5TH INTERNATIONAL CONFERENCE

Smart Grid Synchronized Measurements & *Analytics*

An improved method for estimation of line and transformer parameters during transient processes based on synchrophasor technology

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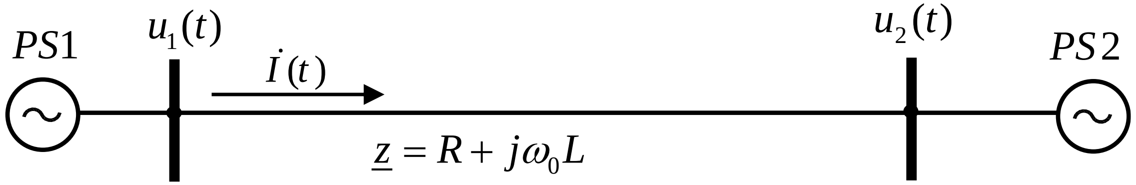
CONTENT

- Development of algorithms based on methods for analyzing synchrophasors of initial electromechanical and electromagnetic transient processes
    - identification of line parameters (RL- and U-shaped equivalent circuits) during electromechanical and external electromagnetic transient processes
    - fast estimation of short-circuit loop impedance in distance protection during transients
    - estimation of line capacity in admittance protection against single-phase ground faults
    - improving differential and distance protection of a power transformer and its condition monitoring system
- Advantages of the developed algorithms in conjunction with digital instrument transformers

Line impedance estimation



$$u_1(t)-u_2(t)=R\cdot i(t)+L\frac{di(t)}{dt}$$

The complex amplitude method

$$u_1(t)\to \dot U_1 e^{j\omega_0 t},\ u_2(t)\to \dot U_2 e^{j\omega_0 t},\ i(t)\to \dot I e^{j\omega_0 t}$$

$$\dot U_1-\dot U_2=\underline{z}\,\dot I$$

$$\underline{z}=\frac{\dot U_1-\dot U_2}{\dot I}$$

$$\hat{\underline{z}}_0(t)=\frac{\dot U_1(t)-\dot U_2(t)}{\dot I(t)}=R_0(t)+j\omega_0 L_0(t)$$

The new method

$$u_1(t)\to \dot U_1(t) e^{j\omega_0 t},\ u_2(t)\to \dot U_2(t) e^{j\omega_0 t},\ i(t)\to \dot I(t) e^{j\omega_0 t}$$

$$\dot U_1(t)-\dot U_2(t)=\underline{z}\,\dot I(t)+L\frac{d\dot I(t)}{dt}$$

Line impedance estimation

variant 1: $\hat{\underline{z}}(t)=\dfrac{\dot{U}_1(t)-\dot{U}_2(t)}{\dot{I}(t)+\underline{k}\cdot\dot{I}'(t)}$

$$\dot{I}'(t)=\frac{d\dot{I}(t)}{dt},\ \underline{k}=\frac{L_{sp}}{\underline{z}_{sp}}$$

$$\hat{\underline{z}}(t)=\hat{\underline{z}}_0(t)\frac{\rho_0}{\rho_0+\rho(t)}$$

$$\rho(t)=\frac{\dot{I}'(t)}{\dot{I}(t)}=\frac{I_m'(t)}{I_m(t)}+j\varphi'(t)=\gamma(t)+j\Delta\omega(t),\qquad \rho_0=\beta+j\omega_0,\ \ \beta=R_s/L_s$$

variant 2: $\hat{L}(t)=\dfrac{\omega_0}{\omega(t)}L_0(t),\quad \hat{R}(t)=R_0(t)-\gamma(t)\hat{L}(t)$

$$\omega(t)=\omega_0+\Delta\omega(t)$$

Line impedance estimation

The methodological error of the traditional method can be estimated

$$\hat{\underline{z}}_0(t) = \frac{\dot{U}_1(t) - \dot{U}_2(t)}{\dot{I}(t)} = \frac{\underline{z}\,\dot{I}(t) + L\dot{I}^{'}(t)}{\dot{I}(t)} = \underline{z} + L \cdot \rho(t)$$

The error is zero only in the absence of transient processes, when ρ(t) = 0.

Let's consider an example where the instantaneous frequency changes linearly

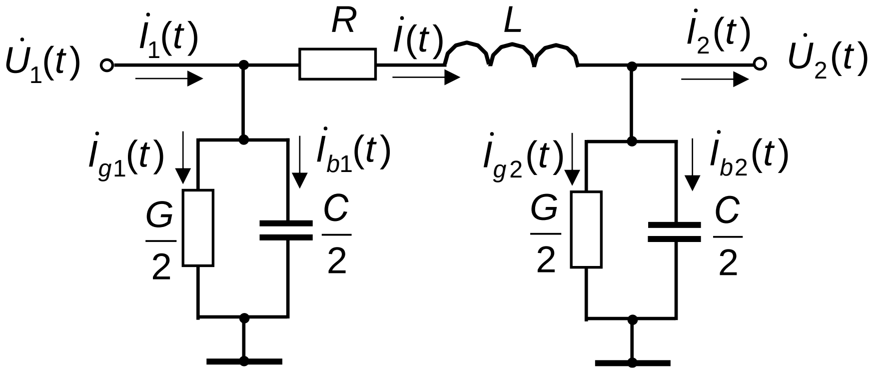
$$\dot{I}(t) = \sqrt{2}^{-1} I_m e^{-j\pi R_f t^2}, \quad \rho(t) = -j2\pi R_f t$$

Total impedance estimation error at zero line resistance

$$TVE(t) \approx \frac{j2\pi R_f}{\omega_0} t \cdot 100\%$$

Line impedance estimation

U-shaped equivalent circuit



The estimate of the line transverse conductivity based on the complex amplitude method is expressed as follows

$$\underline{Y}_0(t) = \frac{\dot{I}_1(t) - \dot{I}_2(t)}{\dot{U}_1(t) - \dot{U}_2(t)} = G_0(t) + j\omega_0 C_0(t)$$

The line capacitance estimation can be obtained from the original differential equations

$$\hat{C}(t) = \frac{\omega_0}{\omega_0 + \Delta\omega_\Delta(t)} C_0(t)$$

The line conductivity is determined by the following expression

$$\hat{G}(t) = G_0(t) - \gamma_\Delta(t)\hat{C}(t)$$

$$\rho_\Delta(t) = \gamma_\Delta(t) + j\Delta\omega_\Delta(t) = \frac{\Delta\dot{U}'(t)}{\Delta\dot{U}(t)}$$

R, *L* are determined by the previously given expressions

Virtual PMU

The abovementioned approach allows the implementation of a virtual PMU for accurate synchrophasor estimation under transient conditions.

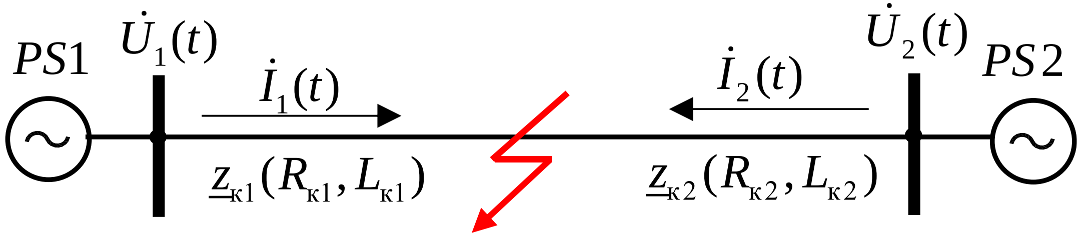
For example, if the voltage and current synchrophasors at the line beginning are known and it is necessary to determine the voltage at the end of the line according to the R-L equivalent circuit, then the following relationship can be used

$$\dot{U}_2(t) = \dot{U}_1(t) - \left(\underline{z} + L \cdot \rho(t)\right)\dot{I}(t)$$

Virtual PMUs provide data verification and estimate voltage and current synchrophasors at substations where real PMUs are unavailable.

The virtual PMU application and analysis of complex instantaneous frequency based on some additional features provide new opportunities for searching for the source of low-frequency oscillations in the power system.

Short-circuit loop impedance estimation



Expressions similar to the method of identifying line parameters

$$\underline{\hat{z}}(t) = \underline{\hat{z}}_0(t)\frac{\rho_0}{\rho_0 + \rho(t)}$$

$$\hat{L}(t) = \frac{\omega_0}{\omega(t)} L_0(t), \quad \hat{R}(t) = R_0(t) - \gamma(t)\hat{L}(t)$$

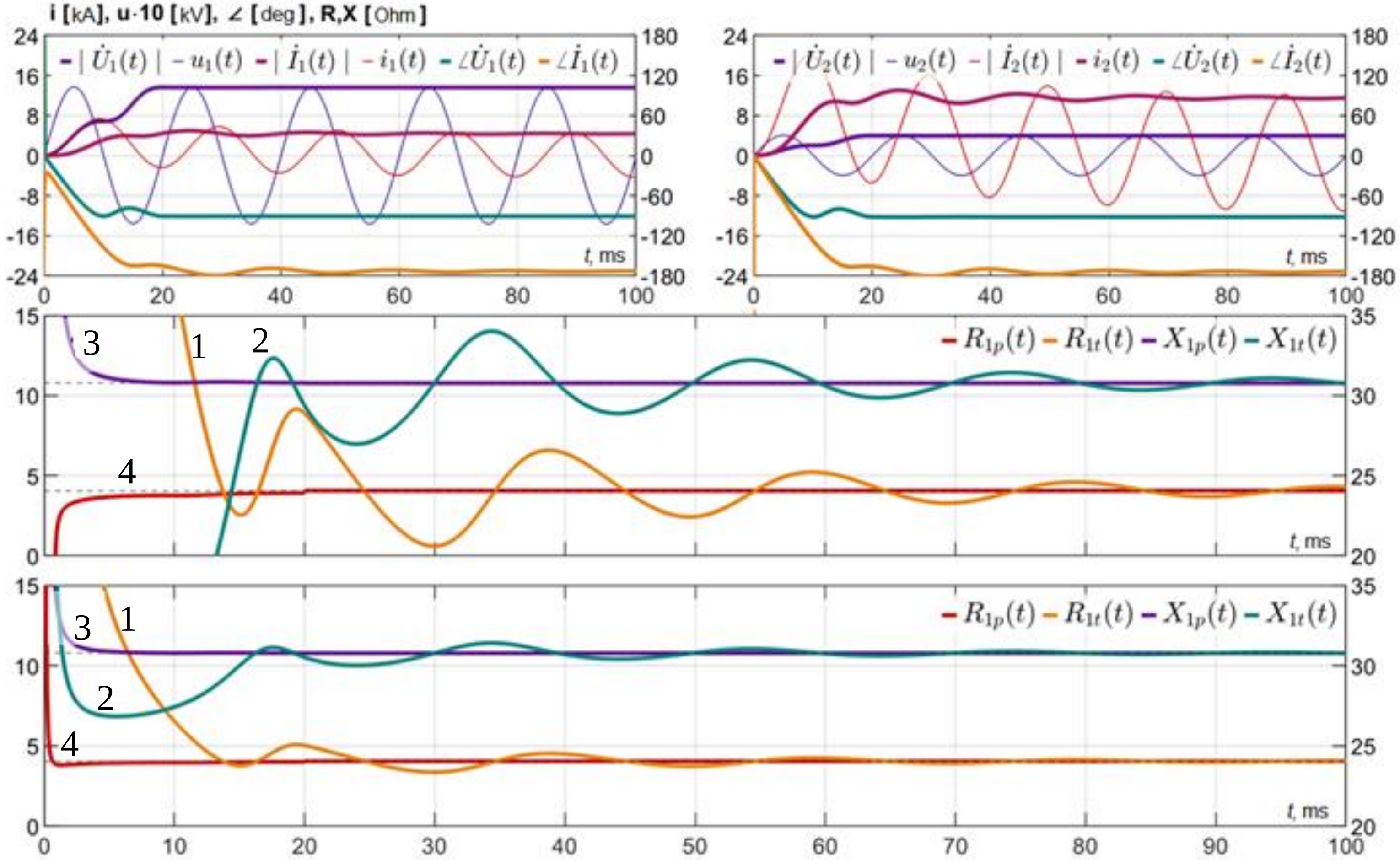
$$\underline{\hat{z}}_0(t) = R_0(t) + j\omega_0 L_0(t)$$

Comparison of one-sided and two-sided synchrophasor measurements

$$\underline{\hat{z}}_0(t) = \frac{\dot{U}_1(t)}{\dot{I}(t)}$$

$$\underline{\hat{z}}_0(t) = \frac{\dot{U}_1(t) - \dot{U}_2(t) + \underline{z}\dot{I}_2(t)}{\dot{I}_1(t) + \dot{I}_2(t)}$$

Short-circuit loop impedance estimation

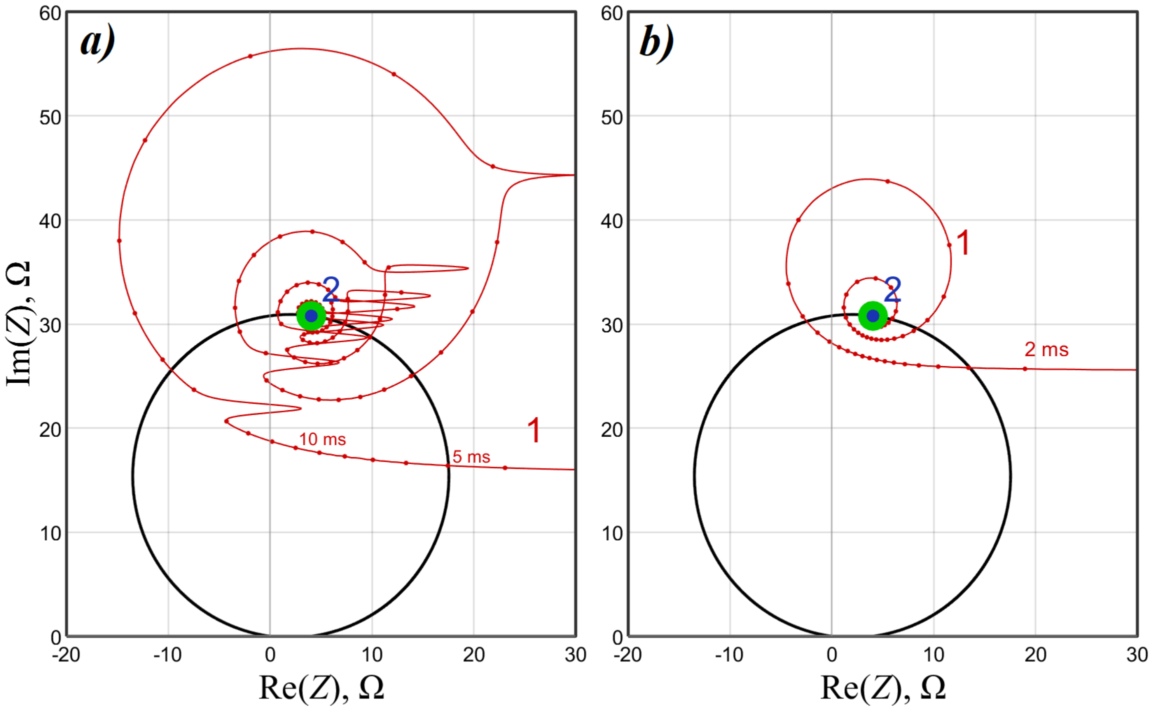


Switching on the line for a short circuit
Curves 1, 2: Fourier Algorithm (FA)
Curves 3, 4: FA + proposed method.

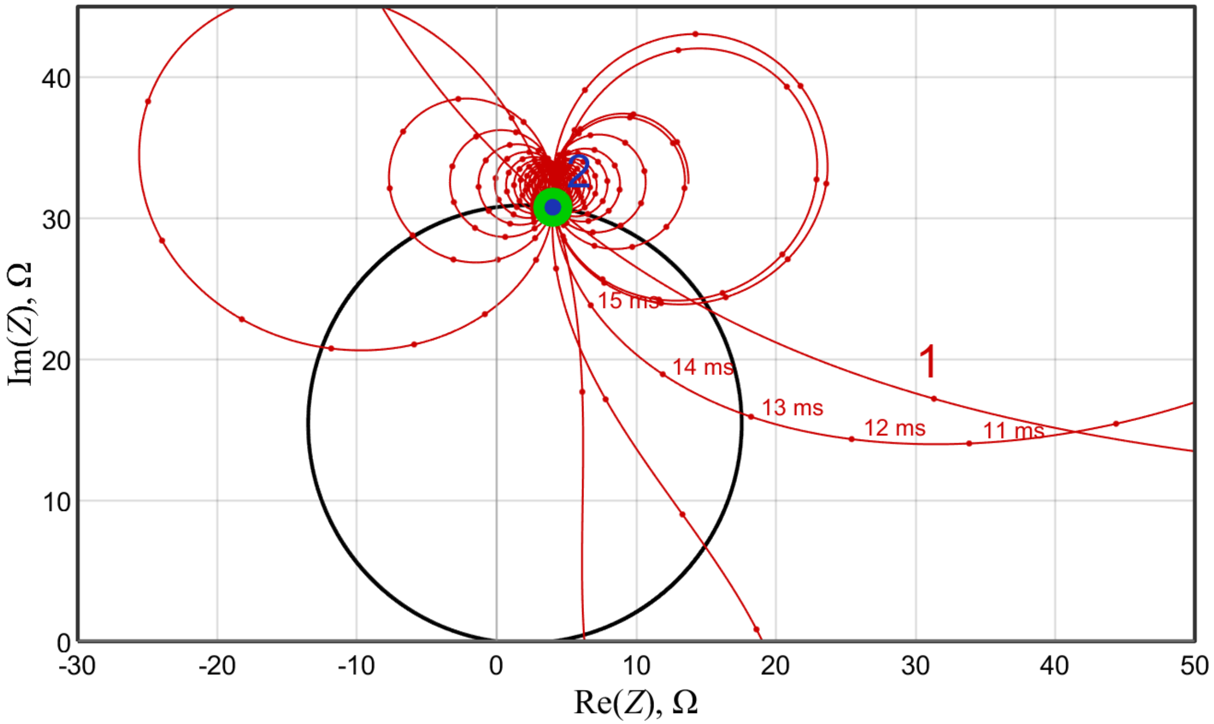
The one-sided synchrophasor measurements

The two-sided synchrophasor measurements

Short-circuit loop impedance estimation

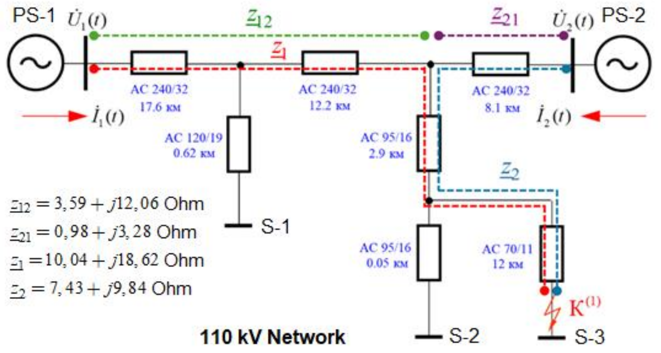


Impedance hodographs:
a) short circuit through a nonlinear arc resistance,
b) electromechanical transient process

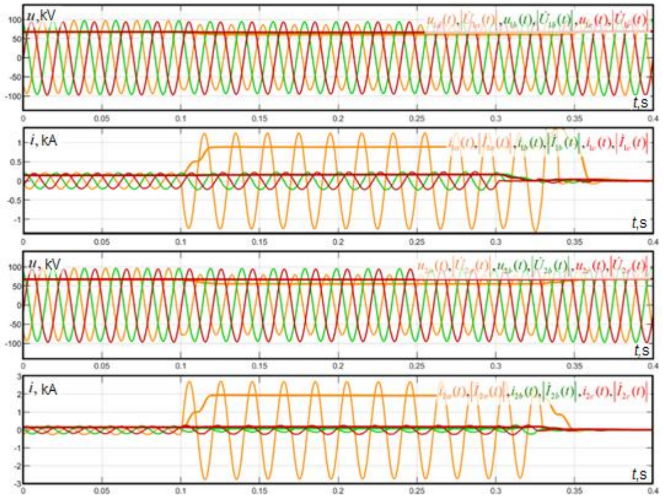


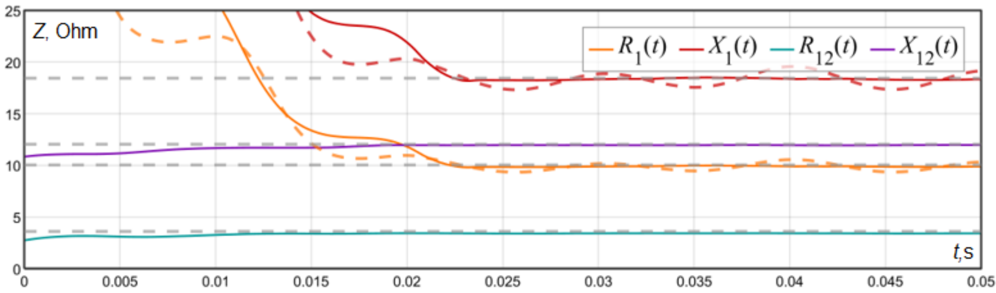
Impedance hodographs for asynchronous mode

Short-circuit loop impedance estimation

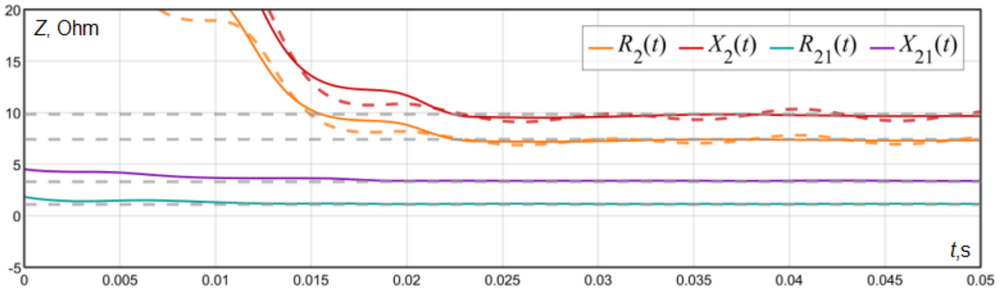


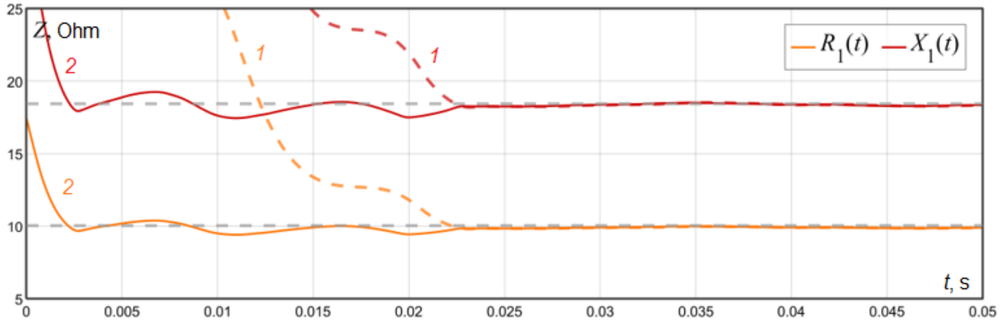
oscillogram of a single-phase short circuit





Single-phase short-circuit loop impedance estimation





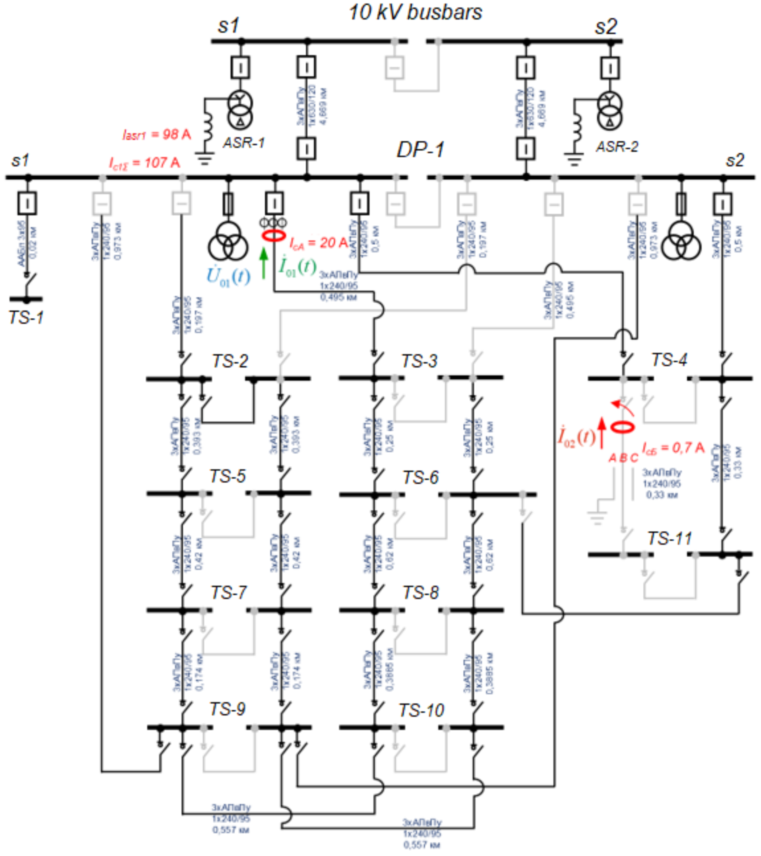
Reducing the influence of initial conditions:
1 – Off
2 – On

Single-phase ground fault protection

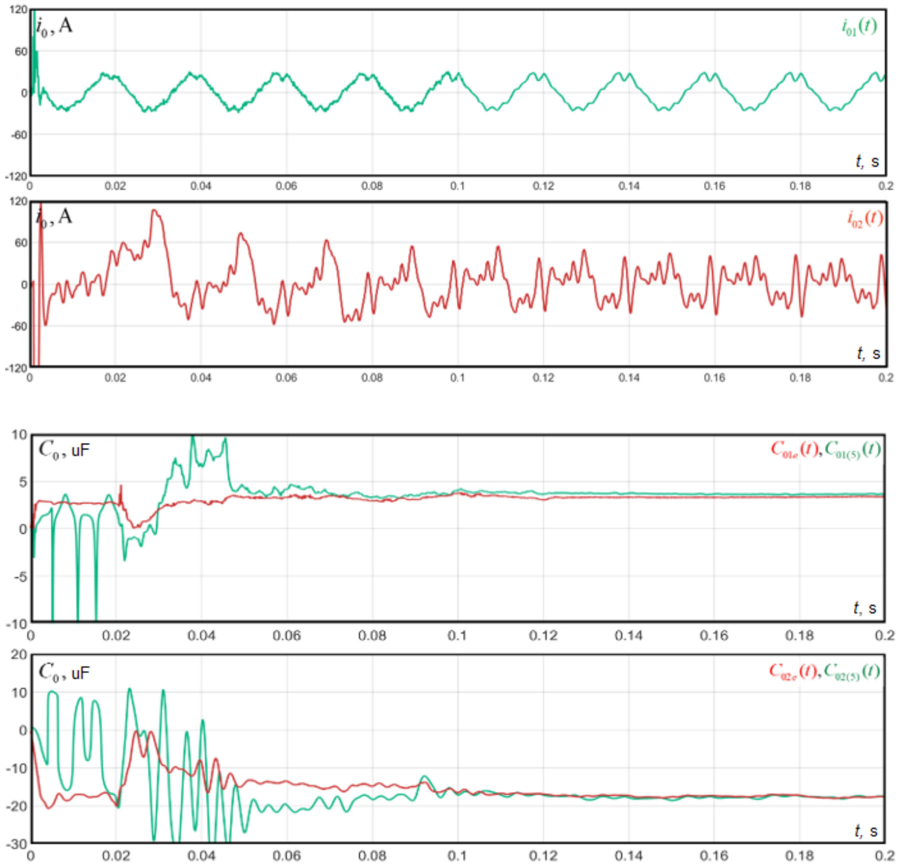
Medium voltage network with ground fault current compensation.

Admittance protection based on zero-sequence (ZS) synchrophasors of fundamental frequency and ZS equivalent harmonic synchrophasors.

$$\hat{C}_0(t)=\frac{\dot{I}_0(t)}{j\omega_0\dot{U}_0(t)+\dot{U}_0'(t)}$$



10 kV network diagram



The transformer differential protection

The transformer differential protection performance can be improved by more accurately estimating the magnitude and phase of the differential current using synchrophasors.
The following expressions represent this estimation method

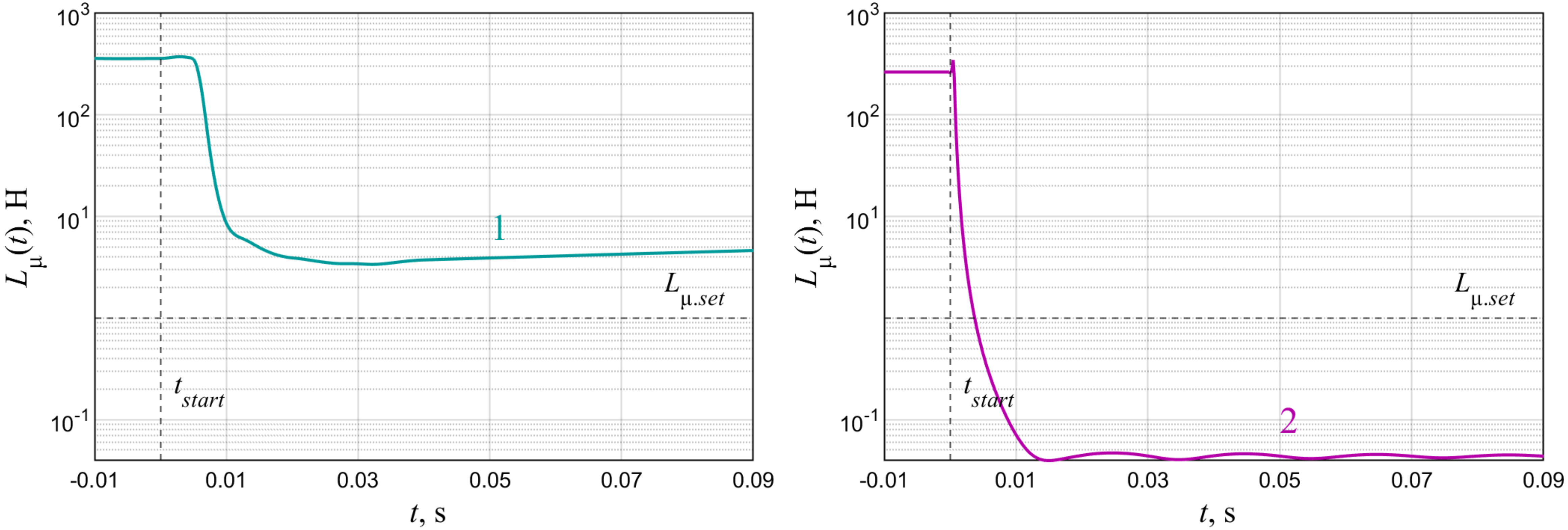
$$I_{\mathrm{d}}(t) = \left|\dot{I}_1(t) + \underline{k}\dot{I}_1'(t) - k_{\mathrm{T}}^{-1}\left(\dot{I}_2(t) + \underline{k}\dot{I}_2'(t)\right)\right|, \qquad \varphi_{\mathrm{d}}(t) = \arg\left(\frac{\dot{I}_1(t) + \underline{k}\dot{I}_1'(t)}{\dot{I}_2(t) + \underline{k}\dot{I}_2'(t)}\right)$$

where $k_{\mathrm{T}} -$ transformation ratio, $\underline{k} -$ a complex coefficient characterizing the transformer winding parameters.

Estimation of magnetizing inductance for recognizing the magnetizing current inrush mode in transformer

$$L_{\mu}(t) = \frac{\dot{U}_1(t) - \underline{z}_1\dot{I}_1(t) - L_1\dot{I}_1'(t)}{\dot{I}_1'(t) + j\omega_0\dot{I}_1(t) - \dot{I}_2'(t) - j\omega_0\dot{I}_2(t)}$$

The transformer differential protection



Magnetizing inductance estimation during an inrush magnetizing current (1) and an internal fault (2)

Digital instrument transformers based on SPT

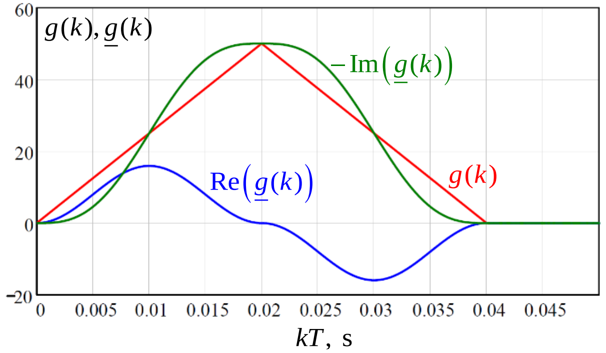
Digital combined instrument transformers for 6-35 kV networks.

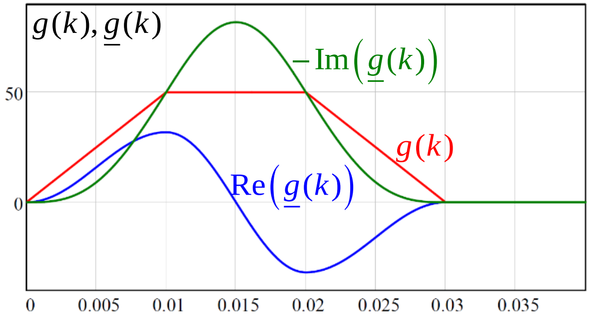
Rogowski coil and capacitive voltage divider.

Wide measuring range, no core saturation or residual magnetization effects.

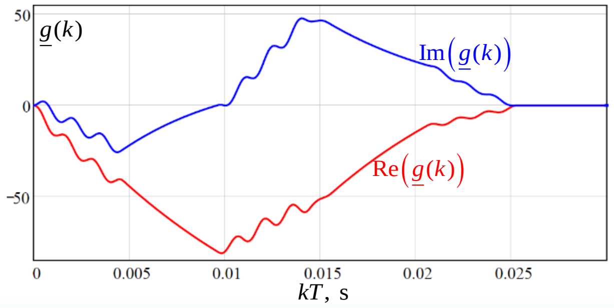
Support for SV and SP streams (current and voltage synchrophasors).

Digital filters with complex pulse function for accurate and fast measurements of current synchrophasors.

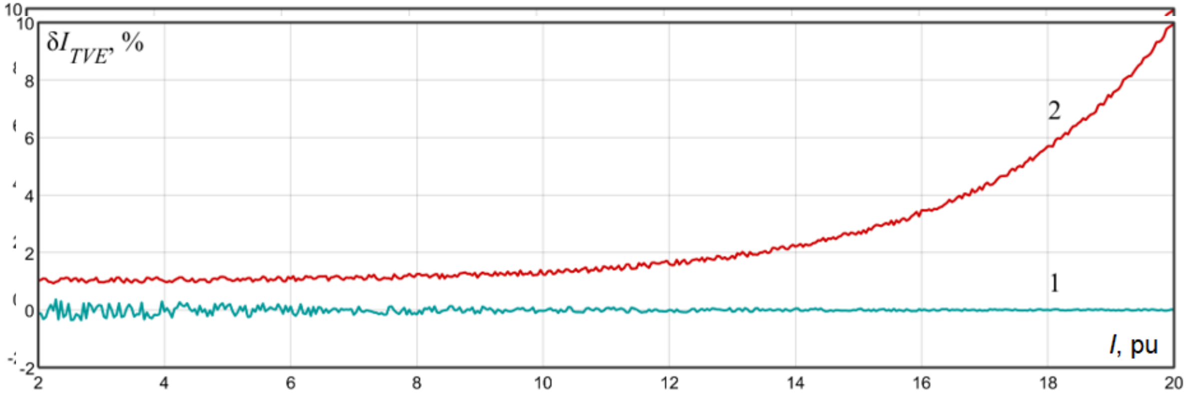




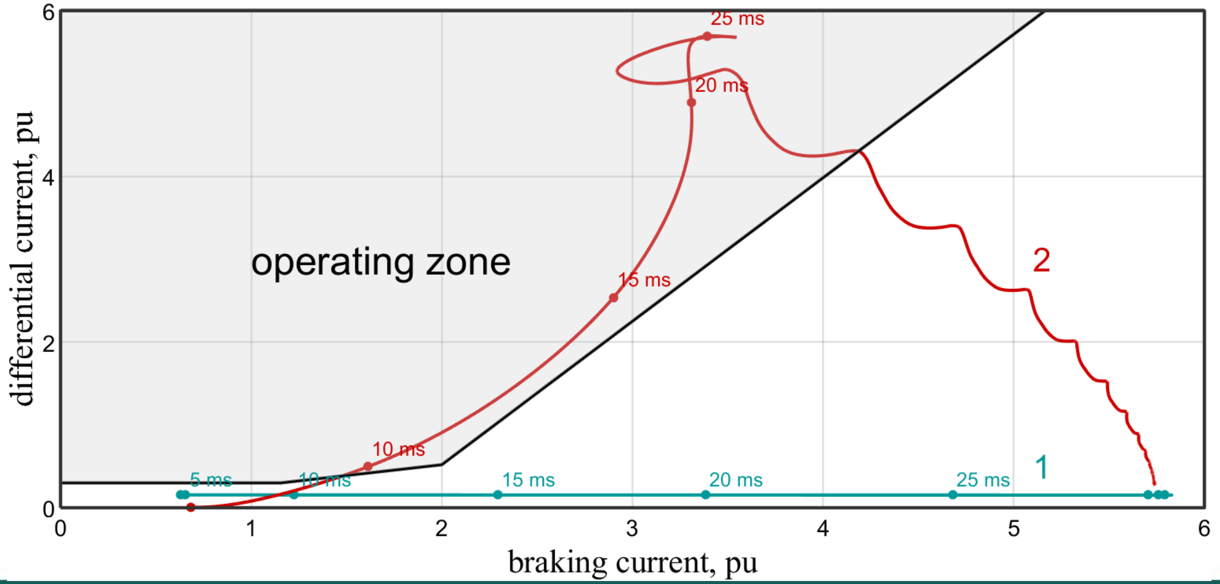
Functions: measurement, protection, emergency event recorder



Digital instrument transformers based on SPT

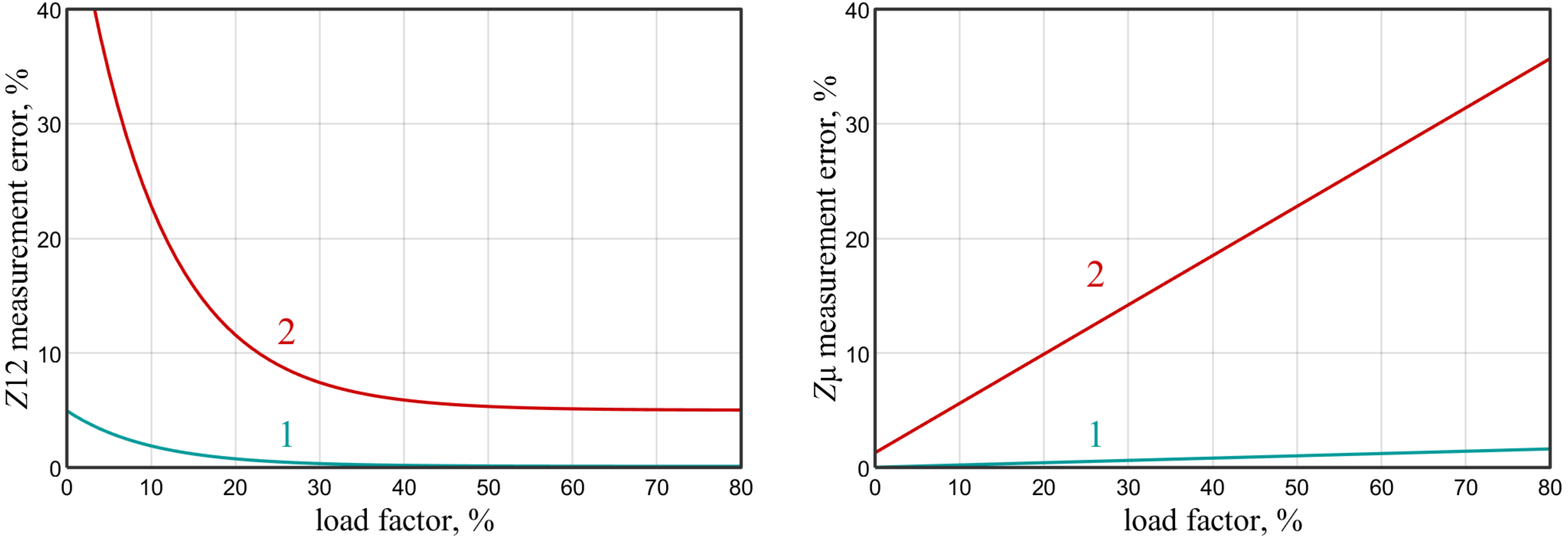


Total vector error of current measurements in a digital (1) and electromagnetic (2) instrument transformers



The selectivity of transformer differential protection during external short circuits is one of its important functions. Figure compares differential protection characteristics based on measurements of digital (1) and electromagnetic (2) current transformers during external short circuits. The protection simulation was performed using data from a real step-down substation.

Digital instrument transformers based on SPT



Transformer parameter’s estimation digital (curve 1) and electromagnetic (curve 2) current transformer

CONCLUSION

The developed methods for assessing line and transformer parameters allow for the improvement of differential and distance protection algorithms, and protection against single-phase ground faults.

The developed methods ensure effective operation of protection during transient processes.

The developed methods are most effective in combination with digital instrument current transformers without saturation and residual magnetization effects.

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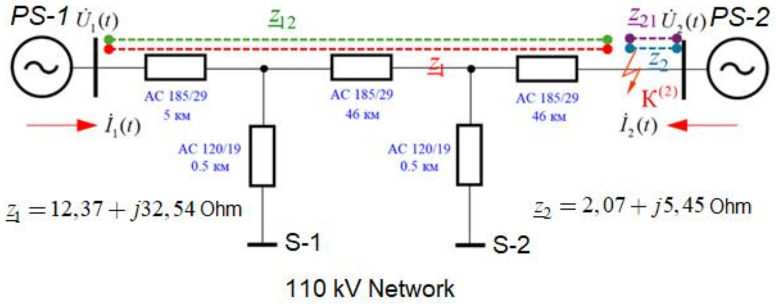
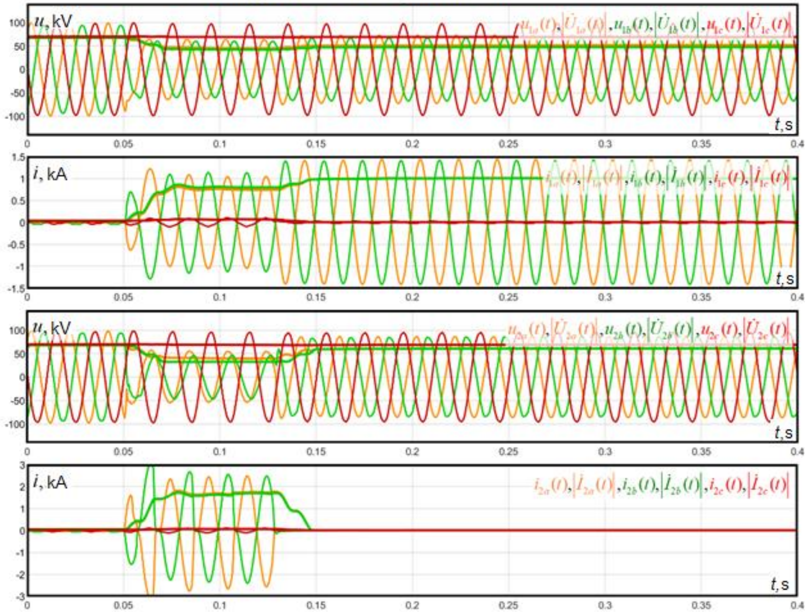
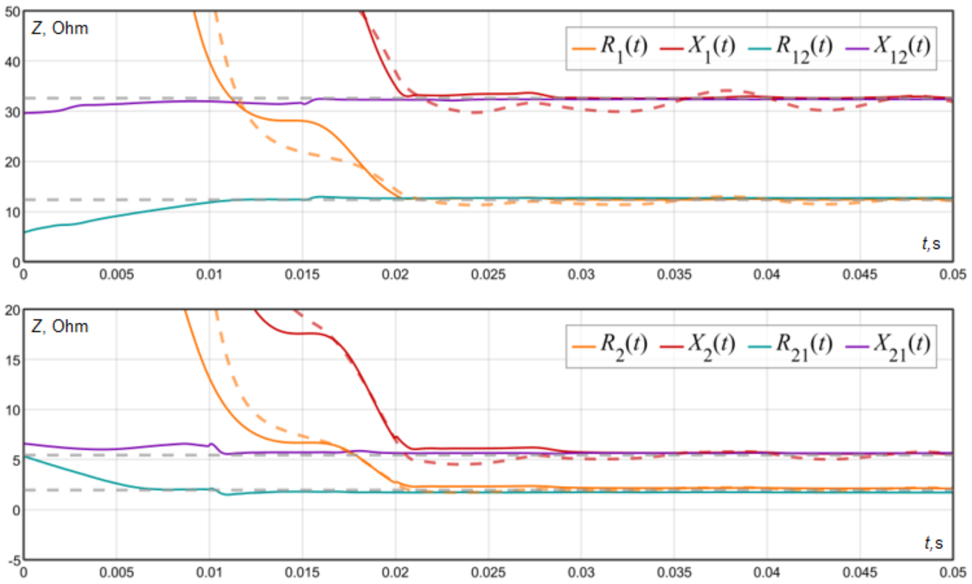
Short-circuit loop impedance estimation



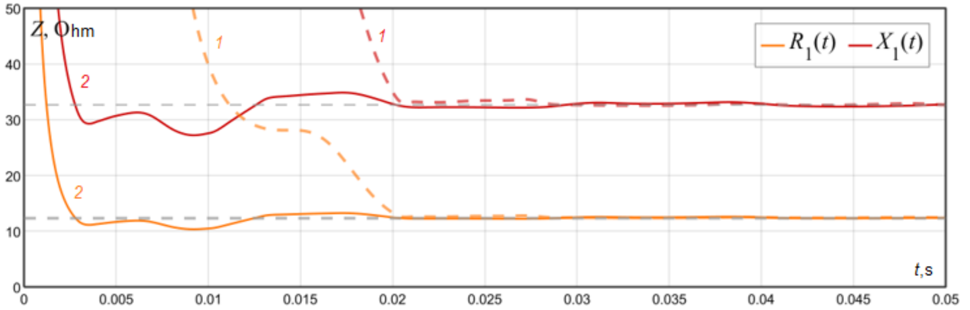
110 kV Network

oscillogram of a two-phase short circuit





Two-phase short-circuit loop impedance estimation



Reducing the influence of initial conditions:
1 – Off
2 – On

ECIT: short-circuit loop impedance estimation