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Numerical Algorithm for Adaptive Autoreclosure and Fault Distance Calculation

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Abstract - This paper presents development and testing of a new numerical spectral domain algorithm devoted to blocking unsuccessful automatic reclosing onto permanent faults and the fault distance calculation. The arc voltage amplitude and the fault distance are calculated from the fundamental and third harmonics of the terminal voltages and currents phasors. From the calculated arc voltage amplitude it can be concluded if the fault is transient arcing fault or permanent arcless fault. If the fault is permanent automatic reclosure should be blocked. The algorithm can be applied for adaptive autoreclosure, distance protection, and fault location. · The results of algorithm testing through computer simulation are given.

1. Introduction

It is well 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 power system transient stability and provide much higher service continuity to the costumes. However, reclosure onto a permanent fault may aggravate the potential damage to the system and equipment.

A few interesting approaches to calculate fault distance and at the same time to make a distinction between the transient and the permanent faults are published [1-3].

In this paper a new numerical spectral domain algorithm for arcing faults recognition and fault distance calculation using Discrete Fourier Technique will be given.

2. Basic Characteristics of a Long Electric Arc

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, distorting it into a near square wave with arc voltage amplitude V_a, what is given in Fig. 1. The sign of the arc voltage wave v_a is the same as sign of the arc current i_a. The value of V_a can be obtained from the product of arc-voltage gradient and the length of the arc path. 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 [4].

In this paper, based on a great number of arc voltage records, the arc voltage wave shape presented in Fig. 2 is accepted.

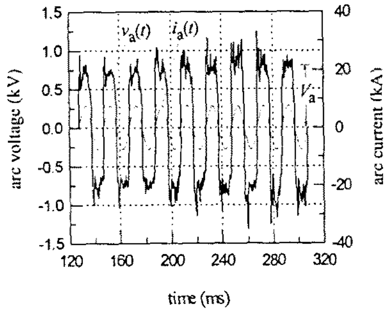

Fig. 1. Real arc voltage and current waveforms.

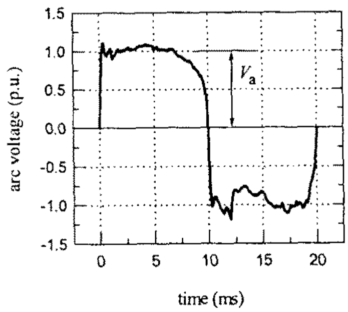

Fig. 2. Typical accepted arc voltage wave shape.

The arc model given in Fig. 2 can be represented by Fourier series containing odd sine components only, as follows:

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

where h = 1, 3, 5, 7, ... is the harmonic order, ω is the fundamental radian frequency 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. These coefficients for the fundamental and for the third harmonic are $k_1 = 1.23$, and $k_3 = 0.393$.

3. The Fault Model

The current path for the most frequent single-phase to ground fault includes the electrical arc and the tower footing resistance. New spectral domain fault model, developed in this paper, is depicted in Fig. 3. From this picture the h-th harmonic of the fault voltage can be expressed by next relation:

$$\underline{V}_{Fh} = \underline{V}_{ah} + R_F \underline{I}_{Fh} \qquad (2)$$

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.

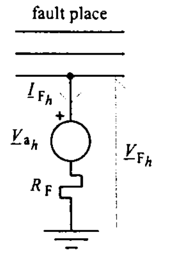

Fig. 3. Fault model given in spectral domain for h-th harmonic.

The arc voltage wave is in phase with the fault arc current. That means that 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:

$$\underline{V}_{a1} = \underline{k}_1 V_a \text{ and } \underline{V}_{a3} = \underline{k}_3 V_a \qquad (3)$$

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 ($\underline{I}_{F1} = I_{F1}\angle\phi$).

In this paper only fundamental and third harmonic fault model will be used for algorithm developing.

4. Algorithm Derivation

Let us assume a single-phase to ground arcing fault 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 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.

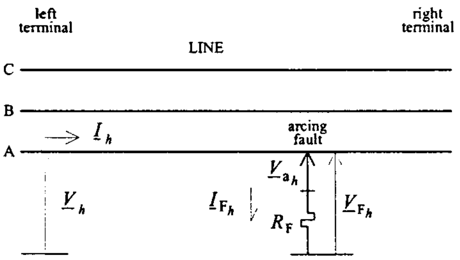

Fig. 4. Single-phase to ground arcing fault on three phase line.

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. Positive and negative sequence equivalent circuits are equal and are depicted in Fig. 5. 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.

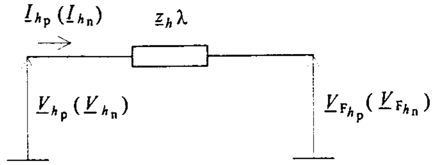

Fig. 5. Positive and negative sequence line equivalent circuit.

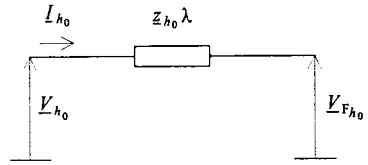

Fig. 6. Zero sequence line equivalent circuit.

For the equivalent circuits depicted in Figs. 5 and 6 the following equations can be written:

$$\underline{V}_{h_p} = \underline{z}_h \lambda \underline{I}_{h_p} + \underline{V}_{Fh_p} \qquad (4)$$

$$\underline{V}_{h_n} = \underline{z}_h \lambda \underline{I}_{h_n} + \underline{V}_{Fh_n} \qquad (5)$$

$$\underline{V}_{h_0} = \underline{z}_h \lambda \underline{I}_{h_0} + \underline{V}_{Fh_0}. \qquad (6)$$

By adding equations (4), (5) and (6), and using basic symmetrical components equations one obtains:

$$\underline{V}_h = \underline{z}_h(\underline{I}_h + \underline{k}_{zh}\underline{I}_{h0})\lambda + \underline{V}_{Fh} \qquad (7)$$

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

Substituting fault model equation (2) in (7), and using relations (3), next faulted loop equations for fundamental and 3-rd harmonic are obtained:

$$\underline{V}_1 = \underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\lambda + \underline{k}_1 V_a + R_F \underline{I}_{F1} \qquad (8)$$

$$\underline{V}_3 = \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\lambda + \underline{k}_3 V_a + R_F \underline{I}_{F3}. \qquad (9)$$

Because the zero-sequence network is passive we can assume that zero-sequence currents supplied from the local and remote systems are in phase. Then fundamental and 3-rd harmonics of fault current can be express as:

$$\underline{I}_{F1} = 3\underline{I}_{F10} = 3c_{F1}\underline{I}_{10} \qquad (10)$$

$$\underline{I}_{F3} = 3\underline{I}_{F30} = 3c_{F3}\underline{I}_{30} \qquad (11)$$

where c_{F1} and c_{F3} are real proportional coefficients.

Now, equations (8) and (9) get the form:

$$\underline{V}_1 = \underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\lambda + \underline{k}_1 V_a + 3R_{Fe1}\underline{I}_{10} \qquad (12)$$

$$\underline{V}_3 = \underline{z}_3(\underline{I}_3 + \underline{k}_{z3}\underline{I}_{30})\lambda + \underline{k}_3 V_a + 3R_{Fe3}\underline{I}_{30} \qquad (13)$$

where $R_{Fe1} = c_{F1}R_F$ and $R_{Fe3} = c_{F3}R_F$.

Complex equations (12) and (13) give system of four scalar equations:

$$\mathrm{Re}\{\underline{z}_1(\underline{I}_1 + \underline{k}_{z1}\underline{I}_{10})\}\lambda + \mathrm{Re}\{\underline{k}_1\}V_a + 3\,\mathrm{Re}\{\underline{I}_{10}\}R_{Fe1} = \mathrm{Re}\{\underline{V}_1\} \qquad (14)$$

$$\mathrm{Im}\{\underline{z}_1(\underline{I}_1+\underline{k}_{z1}\underline{I}_{10})\}\lambda+\mathrm{Im}\{\underline{k}_1\}V_a+3\,\mathrm{Im}\{\underline{I}_{10}\}R_{Fe1}=\mathrm{Im}\{\underline{V}_1\} \quad (15)$$

$$\mathrm{Re}\{\underline{z}_3(\underline{I}_3+\underline{k}_{z3}\underline{I}_{30})\}\lambda+\mathrm{Re}\{\underline{k}_3\}V_a+3\,\mathrm{Re}\{\underline{I}_{30}\}R_{Fe3}=\mathrm{Re}\{\underline{V}_3\} \quad (16)$$

$$\mathrm{Im}\{\underline{z}_3(\underline{I}_3+\underline{k}_{z3}\underline{I}_{30})\}\lambda+\mathrm{Im}\{\underline{k}_3\}V_a+3\,\mathrm{Im}\{\underline{I}_{30}\}R_{Fe3}=\mathrm{Im}\{\underline{V}_3\} \quad (17)$$

from which unknown arc voltage amplitude and fault distance can be calculated.

5. Computer Simulated Tests

The tests have been done using the Electromagnetic Transient Program (EMTP) [5]. The schematic diagram of the 400 kV power system on which the tests are based is shown in Fig. 7. The line parameters were $D = 100$ km, $r = 0.0325$ Ω /km, $x = 0.3$ Ω/km, $r_0 = 0.0975$ Ω/km and $x_0 = 0.9$ Ω/km.

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 $f_s = 6400$ Hz. The duration of data window was $T_{dw} = 20$ ms.

The arc voltage used by EMTP is assumed to be of square wave shape with amplitude of $V_a = 5.4$ kV, corrupted by the random noise. The instant of the fault inception was 23 ms. Fault resistance were $R_F = 2$ Ω.

Impute phase voltages and line currents, measurable at relay place, calculated by EMTP for selected study case are plotted in Figs. 9 and 10, respectively.

The fault distance and arc voltage calculated by algorithm are depicted in Fig. 11. The exact unknown model parameters (λ = 60 km and $V_a = 5.4$ kV) are obtained fast, after 20 ms, and accurate.

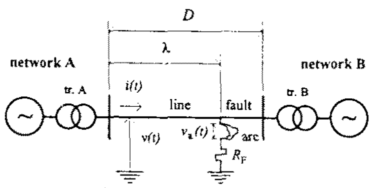

Fig. 7: Test power system.

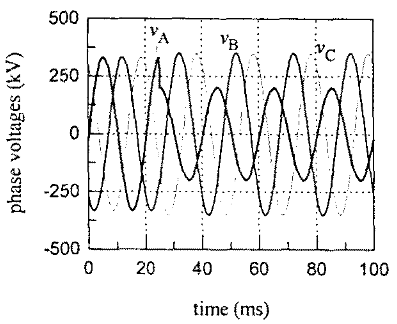

Fig. 9. Distorted input voltages generated by EMTP.

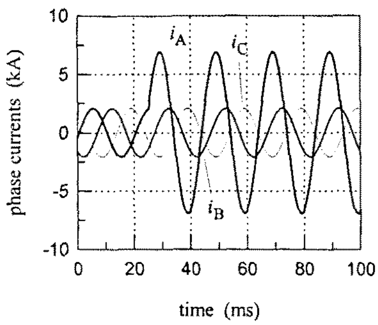

Fig. 10. Distorted input currents generated by EMTP.

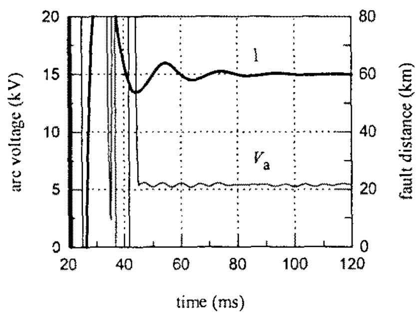

Fig. 11. Calculated fault distance and arc voltage amplitude.

6. Conclusion

A new numerical algorithm for arcing faults recognition and for fault distance calculation is presented. The algorithm 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 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.

References

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