ARCING FAULT DETECTION AND FAULT LOCATION ON HV TRANSMISSION LINES

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Abstract: In this paper a new numerical algorithm for fault distance calculation and arcing fault recognition, based on one terminal data and derived in the time domain, is presented. The algorithm is derived for the case of most frequent single-phase line to ground fault. The faulted phase voltage is modelled as a serial connection of the fault resistance and the arc voltage. The fault distance and the arc voltage amplitude are estimated using Least Error Squares Technique. The algorithm can be applied for distance protection, intelligent autoreclosure and for fault location. The results of algorithm testing through computer simulation and an example of real life data processing are given. *Copyright © 2005 IFAC*

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1. INTRODUCTION

The development of new microprocessor technology gave us an opportunity to improve the hitherto implemented techniques of power system relaying. In this respect, a few interesting approaches to calculate fault distance and at the same time to make a distinction between the transient and the permanent faults, for the purpose of blocking automatic reclosing on transmission lines with permanent faults, are published (Ge, at al., 1989, Aggarwal, at al., 1994, Radojević, at al., 1994, Radojević and Đurić, 1998).

In this paper, a new numerical algorithm for fault distance estimation and arcing faults detection is presented. It is based on the fundamental differential equation describing the transients on a transmission line before, during and after the fault occurrence, and on the application of the Least Error Squares Technique for the unknown model parameter estimation. With the arc voltage involved in the fault model an improved algorithm for the distance protection and fault location is obtained. The arc voltage is assumed to be of square wave shape, in phase with the fault arc current (Radojević, at al., 1994). The estimated value of the arc voltage amplitude could be used to determine which kind of fault was occurred, permanent or transient fault, in order to avoid unsuccessful autoreclosures.

The new algorithm was successfully tested through computer simulated numerous arcing and non-arcing

short circuits. The results of processing real life data recorded in an 110 kV network will be presented.

2. THE FAULT MODEL

The current path for ground faults includes the electrical arc and the tower footing resistance, what is depicted in Fig.1.
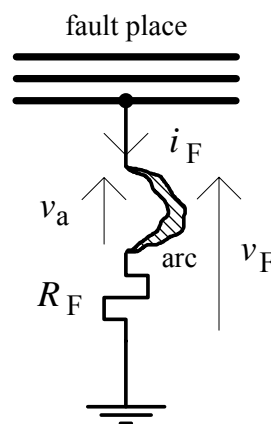

Fig. 1. Fault model.

The fault voltage v_F is a serial connection of the voltage drop on fault resistance R_F and the arc voltage v_a, so $v_F = v_a + R_F i_F$, where i_F is the fault (arc) current.

An arc is a highly nonlinear phenomenon. The arc voltage can be assumed to be of square wave shape,

in phase with the arc current, and corrupted by the random noise. Thus, the faulted phase voltage becomes:

$$v_F = V_a \, \text{sgn}(i_F) + R_F i_F + \xi \qquad (1)$$

where V_a is the arc voltage amplitude and ξ is a random noise.

Function sgn is defined as: $\text{sgn}(x) = 1$ if $x \geq 0$, and $\text{sgn}(x) = -1$ if $x < 0$. The value of V_a can be obtained from the product of arc-voltage gradient and the length of the path, i.e. the flashover length of a suspension insulator string, or flashover length between conductors. Over the range of the arc currents from 100 A to 20 kA the average arc-voltage gradient lies between 1,2 and 1,5 kV/m (Maikapar, 1960).

3. ALGORITHM DERIVATION

Let us consider the most frequent single-phase to ground fault on a three phase transmission line fed from both line terminals, depicted in Fig.2.
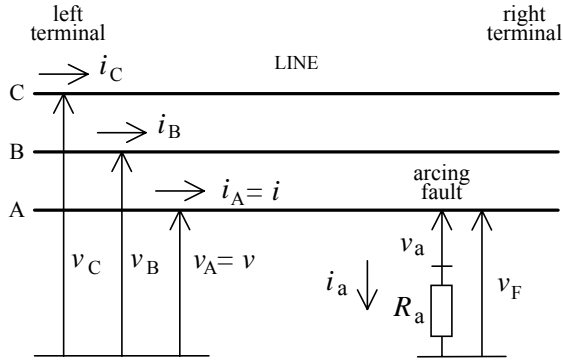

Fig. 2: Single-phase to ground arcing fault.

In Fig. 2, v_A, v_B and v_C are the left line terminal phase voltages, and i_A, i_B and i_C are the left line terminal currents. They are measured input signals to the algorithm. The fault distance and arc voltage amplitude are parameters which should be estimated by the algorithm.

For the known line per unit length resistance r and reactance x, the faulted phase voltage measured by the relay can be expressed as follows:

$$v = \left[r(i + K_R i_0) + \frac{x}{\omega_0} \frac{d}{dt}(i + K_L i_0) \right] \ell + \text{sgn}(i - i_L) V_a + (i - i_L) R_e + \varepsilon \qquad (2)$$

where: ℓ is fault distance, i is faulted phase current, i_0 is zero sequence current measured at relay place, i_L is prefault load current, x_0 is line per unit length zero sequence reactance, r_0 is line per unit length zero sequence resistance, $K_L = (x_0 - x)/x$ and $K_R = (r_0 - r)/r$ are coefficients which can be precalculated, $R_e = k_a R_F$ is an equivalent resistance, ω_0 is the fundamental angular velocity and ε is the error modelling all measuring errors and

errors in modelling the transmission line and electrical arc.

Equation (2) is derived under the assumption that there exists a proportionality between the fault current and faulted phase current measured at relay point minus memorized prefault load current, i.e. $i_F = k_a(i - i_L)$, where k_a is a proportional coefficient. The value of k_a is not necessary to be known in advance.

Equation (2) requires the numerical calculation of the derivative of current (di/dt). The following approximate formula may be used for this calculation:

$$\frac{di(t)}{dt} \approx \frac{i_{n+1} - i_{n-1}}{2T} . \qquad (3)$$

At one line terminal, e.g. the left one, line voltages and currents can be uniformly sampled with the preselected sampling frequency f_S and used as an input to the algorithm. A set of N voltage and $N+2$ current samples can be obtained.

For the k-th sample ($k = 1, \dots , N$), the following holds:

$$v_k = \left\{ r(i_k + K_R i_{0k}) + \frac{x}{2T\omega_0} \left[i_{k+1} - i_{k-1} + K_L(i_{0(k+1)} - i_{0(k-1)}) \right] \right\} \ell +$$
$$+ \text{sgn}(i_k - i_{L_k}) V_a + (i_k - i_{L_k}) R_e + \varepsilon_k . \qquad (4)$$

Discrete-time equation (4) can be rewritten in the following abbreviated matrix form:

$$v_k = a_{k1}\ell + a_{k2}V_a + a_{k3}R_e + \varepsilon_k \qquad (5)$$

where:

$$a_{k1} = r(i_k + K_L i_{0k}) + \frac{x}{2T\omega_0} \left[i_{k+1} - i_{k-1} + K_L(i_{0(k+1)} - i_{0(k-1)}) \right]$$

$a_{k2} = \text{sgn}(i_k - i_{L_k})$, and $a_{k3} = i_k - i_{L_k}$ are timely dependent coefficients.

By writing equation (5) for all N samples, the following matrix equation is obtained:

$$\mathbf{v} = \mathbf{Ax} + \boldsymbol{\varepsilon} \qquad (6)$$

where $\mathbf{v} = [v_1, ..., v_N]^T$, $\mathbf{A}$ is an coefficient matrix whit N rows and 3 colons, given by next equation:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ ... & ... & ... \\ a_{N1} & a_{N2} & a_{N3} \end{bmatrix},$$

$\mathbf{x}^T = [\ell, V_a, R_e]$ is the vector of unknown model parameters, and $\boldsymbol{\varepsilon} = [\varepsilon_1, ..., \varepsilon_N]^T$.

Now, the vector of unknown model parameters may be estimated by using Least Error Squares Technique, i.e. by minimizing the error vector $\boldsymbol{\varepsilon}$:

$$\mathbf{x} = (\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{v}. \qquad (7)$$

The algorithm presented in this paper estimates both the fault distance and the arc voltage amplitude. It provides the solution for the most frequent unsymmetrical single-phase to ground faults.

Before the algorithm starts, using the fault classification techniques, faulted phase and fault type should be determined (Adu, 2002).

The algorithm is not sensitive to decaying transient DC component appearing in fault current, as well as to the changes of power system frequency, which is a drawback of algorithms developed in the spectral domain and on the application of Discrete Fourier Technique. Due to this important feature, the convergence (speed) and accuracy of the algorithm are improved.

Since the fault resistance has been also taken into account, the algorithm covers the cases of high impedance faults.

The existence of a positive arc voltage amplitude value indicates the existence of the arc at the location of the fault, so such faults can be considered as transient faults. In these cases autoreclosure should operate. On the other hand, for arcless (permanent) faults this value is zero (or near zero) and in these cases autoreclosure should be blocked. Such *intelligent autoreclosure technique* can avoid reclosure onto the permanent faults and thus reduce damages on the elements of power system.

4. COMPUTER SIMULATED TESTS

The tests have been done using the Electromagnetic Transient Program (EMTP) (Lönard, at al., 1992). The schematic diagram of the 400 kV power system on which the tests are based is shown in Fig. 3. Here $v(t)$ 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, $x = 0.36\ \Omega$/km, $r_0 = 0.0975\ \Omega$/km and $x_0 = 1.08\ \Omega$/km. Data for network A were: $R_A = 1\ \Omega$, $L_A = 0.064$ H, $R_{A0} = 2\ \Omega$ and $L_A = 0.128$ H. Data for network B were: $R_B = 0.5\ \Omega$, $L_B = 0.032$ H, $R_{B0} = 1\ \Omega$ and $L_B = 0.064$ H. The equivalent electromotive forces of networks A and B were $E_A = 416$ kV and $E_B = 400$ 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 $f_s = 3840$ Hz. The duration of data window was equal to full-cycle ($T_{dw} = 16,66$ ms) and in second case equal to half-cycle ($T_{dw} = 8,33$ ms) of input 60Hz signal.
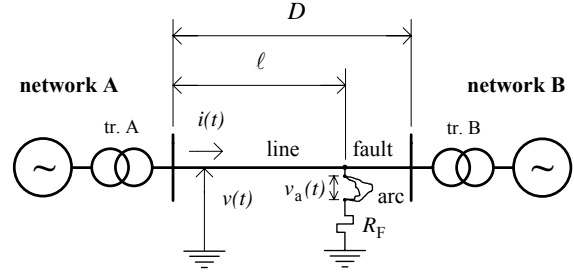

Fig. 3: Test power system.

Results obtained by processing an example of short circuit with arcing ($\ell = 8$ km, $R_F = 2\ \Omega$, $V_a = 3,5$ kV) and arc-less faults ($V_a = 0$ kV) will be demonstrated.

In Figs. 4 and 5 voltages and currents measured by the relay before and during a single-phase line to ground arcing fault are presented, respectively. The fault on the phase A is simulated.

In Fig. 6 and 7, estimated fault distance and estimated arc voltage amplitude for arcing and for arcless fault, obtained by using full-cycle window, are presented. In Fig. 8 and 9, estimated fault distance and estimated arc voltage amplitude for arcing and for arcless fault, obtained by using half-cycle window, are presented.
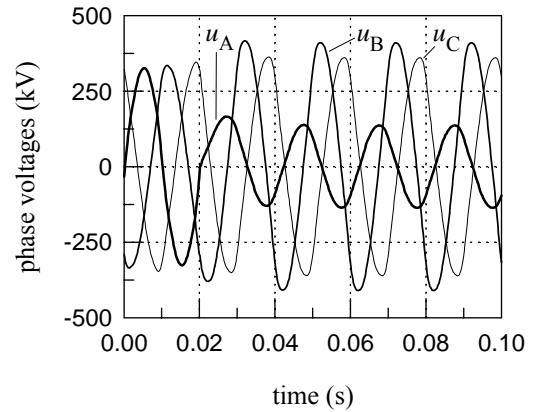

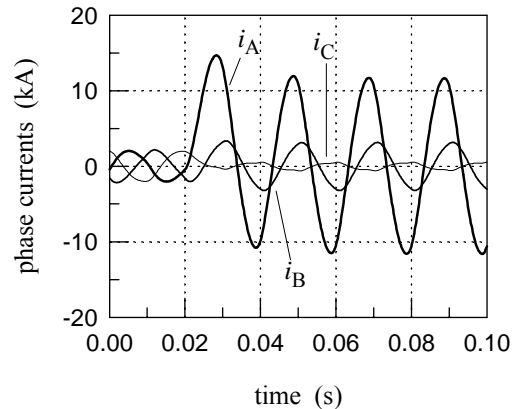Fig. 4. Input phase voltages measured by the relay.

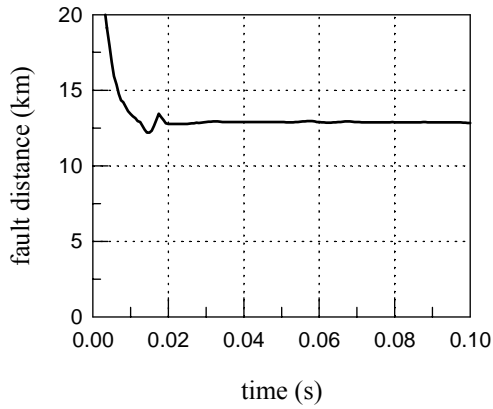Fig. 5. Input phase currents measured by the relay.

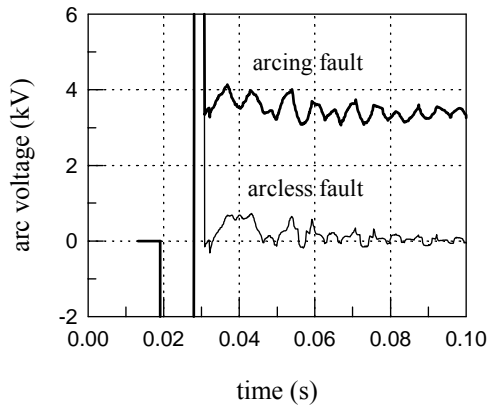Fig.6. Estimated fault distance (full-cycle window).

Fig.7. Estimated arc voltage (full-cycle window).
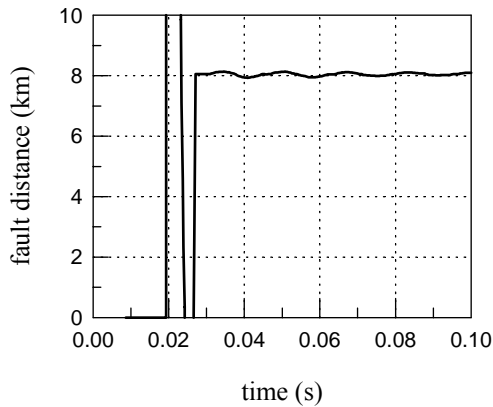

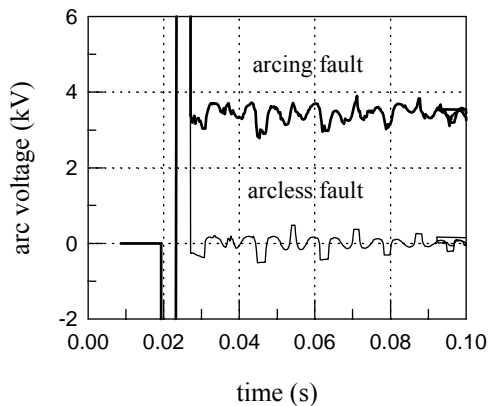Fig.8. Estimated fault distance (half-cycle window).

Fig.9. Estimated arc voltage (half-cycle window)

By comparing the algorithm outputs with known short circuit simulations input data, it was concluded that the estimated distance and arc voltage amplitude were obtained sufficiently accurate.

5. 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. Over 20 faults are analyzed. Here, a typical example of an arcing fault will be demonstrated. In Figs. 10 and 11 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 Figs. 12 and 13. The exact fault location (see Fig. 12) $\ell = 12.8$ km was estimated. Additionally, it is determined that the fault was over an arc with the estimated amplitude plotted in Fig. 13. As it can be observed, the arc voltage amplitude was approximately 1 - 2 kV. This result can be checked by the following analysis: the minimal length of the arc path, determined by the arcing horns distance was 0.85 m and the 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 estimated arc voltage amplitude indicates that the arc was prolonged with regard to its minimal length, equal to the distance between arcing horns.

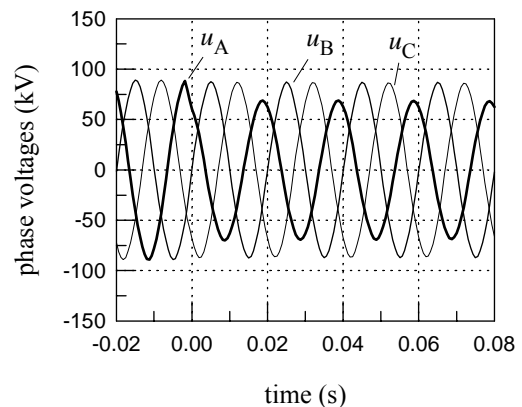By the inspection of the fault analyzed, it was concluded that the estimated distance was the exact one.

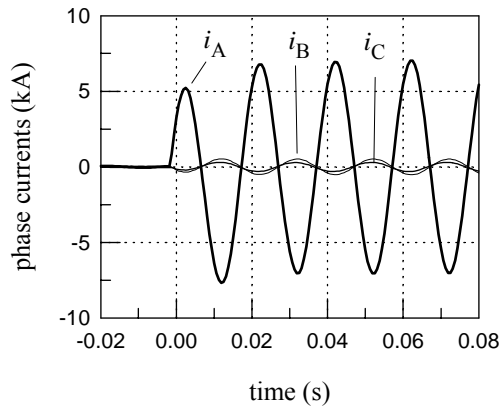Fig. 10. Input voltages measured by the relay.
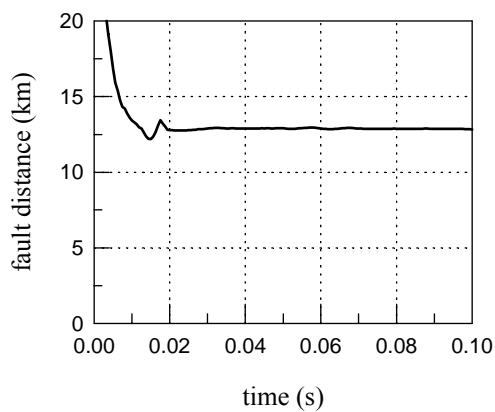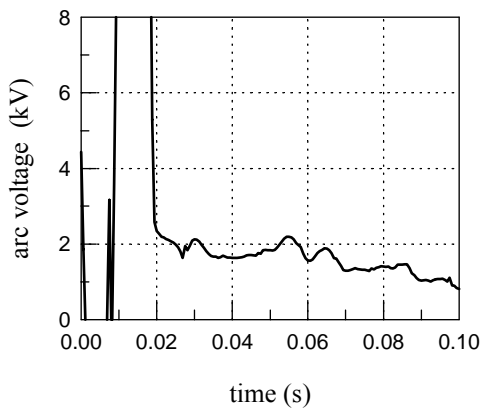
Fig. 11. Input currents measured by the relay.

Fig. 12. Estimated fault location.

Fig. 13. Estimated arc voltage amplitude.

6. CONCLUSION

An efficient numerical algorithm for simultaneous estimation of the fault distance and arc voltage amplitude, as well as for blocking autoreclosure during permanent faults, is presented. The errors caused by the remote end infeed are reduced to the minimum, by using memorized prefault current. It is concluded that the algorithm is not sensitive to frequency changes and to decaying DC component existing in the fault current. The processing of data obtained through computer simulations showed that the algorithm could be applied for the protection of overhead lines. The example of of real life data processing confirmed the results obtained through computer simulations and showed that the algorithm can be applied for the protection of overhead lines.

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