ANALYSIS OF PROTECTIVE RELAYING OPERATION AND RELATED POWER SYSTEM INTERACTION

Mladen Kezunovic, Slavko Vasilic

Texas A&M University
Department of Electrical Engineering
College Station, TX 77843-3128, U.S.A.

Abstract: Advanced techniques for analysing operation of protective relays and related interactions with the power system are discussed. Three major issues are addressed: evaluation of existing physical relays, study of new and/or existing relays using relay models, and assessment of relay operation and its interaction with the power system using models of both relays and power system. The underlying approach is based on an advanced modelling and simulation environment as well as the use of digital power system simulators capable of interfacing with physical relays. Such advanced analysis techniques are needed to provide improved protective relaying reliability and system performance.

Keywords: Power systems, Protection, Modelling, Simulation, Simulators, Transient analysis, Man-machine interfaces.

1. INTRODUCTION

This paper is related to the issue of advanced analysis of operation of protective relays and their interactions with the power system where they are installed. The history of this subject is rather interesting: the analysis of the relaying operation went from "the art" in the early times to a rather precise engineering analysis in the most recent times.

The driving factors for the need to have better and more precise analysis methodology and tools are multiple. They range from the change in the relaying requirements that were introduced by the deregulation to the new relaying performance characteristics that are now available with the microprocessor-based relays. In both cases, evaluating, studying their performance, and designing relays is becoming more demanding and requires different engineering approach where the transient behaviour of relays, instrument transformers and power systems needs to be observed (Kezunović and Kasztenny, 2000).

As a result of the new demand for more precise analysis of relay characteristics as well as relay interactions with the power system and other relays, the use of new tools such as digital simulators and relay models is required. This paper provides a justification for the new needs and presents examples of the new tools and their uses.

Three scenarios for analysis of protective relay operation are identified: evaluation of physical relays, study of the relay performance using relay models, and assessment of an interaction between relays and power systems using modelling and simulation. Evaluation of physical relays requires the use of digital simulators (Kezunović, *et al.*, 1998). Study of the behaviour of the existing or new relay designs may be performed using software models of the device (McLaren, *et al.*, 2001). The interactions between relays and power systems can be presented using advanced software tools that represent both relays and power system in one simulation environment (Kasztenny and Kezunović, 2000).

The paper starts with a background section that introduces the reasons for needing the new analysis tools. After that, each type of the tool is discussed in detail: digitals simulators, relay models, and combined solutions for modelling and simulating operation of multiple relays and related interactions in a given power system. Some conclusions and references are given at the end.

2. BACKGROUND

This section discusses three important background issues associated with an increased need for better analysis of protective relaying operation. The issues have especially new meaning when an increased relaying performance is sought.

2.1 Deregulation, Restructuring and Increased Competition

The mentioned developments have brought forward a need to have more secure and dependable protective relay operation. As a result, standard analysis tools for evaluation, study and assessment of relay operation are insufficient. The tools that allow transient analysis, that resembles the actual power operation, are needed. With this capability it will be possible to investigate protective relay operation for the cases where the system is loaded very close to the limits. Other examples are the cases when new relaying schemes are needed to accommodate for more stringent requirements for protecting the system under cascading failures and/or specific interfaces among independently owned power system parts. All the cases are caused by the competition in the industry creating a requirement that the protection operates more reliably enabling the power system's down time to be reduced as much as possible.

2.2 New Protective Relay Designs and Features

In striving for better performance of the relaying operation, it is important to consider new relay designs and features. This translates into an ability to analyse both new relay products and new protective relay concepts. The new products are introduced to overcome the shortcomings of the previous products and to offer some new capabilities. Typically, to confirm the performance of the new designs, one needs a set of tools that can facilitate the evaluation using transients. Some difficult applications may require introduction of new concepts for relaying. Studying the new concepts requires extensive modelling a simulation capability since the concepts may not yet be implemented in a particular hardware.

2.3 Availability of Advanced Modelling and Simulation Tools

This requirement is brand new. Earlier analysis methodologies for protective relaying did not include extensive use of relay models. As the technology for implementing the analysis tools has improved, the modelling and simulation tools have slowly emerged and evolved. The state of the art on the market is to offer a short circuit programs that will have the relay coordination capabilities based on the simplified (phasor-based) relay models. The next step is to have similar tools except tied to the electromagnetic transient programs and aimed at transient evaluation of relay operation. Such programs are ideal for investigating an interaction among large number of relays protecting a given power system.

3. EVALUATION OF PHYSICAL RELAYS

This section discusses the tools for evaluation of physical relays using "real-world" fault transients (application testing). This is achieved through utilization of digital simulators that allow one to assess both the trip/no trip performance as well as the speed of operation (in the case the relay is expected to operate). The application testing is not a common practice today but may have to be used much more in the future if one wants to evaluate new products and troubleshoot the existing ones.

3.1 Requirements for Digital Simulators

The requirements for the simulator system performing application testing with transients are summarized bellow:

- Possibility to import waveforms with native file formats for different types of recording devices.
- Availability of several signal-editing features to enable customizing replaying of pre-recorded transients.
- Flexibility of utilizing customized interface for simulation tools such as ATP (CanAm UG, 2002).
- Possibility to generate the tests automatically by configuring simulation tools for such a task.
- Capability to perform automated transient testing.
- Ability to create test reports automatically.
- Capability for high-performance waveform reconstruction with respect to D-to-A resolution and sampling rate.
- Possibility of using high power voltage and current amplifiers.

3.2 Portable Digital Simulator Solutions

The simulator technology has matured to the pint where low-cost high-performance solutions may be found on the market (TLI, Inc, 2002). The next step is to provide the diversity needed to meet a variety of testing needs. The hardware interface options to accommodate for different output power levels of the simulators are shown in Figure I.

The software features are expected to provide more flexibility in running transient tests aimed at evaluating application properties of a relay. The methodology of application evaluation will need to be better understood so that an agreeable set of tests may be standardized. At present there is very little guidance on how to perform transients test to assess the application performance of a relay (Kezunovic, *et al.*, 1997). A software configuration that represents a good start for further enhancements in this area is shown in Figure II.

The real-time simulator configurations will become more compact and eventually will be implemented using portable PCs. This will bring the ultimate in flexibility to the users and they will be able to perform the transient tests rather easily both in the field and labs.

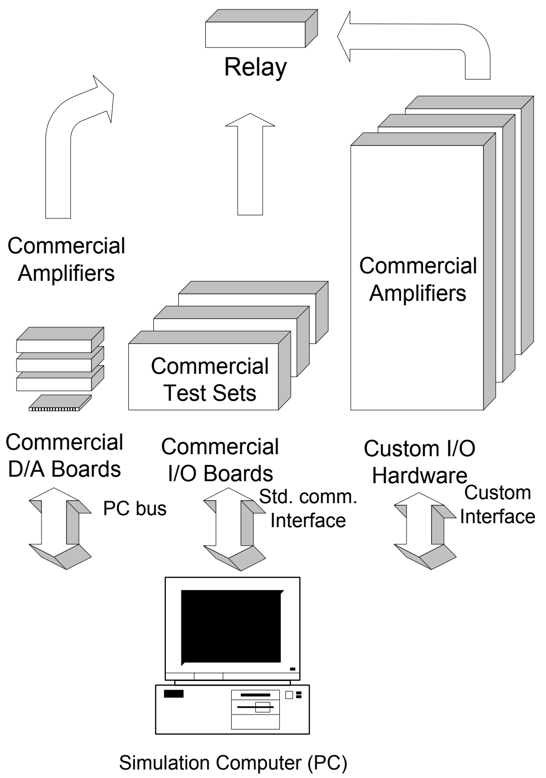

Fig. I. An advanced hardware configuration of an open-loop simulator

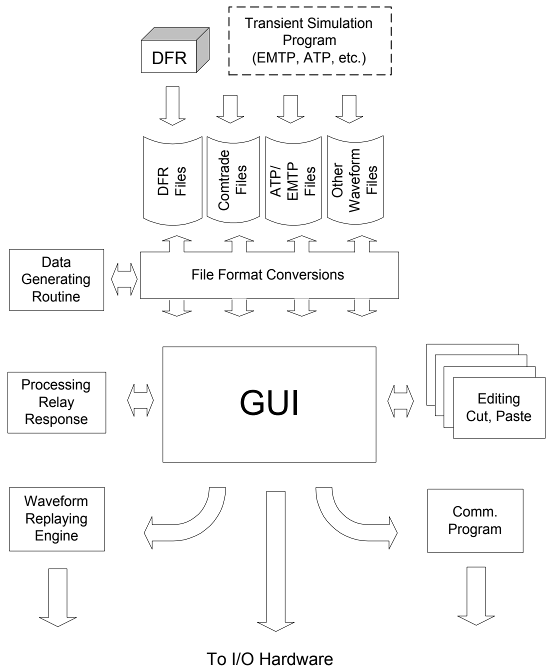

Fig. II. An advanced software configuration for an open-loop simulator

4. STUDY OF EXISTING AND NEW RELAYS USING MODELING AND SIMULATION

This section discusses the application of relay models for study of existing or new relaying concepts. The ability to use the models allows the overall capability to tune performance of the selected relaying solution even better. The next sections give examples of modelling needs and approaches when implementing a modelling and simulation environment for representing distance relays using either an existing commercial or new custom designed software environment for modelling and simulation.

4.1 Use Of a Commercial, General Purpose Software

MATLAB, a high-performance language for technical computation, integrates calculation, visualization and programming in an easy-to-use environment (Mathworks, Inc., 2002). Particular factors that support the choice of MATLAB in modelling the relays are:

(a) The high-volume low-price distribution, which makes the package readily available for all the targeted audiences.

(b) Flexible software structure of MATLAB comprising libraries, models and programs enables one to integrate different relay components in one package conveniently.

(c) MATLAB and its time domain solver, SIMULINK, create a friendly and open system. New models and libraries may be just added to the package without a deep knowledge or modification of the existing parts. This is very useful if the user is involved in further development of the software (modifications, extensions or customisation).

(d) Fast-development with MATLAB using powerful calculation and visualization means of the package enables one to expand the software quickly and efficiently without developing any extra programming tools.

(e) A wide selection of Toolboxes, including comprehensive collections of pre-defined functions for solving application-specific problems, is already available with MATLAB and seems it will be growing even faster in the future. The examples of toolboxes relevant for the protective relaying application include the signal processing, optimisation, neural network and wavelet toolboxes.

(f) Power System Block set, one of the latest extensions of MATLAB enabling one to model the basic components of power systems, provides a vital alternative to EMTP/ATP particularly by permitting modelling of both the power system and its controls in the same environment facilitating closed-loop simulation

Fig. III introduces, as an example, a pre-defined SIMULINK model of impedance (Distance) relaying principle. The model consists of:

- Single-phase model of a two-machine three-line power system with models of the fault and instrument transformers.
- Measuring blocks estimating the voltage and current phasors as well as impedance components.
- Zone comparators checking the impedance location against three impedance zones.
- Displaying elements.

4.2 Use Of Customized Software For Modelling New Relay Designs

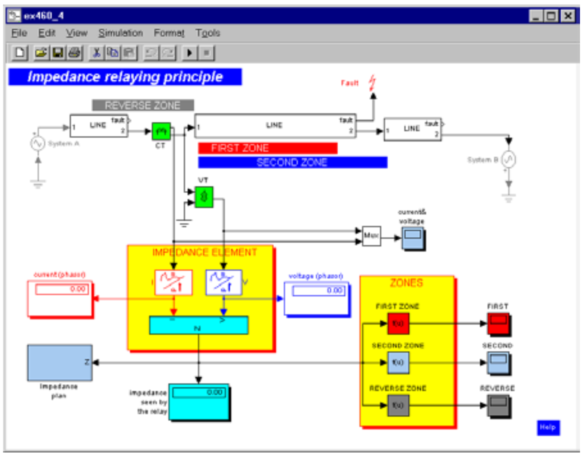

Fig. III. Matlab and Simulink implementation of a Distance Relay model

An example of a neural network based protective relay has been recently widely discussed (Vasilić, *et al.*, 2002). The relay is based on self-organized neural network that establishes the prototypes of typical input patterns, and afterwards employs the prototypes for classification of new inputs (Fig. IV). The design of distance relay using this concept exceptionally depends on the availability of detailed and accurate software model of power network as well as definition and feasibility of a set of scenarios that imitate a realistic network operation.

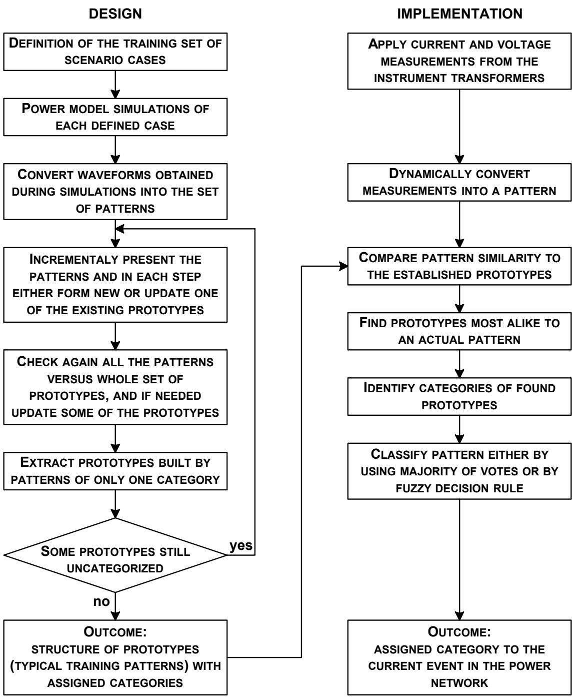

Fig. IV. Design and implementation steps of neural network based relay

Various classification tasks can be inserted into the relay. The most common function is to detect the fault appearance and fault type in selected area in both the forward and reverse direction. Another very important feature is to recognize the zone of protection where fault occurred. For each input pattern that represents an event in the power network the relay assigns a category to that pattern (event) and the number of categories depends on the assigned classification task. If the relay has to detect a type of the fault, there are 12 categories (11 for faults and one for no-fault situation). If it is supposed to simultaneously detect a type of the fault and, for instance, its occurrence in either first or second zone of protection there are 25 categories (11x2 for fault and one for no-fault). The relay model can be trained for both purposes.

The design starts with simulating various fault and disturbance events and operating states, by changing power network topology and parameters. The result of each generated case, voltage and current measurements at the relay location, is being converted into a training pattern by filtering, sampling and using a desired data window. The obtained samples build a pattern with inherited characteristics of simulated event. In the training process, the patterns are presented incrementally and pattern prototypes are constructed. The training is complex incremental procedure of adding new and updating existing prototypes. The outcome of design process is structure of prototypes where each belongs to one of the categories.

In the implementation step the prototypes established during training are dynamically compared with measurements taken from the instrument transformers. The measurements are converted into the patterns before the training process. Then a pattern similarity to all the prototypes is numerically calculated. A subset of the most resembling prototypes is retrieved and their categories identified. The pattern is being classified according to the majority of their categories, or by using fuzzy decision rule. Depending on the recognized event and selected designer's logic, the relay either has to operate or to stay unaffected.

5. ASSESSMENT OF RELAY OPERATION AND RELATED POWER SYSTEM INTERACTION

The problem of proper representation of relay interactions with the power system becomes very important due to the complex topology of the power network. This has created a need for efficient and easy way for modelling and simulating a variety of scenarios by changing the network topology, selecting single or multiple network elements, and choosing the corresponding network parameters. The set of relevant interaction that may appear in the network must be widely studied in advance to properly select relay actions for ambiguous and not easily predicted cases. The techniques and tools available today are not capable of handling a variety of changeable network conditions in an easy way.

5.1 Simulation Environment for representing relay interactions

The solution has to be capable of interconnecting a program for data processing, optimisation procedures, file management, and user-friendly interface. The solution could become powerful tool for fault analysis by overcoming usually tedious tasks of manually creating each single scenario and plugging the input data into the relays.

An example of such a tool, already utilized to enhance relay design and evaluation, is presented in Fig. V. Alternate Transient Program (ATP) for power system transient simulation and MATLAB computational tool have been interfaced for efficient simulation of relay interaction. One of MATLAB's utilities is able to manage ATP input file for all defined cases. It interactively updates ATP input file and invokes ATP program to simulate each scenario from a defined set. Utility for database management organize sets of network outputs to be readily available for later use. The user can pull out outputs of specific simulated scenarios and show its waveforms, use them for the relay design and evaluation, and for showing estimated phasors and impedance trajectories. The libraries of scenario cases, network responses, design parameters, designed relays and relay responses, can be established and used for particular needs.

The utility for relay input signal pre-processing extracts the data obtained through power system simulations, selects desired measurements and converts them into the format needed by the relays. Selecting an analogue filter (type, order and cut-off frequency), sampling frequency, and data window length is also possible.

In the example shown in Fig. V, a software model of a classical distance relay performs voltage and current phasor estimation (using one cycle Fourier algorithm) and impedance estimation. Furthermore, it does overcurrent and undervoltage condition detection, grounded or ungrounded fault detection, R-X impedance trajectory identification and its comparison with selected operating characteristics. The relay final output is information about detected fault type and fault zone. Design parameters for distance relay are distance limits for zones of protection, impedance characteristic selection, delay between zones, overcurrent, undervoltage and zero-sequence thresholds, voltage and current instrument transformers ratios, and positive and zero sequence line impedance.

User interface facilitates creation of scenarios including selecting the combinations of events and setting their parameters. It manages database of simulated cases, relay models and their responses obtained during evaluation. Furthermore it is used for relay input data pre-processing, and to set up relay design parameters. It also shows simulated results (like V/I time waveforms, estimated V/I phasor values, and locus of measured impedance in R-X plain) at the relay location.

5.2 Selecting and implementing complex simulation scenarios

Scenarios are artificially divided into a group of static and dynamic scenarios. Static scenarios include the

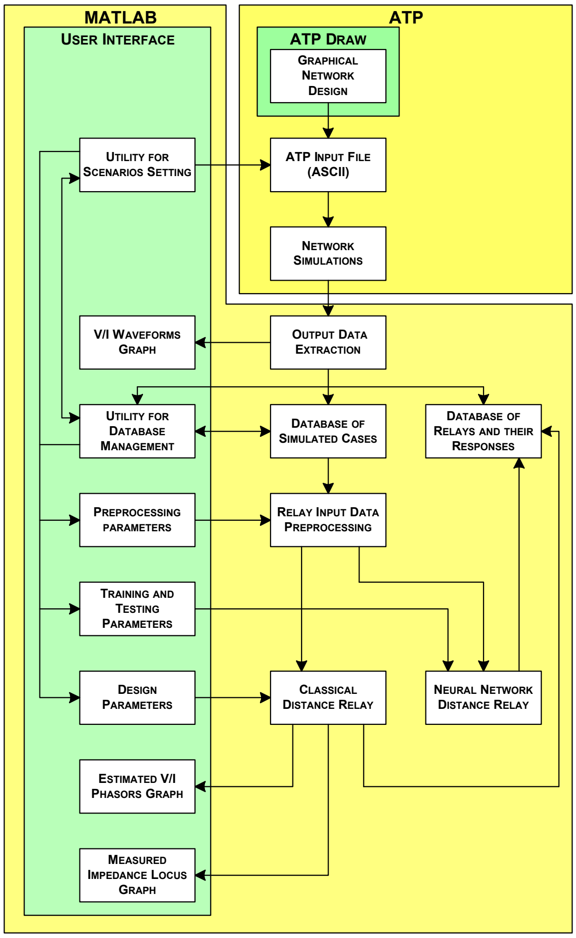

Fig. V. A new software for power system modelling and simulation as well as protective relay design and evaluation

changes in the network topology as well as parameters that stay unchanged in all consecutive simulations for various dynamic events. Examples of such scenarios are week in-feed (by disconnecting some of the equivalent sources), line out of service, line with one end open, system frequency variation, source/load variation, and arbitrary combinations among them (Ristanović, *et al.*, 2001). Line switching is controlled through circuit breaker opening and closing times, corresponding to various fault inception times. Changes of equivalent network sources are established through varying voltage amplitude, phase shift and source impedance. Changes of power system frequency affect all the equivalent sources and frequency dependent lines. If set of values for source parameters and system frequency is given, the running of dynamic scenario cases is repeated for each value. In addition, the general simulation parameters, like simulation end-time and integration step-time are set at this level, providing the user capability to select the simulation time frame and desired accuracy.

Dynamic scenarios are characterized by changing at least one parameter between two consecutive simulation cases. The dynamic scenarios are line fault, line switching, switching on-to fault, cross-country fault, evolving fault, etc. External control of transmission line fault simulations is based on changing the line section lengths to emulate varying fault distance, changing the opening and closing times of phase-to-phase and phase-to-ground switches to imitate fault type and inception time, and varying fault distance. In addition, for evolving faults, varying the delay between primary and secondary fault is included. The possible fault locations cover first, second, third and reverse zone of relay protection, as well as faults on certain number of lines out of these zones. For cross-country faults, the fault is placed on corresponding positions of two parallel lines. As an example, Table 1 gives a listing of the target scenario parameters and corresponding action for updating power network model.

Table 1 Target scenario parameters and corresponding action for updating power network model

Target	Action
Fault type	Adjusting opening/closing times of the phase-to-phase and phase-to-ground switches covering all fault types and various fault angles inside one cycle.
Fault inception time	
Fault location	Adjusting line section lengths from both line ends to the faulted point and covering the faults along entire line.
Fault impedance	Adjusting fault impedance.
Delay between evolving faults	Adjusting various angles between primary and secondary fault inside one cycle.
Line out of service	Hold line breakers permanently open.
Line switching	Adjusting opening/closing times for the circuit breakers and covering various switching angles inside one cycle.
Source/load variation	Adjusting voltage amplitude, phase shift and impedance.
System frequency variation	Adjusting system frequency and frequency of equivalent sources.
Relay location	Activating specific measurement points in the network.
Integration step time	Ajdusting general simulation parameters.
Simulation end time	

All simulation cases can be performed for deterministic or random values of event parameters. Deterministic generation of scenarios is based on specifying several values for each of the event parameters and combining these values to achieve the whole set of scenarios. The other way to create scenarios is only to specify the boundaries (usually imposed by the nature of the event) and then generate randomly the values of parameters for each event to evaluate designed solution in heuristic, not foreseen situations.

6. CONCLUSIONS

The following conclusions can be drawn based on the discussion given in the paper:

- Transient analysis of relay operation and interaction with the power system is essential in improving relaying performance
- The tools to perform the transient analysis are not readily available and used today
- Future development of the required techniques and tools for such an analysis needs to support evaluation of physical relays as well as modelling of relays, power systems and related interactions.

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