A Novel Approach to the Distance Protection, Fault Location And Arcing Faults Recognition

Z.M. Radojević, *S.M., IEEE*, H.-J. Koglin, V.V. Terzija, *S.M., IEEE*

ABSTRACT: In this paper a novel two-stage numerical algorithm devoted to fault distance calculation and arcing faults recognition is presented. The first algorithm stage serves for the fault distance calculation. Fault distance is calculated from the fundamental frequency phase voltages and currents phasors, utilizing the positive- and zero-sequence impedance of the line as an input parameter. The second algorithm stage serves for the arc voltage amplitude calculation. It utilizes the fault distance obtained from the first algorithm stage and the third harmonics of the terminal phase voltages and line currents phasors as input parameters. From the calculated value of arc voltage amplitude it can be concluded if the fault is transient arcing fault or permanent arcless fault. The phasors needed for algorithm development are calculated by using the Discrete Fourier Technique. In the paper the solution for the most frequent phase-to-ground faults is given. The results of algorithm testing through computer simulation and processing of real field data records are given.

Keywords: numerical protection, distance protection, fault location, autoreclosure, arcing faults, spectral analysis.

I. INTRODUCTION

In order to improve the quality of power delivery, a variety of digital devices with fault location modules are developed and proposed in the open literature. Distance relays calculate the fault distance in real-time, while the fault location programs are executed off-line after the fault occurrence using stored fault data. The rapid progress in microprocessor technology gives us a hope that some numerical algorithms devoted to fault location will be used as algorithms for distance protection, particularly the so called "one terminal fault location algorithms", which use only data measured at relay location [1].

In the last decade the problem of blocking automatic reclosing on permanent faults is also investigated. It is known that somewhat about 80% to as high as 90% of faults on most lines are transient. For such faults the service can be restored by automatically reclosing the power circuit breaker. This can improve the power system transient stability and reliability, providing by this much higher service continuity to the costumes. However, reclosure onto a permanent fault may aggravate the potential damage to the system and equipment. For some EHV lines, particularly those near generating plants, the classical automatic reclosing of breakers cannot be used. New numerical protection algorithms gave as opportunity to control the automating reclosing from a substation computer. The main problem to be solved here is to make distinction between permanent and transient faults. Some interesting concepts were proposed in the past. Most of them were based on the analysis of voltage on the opened phase conductor during the reclosing dead time [2-3]. The newly developed algorithms [4-5] where derived by processing line terminal voltage and current during the fault, i.e. before the breaker opening.

In this paper a new numerical algorithm for fault distance calculation and arcing faults recognition developed in spectral domain will be presented. Firstly, the basic characteristics of a long arc in free air will be given. Secondly, the fault model will be presented. Thirdly, the full algorithm for the fault distance and arc voltage amplitude calculation will be derived. Further, the computer simulation tests, as well as, the processing of real field data records will be presented.

II. BASIC CHARACTERISTICS OF A LONG ARC IN FREE AIR

A long electric arc in free air is a plasma discharge, where the plasma allows a current to flow through a gaseous medium. The current can range from few up to thousands of amps. The nonlinear variations of the arc causes the arc voltage waveform distortion, distorting it into a near square waveform characterized by its arc voltage amplitude V_a [6], what is given in Fig. 1. From Fig. 1 it is obvious that the sign of the arc voltage wave v_a is the same as the sign of the arc current i_a. This is a simple proof that an arc has a resistive nature.

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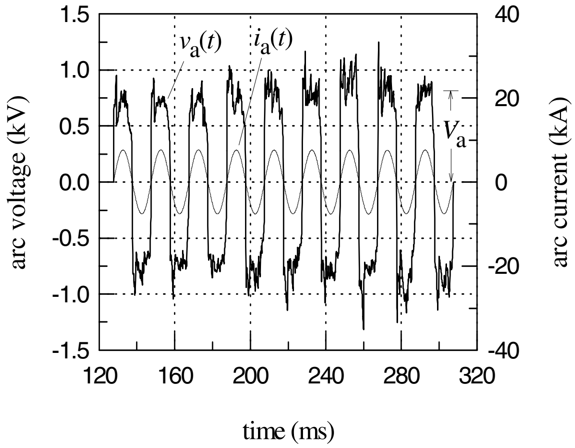


Fig. 1. Real arc voltage and current waveforms.

The arc voltage can be also modeled as a nonlinear arc resistance [7], or by the piecewise arc voltage-current characteristics [8].

In this paper a new approach is chosen. The arc voltage waveform is defined numerically on the basis of a great number of arc voltage records obtained in the high voltage laboratory using a transient recorder with the sampling frequency of 10.417 kHz [6]. The arc voltage model based on the arc waveform from Fig. 2 is accepted. Fig. 2 presents a normalized arc voltage waveform with its arc voltage amplitude $V_a = 1$ p.u. It is assumed that the sign of arc voltage is determined by the sign of arc current. In other words, an arc is considered as a current controlled voltage source.

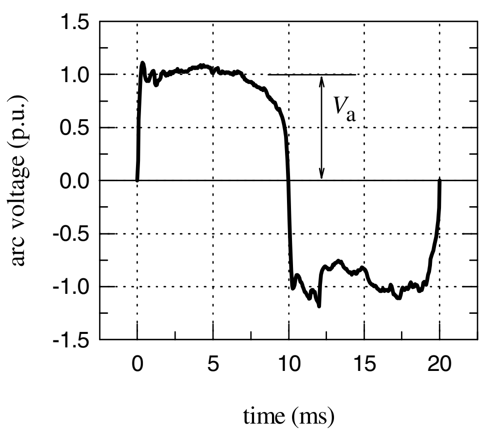


Fig. 2 Typical accepted arc voltage wave shape.

The normalized arc waveform from Fig. 2 has an important feature: it can be represented by Fourier series containing odd sine components only, as follows:

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

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

By using Discrete Fourier Algorithm (DFT) it is simple to obtain the coefficients k_h for the accepted arc voltage model. These coefficients are given in Table 1.

Table 1. Coefficients of the h-th harmonics of the arc-voltage.

h	1	3	5	7
k_h	1.23	0.393	0.213	0.135

In comparison to other models, the advantage of the arc voltage presentation through the sequence of numerical values (equation (6)) is its flexibility. Depending on the modeling application, one can in this way create various waveform shapes and calculate the corresponding coefficients k_h.

III. The Fault Model

Let us consider the most frequent single-phase to ground fault on a transmission line fed from both line terminals. The fault model will be given as a function of faulted phase voltage, fault current and earth return path parameters.

For a pure metallic fault the fault voltage may be selected to be zero. Such cases occur, but relatively seldom. The former model may be extended by including the fault resistance into it. The fault resistance originates from arc resistance and the resistances of tower footing and ground. In this paper an extended fault model with the most important physical features of the problem considered is developed. The current path for ground faults includes here the arc voltage and the fault resistance.

Faulted phase voltage v_F can be given in time domain as follows:

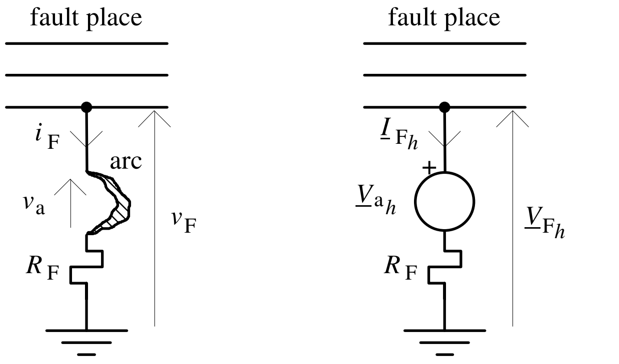
$$v_F(t) = v_a(t) + R_F i_F(t) \tag{2}$$

where v_a is arc voltage, R_F is fault resistance and i_F is fault (arc) current. In Fig. 3.a) the suitable presentation is given.

The new spectral domain fault model, developed in this paper, is depicted in Fig. 3.b). From Fig. 3.a) the h-th harmonic of the fault voltage can be expressed as follows:

$$\underline{V}_{Fh} = \underline{V}_{ah} + R_F \underline{I}_{Fh} \,. \tag{3}$$

where $\underline{V}_{ah}$ is the h-th harmonic of the arc voltage and $\underline{I}_{Fh}$ is the h-th harmonic of the fault (arc) current.



(a) (b)

Fig. 3. Fault model given (a) in time domain and (b) in spectral domain for h-th harmonic.

In this paper only fundamental and third harmonics will be used for further algorithm developing. The reason for such a selection lies in the fact that the amplitude of harmonics is practically inverse proportional to its order (see Table 1). By this, higher harmonics can be neglected and omitted form the consideration.

The amplitude of the h-th arc voltage harmonic can be expressed as follows:

$$V_{ah} = k_h V_a \tag{4}$$

where V_{ah} is the amplitude of the h-th harmonic of the arc voltage. From (4) it follows:

$$V_{a1} = k_1 V_a = 1.23 V_a \quad \text{and} \quad V_{a3} = k_3 V_a = 0.393 V_a \,. \tag{5}$$

As shown in Fig. 1, the arc voltage waveform is in phase with the fault arc current waveform. That means that the phase of the first harmonic of the arc voltage has to be the same as the phase of the first arc current harmonic, i.e. 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. The former observation could be expressed as:

$$\underline{V}_{a1} = \underline{k}_1 V_a \quad \text{and} \quad \underline{V}_{a3} = \underline{k}_3 V_a \tag{6}$$

where $\underline{V}_{a1}$ and $\underline{V}_{a3}$ are vectors of the first and the third harmonics of the arc voltage, $\underline{k}_1 = k_1 \angle\phi$ and $\underline{k}_3 = k_3 \angle 3\phi$ where ϕ is the phase of the first harmonic of the fault current ($\underline{I}_{F1} = I_{F1} \angle\phi$).

IV. Fault Distance and Arc Voltage Amplitude Calculation

Since the fault has an arbitrary location on the line, it is practically impossible to measure the arc voltage. The idea of this paper is the calculation of the arc voltage amplitude from the line terminal voltage and current signals obtainable as uniformly digitized quantities at one of the line terminals. The voltages and currents at the line terminals contain harmonics. The distortions of signal waveforms depend on the fault distance and the arc voltage amplitude. Through spectral analysis it could be concluded that the line terminal voltage and the current contain the harmonics induced by arc voltage, particularly the odd components. These amplitudes are not comparable to the fundamental harmonic amplitude, but in spite of that are mathematically (e.g. by using DFT) recognizable and measurable.

Thus, one of the obvious ways in which arc voltage harmonics could be calculated is to analyze the circuit depicted in Fig. 4. In this circuit all variables have radian frequency $h\omega$ and all the line parameters are calculated in terms of $h\omega$. Index h denotes the order of harmonic.

Let us assume a single-phase to ground arcing fault occurring on a three phase overhead line depicted in Fig. 4. In Fig. 4, 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 the h-th harmonic of the arc voltage, R_F is fault resistance and V_{Fh} is the h-th harmonic of the faulted phase voltage on the fault place. The three-phase circuit from Fig. 4 can be presented by three single-phase equivalent circuits: positive (p), negative (n) and zero sequence (0) equivalent circuits. In Fig. 5 the positive and negative sequence equivalent circuits are equal and are respectively depicted. In Fig. 5, z_h is positive or negative sequence line impedance. The zero sequence equivalent line circuit is depicted in Fig. 6. In Fig. 6 all variables and parameters are zero sequence variables and parameters.

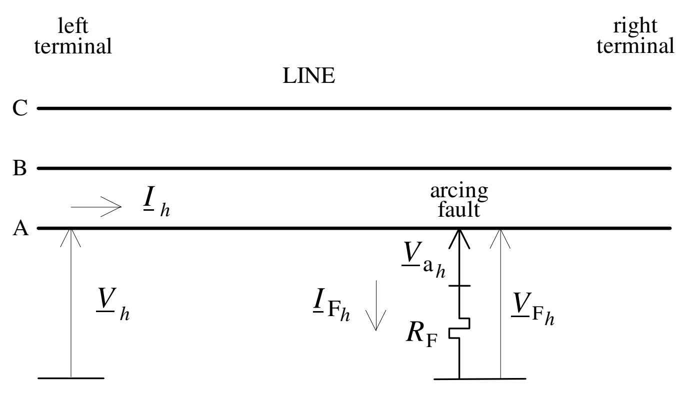


Fig. 4. Single-phase to ground arcing fault on three phase power line.

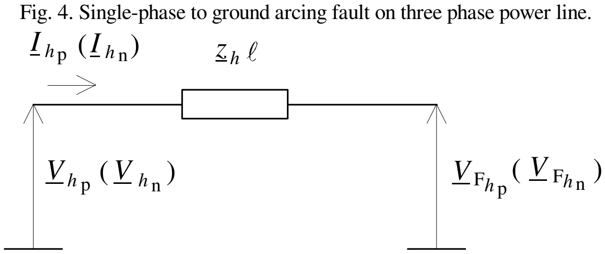


Fig. 5. Positive and negative sequence line equivalent circuit.

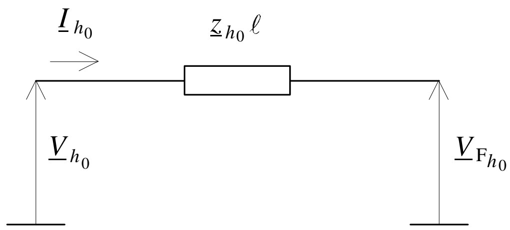


Fig. 6. Zero sequence line equivalent circuit.

For the equivalent circuits depicted in Figs. 5 and 6 the following equations holds:

$$\underline{V}_{h_\mathrm{p}} = \underline{z}_h \ell \underline{I}_{h_\mathrm{p}} + \underline{V}_{\mathrm{F}h_\mathrm{p}} \tag{7}$$

$$\underline{V}_{h_\mathrm{n}} = \underline{z}_h \ell \underline{I}_{h_\mathrm{n}} + \underline{V}_{\mathrm{F}h_\mathrm{n}} \tag{8}$$

$$\underline{V}_{h_0} = \underline{z}_h \ell \underline{I}_{h_0} + \underline{V}_{\mathrm{F}h_0}\,. \tag{9}$$

By adding equations (7-9), and by using the basic symmetrical components equations $\underline{V}_h = \underline{V}_{h_\mathrm{p}} + \underline{V}_{h_\mathrm{n}} + \underline{V}_{h_0}$ and $\underline{V}_{\mathrm{F}h} = \underline{V}_{\mathrm{F}h_\mathrm{p}} + \underline{V}_{\mathrm{F}h_\mathrm{n}} + \underline{V}_{\mathrm{F}h_0}$, one obtains:

$$\underline{V}_h = \underline{z}_h(\underline{I}_h + \underline{k}_{zh}\underline{I}_{h0})\ell + \underline{V}_{\mathrm{F}h} \tag{10}$$

where: $\underline{k}_{zh} = (\underline{z}_{0h} - \underline{z}_h)/\underline{z}_h$ is the zero sequence compensation factor, which can be calculated in advance.

By substituting the fault model equation (3) in (10), the next equation for *h*-th harmonic is obtained:

$$\underline{V}_h = \underline{z}_h(\underline{I}_h + \underline{k}_{zh}\underline{I}_{h0})\ell + \underline{V}_{\mathrm{a}h} + R_\mathrm{F}\underline{I}_{\mathrm{F}h}\,. \tag{11}$$

Equation (9) is used as the fundamental equation for further development of the algorithm for fault distance and arc voltage amplitude calculation.

A. First Stage: Algorithm Fault Distance Calculation

For the fundamental harmonic the *faulted loop equation* (11) can be written as follows:

$$\underline{V}_1 = \underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\ell + \underline{V}_{\mathrm{a}1} + R_\mathrm{F}\underline{I}_{\mathrm{F}1}\,. \tag{12}$$

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

$$\underline{V}_{\mathrm{a}1} = \underline{k}_1 V_\mathrm{a} = k_1\angle\phi V_\mathrm{a} = k_1\frac{\underline{I}_{\mathrm{F}1}}{|\underline{I}_{\mathrm{F}1}|}V_\mathrm{a} = R_{\mathrm{a}1}\underline{I}_{\mathrm{F}1} \tag{13}$$

where $R_{\mathrm{a}1} = k_1\dfrac{\underline{I}_{\mathrm{F}1}}{|\underline{I}_{\mathrm{F}1}|}$ is arc fundamental harmonic resistance.

Zero-sequence network is a passive network, so it can assumed that $\underline{I}_{\mathrm{F}1} = 3\underline{I}_{\mathrm{F}10} = 3c_{\mathrm{F}1}\underline{I}_{10}$, where $c_{\mathrm{F}1}$ is a real proportional coefficient. In case in which only fault distance is to be calculated, the value of $c_{\mathrm{F}1}$ is not necessary to be known in advance.

Using above assumption, equation (12) can be rewritten in the following form:

$$\underline{V}_1 = \underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\ell + R_{\mathrm{Fe}1}\underline{I}_{10} \tag{14}$$

where $R_{\mathrm{Fe}1} = 3c_{\mathrm{F}1}(R_{\mathrm{a}1} + R_\mathrm{F})$.

Complex equation (14) provides us with a system of two following scalar equations:

$$\mathrm{Re}\{\underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\}\ell + \mathrm{Re}\{\underline{I}_{10}\}R_{\mathrm{Fe}} = \mathrm{Re}\{\underline{V}_1\} \tag{15a}$$

$$\mathrm{Im}\{\underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\}\ell + \mathrm{Im}\{\underline{I}_{10}\}R_{\mathrm{Fe}} = \mathrm{Im}\{\underline{V}_1\} \tag{15b}$$

from which the unknown fault distance can be calculated as:

$$\ell = \frac{\mathrm{Re}\{\underline{V}_1\}\,\mathrm{Im}\{\underline{I}_{10}\} - \mathrm{Im}\{\underline{V}_1\}\,\mathrm{Re}\{\underline{I}_{10}\}}{\mathrm{Re}\{\underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\}\,\mathrm{Im}\{\underline{I}_{10}\} - \mathrm{Re}\{\underline{I}_{10}\}\,\mathrm{Im}\{\underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\}} \tag{16}$$

Equation (16) is the essence of the first algorithm stage.

B. Second Stage: Arc Voltage Amplitude Calculation

Equation (11) for the 3-rd harmonic has the following form:

$$\underline{V}_3 = \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\ell + \underline{V}_{\mathrm{a}3} + R_\mathrm{F}\underline{I}_{\mathrm{F}3}\,. \tag{17}$$

The phasor of the 3-rd arc voltage harmonic can be expressed as follows:

$$\underline{V}_{\mathrm{a}3} = \underline{k}_3 V_\mathrm{a} = k_3\angle 3\phi V_\mathrm{a} = k_3\left(\frac{\underline{I}_{\mathrm{F}1}}{|\underline{I}_{\mathrm{F}1}|}\right)^3 V_\mathrm{a} = k_3\left(\frac{\underline{I}_{10}}{|\underline{I}_{10}|}\right)^3 V_\mathrm{a} \tag{18}$$

For a passive zero-sequence network, for simplicity it can be supposed that $\underline{I}_{\mathrm{F}3} = 3\underline{I}_{\mathrm{F}30} = 3c_{\mathrm{F}3}\underline{I}_{30}$, where $c_{\mathrm{F}3}$ is a real proportional coefficient. In case in which only arc voltage amplitude is to be calculated, the value of $c_{\mathrm{F}3}$ is not necessary to be known in advance.

Using equation (18) and above assumption, equation (17) can be rewritten in the following form:

$$k_3\left(\frac{\underline{I}_{10}}{|\underline{I}_{10}|}\right)^3 V_\mathrm{a} + \underline{I}_{30}R_{\mathrm{Fe}3} = \underline{V}_3 - \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\ell \tag{19}$$

where $R_{\mathrm{Fe}3} = 3c_{\mathrm{F}3}R_\mathrm{F}$.

Complex equation (19) provides us with the next two scalar equations:

$$\mathrm{Re}\{k_3(\frac{\underline{I}_{10}}{|\underline{I}_{10}|})^3\}V_\mathrm{a} + \mathrm{Re}\{\underline{I}_{30}\}R_\mathrm{Fe3} = \mathrm{Re}\{\underline{V}_3 - \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\ell\} \tag{20a}$$

$$\mathrm{Im}\{k_3(\frac{\underline{I}_{10}}{|\underline{I}_{10}|})^3\}V_\mathrm{a} + \mathrm{Im}\{\underline{I}_{30}\}R_\mathrm{Fe3} = \mathrm{Im}\{\underline{V}_3 - \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\ell\} \tag{20b}$$

from which the unknown arc voltage amplitude can be calculated:

$$V_\mathrm{a} = \frac{\mathrm{Re}\{\underline{V}_3 - \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\ell\}\,\mathrm{Im}\{\underline{I}_{30}\} - \mathrm{Im}\{\underline{V}_3 - \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\ell\}\,\mathrm{Re}\{\underline{I}_{30}\}}{\mathrm{Re}\{k_3(\frac{\underline{I}_{10}}{|\underline{I}_{10}|})^3\}\,\mathrm{Im}\{\underline{I}_{30}\} - \mathrm{Re}\{\underline{I}_{30}\}\,\mathrm{Im}\{k_3(\frac{\underline{I}_{10}}{|\underline{I}_{10}|})^3\}} \tag{21}$$

For calculated arc voltage amplitude, the algorithm is capable of making the decision whether the fault is with arc (transient fault), or without arc (permanent fault). A fault is transient if the calculated value of the arc voltage amplitude is greater than the product of the arc voltage gradient and the length of the arc path, which is equal or greater than the flashover length of a suspension insulator string. The average arc-voltage gradient lies between 12 and 15 V/cm [8].

V. COMPUTER SIMULATED TESTS

The tests have been provided by using the Electromagnetic Transient Program (EMTP) [10]. The schematic diagram of the 400 kV power system on which the tests are based is shown in Fig. 7. Here $u(t)$ and $i(t)$ are digitized voltages and currents, and D is the line length. The line parameters, calculated via line constants program were $D = 100$ km, $r = 0.0325\ \Omega$/km, $x = 0.3\ \Omega$/km, $r_0 = 0.0975\ \Omega$ /km and $x_0 = 0.9\ \Omega$/km. Data for network A were: $R_\mathrm{A} = 1\ \Omega$, $L_\mathrm{A} = 0.064$ H, $R_\mathrm{A0} = 2\ \Omega$ and $L_\mathrm{A} = 0.128$ H. Data for network B were: $R_\mathrm{B} = 0.5\ \Omega$, $L_\mathrm{B} = 0.032$ H, $R_\mathrm{B0} = 1\ \Omega$ and $L_\mathrm{B} = 0.064$ H. The equivalent electromotive forces of networks A and B were $E_\mathrm{A} = 400$ kV and $E_\mathrm{B} = 395$ kV, respectively. The phase angle between them was 20 degrees.

Single-phase to ground faults are simulated at different points on the transmission line. The pre-fault load was present on the line. The left line terminal voltages and currents are sampled with the sampling frequency $f_\mathrm{s} = 6400$ Hz. The duration of data window was $T_\mathrm{dw} = 20$ ms.

The arc voltage used by EMTP is assumed to be of square wave shape with amplitude of $V_\mathrm{a} = 5.4$ kV, corrupted by the random noise. A typical waveforms of arc voltage obtained through computer simulation are depicted in Fig. 8, where the instant of the fault inception was 23 ms. Fault resistance were $R_\mathrm{F} = 2\ \Omega$.

In Figs. 9 and 10 the input phase voltages and line currents, measurable at the relay location, calculated by EMTP for selected study case, are respectively plotted.

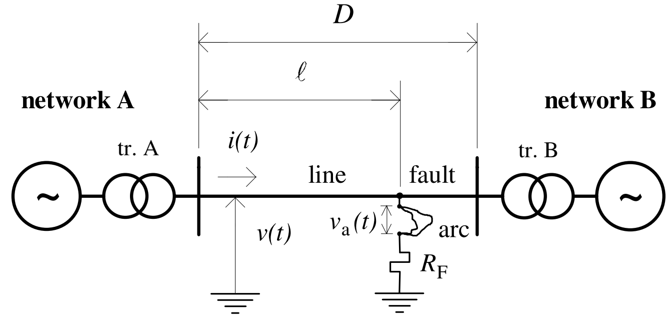


Fig. 7: Test power system.

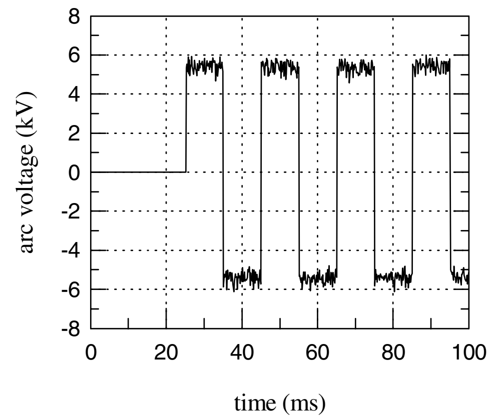


Fig. 8. Arc voltage shape used by EMTP.

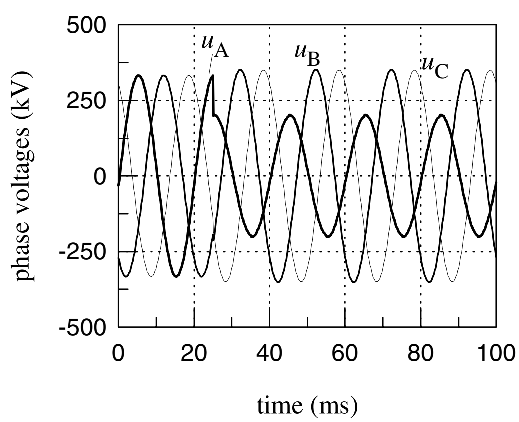


Fig. 9. Distorted input voltages generated by EMTP.

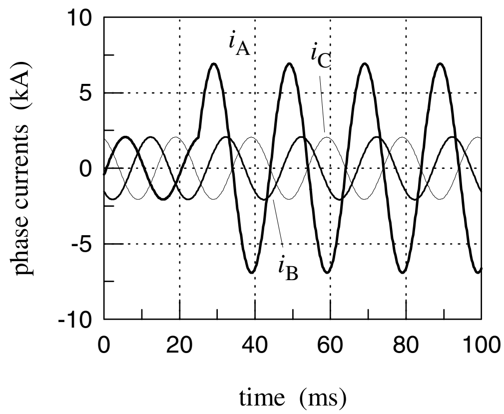


Fig. 10. Distorted input currents generated by EMTP.

In Fig. 11 the fault distance and arc voltage calculated by algorithm are depicted. The exact unknown model parameters ($\ell = 60$ km and $U_a = 5.4$ kV) are obtained fast, after 20 ms, and accurate. From the algorithm speed and accuracy point of view, the results obtained confirm that the algorithm is useful for the application to real overhead lines protection.

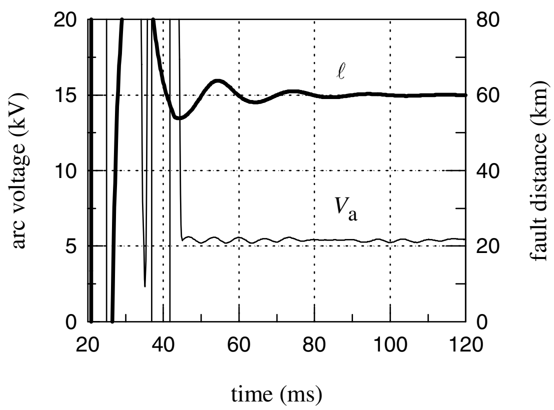


Fig. 11. Calculated fault distance (exact value used by EMTP was 60 km) and arc voltage amplitude (exact value used by EMTP was 5.4 kV).

VI. 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. Here, a typical example of an arcing fault will be demonstrated. In Figs. 12 and 13 voltages and currents measured by the relay before and during a single-phase line to ground fault over arc are respectively presented.

All signals are sampled with the sampling frequency $f_s = 1600$ Hz. The duration of data window was $T_{dw} = 20$ ms.

After data processing, the results of the application of the algorithm presented are depicted in Fig. 14. The exact fault location (see Fig. 14) $\ell = 12.8$ km was calculated. Additionally, it is determined that the fault was over an arc with the calculated amplitude plotted in Fig. 14. As it can be observed, the arc voltage amplitude was approximately 2 kV.

Because the minimal length of the arc path determined by the arcing horns distance was 0.85 m, minimal arc voltage amplitude expected was 1.1 kV, obtained as a product of the minimal arc length and the electric field inside the arc, which is practically constant along the arc and has the average value of 1.3 kV/m. The calculated arc voltage amplitude indicates that the arc was prolonged with regard to its minimal length, equal to the distance between arcing horns.

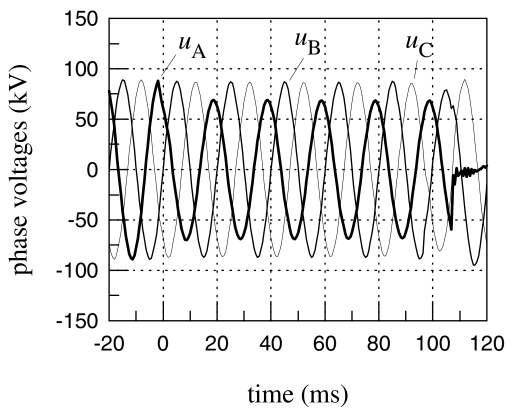


Fig. 12. Input voltages measured by the relay.

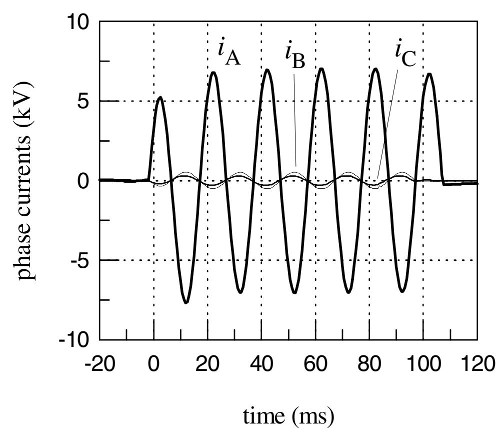


Fig. 13. Input currents measured by the relay.

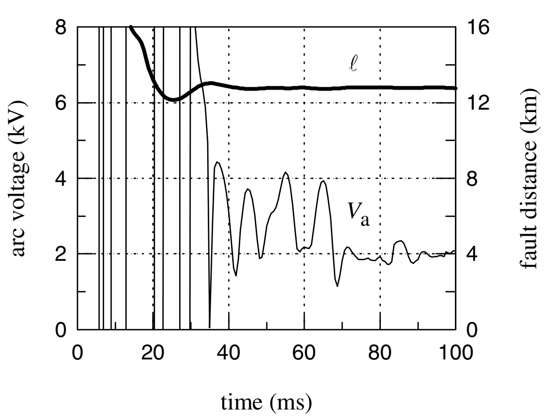


Fig. 14. Calculated fault location and arc voltage amplitude.

By the inspection of the fault analyzed, it was concluded that the estimated distance was the exact one.

VII. Conclusion

A new two-stage numerical algorithm for the fault distance calculation and for 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. It is based on the spectral analysis of the input phase voltages and line currents signals measured by numerical relay. Only fundamental and third harmonic phasors calculated by Discrete Fourier Technique are needed for algorithm development.

The fault distance calculated in first algorithm stage can be used for distance protection or for fault location, whereas the arc voltage amplitude calculated in second algorithm stage can be used for blocking reclosing of transmissions lines with permanent faults.

A new spectral domain fault model with all significant arc features included is given.

The algorithm was successfully tested with data obtained through computer simulation and data recorded in the real power system.

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IX. BIOGRAPHIES

Zoran M. Radojevic (SM'2002) is an assistant professor at the Faculty of Electrical Engineering, Univ. of Belgrade, Serbia and Montenegro.

Hans-Jürgen Koglin received his Dipl.-Ing. degree in 1964 and his Dr.-Ing. degree in 1972 from the Technical University Darmstadt, Germany. Since 1983 he is a full professor at Saarland University in Saarbrücken, Germany.

Vladimir V. Terzija (M'95, SM'2000) is employed with ABB Calor Emag Mittelspannung (Ratingen, Germany) as an expert for protection, control and monitoring of medium voltage switchgears.