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Fault simulation environment for power distribution networks with protection operation

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Abstract. Nowadays research and development of power networks towards a new, more intelligent and self-management infrastructure is a topic of great interest, becoming what is known as Smart Grids. In order to achieve all this, programming tools to deal with large volumes of information are required, to model and simulate these future networks.
This paper presents a tool that allows to model distribution power lines from the information contained in a database, being flexible to the changes that can occur in the line. The developed tool has been tested, in simulation of real cases that correspond to sequence of events due to faults and the actions of the protection system (opening and reclosing) to isolate the fault.

Key words

Fault Location, Power Quality Monitoring, Power Distribution, Protection Coordination.

1. Introduction

Power networks are in a process of redefinition and transformation to become what is known as Smart Grids.
These networks will be much more flexible and with enhanced features for an efficient integration of distributed generation (renewable, cogeneration…), active management of demand, the integration of energy storage solutions and management of mobile loads (electric car) [1]-[3].
For all this, new communications and software architectures with higher computing capacity and capable of managing large volumes of information to model, predict and optimize their exploitation and to ensure the quality and efficiency of supply will be required. It implies that great effort in research has to be done in the following years in this topic [3].

The present paper proposes a software tool for automatic generation of models of distribution power lines based on information extracted from a database. The idea is that any change in the network (topology, loads, distributed generation, protective actions, etc.), being reported to the DB, could be automatically upgraded into a network model ready for simulation. This environment has been tested to simulate real faults with the corresponding protection actions.

2. Automatic modeling of distribution lines

The main goal is to create an application able to generate automatically a model of distribution power line using Matlab/Simulink starting from information of electrical parameters collected in a data base, such as line sections, nodes, generators, loads and protections.

Each line section is modeled using a concentrated parameters model that consists of a series resistance and a reactance as shown in Fig. 1.

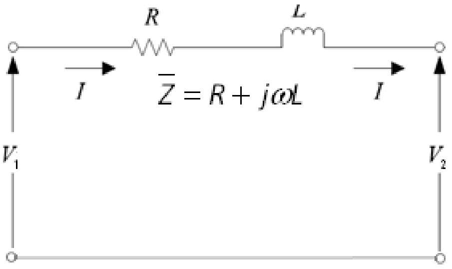

Fig. 1. Line model used.

The line model is automatically generated from the DB, which means that the model can accept modifications to test specific scenarios such as the addition/removal of new line sections or the connection/disconnection of distributed generators to the network. This condition is linked with the definition of Smart Grid.

The model includes the protection elements to simulate transients occurring during the actuation of these elements when a fault occurs.

A data structure used, consisting in a n-Ary tree, has been used to represent the topology of the network. This data structure consists of a hierarchical and recursive ordination of sub-trees containing the line segments connected in a node. This type of structure is also advantageous because the distribution power systems tend to be radial and thus reduce the complexity of representation, the route to the tree is simple using

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recursion, and this type of structure is compatible with the use of fault location algorithms [6], [7].

Fig. 2. shows an example of n-Ary tree.

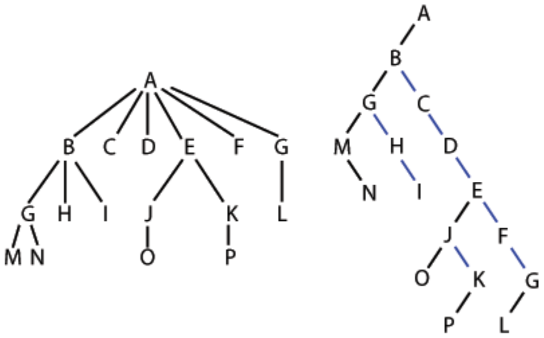

Fig. 2. n-Ary tree structure.

Fig. 3. shows an example of the representation of a distribution line with Simulink. It contains sections, nodes, loads, intermediate protections, distributed generators, a fault point, and header protection. An over current protection with a reclosing strategy has been implemented in this element [4].

3. Protection operation

A. Event sequence

A line protection is a logical device whose function is to compare one or more input signals with respect a reference. If the input value deviates from the reference value adjustment (threshold) then an action is performed, opening, reclosing or alarm [4].

The current is the more used variable to detect failures into the electric system, given the high increase that is recorded into its values when a fault occurs.

When a fault occurs in an electrical network, the system protections actuate to remove or to isolate the point or network section failed and be able to supply energy to the rest of the system. Faults cause voltage sags whose duration depends on the time of operation of the protection system. Then, voltage sags are a reflection of the failures that occur in the system. The records of these events allow analyzing fault magnitude, location, etc [5].

The open device operation protects the system of the consequences of the fault and often the protection system incorporates a locking mechanism (automatic reclose) that allows testing whether the fault is permanent or not. These operations can be executed several times closing both automatic and manually.

Fig. 4. shows an example of a sequential operation of openings and closings of protection line when the system detects a fault, which is recorded as a sequence of events (voltage sags), understood the value 1 when the protection is closed, and value 0 when the protection is open.

The actions have a certain time setting shown in Fig. 4. these are the following:
The time t1 is an automatic reclose (500 ms).
The time t2 is an automatic reclose (40-60 s).
The time t3 is a manual reclose (1-3 min).
The time t4 is a manual reclose (8 min).
The reclose time t4 is a manoeuvre in situ (25 min).

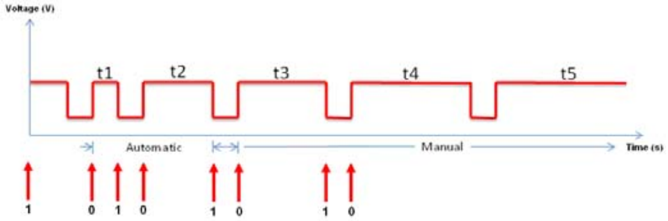

Fig. 4. Event sequence of a line protection

Faults and the corresponding protection actions are typically recorded at the substation as sequence events.

Fig. 5. shows a substation scheme where the most representative elements such as line and substation protection, measuring point, etc, can be observed.

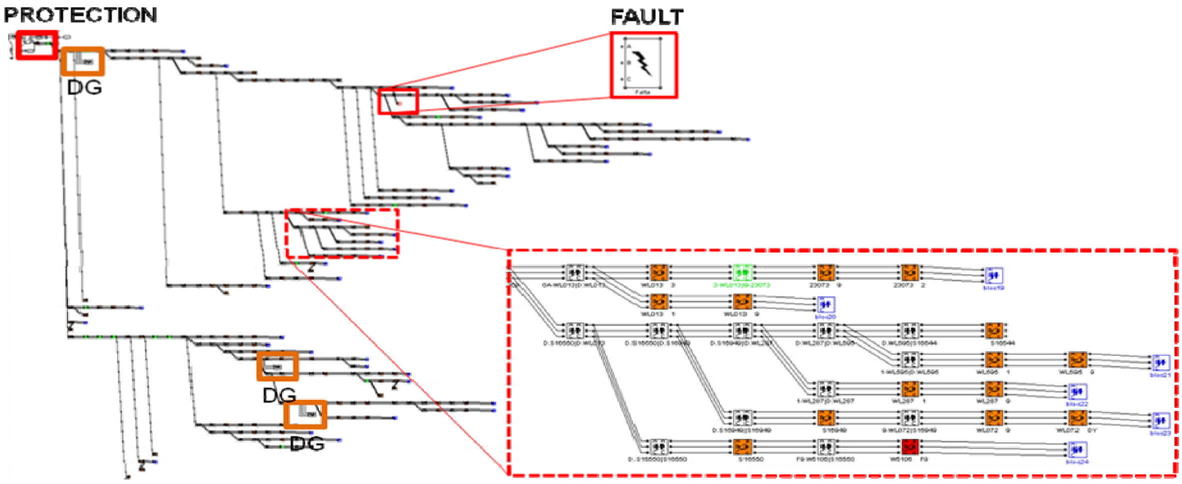

Fig. 3. Model of electric distribution line with protections, distributed generation and fault created with application.

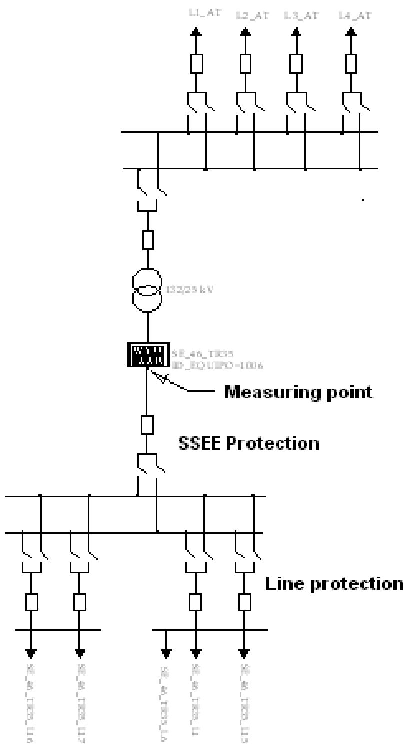

Fig. 5. Substation scheme with protections

B. *Example of an event sequence*

Table I shows a protection event sequence associate to a real fault. In this case, there are two openings of the protection to isolate the fault.

Table I. Event sequence example

SSEE	Start event	Start (ms)	Duration (ms)
SSEE1 L1 (TR2)	5:27:26	89	284
SSEE1 L1 (TR2)	5:27:27	348	260
SSEE1 L1 (TR2)	5:28:27	579	

Figure 6 shows the representation of the temporal sequence events shown in Table I.

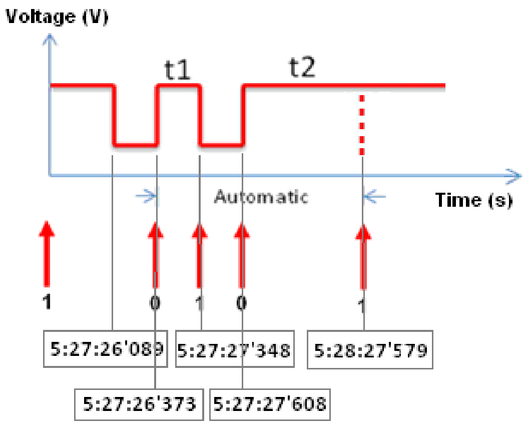

Fig 6. Time representation of the event sequence example.

4. Simulation of real sequence events

This section is devoted to the simulation of the real sequence event shown in Section 3.B. In order to simulate this case it is necessary to use the programming environment developed to generate automatically the line model, and the following information is needed.

1) Information about the line and fault location.
2) Voltage and current records corresponding to the fault.
3) The temporal event sequence related to the opening and closing of the line protection during the fault.

All this information is needed to generate the model, that represents the line faulted, and to simulate from this sequence of events associated to protection actions to isolate the fault.

A. *Estimating fault impedance*

The line model is generated starting from the impedance lines, load values and substation information contained in the database.

The information about the fault, that is an estimation of the fault impedance, can be calculated empirically, from the current and voltage values recoded at the substation during the fault occurred. These records are represented in the Fig. 7 and 8.

At the substation instantaneous values are recorded but fundamental RMS values can be obtained by applying the Fourier transform to one cycle of the waveform.

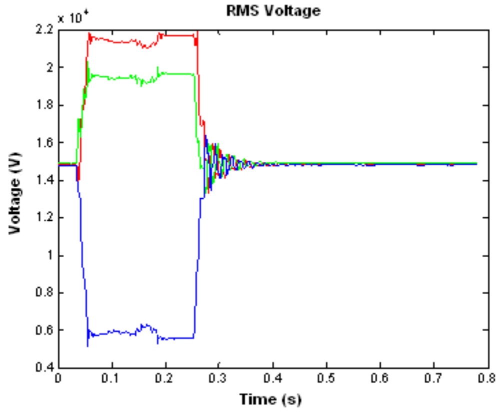

Fig. 7. Representation of RMS voltage values

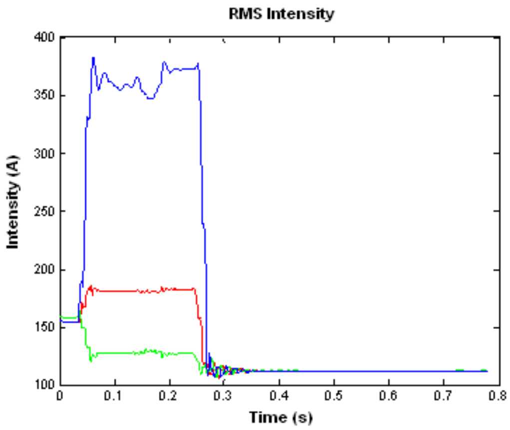

Fig. 8. Representation of RMS intensity values

From the RMS voltage and current values the impedance seen by substation can be calculated. This impedance is illustrated in Figure 9.

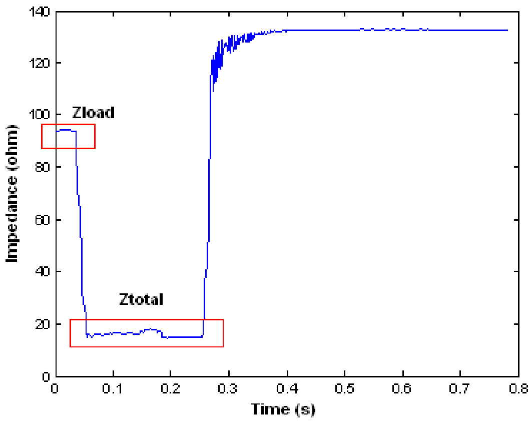

Fig. 9. Impedance seen from substation

The following method is used to calculate the fault impedance [8].

Since the voltage and current waveforms are measured at the substation, the current seen by the protective device Iempirical can be estimated.

One way to estimate the current is to assume:

1) The current before the fault is dominated by the current during the fault.
2) Loads behave as a constant impedance element.
3) The load impedance is in parallel with the impedance to the fault during the fault condition (Fig. 10).

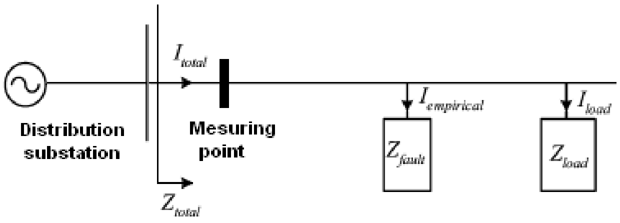

Fig. 10. Equivalent circuit for estimating the fault impedance.

The estimation begins with computations of voltage and current phasors before and during the short-circuit condition, VpreFault, Iprefault, VduringFault, Iduringfault. The load impedance seen from the power-quality monitor before the fault occurs can be estimated as follows:

$$\overline{Z}_{load} = \frac{\overline{V}_{prefault}}{\overline{I}_{prefault}} \tag{1}$$

During the fault condition, the impedance seen by the substation is the parallel of the load and fault impedance:

$$\overline{Z}_{total} = \frac{\overline{V}_{duringfault}}{\overline{I}_{duringfault}} \tag{2}$$

The fault impedance Zfault can be estimated as follows:

$$\overline{Z}_{total} = \frac{\overline{Z}_{fault} \cdot \overline{Z}_{load}}{\overline{Z}_{fault} + \overline{Z}_{load}} \tag{3}$$

$$\overline{Z}_{fault} = \frac{1}{\dfrac{1}{\overline{Z}_{total}} - \dfrac{1}{\overline{Z}_{load}}} \tag{4}$$

In this example resistance fault value is 15.35Ω.

Zload remains the same value as before the fault condition.

B. Estimating power consumption

The information available from the database of load power refers to its nominal power. However, the consumed power is not constant nor the nominal value in the database. Therefore, to model the system accurately the actual state of the load system, when the fault occurs is estimated.

The consumption of the system is calculated according to the current line that is fed from the fault register. A coefficient, understood as a performance, is calculated and it is applied to the nominal values of the loads contained in the database. The prefault current indicates the charge status of the substation. It is considered that the load status of the substation is the same as the line. Fig. 8 shows the RMS currents recorded at the substations.

The nominal power of the line contained in the database is calculated as follows:

$$P_{n\_BDD} = \sum P_1 + P_2 + P_{i\_load} \cdots + P_{n\_load} \tag{5}$$

In the example case it is 14.20 MW.

The real power of the line is calculated from the RMS voltage and current values obtained from the fault record from one phase.

$$P_{r\_register} = 3 \cdot V_{prefault} \cdot I_{prefault} \cdot \cos(\alpha) \tag{6}$$

From the record information the $V_{prefault}$, $I_{prefault}$, and α can be obtained. The value for this case is 6.92MW.

From the power calculated by (5) and (6) a performance coefficient can be estimated as following:

$$\eta_{power} = \frac{P_{r\_register}}{P_{n\_BDD}} \tag{7}$$

The value of η_{power} is 0.48 in this example.

The value of the load in the model takes the value of the database load multiplied by the charge state system.

$$P_{i\_mo} = \eta_{power} * P_{i\_load} \tag{8}$$

The procedure is the same for reactive power.

C. Using fault simulation environment

The model can be generated with database line information and estimation of its load estate, the impedance fault, and the software environment described in Section 2.

Fig. 11 shows the model representation of the line of example. The n-Ary tree structure can be observed, with all the elements that make up the line, such as line sections (black blocks represent overhead sections and green blocks, underground sections), loads (blue blocks) and the fault section for which its localization is known, it has been extracted from the record. The line model contains the header protection which control strategy has been implemented to simulate the event sequence that would be recorded.

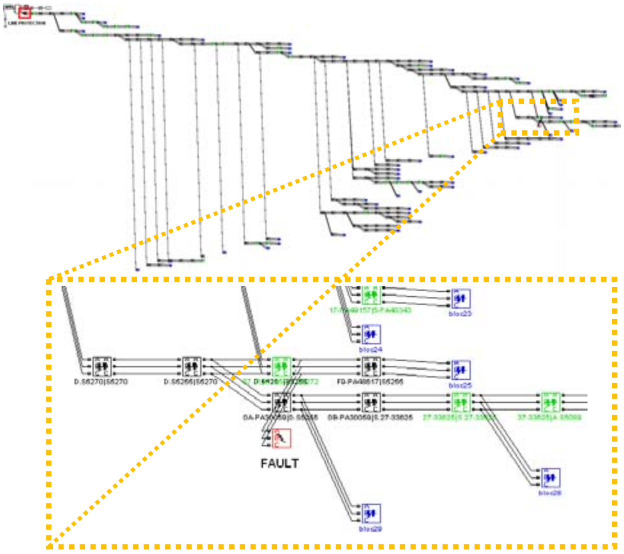

Fig. 11. Line model representation

D. Model validation

The model can be verified, comparing the instantaneous voltages and currents recorded at the substation with the obtained by simulation. Figure 12 shows the instantaneous voltage and current graphic corresponding to the real fault record.

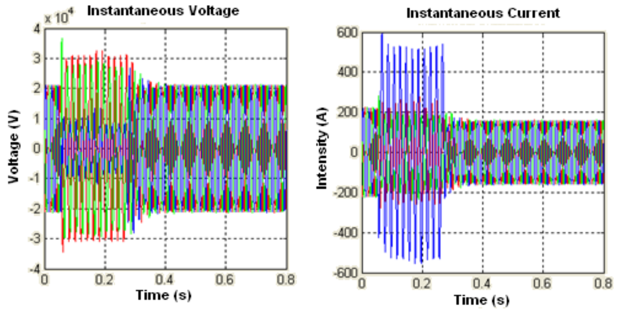

Fig. 12. Instantaneous voltage and current fault record

Figure 13 shows the instantaneous voltage and current graphic corresponding to the model simulation.

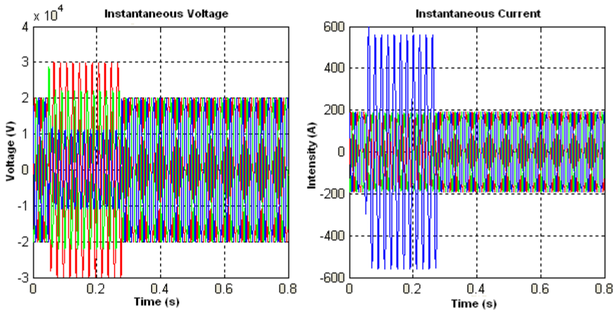

Fig. 13. Instantaneous voltage and current simulated

As can be seen in Fig. 12 and 13, voltage and currents take similar values. From this verification it can be concluded that the fault line model is accurate.

We must say that to check this verification the relative errors from the simulated values respect to the real record are calculated.
The error in the voltage phase faulted RMS is 9.18%.
The error in the current phase faulted RMS is 6.67%.

E. Event simulation

The simulation of real events sequence (opening and reclosing protection) corresponding to the fault record described in Section 3.B has been performed with the model and implementing the control strategy for action protection. Fig. 14 shows the simulation results: the faulted phase RMS current (a), with its sequence of header protection actuation depending on the value of the current. When the overcurrent due to the fault is detected the protection opens according to a predefined time delay calculated from the modeling of the reverse curves time operation - intensity [4] and after a certain time it recloses (in this case 500 ms). In case of the cause of the fault extinguishes, the protection remains closed otherwise, the protection will open again according to the predefined sequence action.

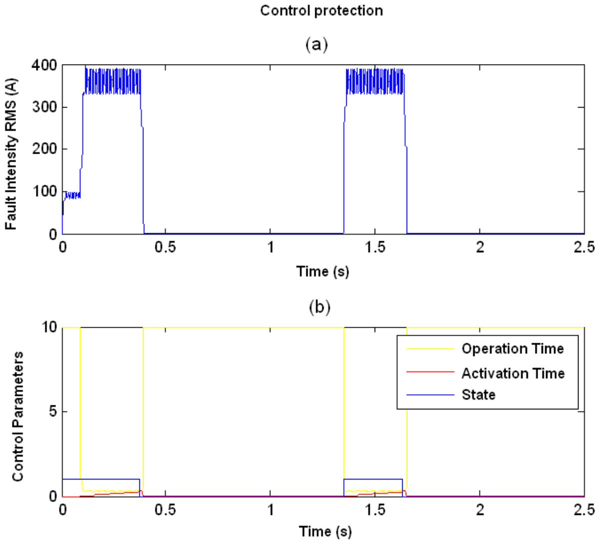

Fig. 14. Sequence operations of the protection

Fig. 15 shows the simulation results: instantaneous current and voltage values measured at the header of the line, where it can be seen how the times of opening and closing protection are approximately the same such as defined in Table I and Fig. 6.

In the power distribution systems the most normal is that the protection acts in the three phases to isolate the fault, the intensities will have a null value since no current flows through the network because this is open and just one line is monitored in simulation.

Table II and III show the real and simulation event times respectively as can be seen the real and simulated times are approximately the same.

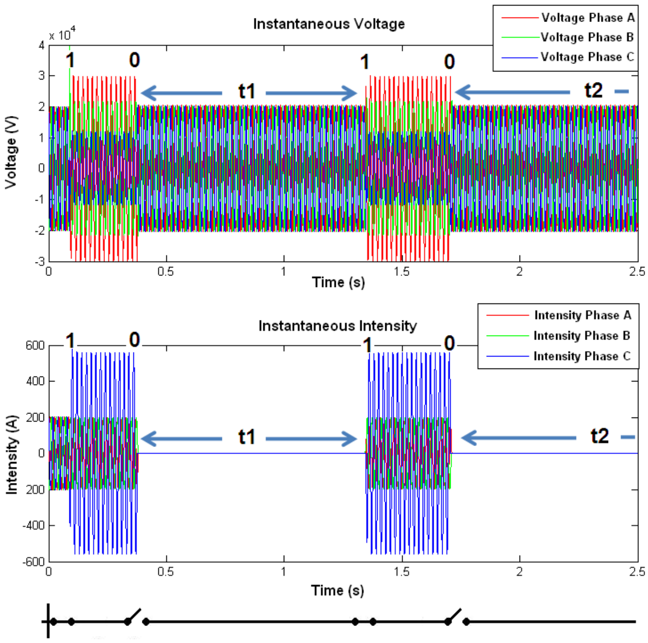

Fig. 15. Sequence operations of the protection

In the simulation, the fault is detected at 88 ms and 286 ms later the protection makes the first opening, 1 s and 347 ms after starting record the protection acts to make the reclose, in this case the fault persists, then the protection will make the second action according to Table III.

Table II. Real event times

SSEE	Start event	Start (ms)	Duration (ms)
SSEE1 L1 (TR2)	5:27:26	89	284
SSEE1 L1 (TR2)	5:27:27	348	260
SSEE1 L1 (TR2)	5:28:27	579	

Table III. Simulation event times

SSEE	Start event	Start (ms)	Duration (ms)
SSEE1 L1 (TR2)	5:27:26	88	286
SSEE1 L1 (TR2)	5:27:27	347	356
SSEE1 L1 (TR2)	5:28:27	578	

5. Conclusions

A software environment has been developed and tested to simulate different situations registered in a substation, including protections at substation for isolating the fault.

Therefore, we have designed and developed a set of blocks that will allow appropriate actions of protection, as the opening time depending on the fault current and the closing action according to the time sequence settings.

The models have been created automatically from the information contained in a database and any change in the network being report to the DB, could be automatically upgraded into a network model ready for simulation. In addition, all types of faults and distributed generation can be simulated (Fig. 3).
The programming environment will be used in the future to investigate the integration of distributed generation in the power distribution systems.

Acknowledgement

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