Improvement of distance protection algorithms based on phasor measurements

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Abstract. Distance protection of overhead lines is widely used and is continually being improved. However, the distance protection cannot work stably and is blocked in several electromechanical transients. Additionally, a non-linear arc can affect the stability of the distance protection in case of a short-circuit. The authors consider ways to improve distance protection during such transients. In particular, this paper proposes the use of synchronized phasor measurement technology to improve the efficiency of distance protection.

This paper considers a new approach for the analysis of electromechanical and electromagnetic transients in a power system using process synchrophasors. As examples, cases of a short-circuit in a line with one-way and two-way powers are considered. The authors consider the influence of a non-linear arc at the fault point and consider the possibility of the coincidence of the electromechanical and electromagnetic transients.

The result is a new algorithm for operating distance protection, an improvement in the parametric method for determining the location of line damage. The calculations performed and mathematical modeling confirm the effectiveness of the proposed algorithm.

1 Introduction

The reliability of the power system is largely dependent on the technical excellence of the relay protection and automation devices. This paper is devoted to the consideration of issues related to improving the efficiency of relay protection devices with synchronized phasor measurement (SPM) technology on the example of improving distance protection (DP).

Improvement of distance protection based on synchronized phasor measurements is considered in several studies [1-3]. However, still one of the main disadvantages of distance protection is the need to block it when some electromechanical processes occur, for example, an asynchronous mode in the power system, power swings [4-6]. Additionally, the sensitivity of distance protection is reduced in the case of short-circuits with an arc.

This paper discusses new algorithm for operating overhead line distance protection, which ensure the correct functioning of the protection both in electromagnetic transients and electromechanical transients, as well as in a combination of these transients and considering the influence of the arc.

2 Theory of process synchrophasors

2.1 Short-circuit process synchrophasors

The term of a process synchrophasor was proposed in [7], where the development of the SPM theory was considered. In this paper, it is assumed that the synchrophasor of the process is the theoretical value of the synchrophasor, which can be obtained analytically or using numerical calculation methods. The concept of a process synchrophasor should be distinguished from the concept of synchrophasor estimation using various well-known methods, for example, the Fourier algorithm. Thus, the authors consider the analysis of process synchrophasors and their components to improve the overhead line distance protection algorithms.

Consider the definition of process synchrophasors using the example of a simple equivalent circuit of a power system and an RL-model of a line with a three-phase short-circuit (Fig.1).

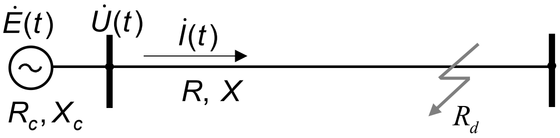

Fig. 1. Equivalent circuit.

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The differential equation of the line in case of a short-circuit in the instantaneous values of current and voltage:

$$u(t) = i(t)R + L\frac{di(t)}{dt}, \tag{1}$$

where R, L - parameters of the short-circuited section of the line.

To obtain this differential equation in the process synchrophasors, one should replace the instantaneous values of current and voltage $u(t)$, $i(t)$ with expressions $\dot{U}(t)e^{j\omega_0 t}$, $\dot{I}(t)e^{j\omega_0 t}$ and substitute them into equation (1). After simple transformations, the following equation is obtained:

$$\dot{U}(t) = \underline{z}\dot{I}(t) + L\frac{d\dot{I}(t)}{dt}, \tag{2}$$

where $\underline{z} = R + j\omega_0 L$.

The solution of the differential equation (2) can be used to determine the current synchrophasor of an electromagnetic or electromechanical transient process for a given synchrophasor of the power system equivalent EMF:

$$\dot{I}(t) = \frac{1}{L}e^{-p_1 t}\int_0^t \dot{E}(\tau)e^{p_1\tau}d\tau, \tag{3}$$

where $p_1 = \beta + j\omega_0$, $\beta = (R_c + R)/(L_c + L)$, $\omega_0 = 2\pi 50$ рад/с, R_c, L_c - parameters of the equivalent power system.

Based on expressions (2) and (3), it is possible to determine, respectively, the total current and voltage synchrophasor of the considered electromagnetic process and its forced and free components [7]. To implement distance protection, it is sufficient to use only the first components of synchrophasors, but the use of total synchrophasors makes it possible to increase the protection speed [7, 8].

Existing distance protection algorithms [4, 5, 6, 9], methods for identifying line parameters [10], assessing the state of a distribution network [11] are based on differential equations with instantaneous values of currents and voltages. The authors propose the use of differential equations in which current and voltage synchrophasors are used instead of instantaneous values. The proposed approach has certain advantages when performing tasks such as the implementation of virtual PMU, the identification of line parameters, and the monitoring of the condition of electrical equipment.

The issue of improving the distance protection of an overhead line in the case of one-sided and two-sided measurement of current and voltage synchrophasors is considered in detail in [8]. In addition, a non-linear arc at the fault location has a negative impact on the short-circuit impedance estimate. Therefore, the compensation of this influence is important for distance protection and especially for line fault location devices.

2.2 Estimation of arc influence

The arc during a short-circuit has a complex non-linear character. Sometimes, in order to carry out simple calculations to analyse the operation of distance protection [5], the arc resistance R_d is chosen to be constant. In this case, the system of equations (1) can be represented as follows:

$$u(t) = i(t)R_\Sigma + L\frac{di(t)}{dt}, \tag{4}$$

where $R_\Sigma = R + R_d$.

Equation (4) can be represented as equation (2) by replacing R with R_Σ. For further calculations, we introduce the following variable:

$$\underline{z}_0(t) = \frac{\dot{U}(t)}{\dot{I}(t)} = R_0(t) + jX_0(t). \tag{5}$$

Thus, equation (4) will have the following form:

$$\underline{z}_0(t) = \underline{z} + L\frac{\dot{I}'(t)}{\dot{I}(t)}, \tag{6}$$

where $\dot{I}'(t) = \frac{d\dot{I}(t)}{dt}$.

Using equation (6), the real and imaginary components of the line impedance and arc resistance can be determined:

$$L = X_0(t)\left[\omega_0 + \mathrm{Im}\left(\frac{\dot{I}'(t)}{\dot{I}(t)}\right)\right]^{-1}, \tag{7}$$

$$R_\Sigma = R_0(t) - L\,\mathrm{Re}\left[\frac{\dot{I}'(t)}{\dot{I}(t)}\right], \tag{8}$$

$$R_\mathrm{d} = R_\Sigma - \frac{L}{L_\mu}R_\mu, \tag{9}$$

$$R = R_\Sigma - R_d, \tag{10}$$

where R_μ, L_μ - unit line parameters per 1 km.

The proposed algorithm for estimating the resistance and inductance of a short-circuited section of the line expands the previously presented algorithms related to compensating for the influence of arc resistance [8].

The considered version of the algorithm for estimating the influence of the arc is simplified. For a more accurate description of the arc, various nonlinear models are used [13, 14]. To take into account the influence of one of these arc models on the operation of distance protection, it is necessary to create a new system of equations that describes the process of a short-circuit in the line.

In any non-linear arc model, its resistance becomes a time-dependent variable $R_d(t)$. Thus, the total line resistance will also change with time. On the other hand, the above expressions (7) – (10) for the line resistance do not change. However, if earlier it was sufficient to use expression (3) to simulate and find the total current synchrophasor and its components, then in the case under consideration the problem becomes more complicated, since in the differential equation one of the coefficients becomes a function of time.

In this case, the analytical solution for definition of the process current synchrophasor has the following form:

$$\dot{I}(t)=\frac{1}{L}e^{-\rho(t)}\int_0^t e^{\rho(\tau)}\dot{E}(\tau)d\tau\,, \tag{11}$$

where $\rho(t)=\int_0^t p(\tau)d\tau$, $p(t)=\beta+\beta_d(t)+j\omega_0$,

$\beta=\frac{R+R_c}{L+L_c}$, $\beta_d(t)=\frac{R_d(t)}{L+L_c}$.

The difficulty in applying expression (11) for calculations lies in the fact that in most nonlinear models the arc resistance depends on the current. Therefore, equation (11) for a number of calculations is more convenient to replace with a system of differential equations, which is solved by numerical methods [14].

One of the best known non-linear arc models is the Mayr model [14]. For the case under consideration, the system of differential equations with a non-linear Mayr arc model and with the use of process synchrophasors will have the following form:

$$\begin{cases}\dfrac{dR_d(t)}{dt}=-\dfrac{R_d(t)}{\tau}\left(\dfrac{\left[\operatorname{Re}\left(\dot{I}(t)e^{j\omega_0 t}\right)\right]^2R_d(t)}{P_0}-1\right)\\[2ex] \dfrac{d\dot{I}(t)}{dt}=\dfrac{1}{L_\Sigma}\left(\dot{E}(t)-\left(\underline{z}_\Sigma+R_d(t)\right)\dot{I}(t)\right)\end{cases}, \tag{12}$$

where $\underline{z}_\Sigma=R_\Sigma+j\omega_0L_\Sigma$, $R_\Sigma=R+R_c$, $L_\Sigma=L+L_c$,

τ - arc time constant, P_0 - arc power constant.

If it is necessary to separate the forced and free components of the current $\dot{I}(t)$, you can use the simple method considered in [7]. In this case, the free component is determined first, and then the forced components.

Further, based on the differential equation (4) with a variable coefficient, the voltage on the substation buses and the arc voltage are determined. For other arc models [14], a similar approach can be used to determine the current and voltage synchrophasors.

3 Simulation and analysis

3.1 Electromagnetic transient

This section discusses several examples of modeling a three-phase short-circuit at the end of the line, taking into account the influence of a non-linear arc. The current and voltage synchrophasors are estimated using the Fourier algorithm.

The authors propose to compare two methods for calculating the line impedance. The first method is based on the traditional approach, when complex current and voltage amplitudes are applied:

$$\underline{z}=\frac{\dot{U}(t)}{\dot{I}(t)}\,. \tag{13}$$

The second method involves the use of expressions (4) - (10) to calculate the line impedance and estimate the distance to the short-circuit point. The purpose of the comparison is to show that the calculation using expressions (4) - (10) allows much more efficient use of current and voltage synchrophasors for estimating the line impedance and, accordingly, for the operation of distance protection.

Modeling is carried out according to the equivalent circuit, which is shown in Fig. 1. Initial data for the first example: frequency f_0 = 50 Hz, EMF system synchrophasor $\dot{E}(t)$ =136.8$e^{-j0.25\pi}$ kV, system impedance $\underline{z}_c$ = 1.2+*j*12.8 Ohm, unit line impedance $\underline{z}_\mu$ = 0.05+*j*0.38 Ohm, line length 30 km, arc time constant τ = 0.0001 s, arc power constant P_0 = 1 MW.

Modeling is done in MATLAB\Simulink. To calculate the process synchrophasors and instantaneous values of current, voltage and arc resistance, the system of equations (12) is used. Fig. 2 shows the instantaneous values of the short-circuit current and the total current synchrophasor module. Fig. 3 shows the change in arc resistance over time.

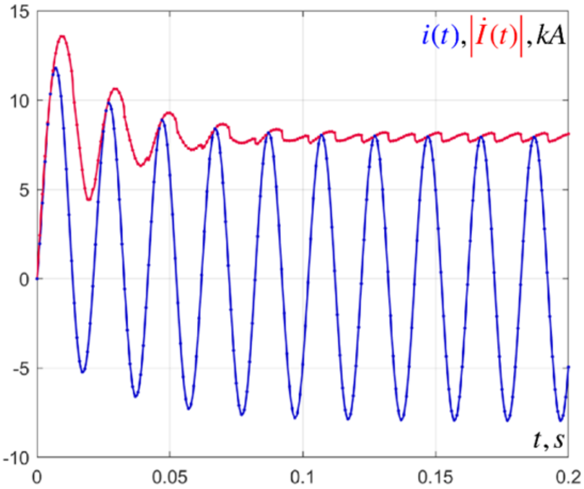


Fig. 2. Instantaneous current values and total current synchrophasor module.

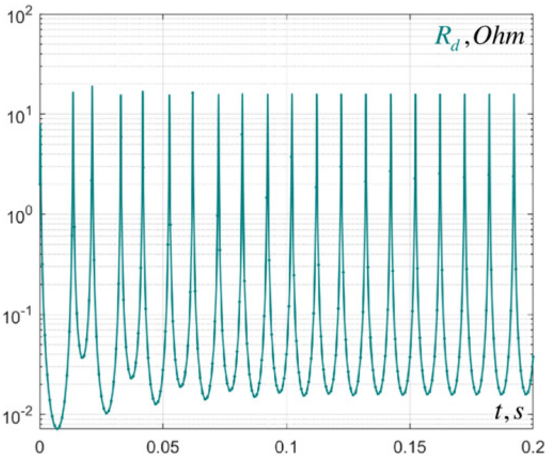
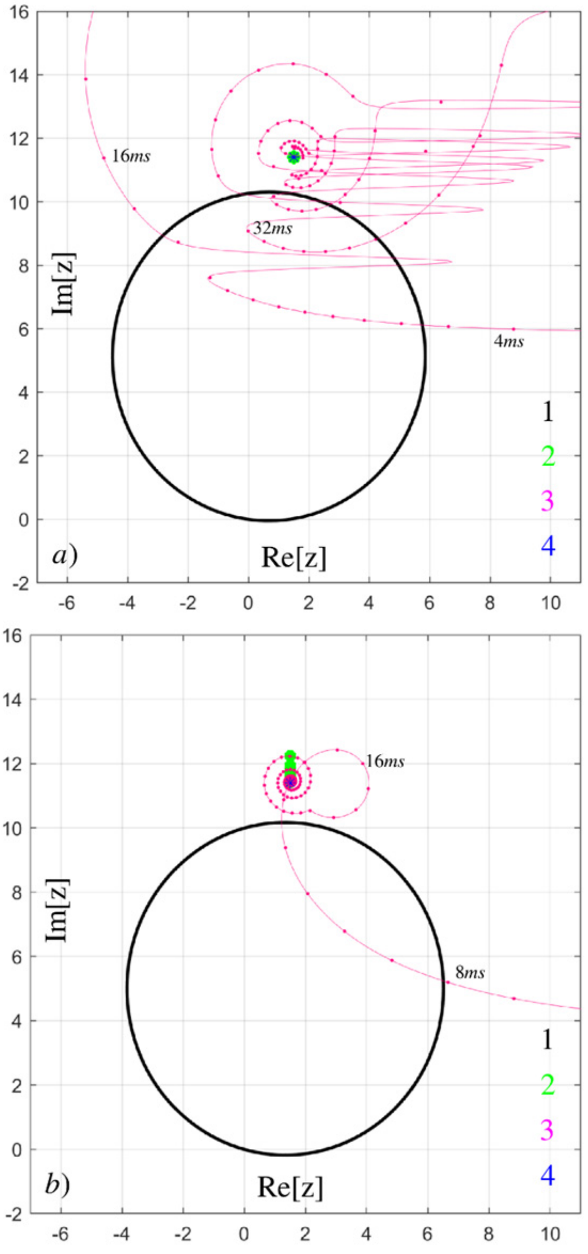


Fig. 3. Arc resistance.

We use a special form of the graph (hodograph) to present the results of calculating the line impedances by different methods. The hodograph shows the dependence of the imaginary part of the line impedance on the real part. The hodograph for the considered example is shown in Fig. 4.



a) calculation via process synchrophasors; b) calculation through the estimation of synchrophasors using the Fourier algorithm; 1 - characteristic of the 1st stage of distance protection; 2 - calculation through expressions (4) - (10); 3 - calculation via expression (13); 4 - line impedance true value
Fig. 4. Line impedance estimation for example 1.

Fig. 4a shows the results of line impedance calculations through process synchrophasors. In this case, for the traditional calculation method (13), the arc resistance is not excluded from the line resistance, so the corresponding changes to the right area are visible on the graph. In addition, the result of the calculation approaches the true value over several periods. As a rule, with such resistance fluctuations, the distance protection is blocked.

Fig. 4b shows the results obtained by evaluating the current and voltage synchrophasors using the Fourier algorithm. The averaging principle of operation of such an algorithm makes it possible to reduce the influence of a non-linear arc. However, line resistance fluctuations continue for more than 20 ms according to the traditional calculation method (13). In the case where the proposed expressions (4) - (10) are applied, the line impedance becomes almost equal to the true value within a few milliseconds (figure 4a, 4b, line 2). The results of calculations according to expressions (4) - (10) can be made even more efficient if specially synthesized filters are used instead of the Fourier algorithm.

3.2 Combination of electromagnetic and electromechanical transient

The second example shows the results of simulating a short-circuit in a line with a simultaneous electromechanical process. The electromechanical transient process is modelled by setting an expression for changing the system EMF. Fig. 5 shows the instantaneous voltage values and voltage synchrophasor module in a substation.

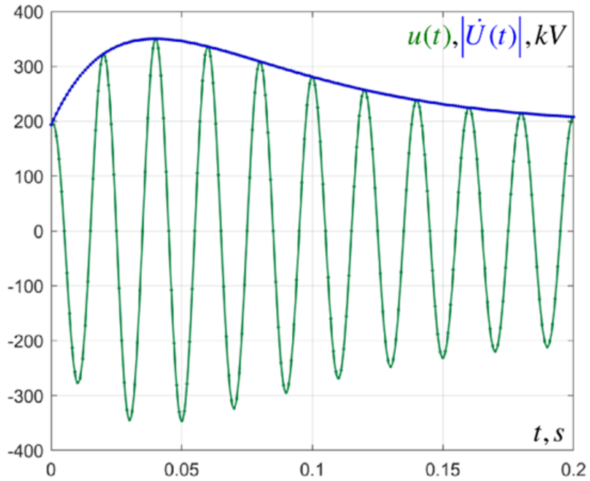
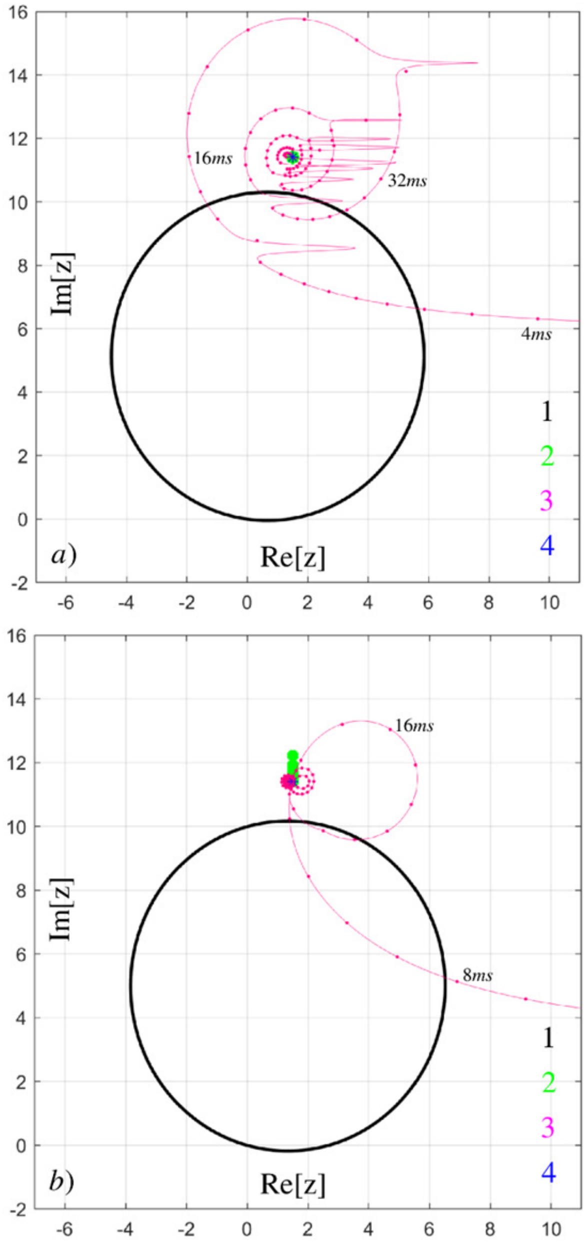


Fig. 5. Instantaneous voltage values and total voltage synchrophasor module.

Fig. 6 shows the hodographs for the example under consideration. As in the previous example, the calculations were carried out for the process synchrophasors (a) and for the synchrophasors estimated using the Fourier algorithm (b).

The simulation results allow concluding that the combination of electromechanical and electromagnetic processes leads to a decrease in the accuracy of calculations by the traditional method (13). In addition, the electromechanical transient negatively affects the operation of the Fourier algorithm, and, as a result, the estimation of current and voltage synchrophasors.

The presence of an electromechanical transient does not adversely affect the evaluation of the line impedance components when using the proposed method (4) - (10).



a) calculation via process synchrophasors; b) calculation through the estimation of synchrophasors using the Fourier algorithm; 1 - characteristic of the 1st stage of distance protection; 2 - calculation through expressions (4) - (10); 3 - calculation via expression (13); 4 - line impedance true value

Fig. 6. Line impedance estimation for example 2.

The authors assume that in the considered examples, the arc resistance has little effect on the line impedance estimation because the calculation was made for a short-circuit at the end of the line. Additional calculations show that with a short-circuit at the beginning of the line, for the case when the system has a large power, the influence of the arc becomes much higher. Therefore, the use of the proposed method for estimating the line impedance has advantages for other modes of power system operation.

3.3 Line with two-way power supply

Next, we consider the case when the line has power sources on both sides. In the graphs and expressions, the number 1 indicates the values related to the first power source, the number 2 to the second.

For the case under consideration, we assume that synchronized phasor measurement devices are installed at the ends of the line. Two-sided measurement of current and voltage synchrophasors has advantages over one-sided measurement, since the SPM technology is focused on distributed data processing and the creation of WAPS.

The equivalent circuit of a power system with two power supplies is shown in Fig. 7.

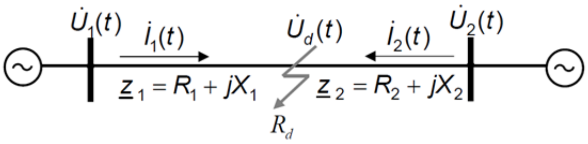


Fig. 7. The equivalent circuit of a power system with two power supplies.

Next, we consider the case when the current phasors $\dot{I}_1(t)$ and $\dot{I}_2(t)$ are not equal to each other (in modulus and phase).

System of equations for the traditional method based on complex amplitudes:

$$\begin{cases} -\dot{U}_1(t)+\underline{z}_1(t)\dot{I}_1(t)+R_d(t)\dot{I}(t)=0; \\ -\dot{U}_2(t)+\underline{z}_2(t)\dot{I}_2(t)+R_d(t)\dot{I}(t)=0, \end{cases} \qquad (14)$$

where $\dot{I}(t)=\dot{I}_1(t)+\dot{I}_2(t)$.

This system makes it possible to eliminate the arc resistance and express the line impedance up to the short-circuit point from one of the sources:

$$\underline{z}_1(t)=\frac{\Delta\dot{U}(t)+\underline{z}\dot{I}_2(t)}{\dot{I}(t)}, \qquad (15)$$

where $\Delta\dot{U}(t)=\dot{U}_1(t)-\dot{U}_2(t)$, $\underline{z}$ - total line resistance.

According to the proposed method, based on process synchrophasors for the equivalent circuit in Fig. 7, the following system of equations is compiled:

$$\begin{cases} -\dot{U}_1(t)+\underline{z}_1(t)\dot{I}_1(t)+L_1\dot{I}'_1(t)+R_d(t)\dot{I}(t)=0; \\ -\dot{U}_2(t)+\underline{z}_2(t)\dot{I}_2(t)+L_2\dot{I}'_2(t)+R_d(t)\dot{I}(t)=0, \end{cases} \qquad (16)$$

where $\dot{I}'_1(t)=\dfrac{d\dot{I}_1(t)}{dt}$, $\dot{I}'_2(t)=\dfrac{d\dot{I}_2(t)}{dt}$.

We make simple transformations of system (16) and introduce the following notation:

$$\underline{z}_{10}(t)=\frac{\Delta\dot{U}(t)+\underline{z}\dot{I}_2(t)+L\dot{I}'_2(t)}{\dot{I}(t)}. \qquad (17)$$

Then components of the line impedance for the proposed method can be calculated using expressions similar to (7) and (8):

$$L_1 = \mathrm{Im}\left[\underline{z}_{10}(t)\right]\left[\omega_0 + \mathrm{Im}\left(\frac{\dot{i}'(t)}{\dot{i}(t)}\right)\right]^{-1}, \tag{18}$$

$$R_1 = \mathrm{Re}\left[\underline{z}_{10}(t)\right] - L_1 \mathrm{Re}\left[\frac{\dot{i}'(t)}{\dot{i}(t)}\right]. \tag{19}$$

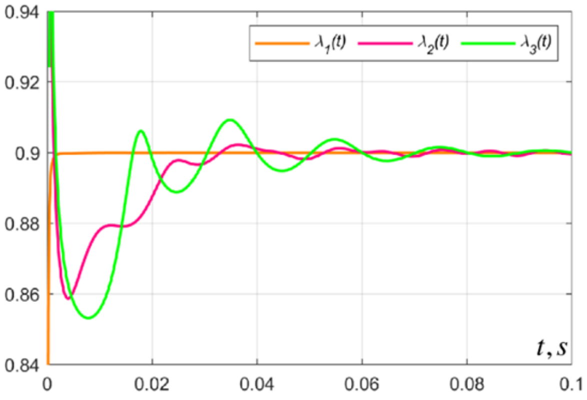
In addition, there is an alternative way to calculate the line impedance, when the related distance to the short-circuit point is first calculated:

$$\lambda_1(t) = \frac{\Delta\dot{U}(t) + \underline{z}\dot{i}_2(t) + L\dot{i}_2'(t)}{\underline{z}\dot{i}(t) + L\dot{i}_2(t)}, \tag{20}$$

where $\lambda_1(t) = \dfrac{\underline{z}_1(t)}{\underline{z}}$.

The presented expression (20) has a similar form with the well-known expressions for calculating the distance to the short-circuit point based on the method of complex current and voltage amplitudes [16-17] and current and voltage synchrophasors [18]. Nevertheless, the feature of the calculation of process synchrophasors presented in the paper makes it possible to take into account additional components necessary for accurate determination of the line impedance at the beginning of the transient process. Accordingly, this ensures the effective operation of distance protection.

As an example, Fig. 8 shows the results of calculating the distance to the short-circuit point using the proposed and traditional algorithm.



1 - calculation by expression (20), 2 - calculation by the traditional algorithm using a synthesized filter, 3 - calculation by the traditional algorithm using the Fourier algorithm
Fig. 8. Calculation of the distance to the short-circuit point.

The traditional algorithm (Fig. 8) corresponds to the expression given in [18]. Fig. 8 considers two calculation options for the traditional algorithm: using a synthesized filter (curve 2) and using the Fourier algorithm (curve 3). Curve 1 corresponds to the proposed algorithm using the synthesized filter.

Fig. 8 confirms that the proposed algorithm allows obtaining accurate values $\lambda_1(t)$ much faster than the traditional algorithm. In addition, the synthesized filter also allows you to get results that are more accurate.

In the normal operation of the power system or in the event of an external short circuit, when $\dot{i}_1(t) = \dot{i}_2(t)$, the following expressions based on current and voltage synchrophasors determine the line impedance:

$$L_1 = \mathrm{Im}\left[\frac{\Delta\dot{U}(t)}{\dot{i}_1(t)}\right]\left[\omega_0 + \mathrm{Im}\left(\frac{\dot{i}'(t)}{\dot{i}(t)}\right)\right]^{-1}, \tag{21}$$

$$R_1 = \mathrm{Re}\left[\frac{\Delta\dot{U}(t)}{\dot{i}_1(t)}\right] - L_1 \mathrm{Re}\left[\frac{\dot{i}'(t)}{\dot{i}(t)}\right]. \tag{22}$$

These expressions are derived according to the Kirchhoff law similarly to (18) and (19).

4 Discussion

In [19], voltage and current synchrophasors are used in a system of differential equations to determine the fault location in a line. However, the author [19] replaces the instantaneous values of currents and voltages with synchrophasors without additional transformations, which causes an error in estimating the distance. To reduce the error, a special algorithm based on the least squares method is used. The authors suggest that the method based on process synchrophasors would solve this problem.

In this paper, the authors present two options for calculating the distance and impedance of the line to the short-circuit point (according to expressions (17)-(19) and (20)). Despite the fact that expressions (17) and (20) are similar, there is an important difference between them. Expression (20) imposes a restriction on the X/R ratio. Taking into account the fact that X/R ratio practically does not change for an overhead line, expression (20) can be more accurate in some cases. However, further research is required to test this assumption.

5 Conclusion

The authors proposed a new algorithm for operating overhead line distance protection, which is described in this paper. This algorithm uses differential equations based on process synchrophasors instead of instantaneous values of variables. This makes it possible to ensure the correct operation of distance protection during electromechanical and electromagnetic transients.

In this paper, the authors considered several options for transients that can affect distance protection. First, this study shows how the use of process synchrophasors can reduce the effect of a non-linear arc during a short-circuit. Secondly, the authors demonstrate the advantages of process synchrophasors in the case when electromechanical and electromagnetic transients occur simultaneously.

The authors provide expressions for one-sided and two-sided measurements of currents and voltages of an overhead line. For two-sided measurement, there are two options for calculating the distance to the short-circuit point. The paper shows that the use of two-sided measurement of voltage and current synchrophasors makes it possible to simultaneously implement several signs of damage recognition.

This paper provides several options for modeling the operation of distance protection based on the proposed algorithm. The results confirm its effectiveness for various transients.

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