophasors of electromechanical and electromagnetic transients allowed the development of distance protection algorithms (one-sided and two-sided measurement). The proposed algorithms provide accurate line impedance estimation under various conditions. In addition, the speed of the algorithms determines the correct operation of distance protection when the measuring current transformers are saturated.

Transient synchrophasors have promising applications in other protections, in particular, in transformer protection and ground fault protection.

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