Distribution Network Simulation for Systematic Relay Testing

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Abstract - **The recent widespread application of digital technology to protective relays gives new opportunities to simultaneously improve reliable and sensitive operation from protective algorithms. However, this also implies an increase of equipment complexity. New forms of testing adapted to this new context are therefore required.**

This paper describes a methodology conceived to fulfil this purpose. It relies on digital simulation of electric power systems to assure a correct description of the complex transient phenomena involved. The proposed method is exemplified with two models of typical medium voltage distribution networks, the second of which includes distributed generation. Different types of faults are simulated, varying some determining factors as the incidence angle or the CT magnetisation curve. An automatic procedure is developed to allow the realisation of sequential testing, including waveform simulation, signal play back by an appropriate test set and data archive. Results of tests applied to overcurrent and over and underfrequency relays are presented. This method shows to be accurate and efficient and it can be easily implemented in many other situations.

Keywords: Protective Relays, Electromagnetic Transients, Digital Simulation, Testing System, Automated Testing.

I. INTRODUCTION

Protective relays play a decisive role in safe and efficient operation of power systems. The responsibility of limiting damages to major equipment imposes the fulfilment of some essential requirements [1]. Among these are speed, dependability (relay operation for any fault occurred inside its protective zone) and safety (no operation in any other circumstances).

Digital relaying gives nowadays a powerful alternative to old electromechanical devices. Not only they support supervisory functions and communication facilities but they also make possible the improvement of relay performance. Robust algorithms like Discrete Fourier Transform (DFT) [2] or Kalman filtering based techniques [3] provide an accurate characterisation of input signals.

Nevertheless, the performance of these algorithms can be affected by the noise inherent to voltage and current signals. This noise adds to the fundamental frequency information, which is, most of the times, the only one required for tripping decision. Electromagnetic transients that follow a fault occurrence in a power system are the main source of noise to be considered. Their unavoidable presence can cause relay malfunction or delayed operation.

New testing techniques should be prepared to deal with the stringent requirements of relay designs and provide their extensive assessment [4]. Realistic waveforms originating from power system digital simulation must be considered as well as the ability to generate a large number of test runs. In this paper, EMTP was used to simulate accurately different fault conditions in two typical European MV distribution networks. Overcurrent and over and underfrequency relays were tested using simulation results. An automated procedure made possible an extensive testing in a relatively short time.

The presented method is based on the decomposition of the input files for EMTP, according to a few important parameters of the Power System. These include CT characteristics and fault locations, for example. Those partial files are next concatenated by a batch file which proceeds combining different versions of the data files, so that a large quantity of different system instances are ran by EMTP. Each run produces an output file. This technique has been applied before for stochastic analysis of simulated algorithms [3] or the transients themselves [5]. This time, however, output files were automatically injected into a real relay under test, its behaviour being traced by the same equipment that injects the signals. This equipment was programmed for this function based on a suitable tool.

The description of the testing equipment and of the simulation tools used in this work is presented after a brief discussion of present day testing practices. The relay applications chosen to illustrate this methodology and some typical problems associated with them are then succinctly described. The next parts of the paper correspond to the main stages of the developed method. Firstly, the system modelling is examined. Some test cases exemplify the kind of phenomena the system models can deal with. Next the automated testing procedure is analysed. Results of the application of this method to the above mentioned relaying functions are reported. These functions are part of new product developments from EFACEC, a Portuguese manufacturer of electric and electronic devices and systems.

II. SIMULATION AND TESTING TOOLS

Relay testing is traditionally performed with specific test sets. Several options are available for relay vendors to carry out this task [6]. Old analogue devices only support non-automated phasor testing and soon will become obsolete. Their main application will remain relay commissioning. On the other hand, new developments of digital simulator designs provide today very powerful testing tools. The ability to consider real-time interactions between the relay and the power system is an important advantage of these systems. Unfortunately they are still very expensive, as they demand a considerable processing capacity.

In the present study an intermediate solution between the two mentioned was taken to carry out such tests. Figure 1 shows this testing system. This solution is based on separate tools for simulation and replaying of test waveforms, as can be seen in Fig. 2.

For transients simulation it was used EMTP because of its wide application and the several models of power system elements available [7]. Very often these models meet the test requirements and the waveforms produced match almost perfectly the true signals. On the other hand, a standard portable test set controlled by a user-friendly graphical interface was used to replay the simulation results and trace relay operation. This device provides very accurate transient test waveforms and a good time resolution.

The described system is an open-loop simulator. Although considering the natural limitations of this kind of test sets, namely the inability to process real-time simulation, with this solution it becomes possible to cover more complex applications due to less processing capacity required.

III. CHARACTERIZATION OF TESTED RELAYS

Some decades ago each relay implemented one single protective function. An integrated protective unit can perform today all these functions. The presented testing methodology was applied to state of the art multifunctional digital protective relays in order to evaluate their performance.

The relays under test are suitable for protection of medium voltage transmission lines. Overcurrent and frequency functions are some of the most significant elements of those systems usual protection schemes. The following discussion presents some of the typical problems inherent to their application.

Distribution networks with a radial topology can be efficiently protected against phase-to-phase faults by inexpensive relays based on the overcurrent criterion [8]. Despite of their simple operation principle (the high ratio

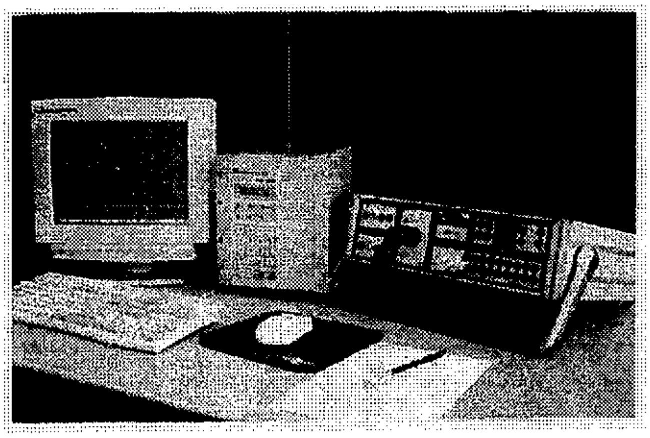

Fig. 1. Testing system.

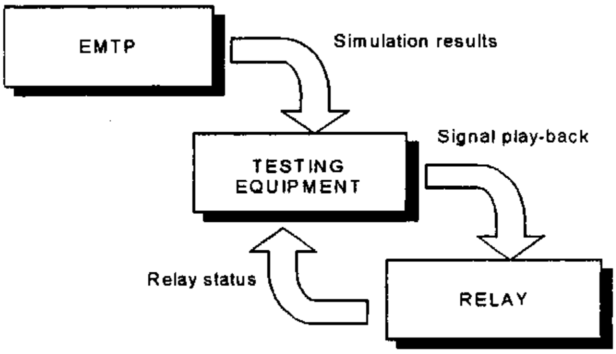

Fig. 2. Schematic diagram of the open-loop simulator.

between fault and load currents), they are also affected by system transients, mainly when a fast tripping decision is required.

However, phase to ground faults can be a particularly difficult case in networks with insulated, compensated or even impedance neutral earthing. The magnitude of zero sequence current can be not significant enough to discriminate between the faulted feeder and the other ones. A directionality criterion is often required.

Other usual problems are non-linear effects caused by instrument transformer saturation under extremely severe fault conditions.

On the other hand, dispersed generation makes selective behaviour of protective systems much more demanding. One of the most important problems the protective systems have to deal with is the identification of islanding events. These conditions can usually be detected using relays working with frequency measurements.

IV. POWER SYSTEM MODELING

This chapter gives an overview of the two power system models used in the subsequent tests. The first system (system A) is a 15 kV aerial distribution network. The number of feeders chosen is a trade-off between the usual network extension and typical line lengths. The goal is to obtain a realistic description doesn't leading to a cumbersome model. Figure 3 is a one-line diagram of system A.

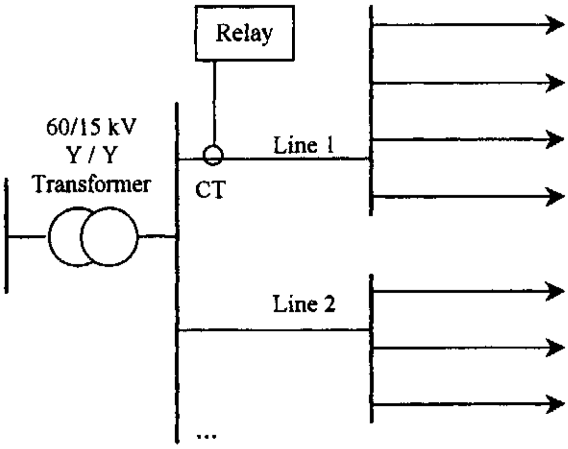

Fig. 3. One-line diagram for system A.

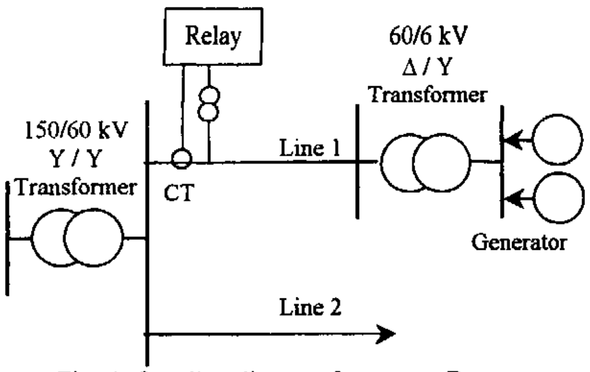

Fig. 4. One-line diagram for system B.

The other system (referred as B) is represented in Fig. 4. One 60 kV line connects to a small hydro-power plant. with two 5 MVA synchronous generators. In both systems relay location is marked.

A brief description of the system element models used is presented in the following sections, as well as some reasons for their choice.

IV.a. Transformer

The 60/15 kV Wye/Wye transformer was modelled with three single-phase transformers conveniently connected. Several options of the neutral earthing impedance of the 15 kV windings were considered. Core saturation was not modelled because short-circuit conditions usually reduces flux values. However, as it was done in [5] a circuit such as the one presented in Fig. 5 was added to the winding leakage impedance to model the increase of conductor resistance with frequency due to skin effect. This was done for system A, where transients have a broad range of frequency components of interest. For system B that circuit was not included according to the low frequency transients of the studied phenomena.

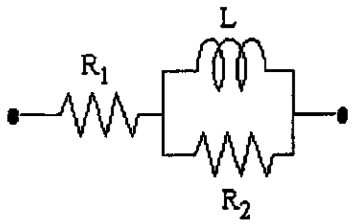

Fig. 5. Equivalent circuit to model skin effect on transformer windings.

IV.b. Aerial lines

As for transformers and for the reasons already mentioned, aerial lines were modelled in two different ways according to the corresponding system. For system A it was chosen a frequency dependent line model (J Marti model) which gives an accurate and, at the same time, numerically efficient solution. For system B, lines were modelled with coupled lumped three-phase R-L circuits.

IV.c. Load

To obtain a good representation of pre-fault conditions the feeders were not open-circuited. Load was modelled with three-phase R-L circuits connected in delta as usual. Their parameters were tuned to obtain load currents of about 100-200 A in the main feeders, with a typical power factor around 0.8-0.9 inductive.

IV.d. Fault arc

The fault arc was simply modelled using a constant resistor. More sophisticated models including the arc resistance dependence on the fault current or the dynamic arc behaviours were not considered because their values are not significant for the short dimensions of distribution isolators particularly when compared to the earthing resistance.

IV.e. Current transformers

CT models were built from a single phase transformer equivalent circuit with core saturation. The magnetisation branch was represented as a piecewise linear inductor, which, for a sufficiently small integration step, gives satisfactory results [9]. The magnetisation characteristic was adapted from that included in routine HYSDAT from EMTP but not considering a hysteresis cycle. Six points were enough to define accurately the curve (Fig. 6). Initial conditions for simulation were easily obtained even including this non-linear element. All the simulations started from a pre-fault condition for which CT magnetisation inductance remains with its unsaturated value.

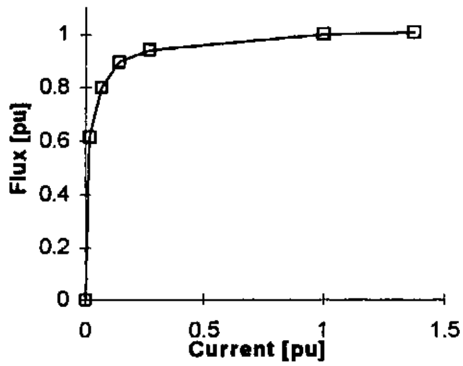

Fig. 6. Flux-current characteristic for CT non-linear inductance (values referred to saturation point).

IV.f. Generator

The synchronous machines were modelled with type-59 element, which is appropriated for detailed electromechanical transient studies as the proposed ones. All the machine values were relative to data collected from generator of existent plants.

V. EXAMPLES OF TEST CASES

Some examples of fault simulations relating to the previously described systems are now presented. The three phase currents observed for a three-phase fault occurred in line 1 of system B are shown in Fig. 7. A significant dc decaying component is the dominant transient. Its presence causes CT transient saturation. This can be noted by the

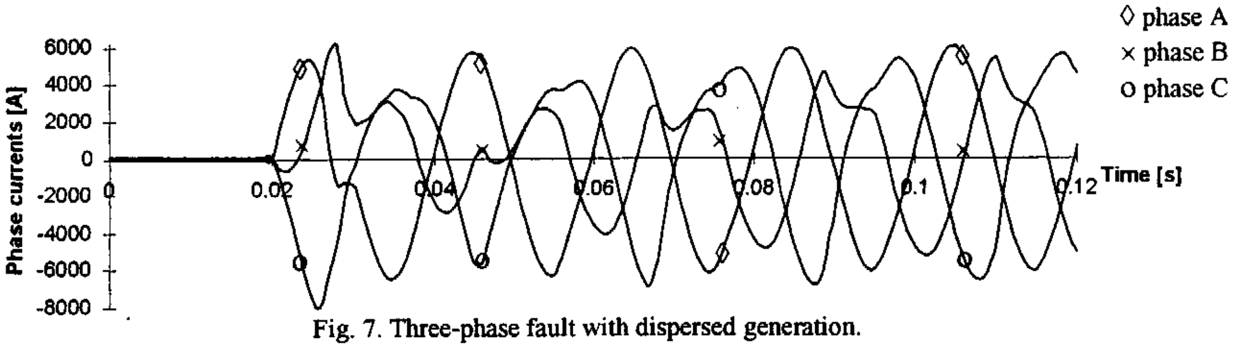

Fig. 7. Three-phase fault with dispersed generation.

current signal distortion after fault inception that causes a significant decrease of the fundamental frequency component magnitude.

Figure 8 refers to a close-in phase to ground fault occurred in line 1 of system A, with insulated neutral earthing. Phase currents are shown in Fig. 8.A. Figure 8.B makes a comparison between zero sequence currents from the faulted line and another substation feeder (line 2). Transient waveforms can be several times greater than ac steady state. That illustrates the weakness of the signal to noise ratio in traditional approaches to this kind of fault by protective relaying.

Figure 9 shows the evolution of synchronous machine speed after a fault occurrence in the 150 kV network. This quantity gives a measure of frequency variation in the 60 kV system. After fault clearance this system remains isolated and frequency decreases rapidly due to generator incapacity to supply the load alone. Generator small inertia leads to a great frequency rate of change.

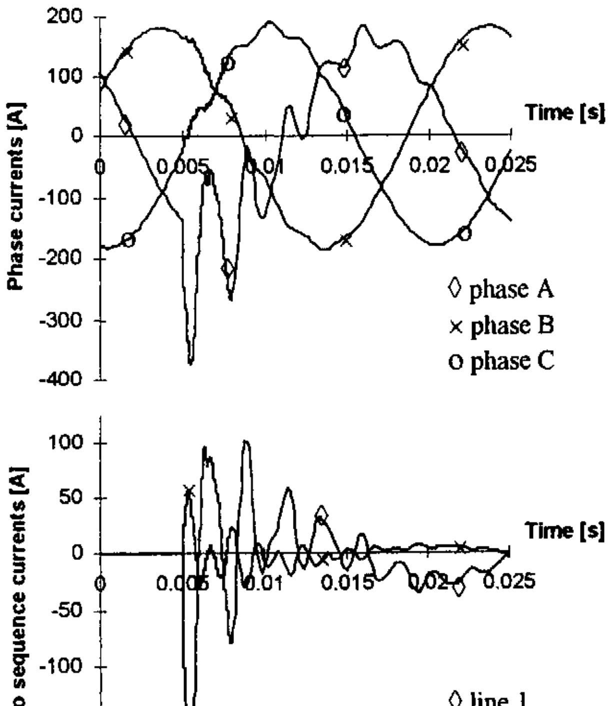

Fig. 8. Phase to ground fault in system A.

VI. TEST AUTOMATION

The three referred cases exemplify some fault conditions for which it would be interesting to assess relay performance. However, it's usually important to test the relay design with a larger set of cases, in order to proceed to a statistical analysis of tests results. This can also be done with the aim of an easiest detection of some relay misoperation. Those cases can be obtained varying some characteristic parameters of the system, as the fault location, the network structure or the fault arc resistance. The simultaneous variation of all these parameters can lead to a great number of test runs. Manual testing would become certainly an inefficient and slow process. The batch procedure described in Fig. 10 avoids these difficulties.

The first step is the creation of the input file for EMTP. The original file containing the description of the entire system is decomposed into partial files, each one corresponding to one of the chosen parameters. Then, there are created as many copies of each of those files as the number of options considered for that particular characteristic. Only its value is modified the rest of the file being left unchanged. Each of these files has a name which includes a common identifier indicating the corresponding parameter and a number that distinguishes it from the other files of the same type.

The concatenation of these files, one of each type, generates as many EMTP cases as the number of possible combinations of the several parameters, as described in Fig. 11. This procedure avoids the need to previously create all the files manually.

The voltage and current waveforms corresponding to the generated data file are then simulated by EMTP.

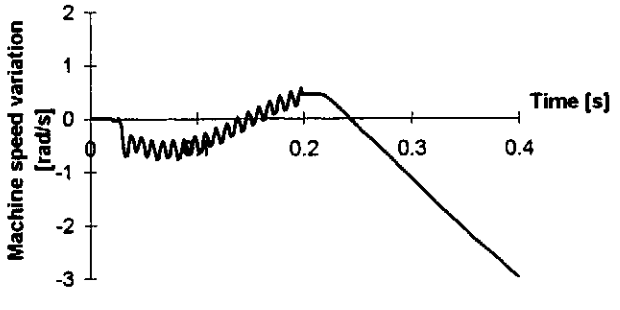

Fig. 9. Speed evolution of dispersed generators following a fault.

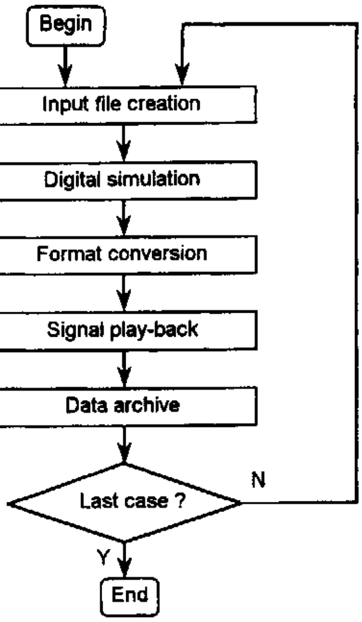

Fig. 10. Batch process for tests management.

Before these signals can be replayed the output file must be converted to a normalised format accepted by the test set interfacing program. It was adopted the standard file format COMTRADE (Common Format for Transient Data Exchange) according to IEEE C37.111 standard.

After this step, the converted file is loaded by the test set interfacing program. Some available options, like signal processing facilities, are used: copying a single cycle of system electrical quantities generated by EMTP extends the pre-fault time. This additional step substantially reduces the time spent on waveform simulation. Finally, voltage and current waveforms are replayed and all the relay binary output transitions are reported.

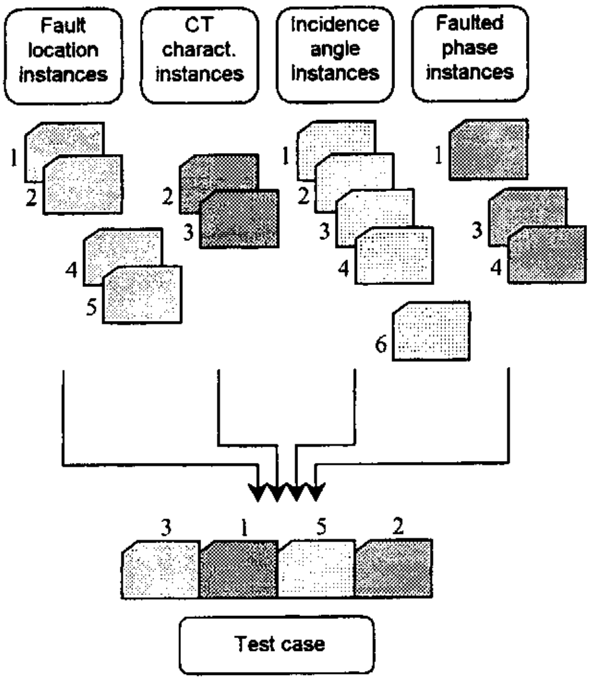

Fig. 11. EMTP input file creation.

The described sequence is repeated as many times as the total number of different system instances previously defined. After the conclusion of all the runs, the corresponding report is generated and the main information can be extracted and analysed in detail.

VII. PERFORMANCE RESULTS

Table 1 gives the execution time of a single test run for both systems A and B. These results were obtained in a personal computer based on a 133 MHz Pentium processor. For big and complex systems, like system A, digital simulation spends the major part of the total execution time. Sequences with a large number of test runs represent a high computer burden and may need an extra amount of processing capacity. On the contrary, the test set operation time in not significantly affected by the change of system.

VIII. APPLICATION EXAMPLE

The presented methodology is exemplified with the test of the phase overcurrent function using transient simulations from system A. The 450 different phase-to-phase fault conditions considered were obtained varying the following system parameters:

- Fault location: 5 locations equally spaced along line 1.
- CT characteristics: 3 options, varying the saturation point of the ψ (i) magnetisation characteristic (defined by the coordinates (ψ_{sat}, i_{sat})).
- Faulted phases: the 3 possible combinations (A-B, B-C, and C-A faults).
- Incidence angle: 10 options, with time intervals of 2 ms between consecutive instances.

The high set overcurrent function is set to operate instantaneously for faults in the first half of line 1. The low set function operates for any fault occurring on the line, with a step timing of 0.11 s.

Table 2 presents the obtained results. They are organised according to fault location and CT characteristics. Each table entry corresponds to the mean of 30 cases.

Tab. 1. Execution times for a single test run.

	Performed task	Time [s]	
		System A	System B
EMTP	Input file creation	1	1
	Digital simulation	40	10
	Conversion to COM-TRADE	5	4
TEST SET	System initialisation	20	20
	File read and process	8	8
	Signal play-back and data archive	10	10
TOTAL		84	53

Tab. 2. Results of phase overcurrent function testing.

Fault location (% of line 1 length)	i_{sat}=500A Ψ_{sat}=0.01Vs Start [ms]	i_{sat}=500A Ψ_{sat}=0.01Vs Trip [ms]	i_{sat}=2000A Ψ_{sat}=0.04Vs Start [ms]	i_{sat}=2000A Ψ_{sat}=0.04Vs Trip [ms]	i_{sat}=5000A Ψ_{sat}=0.1Vs Start [ms]	i_{sat}=5000A Ψ_{sat}=0.1Vs Trip [ms]
0%	36.3	44.1	34.7	35.6	34.3	34.8
25%	38.6	55.9	37.4	39.2	37.8	39.2
50%	39.8	108.9	37.9	109.0	39.4	108.2
75%	39.7	110.7	41.6	110.4	41.4	111.6
100%	42.7	111.4	42.8	112.8	42.1	112.5

For faults occurring in the second half of the line only the low set function operates. That agrees with relay settings. The timing accuracy is less than 5%. On the other cases, the relay provides a fast tripping. The operating time increases in the event of CT saturation. This cause current magnitude reduction in the first cycles after fault inception which delays tripping decision.

IX. CONCLUSIONS

This paper presented a new methodology to be applied in protective relay testing. It was conceived to assure a systematic evaluation of protective algorithms under realistic fault conditions. This method serves not only as a practical application of EMTP but it's also a powerful way of overcoming some natural limitations of standard portable test sets.

The use of a simulation program assures an accurate description of the typical transient phenomena that affect relay operation. On the other hand, the automated procedure developed gives an easy and efficient way of making an extensive assessment of relay performance.

The several stages of the proposed method were exemplified with overcurrent and frequency relaying functions using models of distribution networks. However, this procedure can be flexibly implemented in many other situations with other equipment or different types of relays.

X. ACKNOWLEDGMENTS

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