Simulation of Fault Location Algorithms in ATP Program Using "C" Link

Carlos Eduardo de Morais Pereira [1] and Luiz Cera Zanetta Jr [1]

(1) Department of Electrical Engineering and Automation - Escola Politécnica da Universidade de São Paulo - São Paulo, Brazil , 55 11 3091 5276 (email: carlos@pea.usp.br, lzanetta@pea.usp.br)

Abstract – **This paper presents a simulation tool for fault location algorithms and relay application in transmission lines, using the ATP program, its MODELS language and "C" subroutines.**

The tool developed performs all the process of fault location simulation in a single step, without using a post processing stage after ATP execution. This technique also allows the behavior analysis of the fault location algorithm, after operation of circuit breakers, with some advantages.

The transmission line, equivalent network connected to its terminals, switches, fault resistance and voltage sources are modeled in a single ATP file section. The anti-aliasing filtering, with a low-pass Butterworth filter and sampling of voltages and currents are performed by MODELS routine, and the digital filtering and fault distance calculation is implemented in "C" subroutine linked to the MODELS section of the ATP file. The use of the "C" subroutine allows a detailed report of fault location process in an output file, including oscilography similar to digital relays.

The results presented use a high voltage, single circuit, overhead transmission line, considering some fault conditions, such as line length, fault distance, fault resistance, fault type and equivalent parameters.

The fault location algorithms use data of either one or both line terminals, and also simulate an algorithm of data synchronization, when required.

Keywords – fault location, transmission line, protection.

I. INTRODUCTION

The reclosing process of a transmission line after the occurrence of permanent faults depends on several factors, including a fast and accurate location of the fault. Due to its great importance, algorithms for digital fault location [1,2,3] have been studied in the last decades, and in many cases, the fault location is included as an additional function of digital relays, using the same hardware, changing only the source code.

An integrated system for modeling a power system digital relay is an important subject for reliable protection system joined in one program module and it is a very attractive tool for relay application developments. An example of this tool is presented in [4] with the use of MODELS language.

This paper follows the aim above, but including in the same module "C" language routines that allow more general and flexible studies. Using a high level language as "C", interfaced with ATP routines, improves computation time, making possible to use codes developed by manufactures without translation to MODELS language.

This work presents a simulation tool of faults and distance relays performance in transmission lines, with fault location function, using the ATP program [4,5,6,7]. All the functions of the relay, including phasors calculation are programmed in "C" language. The routines in "C" are linked with ATP [8] by means of the MODELS subroutine [9].

One of the advantages is to achieve the fault detection and location in a single simulation of the ATP program, without any post-processing. Another advantage is the modularization of the relay algorithm, allowing the inclusion of different methods of fault location or protection functions.

II. FAULT LOCATION METHODS

The implemented fault location algorithms use to calculate the fault distance, the 60 Hz voltage and current phasors in one or both line terminals.

Two algorithms were implemented; the first one considers data of local terminal only, and is based on references [1,2]. The major difference among these two algorithms is the transmission line model.

The second algorithm, that uses data of both line terminals, is based on reference [3], which presents an accurate method based on two-port representation of a transmission line.

A. Fault Location Using Data from Local Terminal

Reference [1] uses the π-equivalent model, allowing better accuracy, but requiring iterative calculation of fault distance. Reference [2] uses the series impedance model, that neglects the effect of the line length and line capacitance but, in this case, the fault distance is obtained with no need of iterative calculation.

➢ *Series impedance model*

This model is considered in [2] and neglects line capacitance as well as hyperbolic functions, but showed to be suitable for representing short lines ($\ell \le 50$ km).

The constants A, B, C and D are:

$$\begin{matrix} A = 1 & B = Z \\ C = 0 & D = 1 \end{matrix} \qquad (1)$$

Where $Z = z\ell$ and $z = r + jx$.

➢ *Basic Equation*

The basic equation for fault distance calculation [1], for three-phase faults is:

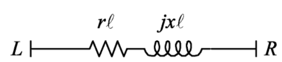

Fig. 1 Series impedance line model

$$\operatorname{Im}\left(\frac{A_1(d)V_L^1 - B_1(d)I_L^1}{C_1(d)V_L^{1^f} - D_1(d)I_L^{1^f}}\right) = 0 \quad (2)$$

Where:

$$V_L^{1^f} = V_L^{1^{pos}} - V_L^{1^{pre}}$$

$$I_L^{1^f} = I_L^{1^{pos}} - I_L^{1^{pre}}$$

Which are the superimposed components.

➢ *Equations used*

The fault location algorithm implemented in the "C" subroutine used the series impedance line model and, for this case, the unknown variable *d* can be isolated. For each fault type a different equation may be used, as follows:

- three-phase fault

$$d = \frac{\operatorname{Im}\left(V_L I_L^{f*}\right)}{\operatorname{Im}\left(z I_L I_L^{f*}\right)} \quad (3)$$

- ground-to-phase fault

$$d = \frac{\operatorname{Im}\left[\left(V_L^0 + V_L^1 + V_L^2\right)I_L^{1f*}\right]}{\operatorname{Im}\left[\left(z_0 I_L^0 + z_1 I_L^1 + z_1 I_L^2\right)I_L^{1f*}\right]} \quad (4)$$

- double-phase fault

$$d = \frac{\operatorname{Im}\left[\left(V_L^1 - V_L^2\right)I_L^{1f*}\right]}{\operatorname{Im}\left[\left(z_1 I_L^1 - z_1 I_L^2\right)I_L^{1f*}\right]} \quad (5)$$

- double-phase-to-ground fault

$$d = \frac{\operatorname{Im}\left[\left(V_L^1 - V_L^0\right)I_L^{0f*}\right]}{\operatorname{Im}\left[\left(z_1 I_L^1 - z_0 I_L^0\right)I_L^{0*}\right]} \quad (6)$$

The symbol * indicates complex conjugate.

In equations (3) to (6) it can be observed that hyperbolic functions were not used, facilitating the computational implementation.

B. Fault Location Using Two Terminal Data

The algorithm used for calculating fault distance using two terminal data is derived from the equation extracted from reference [3], and commonly using positive sequence data:

$$d = \operatorname{atanh}\left(\frac{V_L - V_R\cosh(\gamma\ell) + Z_c I_R \sinh(\gamma\ell)}{Z_c I_L - V_R \sinh(\gamma\ell) + Z_c I_R \cosh(\gamma\ell)}\right)\frac{1}{\gamma} \quad (7)$$

Using series impedance line model, the fault distance can be calculated by solving the following equation, using positive sequence data:

$$d = \frac{V_L - V_R + z\ell I_R}{z\left(I_L + I_R\right)} \quad (8)$$

To improve the accuracy, superimposed phasors components measured in the local and remote terminals may be used:

$$d = \frac{V_L^{1^f} - V_R^{1^f} + z_1 \ell I_R^{1^f}}{z_1\left(I_L^{1^f} + I_R^{1^f}\right)} \quad (9)$$

Where:

$$V_L^{1^f} = V_L^{1^{pos}} - V_L^{1^{pre}} \qquad I_L^{1^f} = I_L^{1^{pos}} - I_L^{1^{pre}}$$

$$V_R^{1^f} = V_R^{1^{pos}} - V_R^{1^{pre}} \qquad I_R^{1^f} = I_R^{1^{pos}} - I_R^{1^{pre}}$$

III. DIGITAL FILTERING FOR PHASOR OBTENTION

The digital filtering algorithm is based on DFT (Discrete Fourier Transform) [10], in association with a digital filter to extract the DC component of the voltage and current data, similar to a mimic impedance filter.

This association presents unitary gain for the fundamental frequency and null gain for the other harmonics.

Before the sampling, the signals were submitted to anti-aliasing filtering performed with Butterworth low-pass filter [10]. The sampling rate adopted was 960 Hz, or 16 samples in a 60 Hz cycle.

The performance of the digital filtering algorithm is presented below, showing its accuracy for obtaining the 60 Hz phasors in a typical voltage and current waveform in a long high voltage transmission line with fault.

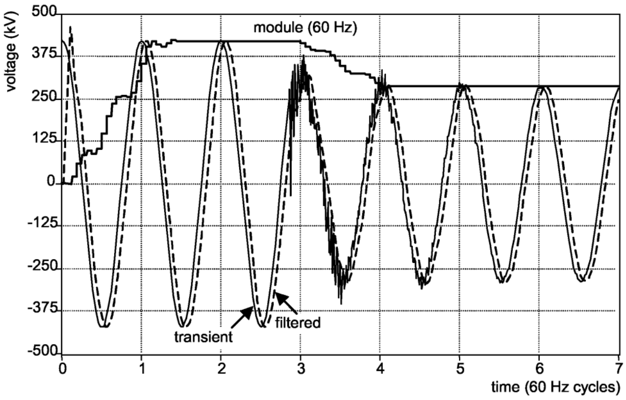

Fig. 2 Voltage in phase A of the local terminal, anti-aliasing filtered signal and magnitude of the fundamental component. (fault AN 150 km)

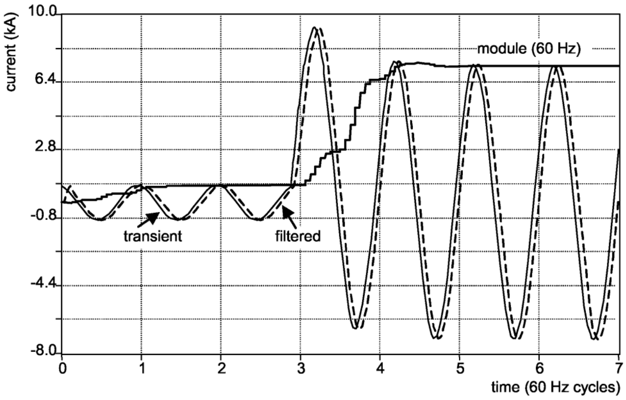

Fig. 3 Current in phase A of the local terminal, anti-aliasing filtered signal and magnitude of the fundamental component (fault AN 150 km)

IV. Simulation Methodology

The algorithm of fault location is implemented in a "C" subroutine, linked with ATP via MODELS language.

The functions performed by MODELS are:

- acquisition of the instantaneous values of voltages and currents in the local and remote terminals;
- anti-aliasing filtering of voltages and currents;
- sampling voltages and currents signals;
- call of "C" subroutine that simulate local distance relay functions (including fault location);
- call of "C" subroutine that simulate remote distance relay functions (including fault location);
- returns the results calculated by the "C" routine to ATP.

The input data supplied by MODELS, to the "C" routine are:

- digital filter coefficients;
- line parameters per line length (r_1, x_1, r_0, x_0), line length and setting of first zone of distance relay;
- six windows of voltage and current samples (v_a, v_b, v_c, i_a, i_b, i_c) 6x20 points, simulation time, and for local relay, positive sequence voltage and current of remote terminal, calculated by the another relay, for fault location using two terminal data.

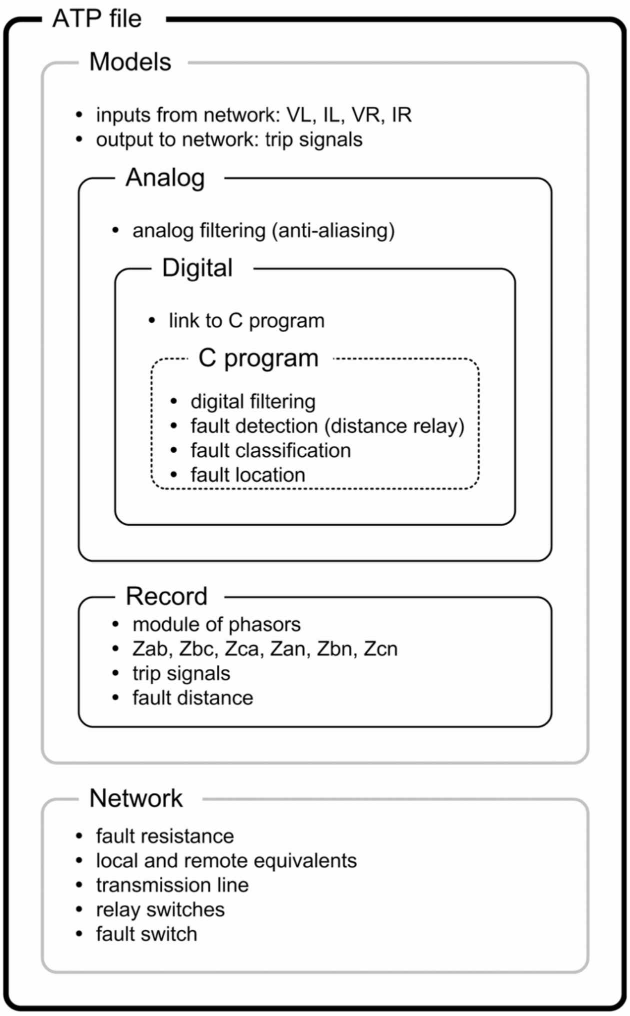

Fig. 4 Block diagram of simulation methodology

The functions performed by "C" program are:

- digital filtering;
- fault detection;
- fault classification;
- fault location.

The output data returned to MODELS (for plotting) are:

- fundamental (60 Hz) magnitude of voltage and current signals;
- trip signal (first zone);
- loop impedances (Z_{AB}, Z_{BC}, Z_{CA}, Z_{AN}, Z_{BN}, Z_{CN});
- fault distance.

The "C" program also creates a COMTRADE format (Standard Common Format for Transient Data Exchange for Power Systems, standard no. IEEE C37.111-1991) output files containing the voltage and current samples, and implemented functions.

V. Simulations Results

In the ATP simulations, the following network (Fig. 5) was used, containing a transmission line, relays and equivalent at both line terminals.

The line operating voltage is 500 kV, with a typical tower, as depicted in Fig. 6.

The line lengths used are 100 and 400 km, to illustrate the fault location algorithm performance for short and long lines, taking into account the line modeling using only series impedance.

The first zone setting adopted was 80% for reactance and 50 Ω for resistance tolerance. The positive sequence pa-

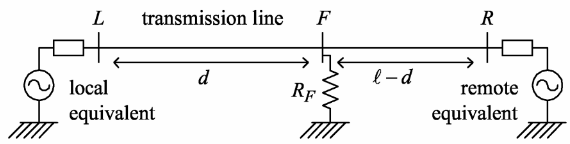

Fig. 5 Network for test of the fault location algorithms

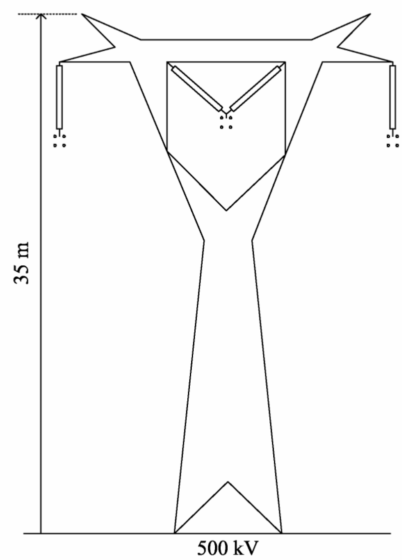

Fig. 6 Tower configuration of simulated lines

rameters of the line are r_1=0.02558 Ω/km, x_1=0.3264 Ω/km. For 400 km line length, with the setting adopted to the first zone, the characteristic polygon is depicted in Fig. 7.

The Fig. 8 and Fig.9 show the Z_{AN} impedance along the time and it's trajectory in *RX* plane, calculated by the local terminal relay, for a phase-to-ground fault at 150 km from the local terminal, with 10 Ω of fault resistance.

In Fig. 10, a detail of the trajectory for post-fault time is shown, with axis limits corresponding to the first zone polygon in the first quadrant (*R* and *X* positive).

The fault parameters analyzed were fault distance, fault resistance and line length, for phase-to-ground and three-phase faults. The results are related to fault distances calculated by local terminal relay, that uses two fault location algorithms (one and two terminal data) and also the fault distance calculated by the remote terminal relay, that uses only one-terminal fault location algorithm.

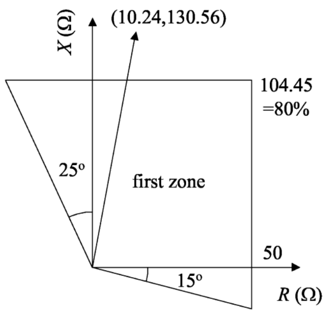

Fig. 7 First zone polygonal characteristic

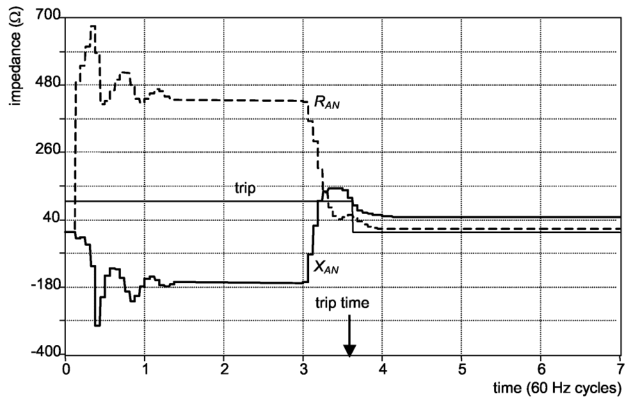

Fig. 8 Z_{AN} impedance and trip signal in function of time

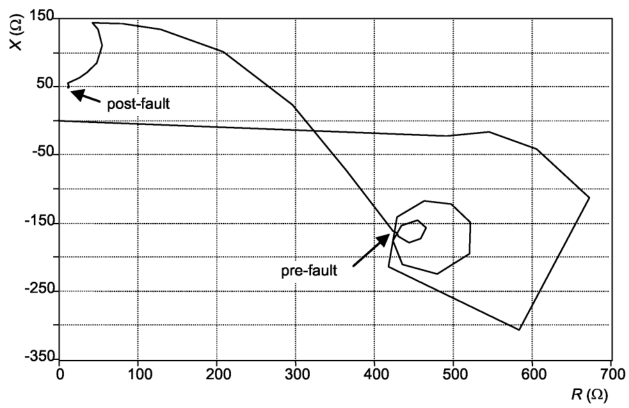

Fig. 9 Trajectory of Z_{AN} impedance in RX plane

In Fig. 11 it's shown the fault distance in function of time for a phase-to-ground fault at 150 km of the local terminal in the 400 km line.

In references [5,6], several fault location algorithms using ATP, MODELS and MatLab routines are compared. Such two steps may be somewhat inconvenient and time-consuming to organize the calculations using a proprietary tool such as MatLab. The following cases review some results, which are easily obtained with the developed tool, suitable for studies of relay implementation.

A. Fault Location Results for Long Transmission Line

In this case the line length is 400 km, and the objective is to verify the effect of neglecting both the capacitance of the line and the hyperbolic corrections.

➢ *Influence of the Fault-Distance*

The fault parameters are:

- fault type: phase-to-ground and three-phase faults
- fault resistance: 10 Ω

The two-terminal method presents better accuracy and the one-terminal method is more accurate for faults near to the local terminal and phase-to-ground faults as depicted in Table I and Fig.12.

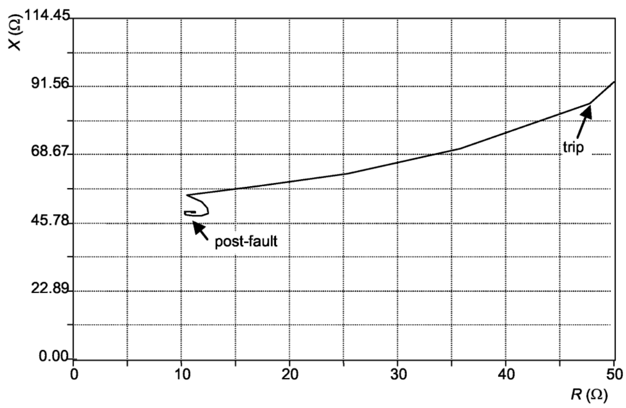

Fig. 10 Detail of the trajectory of Z_{AN} impedance in *RX* plane (post-fault).

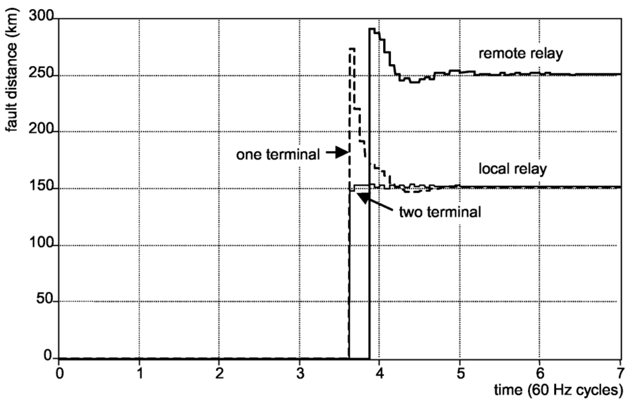

Fig. 11 Fault-distance calculation by local and remote relays

Table I Fault distance variation effect

		calculated fault-distance (km)		
		local terminal relay		remote relay
	fault distance (km)	one-terminal (1T)	two-terminal (2T)	one-terminal
Phase-to-ground fault	50	50.085	54.105	353.48
	100	100.32	103.23	304.19
	150	150.74	151.78	251.84
	200	201.68	200.05	200.83
	250	253.73	248.23	150.33
	300	306.33	296.57	100.06
three-phase fault	50	50.305	53.892	371.79
	100	100.82	103.29	314.79
	150	152.14	151.9	258.48
	200	204.64	199.91	204.5
	250	259.09	248.14	151.99
	300	315.33	296.59	100.71

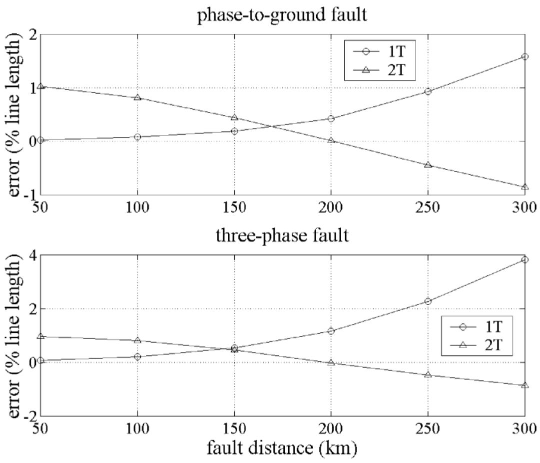

Fig. 12 Influence of the fault-distance – long line

Table II Fault resistance variation effect

		calculated fault-distance (km)		
		local terminal relay		remote relay
	fault resistance (Ω)	one-terminal	two-terminal	one-terminal
Phase-to-ground fault	0	150.72	151.50	252.54
	1	150.72	151.54	252.45
	5	150.72	151.68	252.15
	10	150.74	151.78	251.84
	20	150.82	151.86	251.36
	50	151.14	151.90	250.14
three-phase fault	0	151.87	151.74	259.31
	1	151.94	151.77	259.25
	5	152.07	151.87	258.88
	10	152.14	151.90	258.48
	20	152.35	151.92	257.95
	50	152.91	151.92	256.24

➢ *Influence of the Fault Resistance*

The fault parameters are:

- fault type: phase-to-ground and three-phase faults
- fault distance: 150 km

Table II show that for long lines the simulated algorithms are low sensitive to the fault resistance.

B. Fault Location Results for Short Transmission Line

In this case the line length is 100 km, more adequate to the line representation with only series impedance.

➢ *Influence of the Fault-Distance*

The fault parameters are:

- fault type: phase-to-ground and three-phase faults
- fault resistance: 10 Ω

In these cases the two algorithms present good accuracy for all fault distances as shown in Table III and Fig. 13.

➢ *Influence of the Fault Resistance*

Table III Fault distance variation effect

		calculated fault-distance (km)		
		local terminal relay		remote relay
	fault distance (km)	one-terminal	two-terminal	one-terminal
Phase-to-ground fault	15	15.169	15.193	84.006
	25	25.161	25.145	74.428
	35	35.148	35.092	64.663
	50	50.117	50.001	49.864
	60	60.084	59.94	39.946
	75	74.99	74.855	25.026
three-phase fault	15	15.407	15.191	83.706
	25	25.388	25.145	74.196
	35	35.362	35.091	64.517
	50	50.308	50.001	49.816
	60	60.254	59.940	39.945
	75	75.108	74.855	25.084

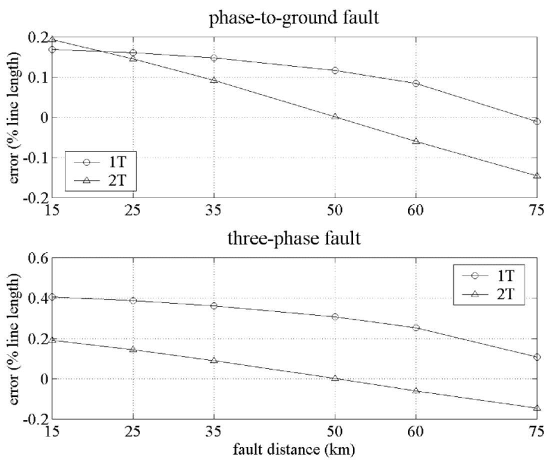

Fig. 13 Influence of the fault-distance – short line

Table IV Fault resistance variation effect

		calculated fault-distance (km)		
		local terminal relay		remote relay
	fault resistance (Ω)	one-terminal	two-terminal	one-terminal
Phase-to-ground fault	0	15.001	15.189	85.056
	1	15.023	15.186	84.97
	5	15.085	15.193	84.531
	10	15.169	15.193	84.006
	20	15.337	15.192	82.916
	50	15.826	15.192	79.349
three-phase fault	0	14.992	15.183	85.338
	1	15.045	15.175	85.236
	5	15.207	15.189	84.546
	10	15.407	15.191	83.706
	20	15.799	15.191	81.959
	50	16.899	15.192	75.913

The fault parameters are:

- fault type: phase-to-ground and three-phase faults
- fault distance: 15 km

The results (Table IV, Fig. 14) show that the two-terminal algorithm is insensitive to fault resistance, whereas the one-terminal algorithm is less accurate as fault resistance grows, mainly for three-phase faults distant from the relay. For short lines, the influence of fault resistance on the accuracy is more important than the cases with long lines.

C. Test of Data Synchronization Algorithm

The tests of data synchronization algorithm for the two-terminal method was performed for the following fault parameters:

- fault type: phase-to-ground
- fault distance: 150 km
- fault resistance: 10 Ω
- line length 400 km

The unsynchronization was simulated considering the time reference at the remote terminal delayed related to the local terminal.

Figure 15 illustrates a case of time delay of 8 samples, which corresponds to 8.333 ms or 180 electrical degrees. The solid curve does not present time delay.

As shown in Table V, the synchronization algorithm calculated the delay correctly, allowing an accurate fault location even in cases of unsynchronized data.

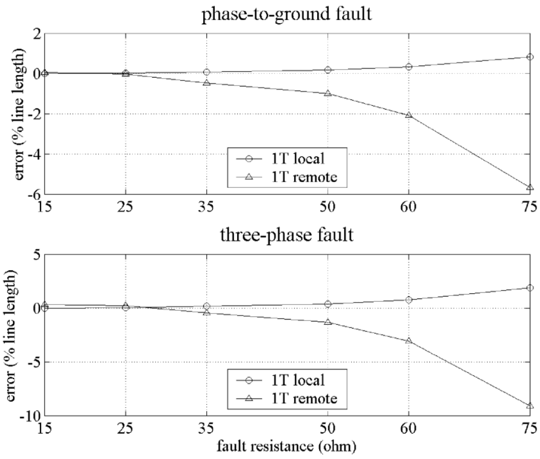

Fig. 14 Influence of the fault-resistance – short line

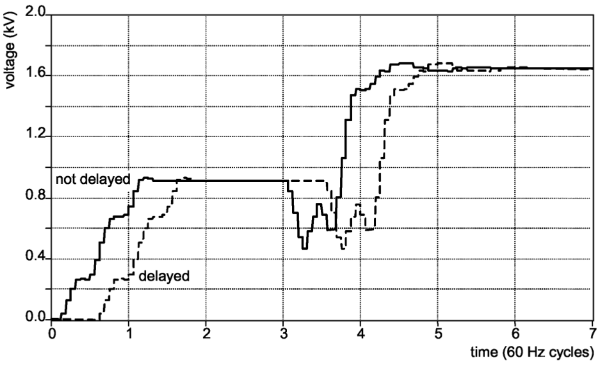

Fig. 15 Fundamental component of phase A current, without delay and with 8 samples delay

Table V Delaying effect, between remote and local terminal data

simulated delay *R-L*		calculated delay	calculated fault-
samples	degrees	(degress)	distance (km)
0	0	-0.00189	151.82
2	45	44.997	151.84
4	90	89.995	152.11
6	135	135.0026	151.44
8	180	179.998	152.50

VI. Conclusions

This paper presents a tool to simulate some relay functions, mainly fault location, in a one step ATP simulation, in which the relay algorithm is implemented in "C" language. This implementation could be done using only MODELS language but, in this case, the advantage of implementation in a common and flexible programming language as "C" would be lost.

This technique is also useful for relay calibration and allows analyzing the behavior of the electrical network after relay tripping, including opening and reclosing of the transmission line.

About the fault location algorithms, it was verified that for short transmission lines with low fault resistance the results were very accurate. This implied the use of simplified algorithms modeling the line as series impedance only, neglecting capacitance and hyperbolic corrections. However, results for cases of long lines with low fault resistance, and phase-to-ground faults, which are the most common faults, showed to be also accurate enough.

VI. References

[1] T. Takagi et al., "Development of a New Type Fault Locator Using the One-Terminal Voltage and Current Data," *IEEE Transactions on Power Apparatus and Systems*, vol 100, n.5, 1981, pp. 1316-1323.

[2] T. Takagi et al., "A new Algorithm of an Accurate Fault Location for Ehv/Uhv Transmission Lines: Part I – Fourier Transformation Method," *IEEE Transactions on Power Apparatus and Systems*, vol 101, n. 8, 1982, pp. 2892-2898.

[3] A.T. Johns, S. Jamali, "Accurate Fault Location Technique for Power Transmission Lines," *IEE Proceedings Generation, Transmission and Distribution*, vol. 137, n. 6, 1990, pp. 395-402.

[4] C.H. Kim, M.H. Lee et al "An Implementation of Fourier Transforms based on Distance Relaying Algorithm using EMTP Models," IPST 1997 – International Conference on Power System Transients, Seattle, 1997, pp 440-445.

[5] C.E.M. Pereira, L.C. Zanetta Jr, "Analysis of Fault Location Algorithms with Electromagnetic Transient Program," IPST 2001 – International Conference on Power System Transients, Rio de Janeiro, vol 2, 2001, pp 441-446.

[6] C.E.M. Pereira, and L.C. Zanetta Jr, "Fault Location in Transmission Line Using Two-port Representation," IEEE/PES T&D 2002 Latin America, 2002.

[7] T. Funabashi, L. Dubé et al, "Analysis of Fault Location Algorithms with Electromagnetic Transient Program," IPST 1997 – International Conference on Power System Transients, Seattle, 1997, pp 434-439.

[8] Leuven EMTP Center, *ATP: Alternative Transients Program Rule Book*. Leuven, U.K., 1987.

[9] L. Dubé, *Users Guide to Models in ATP*, 1996.

[10] A.V. Oppenheim, R.W. Schafer, *Digital Signal Processing*. Englewood Cliffs, N.J., Prentice-Hall, 1975.