Influence of Fault Arc Characteristics on the Accuracy of Digital Fault Locators

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***Abstract*—This paper has proposed a time domain model of a fault locator with special reference to fault arc nonlinearities by applying the MODELS language of the EMTP. It has been found that an impedance relay type locator is significantly influenced by the fault arc nonlinearities, while the current diversion ratio method is not influenced. This validates the advantage of the current diversion approach over the impedance approach.**

***Index Terms*—ATP-EMTP, fault arc, fault locator, MODELS, time domain model.**

I. Introduction

MANY fault locator algorithms were developed to be operated on digital relay data [1]–[7]. The methods were derived from frequency domain equations and were established by a phasor simulation. The algorithms were based on the assumption that a fault arc was linear and showed a constant impedance. It, however, is shown that a fault arc in air is physically nonlinear.

To study the influence of the nonlinearity on the accuracy of a digital fault locator, a time domain simulation must be performed considering the nonlinear characteristic of the fault arc. Time domain models of the protective relay [8]–[10] were developed by using the module Transient Analysis of Control System (TACS) [11], [12] of the EMTP for representing the blocks of a relay simulation.

The present paper proposes a time domain model of a fault locator with special reference to the nonlinearities of a fault arc by applying the MODELS language in the ATP-EMTP [13]. The influence of the arc nonlinearity on fault location is investigated. Also, the advantage of the current diversion ratio method of fault location [4] over the impedance approach [1] is discussed.

II. Digital Fault Locator Algorithm

Digital fault locator algorithms are divided into two categories, one using data from one terminal of a transmission line [1]–[4], and the other using data from both terminals [5]–[7]. The former is superior in the economical viewpoint because it requires no data transfer along long distance. The latter is superior in the accuracy viewpoint of fault location, but requires a data transfer system.

This paper deals with a one-terminal type fault locator. The reason is its simplicity of input data and a formula used. The power systems to which the fault locator is applied, are the high-resistance grounded systems widely used in Japan. The focus is on a phase-to-ground fault because this type of a fault occupies 90% of transmission line faults. One application is for a radial circuit and another is for a double circuit. Corresponding locating formulas in a frequency domain are summarized below.

Method-1: Impedance relay type method [1]

$$d = \frac{I_m\left(V \cdot I_{pol}^*\right)}{I_m\left(V_u \cdot I_{pol}^*\right)} \tag{1}$$

where

$$V_u = Z_s \cdot I + \sum Z_m I_{other}.$$

Method-2: Current diversion ratio method [4]

$$d = \frac{2 \cdot \mathrm{Re}\left(I_{0m} \cdot V_{pol}^*\right)}{\mathrm{Re}\left\{(I_0 + I_{0m}) \cdot V_{pol}^*\right\}} \bullet d_1 \tag{2}$$

where

d	distance from location point to fault point
d_1	transmission line length
$\mathrm{Re}(A)$	real part of A
$\mathrm{Im}(A)$	imaginary part of A
A^*	conjugate of A
V	faulted-phase voltage of locator terminal
V_u	line drop voltage per unit length
V_{pol}	polarized voltage e.g., $V_{pol} = V_{BC}\angle 90°$ in case of phase-a locating
Z_S	self impedance per unit length
Z_m	mutual impedance per unit length
I	faulted-phase current of locator terminal
I_{other}	unfaulted phase current of locator terminal $I_{pol} = 3 \cdot I_o = I_a + I_b + I_c$
I_0	zero sequence current of faulted line
I_{0m}	zero sequence current of another line.

Briefly speaking, the impedance relay type method makes fault location by dividing the fault phase voltage by the line voltage drop per unit length. The current diversion ratio method is applicable only to a loop-network. It, paying attention to that a fault

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current divides to the faulted circuit and the sound circuit, calculates the distance on the assumption that the faulted circuit's voltage drop equals to the sound circuit's one. Voltage drops for the both circuits are:

$$V_o = d_1(Z_{0S}I_0 + Z_{0m}I_{0m}) \tag{3}$$

$$V_o = d_1(Z_{0S}I_{0m} + Z_{0m}I_0) + 2(d_1 - d)(Z_{0S}I_{0m} - Z_{0m}I_{0m}) \tag{4}$$

where
- V_o zero sequence voltage of locator terminal
- Z_{0S} zero sequence self impedance per unit length
- Z_{0m} zero sequence mutual impedance per unit length

From these equations the distance is calculated as:

$$d = \frac{2 \cdot I_{0m}}{I_0 + I_{0m}} \bullet d_1. \tag{5}$$

In (2), polarized voltage is used not to make the denominator zero.

III. Fault Locator Model Description

A time domain model of a fault locator is represented using the MODELS language in the ATP-EMTP. The model basically consists of five parts, which are processed sequentially.

Block-1: Input Analog Filter: Block-1 is used to eliminate, before sampling, any harmonics existing in the measured signals near the sampling frequency. The filtering is applied to all voltage and current measurements used by the fault locator. The filter is represented by a constant-coefficient Laplace transfer function.

Block-2: Sampling/Hold and Digital Filters: Block-2 represents analog to digital conversion applied by the digital fault locator. The filtered signal is sampled 720 times per second for the 60 Hz system. This sampling is modeled by placing the digital filter in a sub-model that uses a larger time step corresponding to the required sampling period. The size of the sampling interval is specified when the model is used. Its value is then used automatically by the model as the model's time step. As for the digital filtering, it is represented by a constant-coefficient Z transfer function.

Block-3: Magnitude and Phase Calculation: In block-3, the real and imaginary parts of the phasor representation of the sampled and filtered signal are calculated using a single term of the discrete Fourier series evaluated at the power frequency.

Block-4: Fault Locating Algorithm: Block-4 describes the fault location derived in the time domain. For both the impedance relay type calculation and the current diversion ratio calculation, the phasor equation is expanded in terms of the real and imaginary parts of the currents and voltages. For the impedance relay type model, the fault distance is calculated as shown in (1). In the case of the current diversion ratio method, the fault distance is calculated according to (2).

Block-5: Statistical Output Procedure: Block-5 is the statistical procedure applied to reduce the error due to the nonlinearity of the fault arc resistance. The three most recent values of the calculated fault distance are stored and updated at each sampling. The differences between the distance values are also stored and updated. The differences are used to determine if the calculated values converge to within 0.5 km. The final variable will then show a nonzero value whenever the distance calculation has converged.

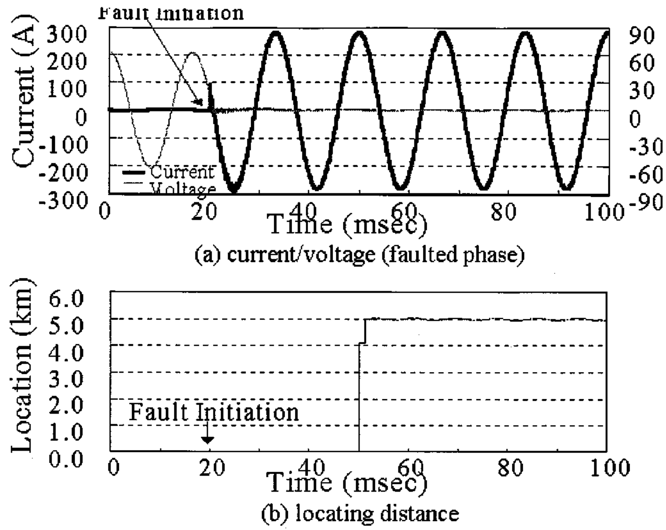

Fig. 1. Calculated results for the impedance relay type method (fault resistance $= 0.1$ mΩ).

IV. Simulation Examples (Basic Cases)

The test system is 60 Hz, 77 kV system. The line length d_1 is 20 km and the fault point is 5 km from the locating terminal. Data of the model systems are:

- Source impedance $= 0.19981 + j2.0052$ (Ω)
- Substation neutral current in short circuit case $= 200$ (A)
- Self impedance $= 0.2479 + j0.6571$ (Ω/km)
- Mutual impedance within a circuit $= 0.1257 + j0.2700$ (Ω/km)
- Mutual impedance which between circuits $= 0.1258 + j0.2290$ (Ω/km)
- Self capacitive admittance $= 2.5320$ (μ S/km)
- Mutual capacitive admittance within a circuit $= -0.4514$ (μS/km)
- Mutual capacitive admittance between circuits $= -0.1996$ (μS/km)

For both the impedance relay type and the current diversion ratio methods, two fault resistance values 0.1 mΩ and 20 Ω are simulated. The calculated results for the radial circuit are shown in Figs. 1 and 2. The oscillation which appears in the terminal current and voltage immediately after the fault occurrence is caused by the harmonics due to the line capacitance. But the harmonics can be eliminated by a filter, and don't have a large influence on the locating distance. Fault locating is delayed by about 30 msec from the fault initiation. The delay is caused by a digital filter, Fourier transformation, and output procedure, respectively.

When the fault resistance R_f is 0.1 mΩ, the error is nearly zero. When R_f is 20 Ω, the error is about 0.4 km. These errors due to neglecting the capacitance are acceptable. The fault resistance value doesn't have a large influence on fault location

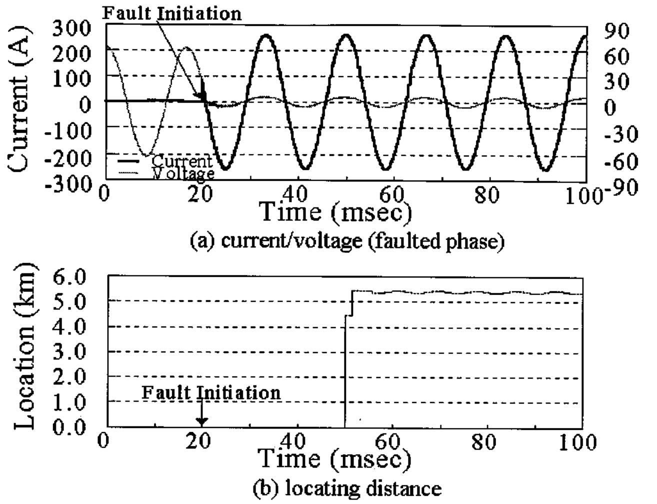

Fig. 2. Calculated results for the impedance relay type method (fault resistance $= 20\ \Omega$).

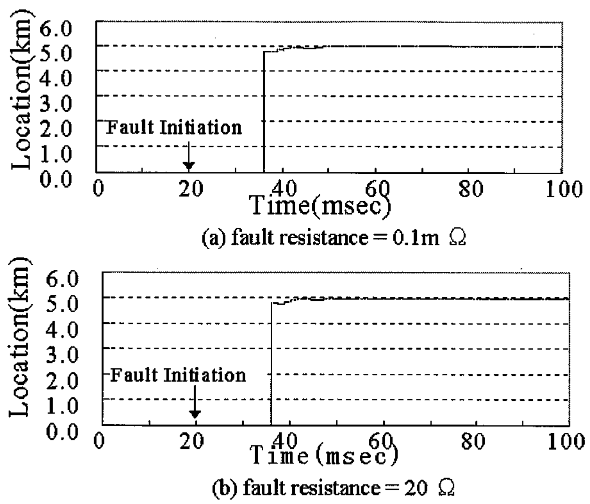

Fig. 3. Calculated results for the current diversion ratio method.

even in the presence of capacitance to the ground. Calculated results by the current diversion ratio method are shown in Fig. 3. The terminal current and voltage are nearly the same as those in Figs. 1 and 2. The location error is nearly zero. The fault resistance value has no influence on the location error when the resistance is held constant.

V. Influence of Fault ARC Characteristics

The case where a nonlinear arc resistance model is added to the fundamental network is examined. Many fault arc models have been proposed. This paper adopts nonlinear arc resistance models [14], [15] and represents those by using the MODELS language.

Model-1: Square Voltage Model: Model-1 is a simple nonlinear resistance with the arc voltage represented as a square wave [14].

$$R = \frac{Va}{|i|} \tag{6}$$

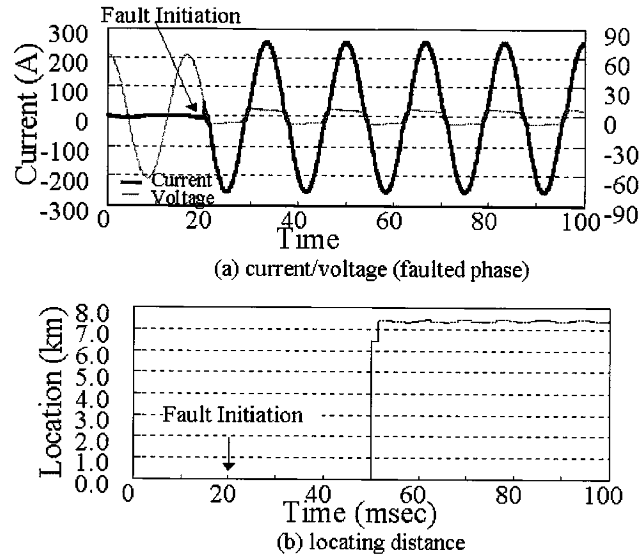

Fig. 4. Calculated results for the impedance relay type method (Model-1 arc resistance).

where:

- R arc resistance
- i arc current
- Va amplitude of the square wave voltage approximation (10% of phase voltage RMS value = 6.287 02 kV)

Model-2: Kizilcay's Time Dependent Model: Model-2 describes the dynamic behavior of a fault through air based on measurement with various system voltage and types of insulation [15].

$$R = \frac{1}{g} \tag{7}$$

$$\frac{dg}{dt} = \frac{1}{\tau}(G - g) \tag{8}$$

$$G = \frac{|i|}{(u + Rarc \cdot |i|) \cdot len} \tag{9}$$

where:

- R arc resistance
- g time-varying arc conductance
- G stationary arc conductance
- i arc current
- τ arc time constant (0.4 ms)
- u constant voltage parameter per arc length (14.3 V/cm)
- $Rarc$ resistive component per arc length (0.55 mΩ/cm)
- len time-dependent arc length (58 cm)

In Model-2 the arc length is assumed to be constant (58 cm for the 77-kV system), because of the short arc length. Parameters value τ, u and $Rarc$ are derived from the measurements shown in [15], [16].

$\tau = 0.4$ (ms)
$u = 0.83 \times 1000/58 = 14.3$ (V/cm)
$Rarc = 32/58 = 0.55$ (mΩ/cm)

Calculated results are shown in Figs. 4 and 5. As the location errors produced by the current diversion ratio method are nearly zero, the graphs of those results are omitted. It is clear that the impedance relay type method produces a large error, while the

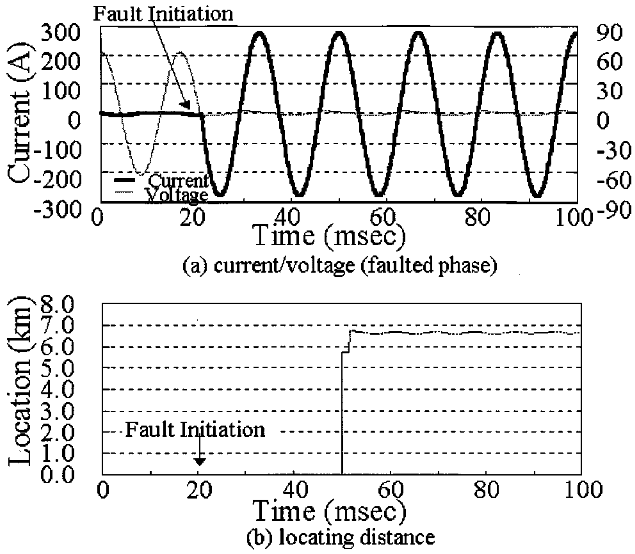

Fig. 5. Calculated results for the impedance relay type method (Model-2 arc resistance).

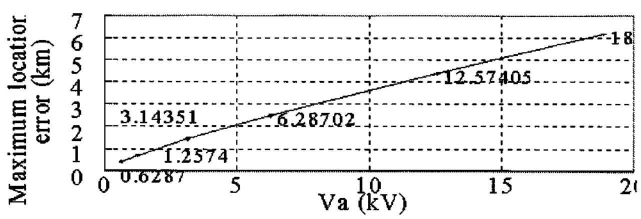

Fig. 6. Sensitivity analysis of Model-1 parameters for the impedance relay type method.

current diversion ratio method is not influenced by the arc resistance nonlinearity.

The influence of model parameters are investigated. For Model-1:

Va (kV)	1, 2, 5, 10, 20, 30% of phase voltage RMS value

For Model-2:

τ (ms)	0.2, 0.4, 0.6, 0.8
u (V/cm)	14.3 ±10%, ±20%
$Rarc$ (mΩ/cm)	0.55 ±10%, ±20%
len (cm)	58 +10%, +20%

The calculated results are shown in Figs. 6 and 7. As the location errors produced by the current diversion ratio method are nearly zero, the graphs of those results are omitted. From the figures it is concluded that the locating error is proportional to the parameter values except $Rarc$. Stronger nonlinear characteristics of the of fault arc produce larger fault location errors.

VI. Conclusion

This paper studied the influence of fault arc nonlinearity on the accuracy of digital fault locators. Time domain model of a digital fault locators were represented using the MODELS language in the ATP-EMTP. Various types of faults were simulated, with constant and with nonlinear resistance. The simulation results showed that the impedance relay type method is influenced by the nonlinear representation of the a fault arc, while the current diversion ratio method is not. A sensitivity analysis of the locating error with respect to the model parameters of the nonlinear arc resistance was performed for the impedance relay type method. It showed that increasing the degree of nonlinearity increases the location error.

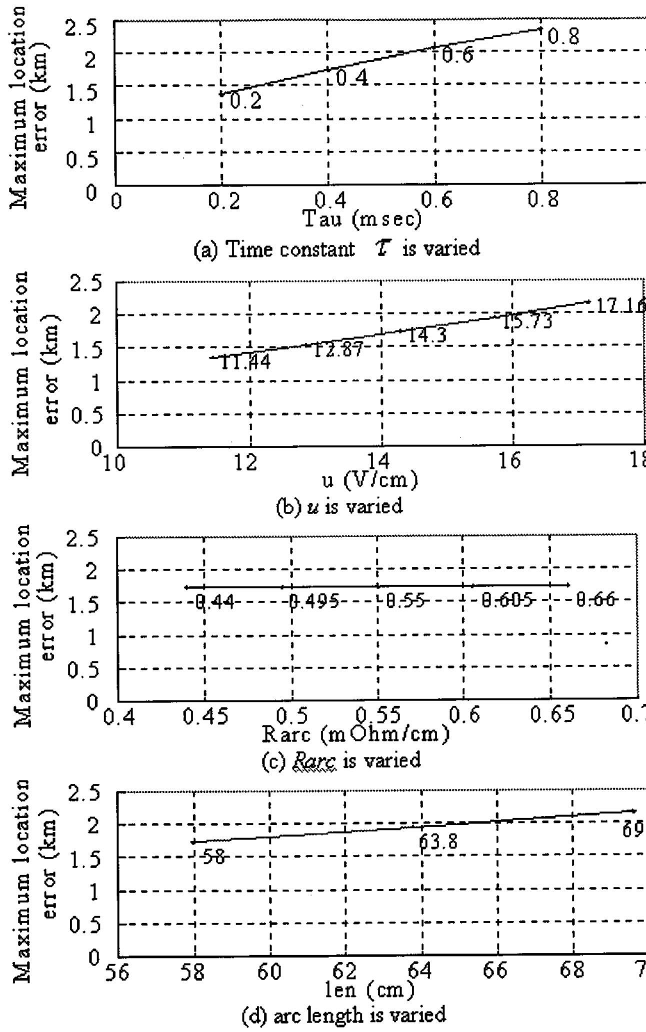

Fig. 7. Sensitivity analysis of Model-2 parameters for the impedance relay type method.

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