Real-Time Implementation of a Fault Location Algorithm for Homogeneous Systems

J. C. Peqqueña-Suni, J. A. Martinez-Velasco, J. Mahseredjian, O. Saad, E. Ruppert

***Abstract*--This paper presents the implementation of a distance relay model in a real-time simulation platform. The relay is basically used in this work to locate faults in radial homogeneous (i.e., all sections have the same per unit parameters) transmission and distribution systems. The device can also be used to estimate the fault impedance, assuming it is a constant resistance. The document presents a sensitivity study of the fault location algorithm; that is, the paper analyzes the performance of the algorithm for estimating the fault distance and the fault resistance as a function of several parameters involved in the transient simulation; namely, the time-step size, the fault distance and resistance values, as well as the system structure and model. Some important issues for real-time implementation are also discussed.**

***Keywords*: Transmission system modeling, distribution system modeling, relay modeling, fault location, EMTP, MATLAB, real-time simulation.**

I. Introduction

PROTECTION systems are critical power system components whose behavior is an important aspect of the power system response to a transient event. A detailed model of a protection system is complex and will usually consist of three major parts: instrument transformers, protective relays, and circuit breakers.

The modeling of a protection system as part of the power system model permits the analysis of a closed-loop interaction (the power system affects the protection system through the instrument transformers, the protection system can modify the topology of the power system by opening and closing circuit breakers), which is an important aspect when analyzing the performance of the real power system under transient conditions [1],[2].

An important milestone in protection system analysis and design has been the development of real-time simulation platforms that permit testing actual relays without recurring to any relay model and take advantage of the advanced status of power system modeling for transient simulations [3]-[5].

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A relay model that could mimic the behavior of the actual relay can be useful for several purposes. For instance, it may be used in the design stage, to analyze system performance, or to study the impact of relay operation on system security. Relay models may theoretically reproduce relay characteristics, input pre-processing, measurement processes and the outputs provided by actual relays [6].

A successful relay model will produce outputs very close to those derived with the actual relay for the same inputs under transient and steady state conditions. However, the relay model may have no direct correspondence to the code within the relay. The main limitation of a relay model is usually the level of the approximation used to represent the actual relay, although the limits of relay models are relative depending on the purpose of using these models. When developing a relay model, it must be assumed that relay manufacturers will make available only limited information regarding relay design and its behavior.

This paper presents the implementation of a distance relay model in a real-time simulation platform. The model is based on a model previously implemented in EMTP-RV [7] for transmission level studies [8]. In its present version, the new relay can work as a fault location device that can be applied to study radial homogeneous systems.

Given that EMTP-RV code cannot be directly uploaded to a real-time simulation platform, the first task of this work was to translate the relay code to MATLAB, a simulation environment used by some real-time simulators [9].

The main goals of this paper are: (i) developing a relay model for implementation in a real-time simulation platform; (ii) exploring the options of the implemented relay algorithm for fault location at both transmission and distribution levels; (iii) testing the performance of the relay algorithm when considering different modeling guidelines, mostly the various models that can be used for representing overhead lines (i.e., lumped-parameter and distributed parameter models).

The simulation environments used in this work are EMTP-RV and MATLAB/Simulink for off-line simulations, and Opal-RT [9] for real-time implementation.

II. Distance Relay Modeling

A. Background

This section provides a brief overview of the distance relay implemented in EMTP-RV. Since only the fault location capabilities of the model are analyzed in this paper, a short summary of the model will suffice.

The implemented model belongs to the category of transient-based relay models [6]; that is, the model extracts inputs from instantaneous samples obtained from a transient simulation. Transient models are needed when the relay behavior under actual fault conditions is evaluated; they correctly represent the dynamics and frequency response of the power system, take into consideration transient voltages and currents, and include the dynamics of the relay.

The relay model structure can be summarized as follows: (1) the algorithms are activated whenever a transition from a steady state to a dynamic state is detected; (2) once it is activated, the relay confirms the existence of a fault; (3) the next step is aimed at determining the phases involved in the fault; (4) the direction is subsequently obtained; (5) finally, the fault location and resistance are calculated. The subject of this paper is to analyze the behavior of the last step.

B. Fault Location Procedure

Reference [10] classifies fault location algorithms into four categories: (i) techniques based on fundamental-frequency currents and voltages, (ii) techniques based on traveling-wave phenomenon; (iii) techniques based on high-frequency components of currents and voltages generated by faults; and (iv) knowledge-based techniques. The algorithm used in this work belongs to the third category. See also reference [11].

Due to room limitations, only the single-phase-to-ground algorithm is detailed and tested in this work.

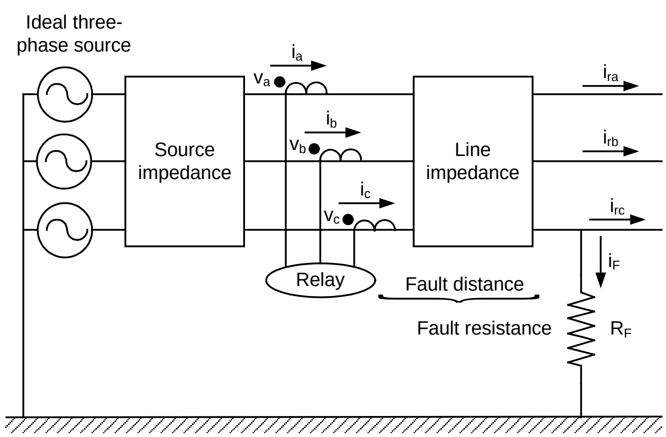


Fig.1. Equivalent circuit of the faulted system.

Assume the faulted system is represented by the circuit depicted in Fig. 1, in which the fault impedance is a resistance. The voltage equations in the time-domain in case of a single-phase-to-ground fault on phase *a* may be expressed as follows [8]:

$$v_{aN} = \left(R_1 i_a + (R_0 - R_1)\frac{i_R}{3} + \sum_{j=a,b,c} L_{aj}\frac{di_j}{dt} \right)\ell_D + R_F i_F \quad (1)$$

where

$$i_R = i_a + i_b + i_c \quad (2a)$$

$$L_{aa} = L_s = \frac{L_0 + 2L_1}{3} \quad (2b)$$

$$L_{aj} = L_m = \frac{L_0 - L_1}{3} \qquad \text{when } a \neq j \quad (2c)$$

ℓ_D is the line length, R_F is the fault resistance, R_1 and R_0 are the per unit length positive- and zero-sequence resistances, respectively, whereas L_1 and L_0 are the per unit length positive- and zero-sequence inductances, respectively.

The unknown values to be determined are ℓ_D and R_F. From the integration of equation (1) the following form is derived when using a trapezoidal approximation:

$$\frac{\Delta t}{2}\left(v_{aN(k+1)} + v_{aN(k)}\right) = \begin{pmatrix} \frac{\Delta t}{2} R_1\left(i_{a(k+1)} + i_{a(k)}\right) \\ + \frac{\Delta t}{2}\frac{(R_0 - R_1)}{3}\left(i_{R(k+1)} + i_{R(k)}\right) \\ + \sum_{j=a,b,c} L_{aj}\left(i_{j(k+1)} - i_{j(k)}\right) \end{pmatrix}\ell_D + \frac{\Delta t}{2} R_F\left(i_{F(k+1)} + i_{F(k)}\right) \quad (3)$$

The following relationships can be then established:

$$A = \frac{\Delta t}{2} R_1\left(i_{a(k+1)} + i_{a(k)}\right) + \frac{\Delta t}{2}\frac{R_0 - R_1}{3}\left(i_{R(k+1)} + i_{R(k)}\right) + L_s\left(i_{a(k+1)} - i_{a(k)}\right) + L_m\left(i_{b(k+1)} - i_{b(k)} + i_{c(k+1)} - i_{c(k)}\right) \quad (4a)$$

$$B = \frac{\Delta t}{2}\left(i_{F(k+1)} + i_{F(k)}\right) \quad (4b)$$

$$E = \frac{\Delta t}{2}\left(v_{aN(k+1)} + v_{aN(k)}\right) \quad (4c)$$

The system of equations that results from the integration of the voltage equations during two consecutive time steps may be written as follows:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} \ell_D \\ R_F \end{pmatrix} = \begin{pmatrix} E \\ F \end{pmatrix} \quad (5)$$

where the calculation of coefficients *C*, *D* and *F* is based on the same expression used for coefficients *A*, *B*, and *E*, respectively; only the values to be used are different since they are calculated for the subsequent time step.

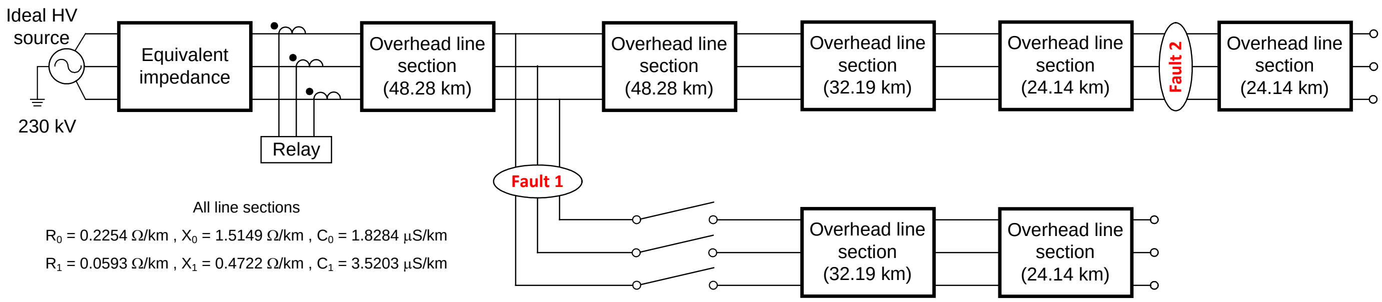
Solving for the fault distance and the fault resistance, the following form is derived:

$$\begin{pmatrix} \ell_D \\ R_F \end{pmatrix} = \frac{1}{AD - BC}\begin{pmatrix} D & -B \\ -C & A \end{pmatrix}\begin{pmatrix} E \\ F \end{pmatrix} \quad (6)$$

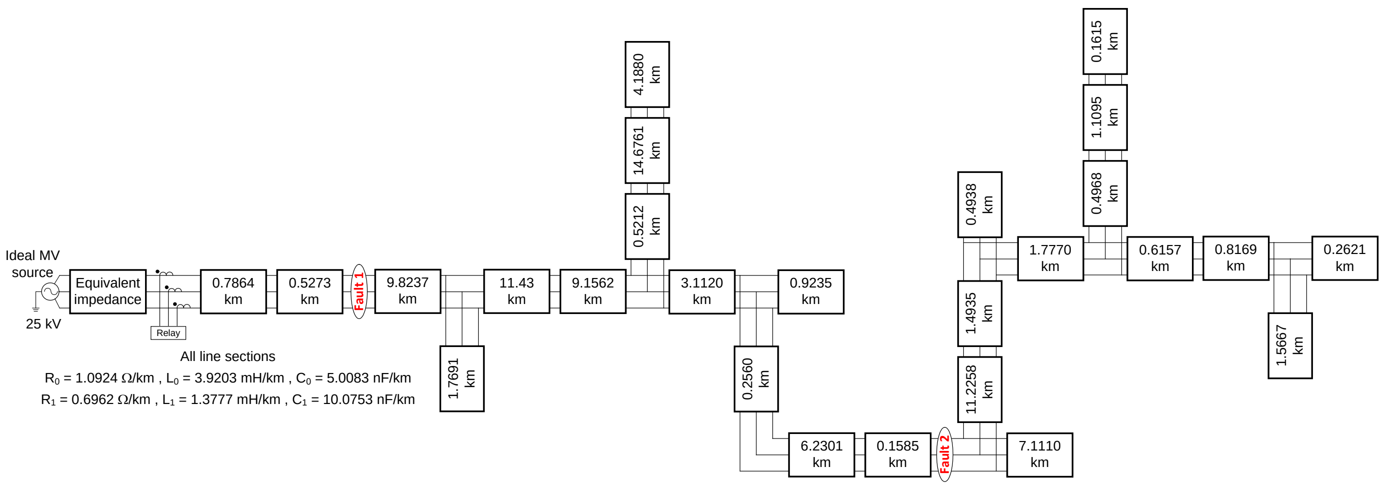
III. Test Systems

Fig. 2 shows the diagram and some of the main characteristics of the test systems used in this work. The power frequency of both test systems is 60 Hz.

The models of both systems have some common features that make them adequate for testing the fault location algorithm presented in the previous section: (i) they are radial; (ii) all line sections of one system are single and homogeneous (i.e., all sections have the same per unit parameters). Obviously, this later characteristic can be a realistic assumption for transmission systems, but it is not for distribution systems whose sections are non-homogeneous.



a) Transmission test system – 230 kV



b) Distribution test system – 25 kV

Fig. 2. Diagrams of the test systems.

The line parameters are taken from [12] for the transmission test system, and from [13] for the distribution test system. Note, however, that the configurations used in this work are not those presented in the original references. In the case of the distribution systems, line sections with a too-short length have been removed, and so has been any branch with a transformer. In the case of the transmission system, only single-line sections are assumed and some line sections have been added. The study has been carried out without including instrument transformers in the system model, which is equivalent to assume that input waveforms are not distorted by instrument transformers.

IV. Simulation Results

A. *Introduction*

An important parameter that may affect the behavior of the fault location algorithm is the time-step size (Δt) used in simulations. Before presenting the main results and conclusions of the present study, it is important to analyze this influence.

Figs. 3 and 4 show some simulation results that need to be considered for the further analysis; they present the relay response for calculations of the fault distance and resistance as a function of the time-step size used in simulations. Note that all plots of each figure are presented with the same scales.

Two important conclusions can be derived from these plots: (i) both distance and resistance values exhibit oscillations that decrease with Δt (i.e., the smaller the time-step size, the smaller the oscillation magnitudes); (ii) regardless of the oscillations, it is possible to distinguish a central value in each plot. In the case of the fault resistance, this central value remains nearly constant (i.e., it does not vary with Δt, see Fig. 3), while it shows some variation for the calculation of the fault distance; that is, the plots of Fig. 4 show that the central value does not remain the same as Δt varies (the deviations are below and above of the correct value), although these variations are rather small in percentage.

It is important to mention that the oscillations around the central value are not symmetrical and do not follow a given pattern, see Figs. 3a and 4a; in addition, it is not easy to decide what is the central value in some cases, so rather than very accurate conclusions, the results derived from the sensitivity analysis have to be seen as a trend of the fault location algorithm response.

B. *Sensitivity Study*

Two different constant-parameter models have been implemented (in both EMTP-RV and MATLAB/SIMULINK) for each line of both test systems: lines are represented with distributed and lumped (PI approach) parameters. Given that the fault location algorithm assumes a lumped-circuit approach to obtain the distance and the resistance values, it is important to know whether important differences can result or not from the usage of one or the other modeling approach.

Some aspects that can affect the calculations are the system loads and the presence of tapped lines upstream the fault location. In this study, all simulations were performed without including loads in the system models, but the influence of the tapped lines has been analyzed.

Another important aspect is the time-step size when simulating the distribution system with lines represented by a distributed-parameter model. Given the length of some line sections of the distribution system this value has to be lower than 0.5 μs when simulating that system. Since the real-time simulation platform used in this study cannot run in real time with such a small value, the distributed-parameter approach was not considered in this analysis for the distribution system. As it will be shown, this is not an important drawback.

The test systems were simulated considering different fault locations and several values of the fault resistance. The fault resistance has been varied between 1 and 50 Ω, while two different fault locations were considered for each test system, see Fig. 2. In addition, the transmission system was also simulated without the tapped sections when the fault was located downstream the deviation, see Fig. 2a.

The main goal of the study is to find out the influence of these two variables on the relay response as a function of the time-step size. Due to room limitation, only a few results are presented here.

The plots of Figs. 5 and 6 will be used to illustrate the performance of the fault location algorithm and serve to justify the main conclusions. The error in these figures is defined by means of the following expression:

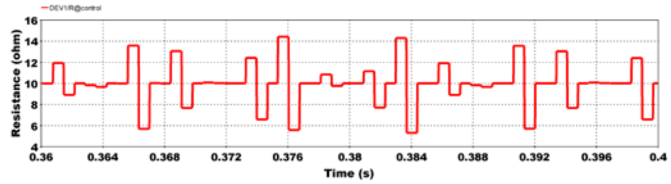
$$Error(\%) = \left| \frac{V_{estimated} - V_{theoretical}}{V_{theoretical}} \right| \cdot 100 \qquad (7)$$

From the results depicted in Figs. 5 and 6, the following conclusions may be derived:

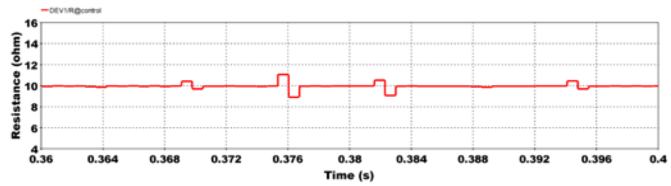
- The relay response is not sensitive to the time-step size, neither for the calculation of the resistance nor for the estimation of the fault location. Remember that Δt has some influence on the waveforms (see Figs. 3 and 4).
- The error when estimating the fault location depends on the fault resistance value (the higher the resistance value the larger the error), see Figs. 5a and 6a. However, some differences in the pattern can be found depending on the system being simulated; just compare Figs. 5a and 6a.
- The influence of the fault resistance with a fix fault location exhibits a nearly opposite pattern: the error increases as the fault resistance value decreases. In general, the error when calculating the resistance value is too high for low resistance values.

As already mentioned, Figs. 5 and 6 show only a small percentage of the results obtained in this study, although the pattern has been similar in all studies and there have been some cases for which the estimation of either the resistance or the distance was difficult. Take into account that average values of time-domain responses cannot be used for an accurate approximation.

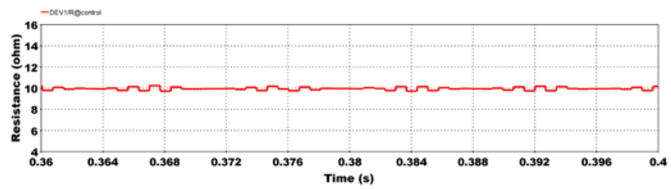
The main conclusions from the entire study may be summarized as follows:



a) Time-step size Δt = 20 μs

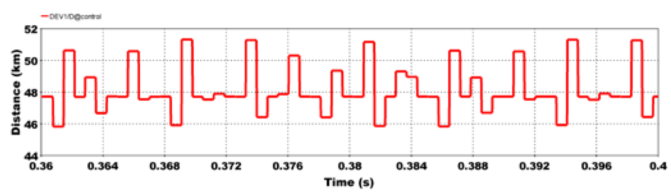


b) Time-step size Δt = 5 μs

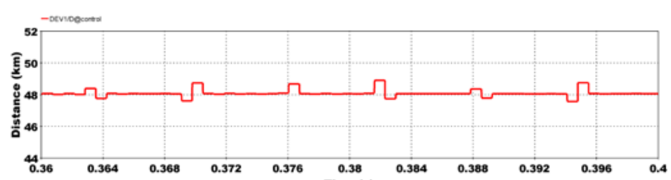


c) Time-step size Δt = 1 μs

Fig. 3. Relay response - Transmission system. Fault resistance = 10 Ω (Fault location = 48.28 km from source; distributed-parameter model).



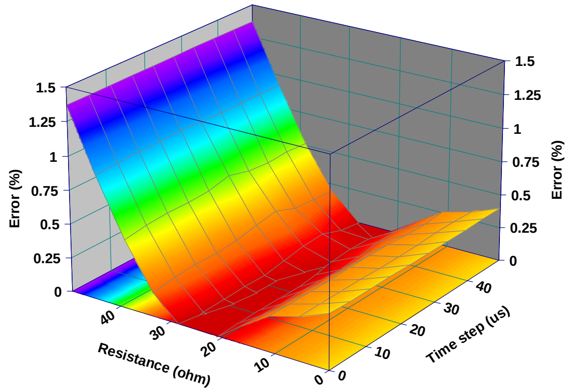
a) Time-step size Δt = 20 μs



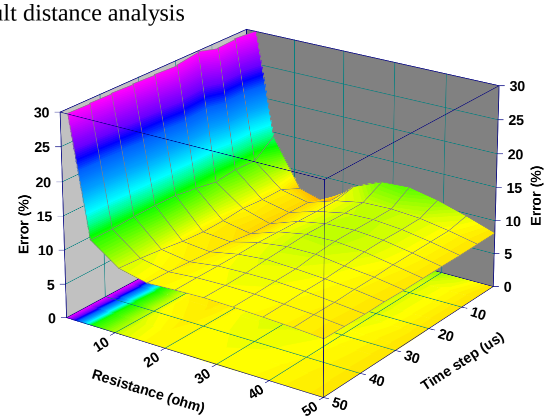
b) Time-step size Δt = 5 μs

c) Time-step size Δt = 1 μs

Fig. 4. Relay response - Transmission system. Fault location = 48.28 km from source (Fault resistance = 10 Ω; distributed-parameter model).

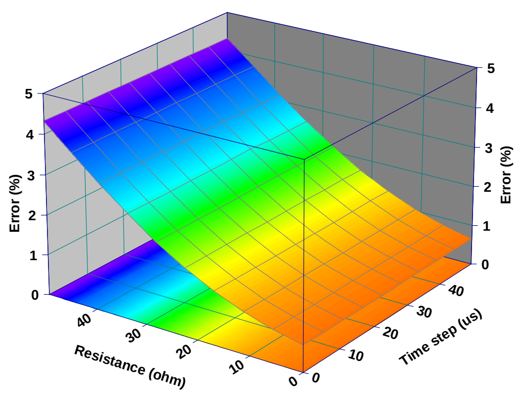


a) Fault distance analysis

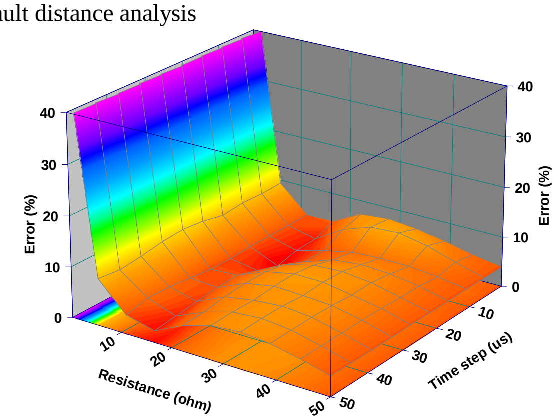


b) Fault resistance analysis

Fig. 5. Untapped transmission system analysis – Distributed-parameter model, MATLAB simulation (D = 152.88 km).



a) Fault distance analysis



b) Fault resistance analysis

Fig. 6. Full distribution system analysis – Lumped-parameter model, MATLAB simulation (D = 41.48 km).

- The influence of the time-step size is almost negligible on the results if only central values are of concern. However, the waveforms for both the distance and the resistance are significantly influenced by Δt, as shown in Figs. 3 and 4. Given that it is not always easy to distinguish the central value, a small Δt is generally recommended. This may justify the application of a real-time simulation platform when simulating large systems.
- The implemented algorithm is accurate for the estimation of the fault location, regardless of the fault resistance value; errors were always below 10%.
- The accuracy of the algorithm is very poor for estimating the fault resistance when this resistance is small; e.g., for resistance values below 5 Ω the deviation of the calculated value with respect to the theoretical one can exceed 50%.
- Differences exist between the results derived from EMTP-RV and MATLAB models, but they are small.
- Some differences can also exist when the simulated system is untapped; in the case of the test system analyzed in this work, they are small.
- Errors are too large when the fault resistance is small, and in such cases the differences between the results obtained when using different tools or different line models can also be large.

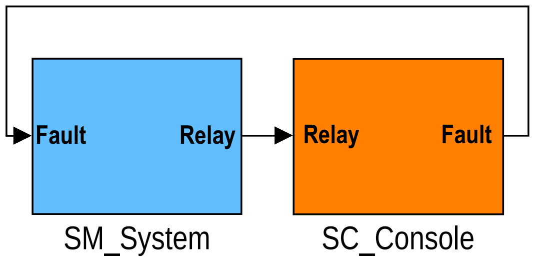
A general conclusion is that the algorithm is accurate enough for estimating the fault location but it fails for calculating the fault resistance when this resistance is small.

V. Implementation of the Fault Locator in a Real-Time Simulation Platform

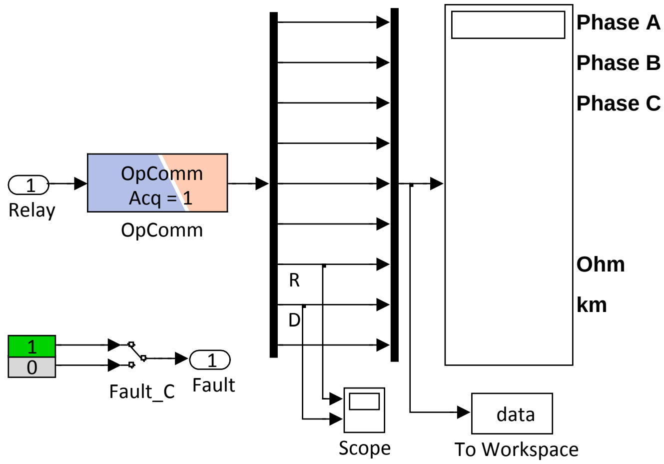
The implementation of the fault location algorithm in the real-time simulation platform is straightforward once the model is running under the MATLAB/Simulink environment [9]. The configuration chosen for real-time implementation is the same for both the transmission and the distribution systems: a master subsystem, in which both the system and the fault locator (distance relay) models are embedded, and a console subsystem, from where the system is observed and the fault timing is controlled, see Fig. 7.

The most important issues of the models implemented in the real-time simulation platform and their behavior are discussed below.

- The main barrier of the platform used for this study was the time-step size to be specified in simulations: it could not be smaller than 1 μs. This was unimportant except for distribution systems, in which short length line sections can impose a very short time-step if distributed-parameter line models are to be used. Given the line lengths of the distribution system studied in this work, time-step sizes below 0.5 μs were required. Consequently, the distributed-parameter model of the distribution system could not be run on-line. An alternative to overcome this limitation was not using a synchronized mode; that is, not running that model in real time.



a) Implemented model (master and console subsystems)



b) Console subsystem details

Fig. 7. System configuration implemented in the real-time simulation platform.

- The console subsystem has been designed to display the fault distance and resistance, as well as the phases affected by the fault, see Fig. 7b.
- The behavior of the models is that of the models implemented in MATLAB/Simulink .

VI. Conclusion

This paper has presented the implementation in a real-time simulation platform of a fault location algorithm that uses voltage and current samples obtained from transient simulations, and is aimed at locating faults in homogeneous radial systems assuming that the fault impedance is a resistance.

The test studies have been carried out using both lumped- and distributed-parameters models of two test (transmission and distribution) systems. The sensitivity study has proven that the algorithm accuracy does not depend on the time-step size, and is not affected by the line models used in simulations. However, the time-step size has a significant influence of the resulting waveforms, and it is not easy to estimate the resulting values when the time-step size is large. Consequently, a small time-step size is recommended (i.e., in the order of 1 µs or less) even when a lumped pi-circuit is used to represent line sections.

A significant experience is already available on fault location procedures, although most approaches are based on phasor results. Recent works use PMU measurements [14], distributed-parameter line models [15], or consider the influence of multiple derivations [16], current transformer saturation [17], and intermittent faults [18].

From a practical point of view, the algorithm presented in this paper has some important limitations as it is only valid for radial systems with homogeneous line sections. Therefore, future improvements should also be addressed to improve its accuracy and to make it cope with multi-ended non-homogenous systems.

VII. References

[1] R.E. Wilson and J.M. Nordstrom, "EMTP transient modeling of a distance relay and a comparison with EMTP laboratory testing," *IEEE Trans. on Power Delivery*, vol. 5, no. 3, pp. 984-990, July 1993.

[2] J.N. Peterson and R.W. Wall, "Interactive relay controlled power system modeling," *IEEE Trans. on Power Delivery*, vol. 6, no. 1, pp. 96-102, January 1991.

[3] P.G. McLaren, R. Kuffel, R. Weirckx, J. Giesbrecht, and L. Arendt, "A real time digital simulator for testing relays," *IEEE Trans. on Power Delivery*, vol. 7, no. 1, pp. 207-213, January 1992.

[4] D.S. Ouellette, W.J. Geisbrecht, R.P. Wierckx, and P.A. Forsyth, "Modelling an impedance relay using a real time digital simulator," 8th *IEE Int. Conf. on Developments in Power System Protection*, April 2004.

[5] C.A. Apostolopoulos and G.N. Kornes, "Real-time implementation of digital relay models using MATLAB/SIMULINK and RTDS," *European Transactions on Electrical Power*, vol. 20, no. 3, 290-305, April 2010.

[6] CIGRE Working Group B 5.17, Relay Software Models for Use with Electromagnetic Transient Analysis Program, CIGRE Brochure 295, June 2006.

[7] J. Mahseredjian, S. Dennetière, L. Dubé, B. Khodabakhchian, and L. Gérin-Lajoie, "On a new approach for the simulation of transients in power systems," *Electric Power Systems Research*, vol. 77, Issue 11, pp. 1514-1520, September 2007.

[8] R. Bouchet, O. Saad, and A. Xémard, "Module de protection générique sous EMTP-RV," Hydro-Québec, Juillet 2007.

[9] S. Abourida, C. Dufour, J. Bélanger, and V. Lapointe, "Real-time, PC-based simulator of electric systems and drives," *IPST*, New Orleans, 2003.

[10] M. Mohan Saha, J. Izykowski, and E. Rosolowski, *Fault Location on Power Networks*, Springer, 2010.

[11] IEEE Std C37.114-2004, IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines.

[12] IEEE Power System Relaying Committee, EMTP Reference Models for Transmission Line Relay Testing, 2005. Available at www.pes-psrc.org.

[13] IEEE Distribution System Analysis Subcommittee, IEEE 34 Node Test Feeder. Available at http://www.ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html.

[14] Q. Jiang, X. Li, B. Wang, and H. Wang, "PMU-based fault location using voltage measurements in large transmission networks," *IEEE Trans. on Power Delivery*, vol. 27, no. 3, pp. 1644-1652, July 2012.

[15] H. Nouri and M.M. Alamuti, "Comprehensive distribution network fault location using the distributed parameter model," *IEEE Trans. on Power Delivery*, vol. 26, no. 4, pp. 2154-2162, October 2011.

[16] C.E. Morais de Pereira and L.C. Zanetta, Jr., "Fault location in multitapped transmission lines using unsynchronized data and superposition theorem," *IEEE Trans. on Power Delivery*, vol. 26, no. 4, pp. 2081-2089, October 2011.

[17] C.E. M. Pereira and L.C. Zanetta, Jr, "Optimization algorithm for fault location in transmission lines considering current transformers saturation," *IEEE Trans. on Power Delivery.*, vol. 20, no. 2, pp. 603–608, April 2005.

[18] M.M. Alamuti, H. Nouri, R.M. Ciric, and V. Terzija, "Intermittent fault location in distribution feeders," *IEEE Trans. on Power Delivery*, vol. 27, no. 1, pp. 96-103, January 2012.