Numerical Algorithm for Fault Distance Calculation and Arcing Faults Detection on Transmission Lines Using Single End Data

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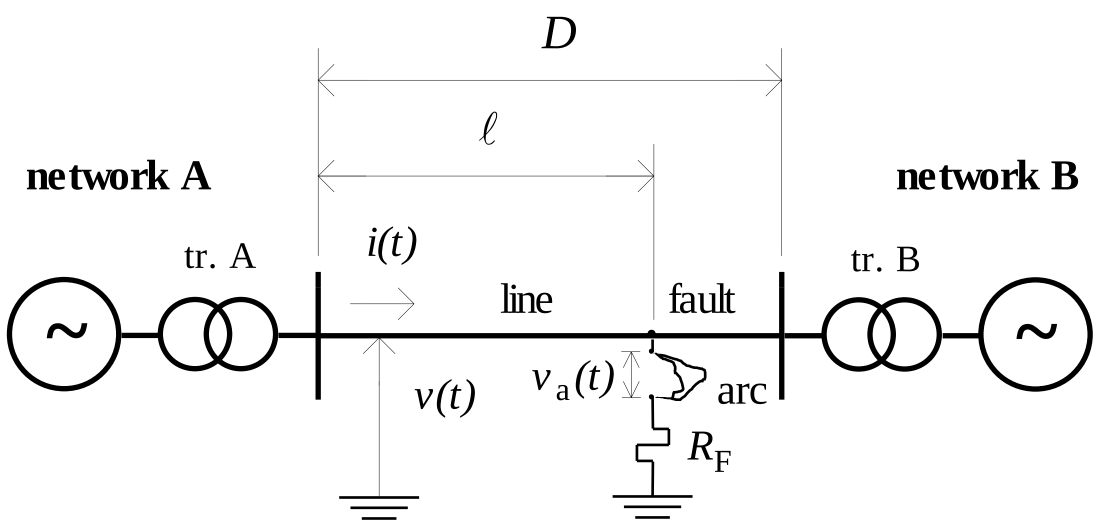
Introduction

A numerical algorithm for fault distance calculation and arcing faults detection on transmission lines will be presented.

The most frequent single-phase to ground fault will be considered.

The current path for ground faults will include the electrical arc and the tower grounding resistance.

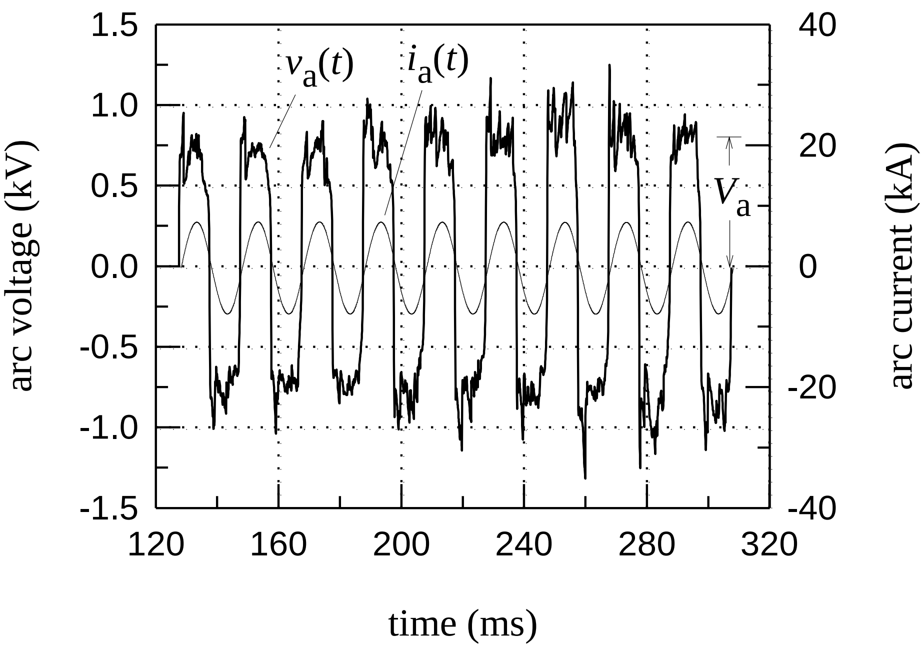


The fault distance will be calculated using the fundamental harmonics of the phase voltages and line currents.

The arc voltage amplitude will be calculated using the fault distance and the third harmonics of the phase voltages and line currents.

From the calculated value of the arc voltage amplitude it can be concluded if the fault is arcing fault or arcless fault.

Long Electric Arc Characteristics

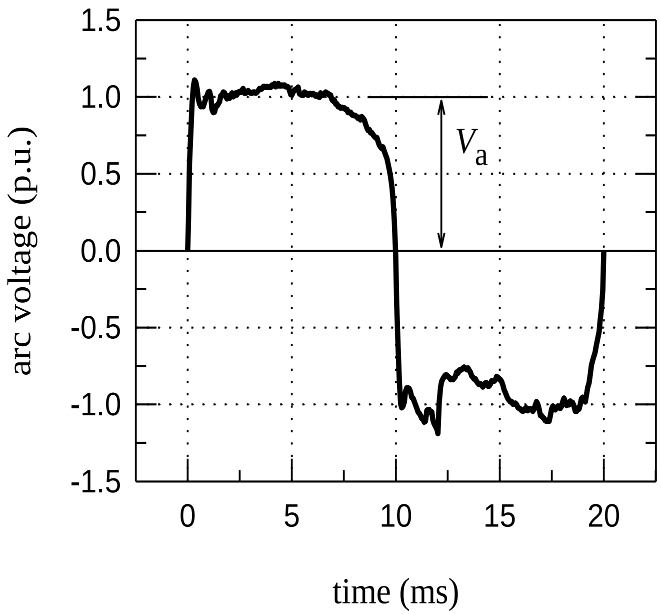


Real arc voltage and current waveforms

The long electric arc in free air is a plasma discharge.

The highly nonlinear variations of the arc resistance causes the arc voltage waveform distortion into a near square wave with arc voltage amplitude V_a.

The sign of the arc voltage wave v_a is the same as sign of the arc current i_a.



Typical accepted arc voltage wave shape.

The arc model can be represented by Fourier series containing odd sine components only

$$v_a(t) = \sum_{h=1}^{\infty} k_h V_a \sin(h\omega t)$$

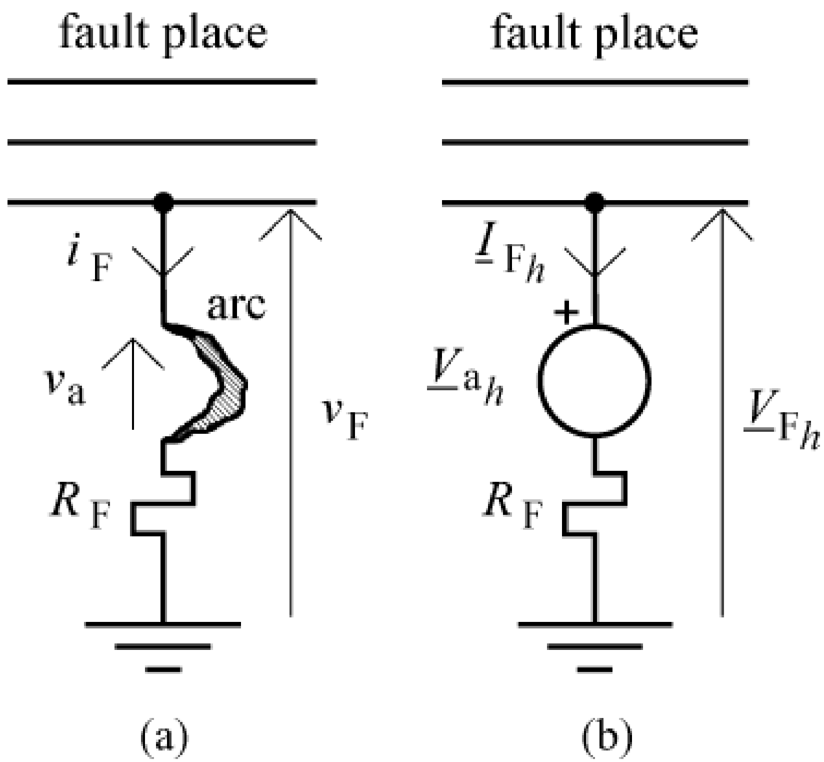
where

$h = 1, 3, 5, 7, \ldots$ is the harmonic order, and
k_h is the coefficient of the h-th harmonic.

Using the DFT algorithm it is easy to obtain coefficients k_h for accepted arc voltage model.

h	1	3	5	7
k_h	1.23	0.393	0.213	0.135

The Fault Model



Fault model given
(a) in time domain, and
(b) in spectral domain for the *h*-th harmonic.

The current path includes the electrical arc and the tower footing resistance.

The *h*-th harmonic of the fault voltage can be expressed by next relation

$$\underline{V}_{Fh} = \underline{V}_{ah} + R_F \underline{I}_{Fh}$$

where

$\underline{V}_{ah}$ is *h*-th harmonic of the arc voltage, and

$\underline{I}_{Fh}$ is *h*-th harmonic of the fault (arc) current.

ϕ

The phase of the first harmonic of the arc voltage has to be the same as the phase of the fault current.

The phase of the third harmonic of the arc voltage has to be three times greater than the phase of the first harmonic of arc current.

This observation could be expressed as:

$$\underline{V}_{a1} = \underline{k}_1 V_a$$

$$\underline{V}_{a3} = \underline{k}_3 V_a$$

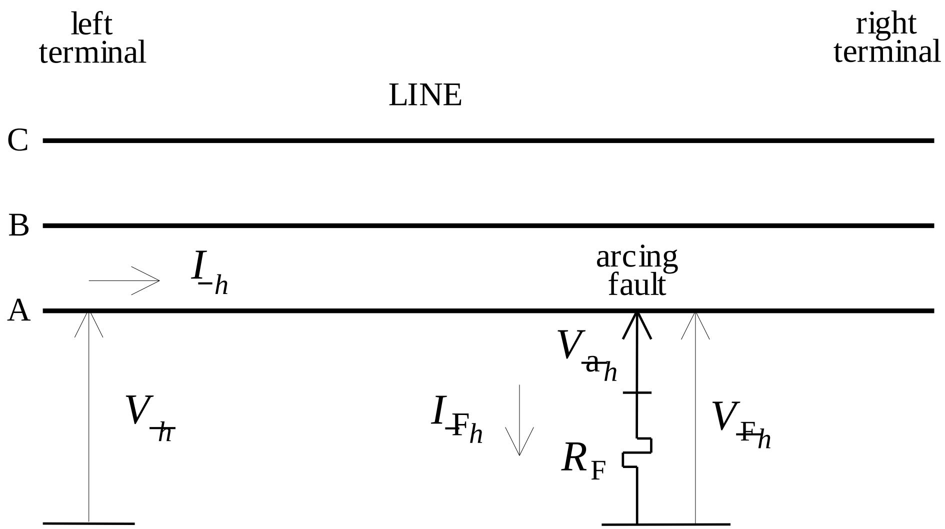
where:

$\underline{V}_{a1}$ and $\underline{V}_{a3}$ - are vectors of the first and the third harmonics of the arc voltage

$\underline{k}_1 = k_1 \angle \phi$ $\underline{k}_3 = k_3 \angle 3\phi$

ϕ is the phase of the first harmonic of the fault current

The Faulted Loop Equation



Single-phase to ground arcing fault on three phase line

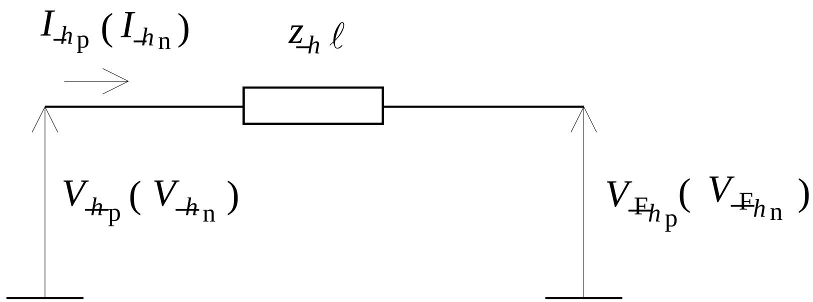
V_h is the h-th harmonic of the left line terminal phase voltage,

I_h is the is the h-th harmonic of the left line terminal current,

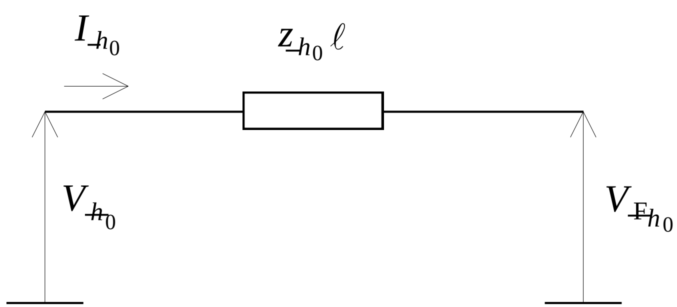
V_{ah} is is the h-th harmonic of the arc voltage,

R_F is fault resistance, and

V_{Fh} is is the h-th harmonic of the faulted phase voltage on the fault place.



Positive and negative sequence line equivalent circuit



Zero sequence line equivalent circuit

The three-phase circuit can be presented by three single-phase equivalent circuits: positive (p), negative (n) and zero sequence (0) equivalent circuits.

z_h is positive or negative sequence line impedance for the *h*-th harmonic, and

z_{h0} is zero sequence line impedance for the *h*-th harmonic.

All voltages and currents are sequence networks variables.

For the equivalent sequences circuits the following equations can be written:

$$\underline{V}_{h_\mathrm{p}} = \underline{z}_h \ell \underline{I}_{h_\mathrm{p}} + \underline{V}_{\mathrm{F}h_\mathrm{p}}$$

$$\underline{V}_{h_\mathrm{n}} = \underline{z}_h \ell \underline{I}_{h_\mathrm{n}} + \underline{V}_{\mathrm{F}h_\mathrm{n}}$$

$$\underline{V}_{h_0} = \underline{z}_h \ell \underline{I}_{h_0} + \underline{V}_{\mathrm{F}h_0}$$

By using basic symmetrical components equations:

$$\underline{V}_h = \underline{V}_{h_\mathrm{p}} + \underline{V}_{h_\mathrm{n}} + \underline{V}_{h_0}$$

$$\underline{V}_{\mathrm{F}h} = \underline{V}_{\mathrm{F}h_\mathrm{p}} + \underline{V}_{\mathrm{F}h_\mathrm{n}} + \underline{V}_{\mathrm{F}h_0}$$

finally the following faulted loop equation can be written:

$$\underline{V}_h = \underline{z}_h (\underline{I}_h + \underline{k}_{\mathrm{z}h} \underline{I}_{h0}) \ell + \underline{V}_{\mathrm{F}h}$$

where $\underline{k}_{\mathrm{z}h} = (\underline{z}_{0h} - \underline{z}_h) / \underline{z}_h$ is the zero sequence compensation factor.

Fault Distance Calculation

Substituting fault model equation into faulted loop equations for fundamental harmonic, we get:

$$\underline{V}_1 = \underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\ell + \underline{V}_{a1} + R_F\underline{I}_{F1}$$

The phasor of the fundamental harmonic of the arc voltage can be expressed as:

$$\underline{V}_{a1} = \underline{k}_1 V_a = k_1\angle\phi V_a = k_1\frac{\underline{I}_{F1}}{\left|\underline{I}_{F1}\right|}V_a = R_{a1}\underline{I}_{F1}$$

where

$$R_{a1} = k_1\frac{\underline{I}_{F1}}{\left|\underline{I}_{F1}\right|}$$

is is the arc resistance for the fundamental harmonic.

Negative-sequence network is passive, so the fault current can be approximated by next relation:

$$\underline{I}_{\mathrm{F1}} = 3\underline{I}_{\mathrm{F1n}} = 3c_{\mathrm{F1}}\underline{I}_{\mathrm{1n}}$$

where c_{F1} is a real proportional coefficient, and I_{1n} is negative-sequence current measured at the relay place. The value of c_{F1} is not necessary to be known in advance.

Using above assumption, faulted loop equation gets the form:

$$\underline{V}_1 = \underline{z}_1(\underline{I}_1 + \underline{k}_{\mathrm{z1}}\underline{I}_{10})\ell + R_{\mathrm{Fe1}}\underline{I}_{\mathrm{1n}}$$

where

$$R_{\mathrm{Fe1}} = 3c_{\mathrm{F1}}(R_{\mathrm{a1}} + R_{\mathrm{F}})$$

From the complex faulted loop equation the unknown fault distance can be calculated as:

$$\ell = \frac{\mathrm{Re}\{\underline{V}_1\}\,\mathrm{Im}\{\underline{I}_{\mathrm{1n}}\} - \mathrm{Im}\{\underline{V}_1\}\,\mathrm{Re}\{\underline{I}_{\mathrm{1n}}\}}{\mathrm{Re}\{\underline{z}_1(\underline{I}_1 + \underline{k}_{\mathrm{z1}}\underline{I}_{10})\}\,\mathrm{Im}\{\underline{I}_{\mathrm{1n}}\} - \mathrm{Re}\{\underline{I}_{\mathrm{1n}}\}\,\mathrm{Im}\{\underline{z}_1(\underline{I}_1 + \underline{k}_{\mathrm{z1}}\underline{I}_{10})\}}$$

Arc Voltage Amplitude Calculation

After calculating the fault distance we can calculate the fundamental and the third harmonic of the fault place voltage:

$$V_{F1} = \left|\underline{V}_{F1}\right| = \left|\underline{V}_1 - \underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\ell\right|$$

$$V_{F3} = \left|\underline{V}_{F3}\right| = \left|\underline{V}_3 - \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\ell\right|$$

Fault place equations for fundamental and third harmonics are:

$$\underline{V}_{F1} = \underline{V}_{a1} + R_F \underline{I}_{F1}$$

$$\underline{V}_{F3} = \underline{V}_{a3} + R_F \underline{I}_{F3}$$

From those two complex equations we can obtain next two scalar equations:

$$V_{F1} = \left|\underline{V}_{a1} + R_F \underline{I}_{F1}\right| = V_{a1} + R_F I_{F1}$$

$$V_{F3}^2 = V_{a3}^2 + (R_F I_{F3})^2$$

For the negative-sequence network we can suppose that:

$$I_{\mathrm{F1}} = 3c_{\mathrm{F}} I_{\mathrm{1n}}$$

$$I_{\mathrm{F3}} = 3c_{\mathrm{F}} I_{\mathrm{3n}}$$

Using above equations, fault place equations can get next form:

$$k_1 V_{\mathrm{a}} + I_{\mathrm{1n}} R_{\mathrm{e}} = V_{\mathrm{F1}}$$

$$k_3^2 V_{\mathrm{a}}^2 - I_{\mathrm{3n}}^2 R_{\mathrm{e}}^2 = V_{\mathrm{F3}}^2$$

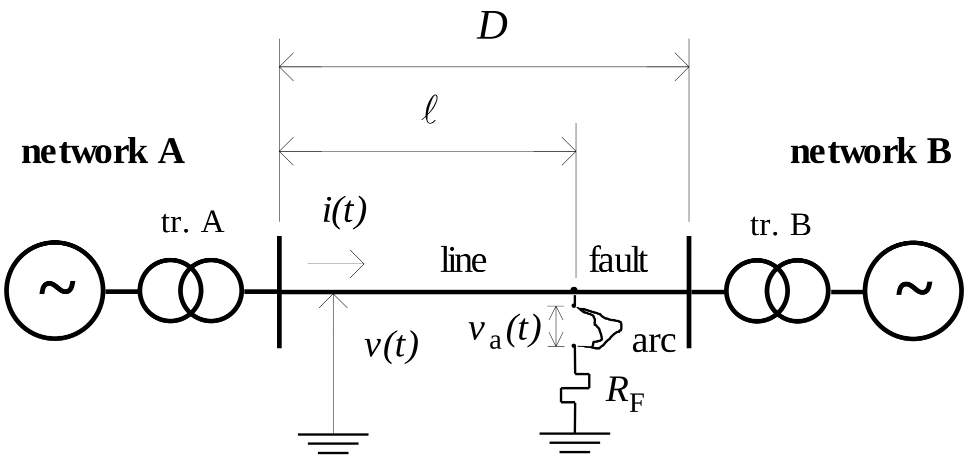
Those equations can be solved by *V*a:

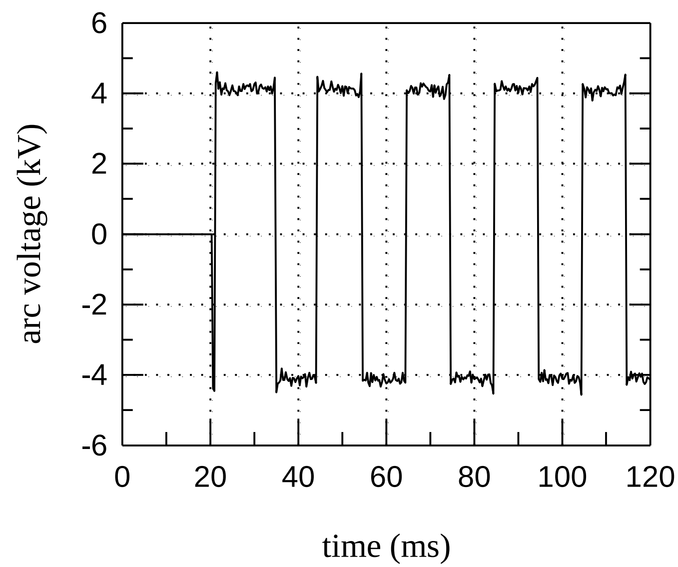
$$V_{\mathrm{a}} = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

$$a = k_3^2 - k_1^2 \left(\frac{I_{\mathrm{3n}}}{I_{\mathrm{1n}}}\right)^2 \quad b = 2V_{\mathrm{F1}} k_1 \left(\frac{I_{\mathrm{3n}}}{I_{\mathrm{1n}}}\right)^2 \quad c = -\left[V_{\mathrm{F1}}^2 \left(\frac{I_{\mathrm{3n}}}{I_{\mathrm{1n}}}\right)^2 + V_{\mathrm{F3}}^2\right]$$

Computer Simulated Tests

The tests have been done using the Electromagnetic Transient Program.

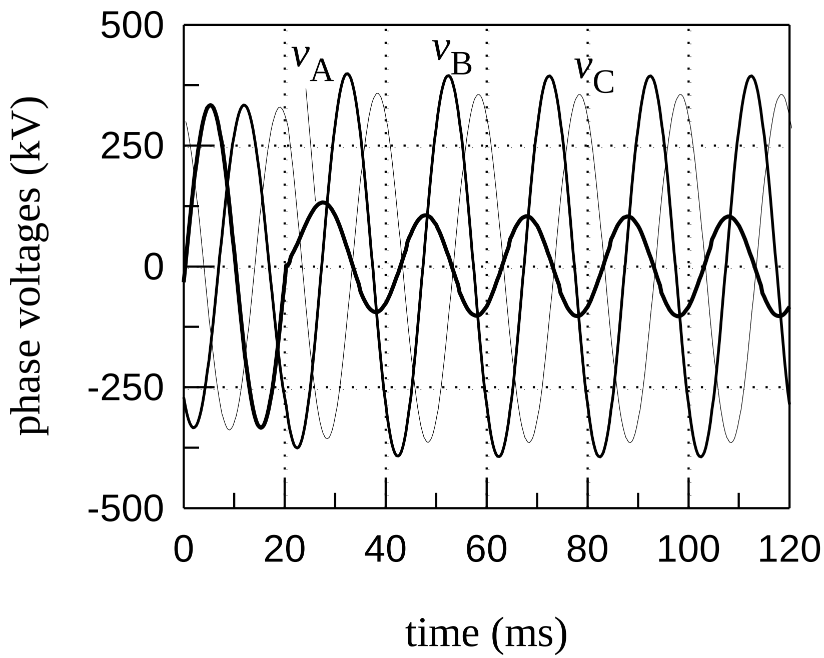




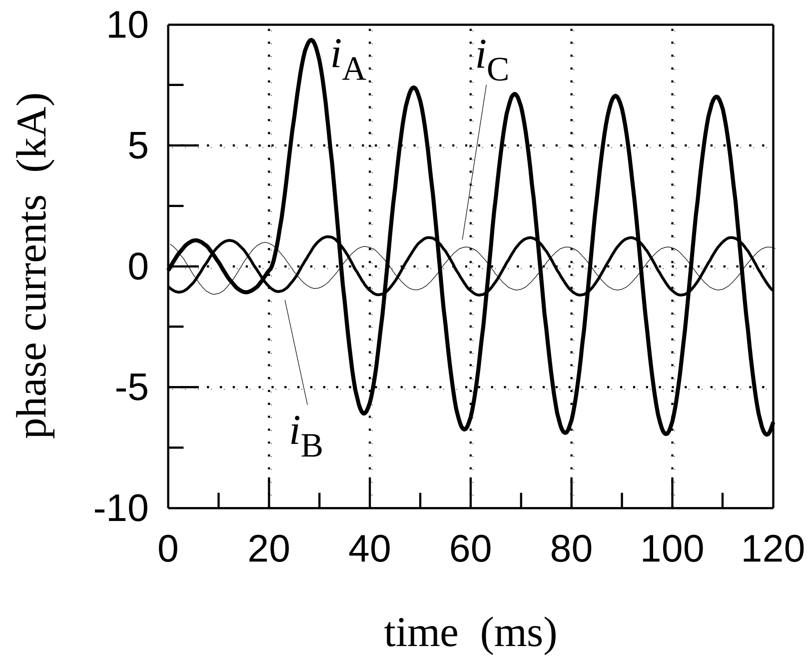
Single-phase to ground faults are simulated at different points on the transmission line.
The arc voltage used by EMTP is assumed to be of square wave shape with amplitude of $V_a = 4$ kV, corrupted by the random noise.
Fault resistance were $R_F = 8$.

Impute phase voltages and line currents, measurable at relay place, calculated by EMTP for the close-in (ℓ = 10 km) fault are plotted in next two figures.

We can see that fault current has high decaying DC component what means that test was performed with the most difficult operating conditions.

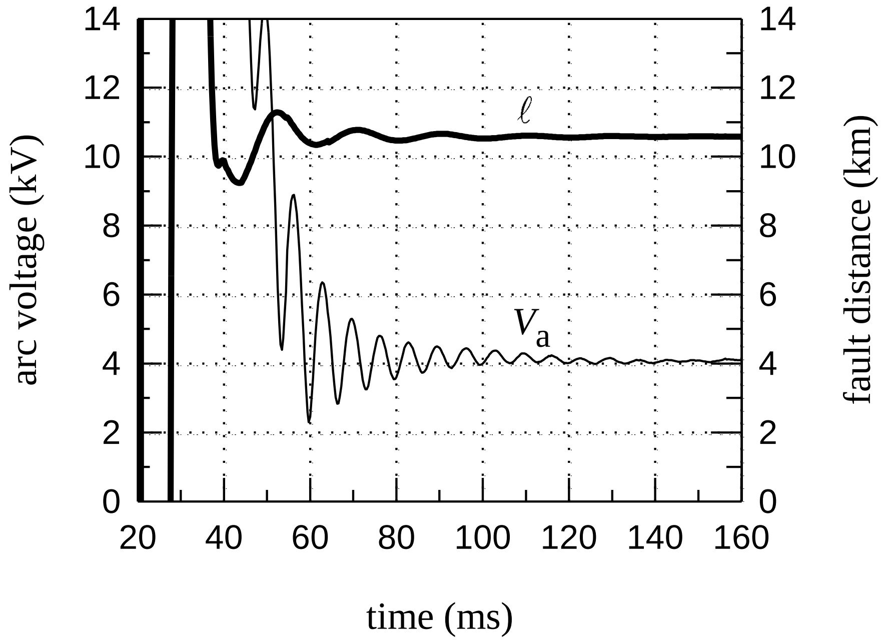


Distorted input voltages generated by EMTP



Distorted input currents generated by EMTP

The fault distance and arc voltage calculated by algorithm are given in next figure:



The exact unknown model parameters (l = 10 km and V_a = 4 kV) are obtained fast and accurate.

Field Testing

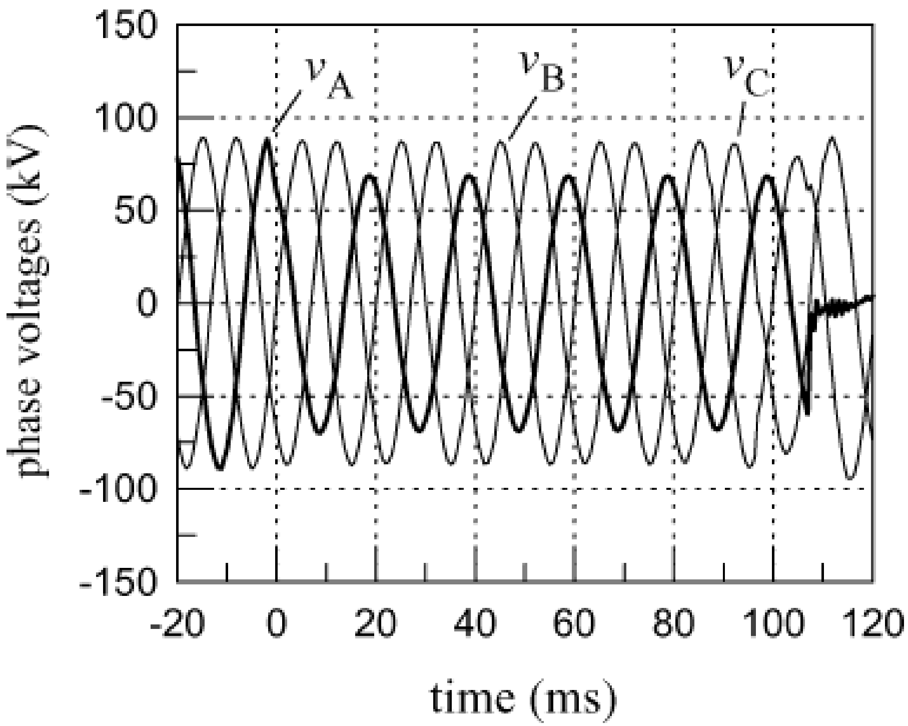
In order to check the validity of the algorithm presented, voltages and currents, recorded during faults on a 110-kV network, are processed.

A typical example of an arcing fault will be demonstrated.

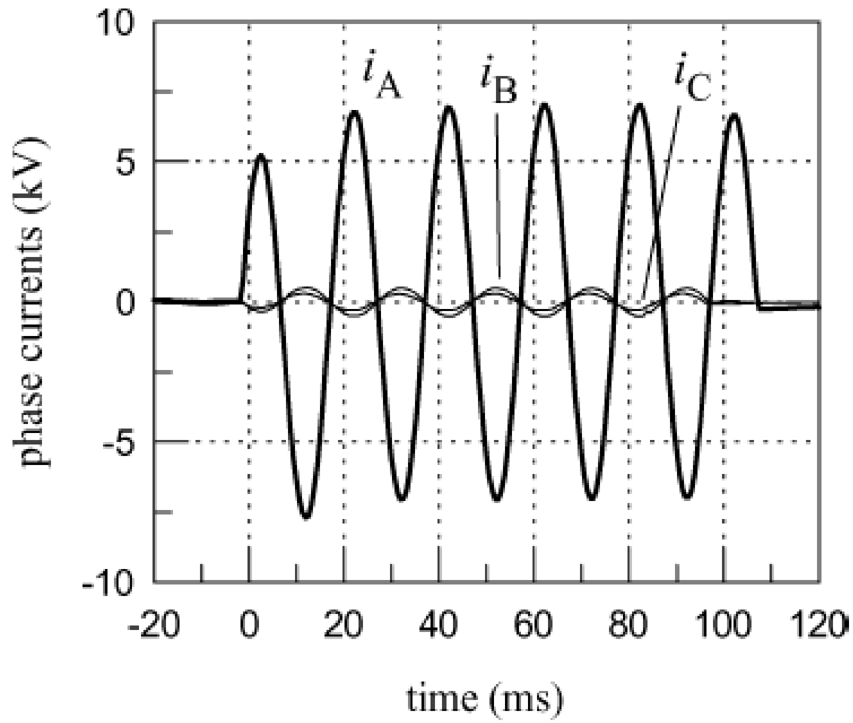
Voltages and currents measured by the relay before and during a single-phase-line-toground fault over arc are respectively presented.

All signals are sampled with the sampling frequency 1600 Hz.

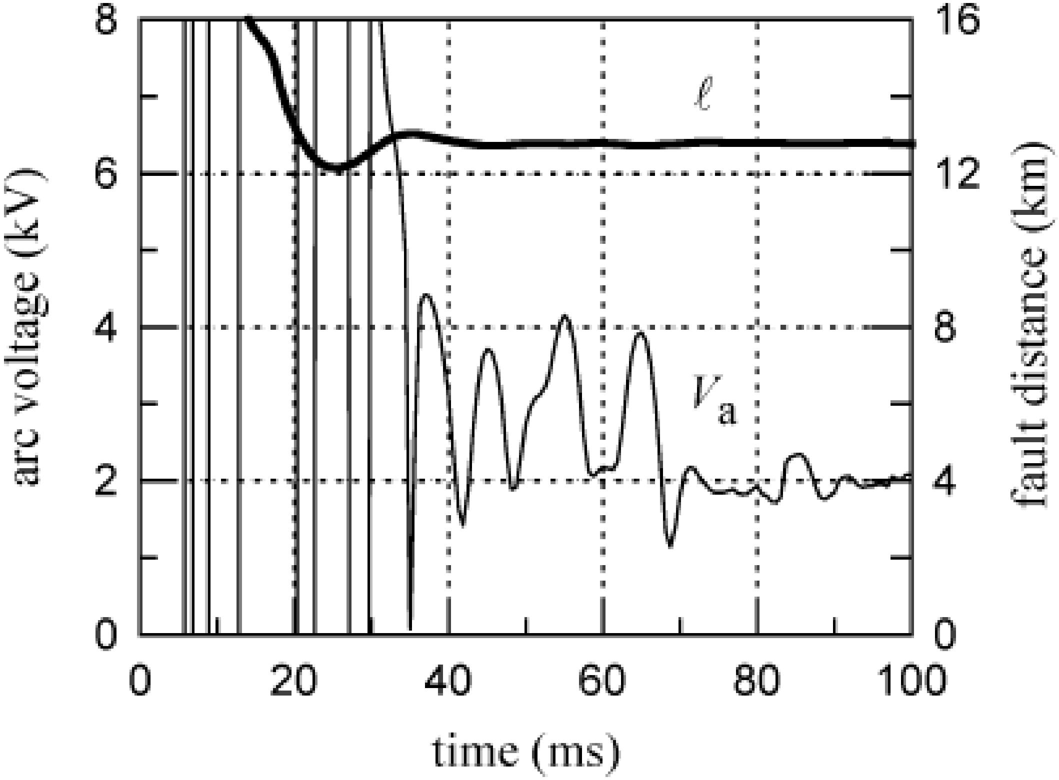
The duration of data window was 20 ms.



Input voltages measured by the relay.



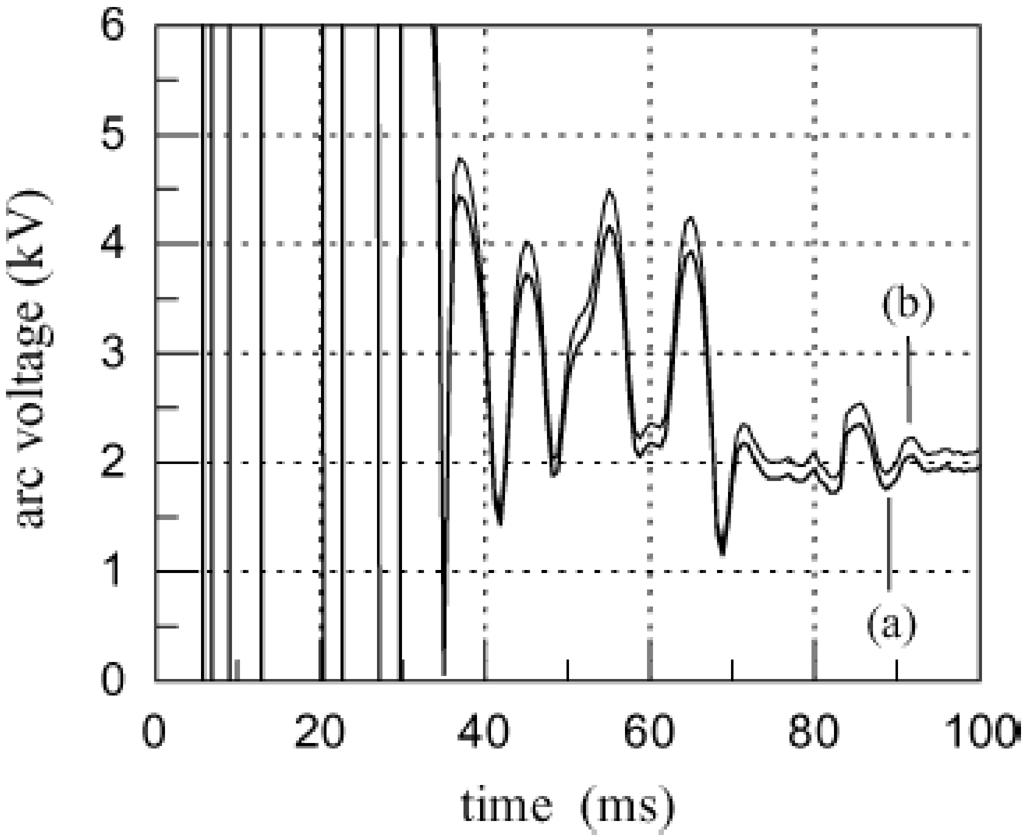
Input currents measured by the relay.



Calculated arc voltage amplitude and fault distance.

The exact fault location 12.8 km was calculated.

The arc voltage amplitude was approximately 2 kV.



Arc voltage amplitude calculated using the arc voltage model given
, curve (a), and using the square-wave arc model, curve (b).

Conclusions

- A new numerical algorithm for fault distance calculation and arcing faults recognition is developed.
- The algorithm is derived by processing line terminal voltages and currents during the period between the fault inception and fault clearance.
- Only fundamental and third harmonic phasors calculated by Discrete Fourier Technique are needed for algorithm development.
- The arc voltage amplitude calculated in algorithm can be used for blocking reclosing of transmissions lines with permanent faults, whereas the fault distance calculated in algorithm can be used for distance protection or for fault location.
- The algorithm was successfully tested with data obtained through computer simulation and data recorded in the real power system.