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**RELAY SOFTWARE MODELS FOR  
USE WITH ELECTROMAGNETIC  
TRANSIENT ANALYSIS PROGRAM**

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# RELAY SOFTWARE MODELS FOR USE WITH ELECTROMAGNETIC TRANSIENT ANALYSIS PROGRAMS

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## **1.0 Introduction**

Relay Models have been used for a long time. The practice started when the manufacturers had to design relays but the understanding of the underlying electromechanical and electromagnetic processes was limited. The manufacturers built prototypes of the designed relays but the prototypes sometimes consisted of only the essentials of the operating mechanisms. The models were then tested and designs were modified using the knowledge gained from testing the prototypes.

The practice of building prototypes remained in use when solid-state technology was introduced in manufacturing relays. The practice continued even after the introduction of digital electronics technology in the form of numerical relays. Gradually, the practice of building prototypes was replaced by using computer programs that modelled the performance of relays.

After the introduction of the use of computers for system analysis, electric power utilities started to develop and include relay models in their fault analysis and transient stability programs. The purpose of these programs was to study the impact of the operation of relays on system performance, specifically on the transient stability and system security. Models of relays are now being used in designing relays, analyzing system performance and studying the impact of relay operation on system security. These models mimic one or more of the following functions.

- The characteristic of relays
- The pre-processing of inputs provided to relays
- The measurement process used in relays
- The handling of the outputs provided by relays

Some early activities consisted of modeling characteristics of inverse time over current relays [186], evaluating the performance of relay algorithms [185], evaluating the suitability of a selected processor for a relay design [121], use of models in emtp programs [179] and role of models in teaching power system protection [145]. The subject of modeling of relays has also received attention of professional organizations and has led to the publication of reports on this subject [11]. This report was prepared because the Power System Relaying Committee of the IEEE Power Engineering Society perceived a need for reviewing this issue.

### **1.1. Scope**

This report discusses the applications of relay models in Section 2. The use of the models by manufacturers, customers and educational institutions are specifically reviewed. This is followed in Section 3 by classifying relay and communication-system models and implementing the models in software packages. The current state-of-the art modeling of power systems, instrument transformers and relays are then discussed in Section 4.

A very important aspect of a report is the direction it provides to the readers for continuing work on the subject addressed in the report. Such a direction is provided in Section 5 in which sources of information for building relay models are identified. The sources include manufacturers, published literature and relay test data. The relay-model building tools, which are available in the market place at this time, are also identified in this section. Information on relay testing and relay setting software packages is also included because those packages can also provide information that may be used in building relay models.

The modeling methodology is then discussed in Section 6. This includes the methods of modeling instrument transformers, signal conditioning filters, analogue to digital converters, and relay dynamics. The modeling of microprocessors and computation of phasors is discussed in this section as well.

Before any models are used in system analysis programs or for designing relays, they must be validated. Therefore, the issue of validation of relay models is addressed in Section 7. Different methods of validation, relay-testing procedures, assessing accuracy of models are discussed as well. Two examples of validating relay models are included.

Because the relay models are interfaced with power-system analysis programs, the interfacing issues are discussed in Section 8. The issues concerning the interfacing within the commercial software packages and with custom developed software are examined. The issue of using the models in open loop, closed loop and semi-closed loop are discussed. A desired approach to evaluating relay performance is to use the data recorded in a power system for testing the performance of a relay. Instead of testing the relays, the data can be used with relay models repeatedly and reasons for inappropriate operation of the relay can be thoroughly investigated. This issue is addressed in this section as well.

Limits of relay models and their use is then discussed in Section 9. The impact of truncation of inputs by A/D converters on the calculation of phasors is briefly discussed. The progression of the computed relaying function after the inception of a fault is demonstrated. Also discussed is the impact of frequency deviation on relay/relay model performance. Accumulation of errors, integrity of hardware components are reviewed as well. Studies that cannot be conducted with models are also identified.

Finally, the possibility of relay engineers using detailed models, which the manufacturers develop for use in their design and analysis studies, is discussed. It is shown that it is possible to provide facilities that would allow a relay engineer to use manufacturers' models with the utility's software without receiving the proprietary information contained in the manufacturers' models. This would allow the utilities to use the detailed relay-models prepared by the manufacturers and would at the same time protect the proprietary information contained in the manufacturers' models.

Finally, a list of references is included for the readers to study this subject further.

## 2.0 Applications of Relay Models

Protective relays are a critical part of the power system. Their actions can modify its topology by opening and closing circuit breakers. Quick isolation of a faulted power system element by protective relays is critical in maintaining stability and continuation of electric service to utility customers. On the other hand, incorrect operation of the protection system, due to a transient power system event, could have detrimental consequences to the continued operation of the power system.

Electrical faults, switching actions by operators, and other power system disturbances, cause a redistribution of the electric and magnetic energy stored in capacitive and inductive elements of the network. This redistribution of electric energy cannot occur instantaneously, and the power system must undergo through a transient state before it reaches a new steady state. During the first few cycles following a power system fault, high-speed protective relays are expected to make a correct decision as to the presence and location of the fault in order to preserve system stability and to minimize the extent of equipment damage. The majority of protective relays make their decisions based on 50 or 60 Hz fundamental frequency voltage and current signals. However, it is precisely at this moment that the voltage and current signals are badly corrupted by fault-induced transients in the form of an exponentially decaying dc component, and with frequencies above and below the fundamental power system frequency. The dynamic performance of protective relays depends to a large extent on their design principle that addresses things such as selectivity, sensitivity, security, and dependability. In addition, the dynamic performance of high-speed protective relays depends to a large extent on the signals produced by instrument transformers, and these signals depend on the overall transient response of the instrument transformers, and the type of transients generated by the power system [1, 2].

Modeling and simulation of electric power systems has been a common engineering practice in many utilities, research centers, and universities for more than thirty years. Computer models of major power system components have been used in software packages such as short circuit programs, load flow and stability programs, and electromagnetic transient programs. Relay system modeling, which affects the operation and topology of the power system, has been performed to a lesser degree.

In the last fifteen years, more and more electrical network calculation programs have been entering the market. The possibilities of using them for protective relay modeling and other protection studies are increasing. Protection system models can be used to:

- Investigate and improve the protection designs and algorithms
- Select the relay types suited for a particular application
- Verify, test, and properly adjust the relay settings
- Investigate the relay behavior during network disturbances
- Make it easier and less costly to test relay designs and principles with relay models instead of using the actual devices
- Enable offline closed loop testing thereby reducing costs
- Select critical test points to decrease the necessary amount of tests with actual relays

### 2.1. Use of Relay Models by Manufacturers

Manufacturers of protective relays use software relay models in the early stage of new relay development process. Relay software model development and testing actually precedes the building of a prototype relay, because it offers the manufacturer the ability to evaluate the relay

design and its applicability prior to building the actual device. This is essential in the development process because, it allows the researchers to test various relaying algorithms, the relay logic, and to make necessary changes without the need to make extensive changes in hardware or software modules of the actual device. Relay algorithm development researchers use relay software models to test different digital signal processing techniques, protection algorithms, the transient response of digital filters, phasor estimating methods, directional or distance element unit performance, and to evaluate new measuring techniques. In addition, some relay manufacturers use closed-loop simulations of relay software models with an electromagnetic transient simulation package, to evaluate the transient behavior of the protective relaying algorithms due to network changes and network switching. In addition, relay system manufacturers use relay software models for marketing purposes. Relay manufacturers can realize the following benefits with the help of software models (see also Section 4.3.4):

- Careful investigation of the protection software (i.e. filter designs, sampling rates, relay algorithms, communication interfaces)
- Fast testing of software changes
- Hardware and software performance tests
- Test the ability of one protection device to cooperate with other devices, such as
  - Station bus system
  - Remote control systems
  - Instrument transformers
  - Parameterization tools
  - Data communication modules
- Test the time behavior of the protection software and hardware with empty transient files

Of course, all of the above possibilities cannot completely replace tests with the actual protection devices. However, tests with relay software models can be realised much easier, faster, and without necessarily using complete set of amplifiers for voltages and currents, circuit breakers, and other equipment. The actions of the relay model can be investigated much deeper with the help of a debug function, rather than performing tests with the actual relay.

Relay software models can also be useful to marketing engineers for:

- Presentation of new types, or versions of protection systems
- Fast variations of parameters to adapt the relay to network conditions
- Easy utilization with network calculation programs
- Investigation of network disturbances with possible protection failure together with clients, with the possibility of quick parameter changes

Before using the relay software model, especially with network calculation programs, for marketing purposes, the conformity between the actual relay and its model has to be tested carefully (see Chapter 7).

## **2.2. Use of Relay Models by Customers**

Software relay models are also very useful to customers like relay application engineers of power utilities, engineering, and industrial companies which apply the relays. At first, these models can be used to evaluate and select the proper type of protection according to network conditions. In this type of evaluation, one can include not only the power system modeling and the protection concepts, but also the instrument transformers, circuit breakers, and data transmission systems. A relay application engineer can use these relay models to select a relay measuring principle, and to

evaluate how different measuring principles perform in a specific power system protection application. In addition, the software relay models can be used to optimize relay settings, and to determine the security and dependability margins by verifying how close a relay comes to operation as opposed to a trip/no trip results of conventional relay testing [3]. Software relay models and fundamental frequency phasor modeling techniques have been used to evaluate the performance of distance relay mho elements under various power system conditions, such as the study of directionality as affected by the different polarizing signals and pre-fault loading [4, 5]. In addition, the relay models have been used to evaluate the differences between negative-sequence, and zero-sequence polarization methods in ground directional relay elements, with an emphasis on selecting the most appropriate polarization method [6].

The interaction of network calculation programs with protection software models can be used to predict protection actions under different system conditions, and to help operation personnel identify power system constraints, or so called “system bottlenecks”, especially in today’s liberalized energy markets.

Several large utilities have invested considerable amounts of money to build relay test laboratories and subject commercial relays to transient waveforms to access their transient performance [7, 8]. Smaller utilities may not be able to invest the money and justify the staff required to operate such extensive relay test laboratories. An alternative to test laboratories would be the use of software relay models with certain limits, which will permit them to participate in the evaluation of the transient response and behavior of relays.

### **2.3. Use of Relay Models for Training and Education**

The application of relay models can effectively support the education of students and engineers and provide substantial cost savings. The general working principles of protection systems can be demonstrated. The interaction between network calculation programs and software protection system models can be shown in an easy manner. Different protection settings and their consequences on the protection behavior can easily be demonstrated.

It is also possible to show the protection coordination process and how it actually works. The protection actions during large network disturbances can be shown and explained especially with highly sophisticated models. The participants can try to improve the settings in order to avoid protection failures and maloperations.

Staff training is possible using real grid and switching states. The protection responses and their influence on the switching state of the grid can be demonstrated by assuming one or two short circuits or overloads.

### **2.4. Conclusions**

Relay software models are useful for relay manufacturers, utilities, customers and also for educational purposes. In general, manufacturers use more sophisticated models to support development and marketing. Representatives of manufacturers can explain the behavior of the relays to their clients with the help of relay models with input from network simulation programs.

It is possible to create more or less sophisticated relay models for different purposes. Simple models need only mathematical equations to describe the pick up and tripping characteristics of the relays. These models can be used to make general decisions for the selection of relay types, and together with network calculation programs they can be used to derive relay settings.

More sophisticated relay models are much more comprehensive, they process voltage and current transient waveforms from emtp simulations, actual fault waveforms captured by numerical relays, or digital fault recorders, and a user can observe their response to these transients. Therefore, it is possible to reaffirm the protection behavior during network disturbances.

## 3.0 Types of Relay Models

The question on how accurately to model the relay has great importance for the relay concept verification and for its performance evaluation. The grade of the original relay approximation in the model depends on many factors, such as, the aim of the simulation (concept verification, performance evaluation, education), available hardware and software, needed accuracy of modeling, and economic considerations.

Over the past 20 years, different types of the relay software models have been developed and used. They may be classified from many different points of view. The classification presented below reflects the main features of the relay model.

### 3.1. Classification of Relay Models

Relay models can be classified based on the:

- source of input phasors used in the relay model
- relaying system structure representation and description
- modeling principles used in the relay model
- hierarchical structure

#### 3.1.1. Based on the source of input phasors

Two different types of relay models can be defined based on the source of the input phasors that are used in the relay model:

- Steady state models
- Transient state models

*Steady state models* are based on phasors calculated from software programs such as:

- Short circuit calculation programs
- Load flow calculation programs
- Power system stability programs

A common characteristic of short circuit and load flow programs is that they only represent one snapshot of the power system state, and do not model the power system element dynamics. Therefore, the phasors calculated by such programs are steady state fundamental frequency phasors. These programs do not include the power system dynamics such as the DC offset current that is common during a fault, or any transients and off-nominal frequencies associated with system faults and switching of power system elements. Power system stability programs model the power system dynamics, and they generate a large number of snapshots of the power system fundamental frequency phasors that can be used in a relay software model. However, the user does not have any control on how the phasors are estimated, and therefore the output of a stability program does not correctly represent the fundamental phasors as they would be estimated by the actual digital relaying algorithm based on instantaneous sampled data.

*Steady state models* are simple relay models, which include mathematical equations that represent the relay characteristic, which is valid for stationary voltages and currents without any consideration of time transients. These models can be used to evaluate the relay design concept and its main characteristics, to make sure that its performance is as expected. The aim of this performance evaluation is to describe the relay's steady-state operating characteristics. The

model should reflect all the relations between phasors in the original relay: scaling coefficients, angles, relations between voltage and current phasors, etc. It should also be possible to get measurements of the corresponding relay characteristics, which can then be compared to the theoretical ones. Generally, this kind of model can be used to:

- Make general decisions regarding the selection of the protection type
- Calculate the relay parameters (or settings) in conjunction with network calculation programs, where the relay model processes the results of load flow and short circuit calculations into setting values for the relay by using its pick up and tripping characteristics
- Evaluate the relay settings which determine the relay actions (pick up or tripping signals) initiated by network calculation results
- Establish relay coordination margins
- Provide simple educational training

Some slow dynamics such as power swings may also be evaluated using static phasor based models.

*Transient relay models* extract their input phasors from instantaneous samples obtained from an electrical transients software program, which models correctly the dynamics and frequency response of the power system, or from sampled data recorded by digital fault recorders or numerical relays during actual power system disturbances.

*Transient relay models* are very sophisticated relay models, which take into consideration not only the stationary but also the time transients of voltages and currents. The time behavior and the dynamics of the relay are included in a transient relay model. Transient model is needed when the relay behavior under actual fault conditions is evaluated. This study is concerned with the relay's ability to respond correctly under fault conditions and its capability to achieve correct operation within expected time interval. The transient model is needed whenever the real situation in the power system is considered, such as the presence of transient DC component in the fault current, power transformer or current transformer saturation, resonance, or ferro-resonance phenomena, power system swings, harmonics, and other low or high frequency transients that are present during system faults or due to switching of power system elements.

This type of model can be used to:

- Investigate the behavior of the relay models with critical transients such as;
  - Presence of transient DC offset
  - Current transformer and capacitive voltage transformer transients
  - Transformer or capacitor inrush currents
  - Arcing faults and time-varying resistance faults
  - High frequency oscillations
  - Series capacitor associated transients, i.e., gap flashing, metal oxide varistor conduction and sub-synchronous oscillations
  - Power system swings and dynamics of rotating machines
- Investigate the protection system behavior during network disturbances (e.g. time sequence of tripping commands or pick up signals)
- Investigate the influence of parameter changing on the transient protection behavior
- Investigate communication interfaces
- Provide advanced educational training with selected problems

### 3.1.2. Based on the relaying system structure representation and description

From the relaying system structure representation and description of the procedure used, the models can be divided into the following two categories:

- Structural models
- Black-box models

The first is an algorithmic approach, applicable when a detailed relay description is available [12]. In that case the *structural model* mimics the actual relay by adequately representing its internal structure and the procedure used. In a software realization of such a model, the procedures directly and adequately perform the relay algorithms, or imitate their performance on the basis of mathematical models of the physical phenomena (For example, in the case of the analog circuits, or the electromechanical relays).

*Black-box* or *input-output model* reflects the relay performance by adequately mapping the series of input signals to the output, without taking into consideration the internal logical or physical structure of the relay. It is, however, important to consider the time relation between consecutive input samples. One suitable technique for preparation of such models is an ANN application. In that case, the ANN can be trained on the basis of data obtained from testing the real relay [12].

### 3.1.3. Based on relay design technology

The relay models reflect the technology used in relay construction. From the point of view of modeling, the following three groups of the relays should be considered:

- Electromechanical relays
- Static relays
- Numerical relays

Generally, the difference is in the method used for measurement, and representation of the logic unit. To model the *electromechanical relays*, one should adequately represent the relay dynamics. Here, usually the state-space technique is applied [13], [28]. In the case of the *static relays*, the electronic linear and non-linear elements should be adequately represented in the model. In the detailed models of the *numerical relays*, the measurement and decision-making algorithms used in the actual relay are simply represented in the same (or very similar) form as in the relay model. In this case, the relay program may be modeled by transferring the relay program to the simulation environment [14]. Numerical relays have analog circuitry, including auxiliary CT's, VT's, and they must be adequately represented and included in the relay protection scheme model [15].

### 3.1.4. Based on the structure and detail

In the hierarchical structure, the hardware and software elements of the digital relays have been reduced to their generic models and may be implemented as blocks. This enables easy definition and configuration of the analyzed object or the algorithm. In this context, one can define the following types of models:

- Model of the individual part of the relay (measurement unit, logic unit etc)
- The relay model
- Model of the protective scheme
- Model of the protective system

This classification is self-explanatory. Model of the protective system consist of the power system, instrument transformers, analog input chain and the communication channels, if they are used in the protection. Each element of such a system can be represented in a form of specialized software with detailed description of the specific original device (relay or their part), or in a more general software object that reproduces the main idea of the original product, or element. From this point of view the software models can be further divided into following two categories:

- Manufacturer specific model
- Generic model

The *manufacturer specific model* (detailed model) reproduces the characteristics, algorithms and behavior of the original relay or its element in detail. Such a model can be prepared only if the relay parameters, structure and even microprocessor programs are known. Where the algorithms, programs and hardware are known in detail, very precise performance can be achieved in the model [27]. Practically, only manufacturers are in a position to design a fairly accurate model. However, the detailed models are also prepared by utilities. Many papers report comparisons of the specific characteristics calculated by the relays and obtained from models [10], [16], [17], [18].

The *generic models* are based on the principle of general representation of the relay performance and characteristics. In many situations such as for education, training, evaluation of the new algorithms and many others, there is no reason to use detailed models of the relay and other elements of the protection system. Probably, the needed detailed information is unavailable. In such a case, a generic model can be used. Such a model simulates the behavior of the original relay and reproduces, in general, its frequency and dynamic features.

Software packages for relaying system simulation usually contain toolboxes, or ready to use sub procedures, organized in software libraries, with generic models of the relay units and relays, in general. Developments and usage of such packages are reported by many authors [14], [17], [19], [20], [21]. The library includes the basic hardware and software components of the relay, such as data acquisition unit with adequate analog filters, digital filters, basic measurement algorithms, comparators, triggering elements and others. A variety of options for all operations have been included in the model. The structure of the model can be fixed. The options of the block, however, enables one to modify the block significantly [22].

Libraries should be organized to provide easy simulation of different type of relays. The models can be grouped in the three main subdivisions [11]:

- Hardware models blockset, which provides simulation of current and voltage acquisition system (as far as numerical relays are considered)
- Measurement unit models, which enables the representation of different algorithms used for determination of the relay criteria values, such as Fourier algorithm, differential equation method, LES algorithms, algorithms for suppressing of DC component and others
- Logic unit models, with a family of different comparators and triggering elements

Some simulation tools also include the number representation issues. This provides the ability to represent the number quantizing errors, which is especially important for accurate modeling of the acquisition system.

Generic models are easy to develop and set up, give considerable insight into the operation of the relay type, but may not be adequate for some marginal cases and for precise timing [11]. Because of this limitation, generic models find best use for checking specific functions, for education and training.

### 3.2. Communication System Model

To analyze the relaying system with aided communication, an adequate software model for the communication equipment should be developed. Preparing this one should answer the following basic question: is the logic representation of the communication sufficient for the considered problem? It is probably adequate for the steady state based approach. In other cases, the communication system must be represented more accurately.

For detailed modeling of the communication system, one should represent basic features of the physical system. This can be summarized as follows:

- Signal form used: analog or digital signal
- Signal transmission media used: wire pilot protection, power line carrier pilot protection, microwave pilot protection, fiber optic communication
- Pilot protection scheme used: unit or non-unit scheme

Each of the above considerations requires a set of adequate models of the communication system or its elements. Simulation of the protection system with communication also demands solution of the sampling coordination in different substations concerning synchronized or non-synchronized sampling.

### 3.3. Software Implementation of Relay Models

The models considered here are implemented in the form of adequate computer programs. In the *software representation* the relay model takes the form of subroutines, which mimic some parts, or the entire relay. The aim is to simulate the computational algorithms and the part of hardware components, which affect them (mainly the measurement and isolating circuits).

There are currently many computer programs available, which can perform detailed and highly accurate primary power system simulations. Such programs containing model of power system components, can produce excellent results for primary power system and control devices.

The computational procedures can be implemented by using electromagnetic transient programs such as EMTP (Electromagnetic Transients Program) with specialized languages such as TACS (Transient Analysis of Control Systems) or MODELS suitable for simulation of the relay algorithms. Models of specific relays can be also incorporated into EMTP through user defined FORTRAN functions [23], [24], [25]. A similar approach can also be implemented in other types of electromagnetic transients programs such as PSCAD/EMTDC, NETOMAC, MORGAT, MICROTRAN and others. Another possibility is to use the more common programming platform such as MATLAB/SIMULINK for simulation of the relay. In that case the input signals can be delivered in a form of a file with the recorded data or directly from the electromagnetic transients program such as PSCAD/EMTDC via adequate interface [10], [22].

The complex relay model is composed of modules representing different parts of the original relay. Contemporary relay designing and evaluation systems are based on the concept of integrated modeling environments. Such systems provide a useful framework for developing and

testing novel relaying algorithms. This concept can be realized in different software and hardware platforms. The specific features of such a system are obtained by utilizing [17], [26]:

- Interactive software that is user friendly and incorporates most of existing algorithms and models of relays
- Hierarchical structure of the simulation environment that gives possibility to set and evaluate different tasks
- Dynamic interaction between power system and protection models
- Flexible management of models and data

The simulation environment can be implemented in software, which is oriented for modeling and simulation, for example, MATLAB/SIMULINK. Such universal tool creates a friendly and open system. The developed software emulates the general philosophy of the used simulation platform. An adequate interface can connect the relay models with the transients simulation program [14], [20]. More information is provided in chapter 8.

The relay simulation can be performed in the open loop or closed loop mode. That requires the relay models to be represented as [14]:

- Models prepared for open loop simulation
- Models prepared for closed loop simulation

The relay model evaluated with the *playback* waveforms in the open loop simulation has no influence on the power system from which the input signals are derived. Therefore, the output and intermediate signals are stored for further analysis. In this case, the model can represent the complete relay or only a separate unit.

In the *closed loop* evaluation of the relay model, it is necessary to include the relay model into the general protective system model. Moreover, it is necessary that the transient simulator must be able to accept the output information from the relay model and to use this information into ongoing simulation (interactive mode). In this case, the relay model should represent the complete relay with the output unit, and any possible communication channel.

The kind of models used should be coordinated with the aim of the relaying system simulation. The steady state based models are used in software packages for choosing appropriate settings for steady state operation of overcurrent relays and distance relays [11].

The relay transient models can be used for more complex evaluation of the relaying system to address typical questions, such as, what type of comparator should be selected for the considered application, what type of the post-processing filter should be used before final tripping decision, etc. Answers to such questions give the application engineer opportunity to better select the relays and their settings.

### 3.4. Conclusions

Software relay models are able to accurately and effectively represent the behavior of physical relays. This is possible if all of the information about the original relay, including algorithms was available for creating the relay models. Moreover, off-line simulations are less expensive than on-line real time testing.

The kind of models used should be coordinated with the aim of the relaying system simulation. From this point of view, one must consider two basic software models of the relay: steady state based models and transient models. Steady state types of models are already in use by relay engineers. Transient models, generic or detailed, are increasingly being used by utilities to verify different application issues.

Software used for relay simulation must be organized in a user friendly program package, which contains different relay models, and separate relay element models. The protection schemes could then be built from the individual components in the model library, providing easy configuration of the complex model.

The communication system representation is important for the comprehensive assessment of the power system protection performance.

## **4.0 Current State of the Art**

A number of researchers have put their efforts in developing new capabilities to analyze the operation of the protection relays. This way, an idea of developing relay software models appeared. These models allow simulating the operational characteristics of the protection devices. Some of the latest documents published in this area have been developed by IEEE WG-C7 [29] and IEEE WG-C1 [30]. These documents cover the most important subjects related to relay model types, software tools, information required for relay modeling, etc.

The existing publications cover all types of relays; electromechanical, static and digital. Relay modeling of static and digital relays has now become common practice for relay design engineers in order to evaluate the performance of various relay algorithms prior to final design decision. Although relays' manufacturing is centred in static and digital ones, it is necessary to keep in mind that the electromechanical relays are elements of high durability and that they are installed in a great number of substations.

In the relay model development there are three important aspects to consider: power system modeling, relay modeling and the interactions between the power system models and the relay models. These interactions define the differences between open-loop and closed-loop methodologies for protection system modeling.

### **4.1. Power System Models**

Accurate simulation requires a large number of different models, even to represent only a small part of a power system. With the growing size of power systems, a very high computational power is needed for the calculations of transients in such a complex model.

Power system modeling is typically performed using an electromagnetic transient program, such as: ATP, EMTP, EMTDC, NETOMAC, Power System Blockset of MATLAB, EUROSTAG, etc. These programs use numerical integration techniques to obtain time incremented solutions for the network voltages and currents. Also, there are steady-state programs (PSS/E, NEPLAN, etc.) for power systems modeling and analysis. Both types of tools ensure extremely good modeling of the power system, for steady state and/or transients conditions. The power system models developed may be validated with the data derived from digital fault recorders installed in the actual system being modeled. Chapter 5 presents the main characteristics of these software tools to simulate steady state and transient performance of the power system.

### **4.2. Instrument Transformer Models**

Since the instrument transformer transients considerably influence the performance of the relays, their simulation must be as realistic as possible. An accurate representation of the transient behavior as well as non-linear phenomena must be achieved.

The transient performance of current transformers (CT) is influenced by a number of factors, with the most significant one being the exponentially decaying DC component of the primary current. Its presence influences the build-up of the core flux, a phenomenon which is likely to cause saturation and subsequently substantial errors in the magnitude and phase angle of the generated signals. The CT core may also retain an unknown amount of flux because of the ferromagnetic character, which can contribute to ct saturation in fault conditions.

The transient response of magnetic voltage transformers (VT) and coupling capacitor voltage transformers (CCVT) depends on several phenomena taking place in the primary network such

as sudden decrease of voltage at the transformer terminals due to a fault or sudden over voltages on the sound phases caused by the line to ground faults in the network. These phenomena can generate high frequency (VT) or low frequency aperiodic (CCVT) oscillations on the secondary side and saturation of the magnetic core.

Models of the instrument transformers are especially important for studying CT saturation, ferro-resonance phenomena, harmonics and sub-harmonics and their effect on the performance of protective relaying. The predominant effect in CTs is saturation whereas the predominant effect in CCVTs and VTs is saturation and ferro-resonance.

Although the instrument transformers have an important influence in the relay model performance, their simulation had not been considered in the early relay models published in the literature. However, because the errors introduced by these devices during fault conditions can affect the accuracy of the protection system models, there are several papers [31-44] that present instrument transformers' models applied to relay modeling.

### **4.3. Relay Models**

Finally, the relay models have to be made so, that their behavior is as close to the behavior of the actual relay as possible. To be able to establish a relay model it is necessary to have a general knowledge of all the aspects implied in the design and operation of the relay for their later modeling. There is a lot of literature published concerning relay software modeling, which cover different topics, such as: phasor and transient models; electromechanical and digital relays; use of different software environments; applications; etc.

#### **4.3.1. Phasor vs. transient models**

The use of phasor models to represent relay characteristics is helpful when investigating the changes in the static characteristics resulting from the changes in other parameters. In the theoretical analysis [45-49], some 'dynamic characteristics' dealing with transient behavior of relays are used. But these characteristics are derived from the phasor concept, which is valid only during the steady state condition, and therefore, they are not generally applicable to transient analysis. This type of relay model is usually included in the general information supplied by the manufacturers and in commercial software packages. However, a considerable amount of information cannot be determined from it (see chapter 3).

The modeling and testing of relays for transient effects was not a critical issue until the introduction of digital relays. As the speed of operation of modern relays becomes faster and the relay bandwidth increases, the transient response of all the elements of the protection system must be studied in greater detail. For that reason, more complex models have to be developed. These models can vary from relay to relay or from application to application, but by identifying basic building blocks that are common to the majority of protective relays, very complex relay operations can be modeled. Some common situations which require transient models for proper evaluation include: transformer or capacitor inrush; ct or cvt transients; ct steady state saturation; presence of harmonics; presence of transient DC offset; evolving faults; power system swings and dynamics of rotating machines; time varying machine impedances; single phase to ground faults on resonant grounded systems; series capacitors and their protection; etc.

Last ten years, most of the papers published in the technical literature on relay models include all power system and protection models (power system, instrument transformers and relay) and cover *transient modeling* of electromechanical [13, 28, 50, 51] and digital [10, 12, 14, 16, 17, 18, 22, 24, 25, 26, 29,30, 52-77] relays.

### 4.3.2. Relay types

Owing to the huge variety of protective relays from different manufacturers and technologies, the modeling approach must cover electromechanical relays as well as digital relays.

The first transient relay models were developed for *electromechanical relays*. Although a great number of relays in service are electromechanical, only a few transient models are available to analyze their transient response in conjunction with instrument transformers and circuit breakers during fault conditions. In Reference 50, the authors present a mathematical model of an electromechanical Mho distance relay. This relay modeling is based on a ninth order state space approach, which can handle non-zero initial conditions to give a detailed representation of the system including the non-linear nature of the torque development. Starting from pre-fault values, the initial conditions for each state variable are fixed and by means of the Runge-Kuta method, the matrix of differential equations that represent the relay behavior is solved. The same mathematical model of the relay is simulated in EMTP software using TACS [13]. This simulation has been validated ensuring that the model is operative during steady state conditions and that it responds properly to different fault configurations. In Reference 28 the same model is developed but using the MODELS option of the EMTP/ATP. In this analysis, the model includes instrument transformer models previously published in other papers. Finally, Reference 51 presents an approach to modeling armature type instantaneous overcurrent relays based on extensive laboratory testing of the device. The relay model presented in the paper includes the mechanical, electrical and magnetic subsystems, coupled together by the analytical formulae describing them.

Despite the good operation of electromechanical relays, remarkable efforts have been made during the last twenty-five years in designing microprocessor-based relays. *Digital relays* combine digital filters, relay characteristics and logic implemented in microprocessors for estimating the operating parameters of a power system. The estimates are then used to calculate other derived quantities. An appropriate logic compares the derived parameters with the desired relay characteristics for making trip decisions. These relays are now produced by the majority of relay manufacturers and are being used by most utilities. In Section 4.3.3, different digital relay models, developed and published in technical literature, are discussed indicating the software tool employed in their modeling.

### 4.3.3. Modeling environment

A software program that mimics relay performance may have no direct one to one correspondence to actual microprocessor machine language coding within the relay. For a successful model, the software in the relay and the software in the electromagnetic transient program must produce the same output for the same inputs under transient and steady state conditions. The relay models have been developed in different environments:

- a) *Relay models based on mathematical equations.* In Reference 52, distance relays are included in transient studies by modeling their operation implicitly as functions of the time intervals that a transient spends within the three zones of the distance relay. Novel concepts are proposed such as the notion of "relay margins" and "vulnerable relays". In Reference 53, the authors provide mathematical models for power system analysis, which describe the relay operations during system contingencies, so that the design and analysis of the protection system can be treated within the unified dynamic formulation. The relay models become a part of an overall system model and allow real closed-loop real time simulations. In this work, general relay models have been used.

- b) Relay models using commercial software programs. Some of them use only one software package (e.g. ATP o EMTP o EMTDC o MATLAB, etc.) while other models combine different software packages linking them by an interface (e.g. ATP and FORTRAN, EMTDC and FORTRAN, ATP and MATLAB, FORTRAN and C++, ATP and C++, etc.). In the interfacing methods, usually, the power system is modeled with ATP or EMTDC and the relay model is developed with a different software.

Below, several relay models are commented. They have been classified according to the function of the software tools used in the relay modeling:

- b.1) The vast majority of the papers cover ATP/EMTP applications. In Reference 26, a model of a directional time overcurrent relay embedded within the EMTP is presented. The embedded approach allows complex, multi-terminal co-ordinated relay simulations with interactive capability. This interactive capability allows examination of transients produced by the operation of one relay and the effect of these transients on other relays in the system. So, several relay modules have been developed for the EMTP: low-pass filter, signal conversion, symmetrical component filter, relay algorithm, trip logic and presence or absence of the blocking or permissive communication signal.

In Reference 18, a model of one measuring unit of a digital relay is presented. It has been made within the TACS option of EMTP. The microprocessor-based relay model has been divided into four sections: input analogue anti-aliasing low-pass filter, analogue to digital converter, Fourier fundamental frequency detecting and the relay measuring principle. These four sections of the model can be used independently of one another and can be assembled in various combinations for other relay studies, so, the effects of using different filter designs, sampling rates, etc, can be analyzed. The relay model has been developed using available published information and making engineering estimates of unknown parameters and it operates in a closed-loop form. Results from the digital relay model have been validated with laboratory testing data.

Other authors [25] present the addition of some critical elements of a protection system to the EMTP, such as: current transformers, capacitor voltage transformers, a mho directional distance relay and a transformer differential relay. Thus, it is possible to simulate the dynamic interactions between a power system and a protection system. This development consists of writing the relay model as a FORTRAN subroutine [54], which must include all the necessary common blocks. This computer relay subroutine is called by an EMTP subroutine, saved as an object file. Then, both the EMTP and the relay subroutine object files are linked to create a run time executable version. To implement the models in a data case, a new executable version of the EMTP must be created.

Later, other developments present the implementation of relays models using the TACS option of ATP version of EMTP [55]. The study shows that models can be constructed using only the standard devices and statements provided by ATP, so no source-code programming is required for the modeling. An inverse-time overcurrent and a distance relay are presented.

Also, using the MODELS option of the ATP [57,58] the integration of the power system and the protective system modeling in one program module has been achieved. The authors have implemented an anti-aliasing low-pass filter and the dc-

offset removal filter in order to extract the fundamental frequency current and voltage components, which are then used for the impedance calculation.

In Reference 24 a systematic approach for teaching digital relay fundamentals is presented. The protection system model implemented in the EMTP contains the following blocks: instrument transformers, the analogue signal conditioning, sample and conversion, magnitude and phase calculation, relay algorithm and trip logic. The strategy includes aspects of digital relaying concerned with processing of sampled data such as instrumentation dynamics, signal conditioning for anti-aliasing, sample and hold and circuit breaker dynamics.

Finally, although most of the papers published about modeling relays have been applied in transmission line protection, there are also some developments specially applied to electrical machines. Reference 70 describes the modeling of a Rate of Change of Frequency (ROCOF) relay using the TACS part of EMTP. This relay model permits investigation into new methods of detecting loss of mains for an embedded generator.

- b.2) Some of the relay models have been implemented in EMTDC software. The implementation of a digital relay model and its validation with an actual relay is presented in References 16, 60 and 61. The relay elements have been incorporated in a relay library in the graphical routine PSCAD under which the study is set up and can be called and attached to a particular line as required. The subroutines for the relay model functions have been written in FORTRAN to be attached to EMTDC. The results show that, even when the digital algorithms are known, there are still elements of uncertainty in the model such as: difficulty to model analogue elements in a digital form, the relay sampling time reference is not synchronized to the timing of the fault arrival, etc. These relay models have been embedded into the RTDS for testing relays.
- b.3) Later developments use MATLAB in the modeling of protection relays. MATLAB's major advantage over the conventional languages is its extensive library of intrinsic functions. This way, Reference 62 describes how to model the dynamic behavior of a quadrilateral or polarized distance relay using MATLAB and the algorithm is based on the calculation of voltage and current phasors using Fourier filters. Problems are expressed directly in their mathematical equation format, solved and displayed without resorting to a traditional low-level programming language. The MATLAB environment stores each variable defined in the text file so that it can be examined after the program is run, simply by typing its filename. The simulated distance relay has been tested using voltage and current signals, generated by ATP, at the relay location both immediately before and during the fault.

Later, in Reference 14 a new approach to modeling of power system, protection system and the interaction between them is presented. The authors propose to represent the power system in the ATP and the protection system models in the software package MATLAB. The interaction between the two systems is implemented using an "interaction buffer", allowing closed-loop simulations. This approach allows relay model to be implemented in any high level language so it can be more flexible and detailed. In Reference 63, a new model for power transformer simulation in ATP/EMTP and a current differential transformer relay represented in MATLAB has been developed. The digital relay modeling technique developed can

be used for modeling other digital relays. Also, a link between EMTP and MATLAB has been developed [66]. The interconnection provides a user defined modeling tool where the high-level computation facilities of MATLAB and its powerful Toolbox can be used in the general network simulator context of the EMTP.

In References 22, 64 and 65, the authors show the capacity of MATLAB, SIMULINK and the Power System Blockset in the modeling of the power systems and relay components in a unified environment. The package emulates the general philosophy of SIMULINK very closely. The hardware and software elements of digital relays have been reduced to their generic models and implemented as input-output blocks, as libraries. For relay elements, for example, those libraries include: data acquisition board, digital filter, digital Fourier Transform, basic measurement, differential equation-based impedance measurement, universal comparator, zone comparator, triggering element, symmetrical components and bias characteristics. Models of protective relays developed using the libraries can be tested with the input signal from Power System Blockset of MATLAB; ATP output files through the developed file converter or DFR data through the developed file converter.

Finally, a generalised modeling package implemented in MATLAB, for generating software models for any microprocessor-based relay using general-purpose hardware is presented in Reference 10. The hardware acts as a relay and its type and function depend on the resident software. The software package contains two program modules. The first module is an interactive environment for collecting relay specifications and display requirements for the model to be generated. The second module is called by the first one and produces the program code for the required relay model.

- b.4) In addition, there are relay models developed with other software tools or techniques. In Reference 72, the software is composed of two main parts. One of them is the primary power system model and the other one is the protection system model. The primary power system model is written in Fortran Language. The protection system module is written in C++ language. The components of the relay are modeled by dividing the relay into many parts. All parts of the relay are modeled by getting information from the relay manufacturer. For example, for the filter the manufacturers have provided all the coefficients. For this reason the model can be considered as almost "real".

New modeling techniques have appeared recently for modeling protection relays using Petri Nets and Artificial Neural Networks. Petri Nets (PNs) is a graphical and mathematical modeling tool capable of modeling the protective system since it can be viewed as a discrete-event system. In References 67 and 68, the authors propose a PN model of an EHV transmission line protection-relaying scheme, which includes three kinds of relays and an automatic recloser.

An Artificial Neural Network represents a parallel multi-layer information processing structure. The characteristic feature of this network is that it considers the accumulated knowledge acquired during training, and responds to new events in the most appropriate manner, given the experiences gained during the training process. An ANN methodology [69] is suggested for protection modeling which eliminates the need to derive complex mathematical formulae for programming purposes, however, once trained, an ANN cannot be modified without requiring the ANN to be retrained.

Other authors have developed an Integrated Modeling Environment (IME) for general modeling of power system protection [12, 17]. In this IME, the Power System module is simulated using ATP software and the Dynamic Protection module is constructed with a hierarchical, object-oriented structure using C++ programming language. The models of different protection schemes are built by means of predefined protection relay sub-models. When the information available is not sufficient to develop an algorithmic model then its behavior is modeled by ANN techniques.

- b.5) Finally, there are different relay models, which have been developed and included, in commercial software. In most cases, they are generic relay models. Section 5.5. comments on these options.

#### **4.3.4. Relay models applications**

When the relay model has been finalized and proven, it becomes an extremely valuable tool for relay testing and evaluation, for the assessment of the relay performance and for any future electrical system. The data can be obtained from either real system or from digital simulators. Some of the different applications have already been mentioned in Chapter 2. In summary, relay models are useful for:

- The evaluation of the performance of various filter designs, sampling rates and relay algorithms, prior to final design decision. Exhaustive tests can be developed without the need for building a prototype.
- The analysis of the optimal operation of protective relays.
- The analysis of the relays' performance when they operate incorrectly or fail to operate on the occurrence of a fault.
- Using as a training tool for students, young engineers and technicians.

With testing idea, relay models can be embedded in the test platforms, where the protection equipment can be tested in the open loop or closed-loop mode.

In the open-loop simulation [13, 16, 28, 50, 51, 57, 60, 61, 62, 70, 71] the response of the device does not need to be fed back to the modelled system. The effect of the circuit breaker of the power system under study is not considered.

On the other hand, testing in closed-loop mode [10, 12, 14, 18, 22, 24, 25, 26, 53, 55, 58, 64, 65] considers the relays under test, initiates tripping and reclosing actions of the primary power system circuit breakers, allowing analysis of the performance of the relays not involved in the initial trip or closing operation.

#### **4.3.5. Other developments**

Besides the developments previously commented, there are some other interesting works being developed by Working Groups of different Institutions, which have not yet been published.

1. The Institute of Electrical and Electronics Engineers (IEEE) has six Technical Subcommittees in the Power System Relaying Committee, in which several aspects related to the design characteristics and operation of the protection relays are analyzed. Different working groups form each one of these Subcommittees. The most relevant WGs related to relay modeling are:

- WG-C5: Deployment and use of disturbance recorders

- WG-C8: Phasor-based models for analyzing relay performance
- WG-D10: EMTP reference models for transmission line relay testing

The resulting reports developed by IEEE Working Groups C5, C8 and D10 will be published as transaction papers.

2. The International Electrical Commission (IEC) has a great number of Technical Committees and Working Groups for all fields of Electrotechnology. The developments carried out for the IEC are more related to instrument transformers than to protection relays. Those, more directly associated with modeling of protection relays are:
  - TC 38/WG-27: “Electronic current transformers.”
  - TC 95/WG-10: “Format for transient data exchange for power systems.”

The reports developed by these Working Groups will be published as IEC Standards.

3. The Conseil International des Grands Réseaux Electriques (CIGRE) has the SC B5 “Protection and Automation” the main task of which is to facilitate and promote the progress of engineering and the international exchange of information and knowledge in the field of protection and automation. Its task is also to add value to this information and knowledge by means of synthesizing state-of-the-art practices and developing recommendations. The SC B5 is formed by WG and Task Forces, all of them studying topics related to the protection relays. The results will be published as Technical Brochures.

## 5.0 Sources of Information for Building a Relay Model

It is possible to develop a complete software model of a protection relay. Performance evaluation of the model can be achieved by using signals generated either analytically or by means of digital simulation of power systems. Modeling and simulation of relays and power systems help in many design, evaluation and testing activities. To develop a reliable software relay model, it is necessary to know the details of the design and the operation characteristics of the modeled relay. This knowledge can be obtained from: technical design characteristics and operation data of all the elements that compose the relay (transducers, filters, A/D converters, etc.), tests results carried out on the relays, and information on the algorithms that govern the operation of the relay.

The development of a software model is relatively simple for digital relays, provided that sufficient information about the algorithms is available. For static and electromechanical relays, and indeed for the analogue sections of digital relays, the problem of detailed modeling is non-trivial. Electromechanical relays are particularly difficult to model because the detailed knowledge of the mechanical design is required. In such cases, it might be impractical to develop a detailed dynamic model. The accuracy of the approximation will depend on a number of factors such as the sophistication of the model, neglected effects, etc.

Conventional sources of information on the technology of protection relays contain the following types of documents:

- Papers in general, textbooks on protective relaying, digital relays and IEEE special publications. Most relaying principles belong to the public domain and in most industrial products, the proprietary information is usually minimal.
- Papers written by the designers of relays or manufacturers representatives. The quality and the amount of information found in these papers depend very much upon the manufacturer's wish to reveal (or to hide) the relay's design details.
- Patents taken out by the manufacturer, if any. This is very often the most detailed source of information.
- The relay manuals published by the manufacturer. Most of the time the "logic diagram of a protection scheme" is available in these manuals.
- Documentation and additional information obtained through direct contacts with the manufacturer.
- Relay models themselves can provide some information about the relay behavior, which then can be utilized to create a different type of relay model. For example vector based static model can be developed on the basis of the existing dynamic model.
- Relay test data can sometimes be used to evaluate the characteristics of the relay and in this way support model development process.

### 5.1. Manufacturers

As a general rule, to be able to develop a software model of a protection relay, the manufacturer should provide information concerning the basic principles, which are used by the relay while processing data and making decisions. A relay engineer using the manufacturer instruction book and some discussion with the manufacturer can create a relay model. Manufacturers usually release a certain amount of information in various forms. The available sources of information may include one or more of the following:

- Service, instruction or technical manuals [78-85]. In most cases these documents contain general product description, which includes technical specifications, functional description of operation, calculation of the settings, maintenance, installation, commissioning and testing.
- Application or relay setting notes [86-90]. Sometimes manufacturers release separate documents describing in detail the application procedures and settings calculation, however, in many cases this information may be included in the general instruction manuals.
- Type testing and approval documentation [91-93]. This documentation is a result of the work done by the approval panel, which presents the results of standard testing procedures assuring that the actual performance of the product is consistent with the technical specification claimed by the manufacturer.
- Relay circuit diagrams, algorithm source code, etc. With some exceptions, this type of data is usually not available from the manufacturer due to confidentiality reasons.
- Technical description of the components [94, 95]. In some cases, especially when modeling static electronic relay devices, it may be useful (or even necessary) to utilise information provided by the manufacturers of electronic components. Most of the manufacturers provide the detailed technical description of their products, which allows building a mathematical model of such components. If the available data is not sufficient for building a complete model, at least it can be used to calibrate generic simulation models such as, a model of the operational amplifier. The electronic component description is usually available in the form of technical data specifications or catalogues. In many cases, the catalogues are obtainable free of charge directly from the manufactures or can be downloaded from the internet. Moreover, some electronic technical data sheets (e.g. [94]) include a ready to use simulation model for the specific simulation software such as, PSPICE [96], which can be used to capture dynamic behaviour of the specific components as well as more complicated circuits. The following items are described in the manufacturer's data sheet: nature and cut-off frequency of the anti-aliasing filter, primary sampling rate and relay's sampling rate.

Generally, the information provided by the manufacturer enables to gain some appreciation of the relay's operating principle. The most fundamental source of information for creation of the detailed dynamic relay model is always the instruction manual. It is understandable that only very occasionally the full range of documentation will be readily available. Especially the circuit diagrams and source code fall into the category, which is unlikely to be available in public domain.

Often the model created on the basis of manufacturers description of operation does not fully correspond to the actual dynamic behavior of the relay. Therefore, it is important to perform an extensive validation procedure in order to assess the accuracy of the simulation results under varying power system fault conditions, and if possible, perform some additional amendments to the relay model. Section 7 of this document elaborates in detail on the relay model validation process and provides relevant examples of relay testing procedures for two dynamic distance relay models. Other specific details can be obtained from the manufacturers' literature [97-99].

It could also be argued that an accurate validated model of the relay (whether developed by the user or provided directly by the manufacturer) could itself be a valuable source of information, especially when a simpler relay model needs to be developed. By simulating various fault scenarios and observing the behaviour of the dynamic model, static characteristics of the relay can be acquired and subsequently used to build a simpler vector based model.

## **5.2. Other Published Literature**

These include mainly books, tutorial courses, patents and papers published in different engineering journals. Power system protection text books (e.g. [100-103]) usually provide general understanding of protection principles which permit to gain an insight into the phenomena involved, whereas, tutorial courses (e.g. [15, 104, 105]) give more specific details about the operation and design characteristics of the topic treated in each course. In order to obtain more details not included in the above-mentioned bibliography, it is recommended to consult reference material published in several engineering journals. References 106-115 are an example of various relay design characteristics.

However, in order to develop an accurate relay model, apart from the design relay parameters, it is also necessary to have some knowledge about other phenomena involved in the relay operation. When a fault occurs, the transient voltage and current values are mainly composed of high frequency and exponentially decaying DC-offset components. The fundamental frequency component of voltages and currents needs to be extracted using filters. Algorithms for estimating phasors are one of the most documented in the field of digital protection. However, only a limited number of algorithms have been used in commercial applications. The full-cycle Fourier filter and so called Cosine filter are the most common in this category.

Digital filters [116-119] use mathematical equations to produce numerical estimates of voltage and current phasors. These filters provide advantages of precision, time invariance, flexibility, size, and cost to offset the disadvantages of additional analog to digital conversion complexity and finite bandwidth related to the sampling rate. In Reference 120, a technique for implementing the sample and hold algorithm is presented, whereas, in the paper [121] the development of a computer aided design tool for developing digital controllers and relays is described, including analog to digital converter modeling. The principal feature of the analog to digital converter is the word length expressed in bits. This characteristic affects the ability of the A/D converter to represent the analog signal in a digital form with sufficient detail.

Other important task with respect to relay modeling is the selection of appropriate trip decision algorithm. It is necessary to know the operating algorithms in order to be able to perform better validation of the relay model. Although the use of phasor evaluation has become almost a standard practice in transmission line protection relays, other algorithms also exist. For example, some algorithms are based on the digital simulation of the differential equations representing the line, when others are based on the digital simulation of an electromechanical cylinder unit. Since these algorithms are in constant evolution, being continually perfected, there are a lot of algorithms in technical papers proposing various operating principles for protection relays. Some of them are reported in References 20, 122-135.

Finally, there are a number of papers [78-94, 10, 12-14, 16-18, 22, 24-26, 28, 50-77] published in various technical journals which often describe different modeling approaches or present instrument transformer together with relay models developed by different researchers. This information is equally valuable and can be utilized to model a relay, or at least, to select the best modeling method.

## **5.3. Relay Test Data Information**

This information includes some additional test data (apart from the standard tests performed by the manufacturers), which might help in better understanding of the relay operation. In the past, it has been difficult to construct an accurate model because of the insufficient availability of test facilities, which would allow the actual relay, and the software model to be fed with exactly the

same transients test waveforms. However, currently protection manufacturers carry out thousands of tests during product development using digital and analogue power systems simulators.

Test methods are evolving and taking advantage of the advances in both test equipment and computers to allow more accurate modeling and testing of instrument transformers and protection relays. Since many devices are now transient-tested using data generated by electromagnetic transient programs, a set of waveforms can be supplied both to the actual relay and to the model. In this way, accurate performance comparison tests can be completed.

As a result of the development of the EMTP, PSCAD/EMTDC, MATLAB/SIMULINK, NETOMAC, EUROSTAG and other fast and reliable simulation environments, digital simulators of power systems have been utilized for the purpose of protective relay testing by providing an interface between simulation computers and relays to be tested (for example, RTDS, ARENE, RTS, DINEMO, etc.). Consequently, several open loop and closed loop real time simulators have been developed which provide an advanced relay testing capability. References 136-153 discuss some developments in digital simulators and relay testing methodologies.

Moreover, many power utilities have Digital Fault Recorders (DFRs) distributed across the whole power system. Waveforms of actual faults recorded in DFR files are another valuable source of information, which facilitate validation and more realistic protection system modeling. However, the dynamic range and accuracy of the DFR measurements can limit accuracy of the information. Often a conversion to COMTRADE format is necessary before this information can be used for relay testing purposes.

Finally, proper settings of protection relays are a prerequisite for a reliable operation. In the determination of the setting values, it is necessary to determine the fault values at various places at the time of fault occurrence. Also, it is necessary to consider the co-ordination task for the adjustment of multiple protective relays and different types of protective relays ranging from electromagnetic to digital ones [155-158, 88-90].

Due to the increased availability of advanced relay testing equipment (such as RTDS, ARENE and others), it is gradually becoming easier to obtain large volumes of empirical data from actual relays. In some cases, especially when the manufacturer's data is not available or the behaviour of the device or some of its components is particularly complex, empirical data can be used to develop a so-called "black box" model. One such relay modeling approach involves the use of a trained neural network (NN) to mimic the behaviour of the device. The data obtained from the relay testing procedures is used partially to construct NN training sets and partially to test the model. In Reference 69, the authors describe a technique where a NN based model of a unit protection system was developed. However, it should be emphasized that the choice of NN type and structure, as well as the selection of proper training data sets, is not obvious in most cases and needs to be carefully assessed. The structure of the NN and the selection of training data have a direct influence on the accuracy and credibility of the results. Moreover, any modification to the relay characteristics usually requires retraining of the NN. These constraints make the use of such "black box" approaches less preferable in many cases when compared to algorithmic approaches.

#### **5.4. Software Tools To Build Relay Models**

In the last two decades, software tools for the simulation of power system have reached very high performance. At the same time computers became faster and have larger storage capability.

It became possible to simulate the dynamic behaviour of very large power systems accurately. The modeling of power system elements has been improved and the simulations can be verified by on site measurements.

Using these new capabilities of software and hardware tools, most designs of modern relays are based on the simulation of the relays using packages like ATP/EMTP, PSCAD/EMTDC, MATLAB/SIMULINK, EUROSTAG, etc. These simulation tools are used by the manufacturers at the development level to assess the reliability and soundness of the algorithms. Once this stage in the development process has been successfully completed, the simulation software is converted into the machine language of the relay's microprocessor. If such a procedure has been followed, and it is most likely to be the case in modern designs, the relay equations in the simulation package constitute the software model of the relay.

Many pre-defined basic components are included in existing power system simulation programs such as ATP/EMTP, PSCAD/EMTDC and Power System Blockset of MATLAB. However, these components are primarily of general nature and need to be calibrated according to the design of the particular relay. For example a model of the transfer function  $G(s)$ , which is included in most packages, can be utilized to build input low-pass filter models present in most protection relays. In order to provide a general overview of the available software tools, some general characteristics of the most common programs used in the development of relay models are described here.

#### **5.4.1. ATP / EMTP (Alternative Transient Program / Electromagnetic Transients Program)**

ATP [159] is the royalty-free version of EMTP [160] and it is widely used for power system transients simulation today. ATP is a universal system for digital simulation of transient phenomena of both electromagnetic as well as electromechanical nature. With this digital program, complex networks and control systems of arbitrary structure can be simulated. It utilizes a constant step integration method with calculation step selectable by the user.

ATP has extensive modeling capabilities and additional important features apart from the computation of transients. It has been continuously developed through international contributions over the past 20 years.

Interfacing capability to the program modules TACS (Transient Analysis of Control Systems) and MODELS (a simulation language) enables modeling of control systems and components with non-linear characteristics.

MODELS [161] in ATP is a general-purpose description language supported by an extensive set of simulation tools for the representation and study of time-variant systems. The description of each model is enabled using free-format, keyword-driven syntax of local context and that is largely self-documenting. MODELS can be used for processing simulation results either in the frequency domain or in the time domain.

Also, ATP has a graphical, mouse-driven preprocessor called ATPDraw [162]. Using ATPDraw for Windows, one builds a graphical picture of an electric circuit by picking objects from menus, connecting and editing objects, and keying data interactively. ATPDRAW then creates the corresponding ATP input data file. More than 65 standard components and 25 TACS objects are available. The user can create additional circuit objects using the Data Base Module feature of ATP.

TPPLOT and PCPLOT are interactive graphical output tools. TPPLOT has extensive features such as mouse support, menus, window plotting, Fourier analysis, COMTRADE format, HPGL, PostScript output, superposition of different plots, X-Y plot, simple MATH operations and more. PCPLOT is a simpler interactive graphical output tool with features such as HPGL output, screen copy, zoom function, etc.

#### **5.4.2. PSCAD/EMTDC**

PSCAD represents a family of simulation products, which will eventually encompass all types of power systems studies, including load flow and transient stability solution engines. Presently, the primary solution engine is EMTDC. EMTDC represents and solves differential equations for the entire power system in the time domain. It is a simulator of electric networks with the capability of modeling complex power electronics, control systems and non-linear networks. When run under the PSCAD graphical user interface, the PSCAD/EMTDC [163] combination becomes a powerful means of visualizing the transient performance of electric power systems. Together they provide a fast, accurate and flexible solution for the simulation of virtually any electrical equipment or system. The user can select time step, which can be varied from nano-seconds to seconds.

EMTDC results are solved as instantaneous values in time, but they can be converted into phasor magnitudes and angles via built-in transducer and measurement functions (such as true-rms meters or FFT spectrum analyzers), much the same way real system measurements are performed. In PSCAD V4, a new component will be available to calculate the impedance vs. frequency spectrum of any system, from any point of the system.

EMTDC utilizes trapezoidal integration at its heart (as does EMTP/ATP), as defined by H. Dommel. In EMTDC however, many series and parallel circuit elements are mathematically collapsed (such as an RLC branch) to reduce the amount of nodes and branches and hence, increase solution speed. The resulting solution is fast, numerically stable and flexible, much more so than other programs.

EMTDC users can easily write their own models, from very simple to very advanced. They can write in Fortran, C and MATLAB. The PSCAD Component Workshop also makes the task of designing the visual appearance of models and the data entry forms easier. All features of the very powerful MATLAB program can be utilized, including the numerical and graphical visualization plot libraries.

#### **5.4.3. MATLAB/SIMULINK - Power System Blockset**

MATLAB [164] integrates mathematical computing, visualization, and a powerful language to provide a flexible environment for technical computing. The open architecture makes it easy to use MATLAB and its companion products to explore data, create algorithms and create custom tools that provide early insights and competitive advantages.

It is possible to take advantage of the broad range of analysis capabilities in MATLAB and the MATLAB toolboxes to analyze and visualize the simulation results. By combining the Power System Blockset with the control design tools available for MATLAB and SIMULINK [165], it is possible to model and simulate the total system and optimize the design of the controller portion of the model. Consequently, it delivers highly accurate simulations of power system models using the variable-step integrators and zero-crossing detection capabilities in SIMULINK and provides discretizing capabilities for faster and real-time simulations.

The Power System Blockset [166] is a state-of-the-art design tool for modeling and simulating electrical power systems within the SIMULINK environment, allowing a model to be built using simple click and drag procedures. It is a powerful solution for modeling the generation, transmission, and distribution of electrical power, especially when designing associated control systems. The block library contains SIMULINK blocks that represent common components and devices found in electrical power networks. The blocks are based on well-known electromagnetic and electro-mechanical equations. These blocks use standard electrical symbols, making it easy to create intuitive graphical models of electrical power systems. The libraries contain models of typical power equipment. These models are proven ones coming from textbooks, and their validity is based on the experience of the Power Systems Testing and Simulation Laboratory of Hydro-Quebec, a large North American utility located in Canada.

The Power System Blockset provides a Power2sys function as a MATLAB m-file, so that it is possible to obtain the state-space representation of the circuit external to the simulation. This function analyses the electrical network topology and computes the equivalent state-space model. With the information provided by this function, one can perform enhanced analyses with tools such as the Control System Toolbox.

To display simulation results, it is possible to connect Power System Blockset measurement blocks to SIMULINK scopes. Alternatively, it is possible to connect the measurement outputs of machines and power electronics blocks directly to SIMULINK scopes.

#### **5.4.4. NETOMAC (NETwork TOrsion MACHine Control)**

NETOMAC [167, 168] is a program for performing calculations related to electrical systems consisting of a network, machines, open-loop and closed-loop control equipment. It has a uniform database. With NETOMAC, differential-equation systems of electrical systems are integrated step by step. Single-phase simulation (stability part) or three-phase simulation (instantaneous-values part) of the networks and machines are possible, depending on the problem being examined. A transition from the instantaneous-values part to the stability part is possible during integration. Calculations of models with different complexity can run simultaneously in the stability part and instantaneous-values part. The simulation of asymmetrical faults is also possible in the stability part. An extended load-flow program precedes the integration part of the program. With this load-flow program, the steady state initial conditions for the time range are calculated.

#### **5.4.5. EUROSTAG**

EUROSTAG [169] is a software package dedicated to the dynamic simulation of electric power systems. It allows simulation of all electrical phenomena in the range of transient, mid and long-term stability. A special integration technique, making use of an automatically and continuously varying integration step-size, is the feature, which allows using a single program and a single model for the whole range of applications. It provides accuracy and robustness for the simulation, even for large deviations from normal conditions. An extended library of standard models is supplied with the program. In addition, EUROSTAG comes with EUROSTAG-G, EUROSTAG-A and EUROSTAG-T modules.

EUROSTAG-G is a graphic pre-processor which enables the customization of standard models or the input of new models, directly on the screen without any programming. This module allows the user to eliminate FORTRAN coding, if there is a need to create a so-called "macroblock" module. In the first stage of the macroblock description, the block diagram of the model is built graphically in an interactive way by means of the catalogue of elementary blocks (summaters, relays, time constants, etc.). Furthermore, due to the integration method, the model defined by

means of the graphical pre-processor is valid for all kinds of simulations. It is no longer necessary to change the model and/or programs according to the type of simulation (transient stability, long term dynamics, etc.) and to try to adapt the initial conditions of one program to the output of another.

EUROSTAG-A module is a graphic post-processor that makes easier both the interpretation of results and editing of reports. Zooming, curve comparison, superposition, change of scale, elimination of time, etc. enables a spontaneous approach to the result analysis. 'Import' functions are provided to compare EUROSTAG results with external quantities such as measures, results of other programs, etc. The 'export' functions also allow integration of the EUROSTAG results into other packages such as spreadsheets or word processors.

EUROSTAG-T module allows the user to obtain a synthetic view of the results. It generates tables based on the initial load-flow solution or based on the results obtained at a given time instant. This tool allows an easy and fast processing of large power systems results. Finally, EUROSTAG is compatible with other existing power system analysis packages, and allows to keep the acquired knowledge and procedures. For instance, there are interfaces between PSS/E and EUROSTAG, for the recovery of static and dynamic data, or between EUROSTAG and MATLAB, for the export of linearized systems.

#### **5.4.6. MATHCAD**

MATHCAD [170, 171] is a powerful, easy-to-use, integrated technical calculation product built to work like a 'live' scratchpad, solving math problems as they are entered on the screen using real math notation. Mathcad provides an interactive environment for solving real-world problems using a comprehensive set of numeric and symbolic mathematical and data analysis features, 2-D and 3-D graphing and visualization capabilities, and tools for collaboration, including built-in Internet connectivity. Mathcad offers the breadth and depth of functionality required to drive nearly every aspect of technical design and incorporates features that allow it to serve as an integrator, linking together a variety of tools that engineers and technical professionals can use. This will help manage the flow of data and calculations, break down complex systems and calculations into components, and make communication of complex calculations and processes easier through self-documentation. The calculations can be rapidly re-run and modified to reach engineering solutions without tedious programming.

It includes newly integrated modeling and simulation functionality fueled by VisSim LE from Visual Solutions. New HTML/MathML support offers users new options for collaboration by enabling them to post dynamic math content on corporate intranets, the Internet or via e-mail worksheets to colleagues. IBM techexplorer™ Professional Edition, is included in all Mathcad editions. Mathcad also integrates with a variety of applications such as the Microsoft Office suite, Visio®, AutoCAD®, SmartSketch®, Axum®, MATLAB®, Excel®, Microsoft Access and any other ODBC-compliant database, to enable users to easily transfer data between applications and even drive other applications with Mathcad design specifications. An advanced feature called MathConnex provides convenient way to integrate engineering graphics and computation. This would allow engineers to "wire" together diverse components to simulate data flow in a network or the dynamics of a machine part in operation.

There are over 300 QuickSheets (templates with built-in formulas) available to simplify common mathematical tasks. Also, it is possible to add extension packs and electronic libraries that customize Mathcad for specific disciplines, including electrical, mechanical, civil, structural and process engineering. For specific technical applications, there are add-on products to address problems for solving and optimization, wavelets, steam tables and signal and image processing.

Improvements in data analysis include new functions that allow the extraction of data from WAV files and co-ordinate data conversion--rectangular to polar, for example. Advanced users can use the SDK to develop C++ components in conjunction with Visual Basic to produce an interface for less experienced users.

#### **5.4.7. DIgSILENT Power System Analysis Software**

The DIgital SIMuLator for Electrical NeTwork calculation program DIgSILENT [172] (now named: PowerFactory) is a fully interactive power system simulation tool, dedicated to electrical power system analysis in order to achieve the objectives of planning and operation optimization. Started in 1993, the new PowerFactory software has been developed using the new object oriented software technology with C++. DIgSILENT PowerFactory provides a wide range of simulation functions such as: AC/DC Power Flow, VDE/IEC Fault Analysis, General Fault / Event Analysis, Dynamic Simulation (RMS), EMT Simulation, Eigenvalue Analysis, Network Reduction, Relay Coordination, Protection Device Response Check, Harmonic Analysis, Reliability Calculation, Economic Dispatch, SCADA / GIS Interface, DSL++ and DPL, Single Line Graphic, Substation Graphic, Virtual Instruments (VIs), Medinas2000 A/D Interface.

In terms of power system protection analysis and modeling the program contains a comprehensive library of the generic protection relay models of various types (dynamic as well as phasor based) and also allows the user to create the custom build models through a special block diagram oriented graphical interface. The models of CTs and VTs are also included in the software.

### **5.5. Other Sources of Information**

Commercially available software programs are mostly interactive with the user and present information in a graphical form. They calculate relay responses to RMS values obtained from the steady state fundamental frequency phasors, mathematical models of the network and power system components. For relay models based on phasors or RMS values, the time of operation is fixed and can only be determined by static characteristic (e.g. instantaneous trip, zone 2 delayed trip, etc.) and does not reflect the variation as a result of the fault transient. The packages such as CAPE, PSS/E or NEPLAN contain extensive libraries of specific or generic relay models which can be a valid source of information for building relay models or protection schemes.

#### **5.5.1. CAPE (Computer-Aided Protection Engineering)**

CAPE [46, 47] consists of a series of core and optional modules for analysis and reporting, linked by a general-purpose database. CAPE does not perform a time-domain simulation, although, CAPE developers are currently in the process of implementing this type of simulation into their package. Presently the program employs an approximation to the time domain called “stepped-event analysis method”, ignoring the transients that occur immediately after the fault.

The software contains various modules. In relation to Network and Protection System Models, half of the CAPE database is devoted to a detailed model of the user’s network and protection system. The other half is the CAPE’s library of relays, instrument transformers, conductors, towers, etc. System data also encompasses the breakers, zones of protection, CTs, aux CTs, summation points, VTs, aux VTs, relays, fuses, and reclosers needed for the coordination analysis and record keeping.

A significant characteristic of the CAPE database design is the modular structure that generalizes the modeling of relays. With this approach, a relay is modeled as a combination of instantaneous-overcurrent, time-overcurrent, directional, distance, timer, auxiliary, and voltage

elements. Modular modeling allows CAPE to analyze everything from relatively simple electromechanical relays to complicated microprocessor-based relays. It also helps to ensure that CAPE will be able to model relays not yet commercially available.

The elements and taps available in a relay cannot be specified correctly unless the relay is modeled by manufacturer's style number. CAPE does this. Fortunately, there is an additional level of modularity in the design of the CAPE relay library that makes it easy for the user to add new relay styles. Tap ranges are modeled like the proverbial "little black box". A major new feature of the Database Editor is a clever facility for representing any number of user-named groups of alternative settings. Groups are easily created and deleted or renamed. They may represent alternative settings supported physically in the relay or they may serve an administrative function, e.g. "Pending," "Approved," "In Service," and so on. Any relay may have any number of such groups, and the currently active group is quickly changed with a mouse click. A setting group may even involve an entirely different style of relay.

The CAPE library is a collection of data that are more or less common to all users. The largest part of the library is its set of detailed relay models. Directional elements may be voltage or current polarized (or both) by zero- or negative-sequence quantities. Distance elements may have more than one unit, typically phase-to-phase and three-phase. Taps for overcurrent and distance elements may be continuous, stepped, or discrete. Manufacturers' catalogue data for fuses, reclosers, CTs, and VTs are also stored in the library.

### **5.5.2. PSS/E (The Power System Simulator)**

PSS/E [48] is a system of programs and structured data files designed to handle the basic functions of power system simulation work. The working database maintains complete symmetrical component networks and dynamic models to represent a power system.

In terms of relay models, the library includes a group of models intended to represent the general principles of relays that are primarily sensitive to apparent impedance. They are not intended to represent exactly any particular product of any relay manufacturer because the range of types is far too broad. These models rather try to represent the basic features of relays with sufficient generality to allow their use for modeling of the effects of actual relays given properly specified data.

The 'detailed' relay models are demanding in terms of data. These detailed models are constructed from a set of basic elements, such as: impedance detection unit, zone timer, circuit breaker timer, circuit breaker, reclosure timer, minimum current detector and blinders.

PSS/E applies a time gating logic to each detailed relay model. This logic can cause the relay model to be executed every "n" time steps instead of every time step.

All the relay models are called from the model library by a standard Fortran subroutine. Therefore, the user may add information to it to do more specific co-ordination of relays rather than just simple supervisory logic built into the models.

### **5.5.3. NEPLAN Software**

NEPLAN [49] is used to analyze, plan, optimize and manage power networks. Industrial and consumer supply grids of all voltage levels, with any desired number of nodes, can be quickly and interactively entered, computed and evaluated. NEPLAN's modular concept means that network planners can put together a planning system specifically tailored to their own individual

needs. From the point of view of relay models, this program includes: Overcurrent Protection (Selectivity Analysis) and Distance Protection.

- Overcurrent Protection (Selectivity Analysis). All types of protective devices with an overcurrent-time characteristic can be entered: fusegear, circuit-breakers, definite-time overcurrent and inverse-time relays, electronic relays. Up to 6 protective functions (blocking of directional and non-directional overcurrent protection) can be assigned to each protective device. Extensive libraries with protective devices from a variety of manufacturers are available, and can be extended if necessary. Relays and current transformers are positioned in the network plan graphically.
- Distance Protection Design. All types of distance protection relays (irrespective of the manufacturer) can be entered. Relays with up to 4 impedance stages, 1 overreach and 1 reverse stage for symmetrical and/or asymmetrical faults can be entered (characteristic, impedances). Possible tripping characteristics: overcurrent, angle-dependent or angle-independent under-impedance, free characteristic in the R-X diagram (polygons, circles), directional/bi-directional end-time, earth fault detection. Back-up (overcurrent time) protection can be incorporated. All fault types, plus sliding faults of the short-circuit current module are allowed for. Mutual impedances and capacitances of the positive and negative-sequence systems are allowed for in the short-circuit current computation. Extensive libraries with data from various producers are available, and can be expanded.

#### 5.5.4. Information about setting programs

The reliable and selective operation of the protection can only be realized by knowledge of the correct settings. Especially the determination of the starting up and tripping values requires large calculation expenses in electrical systems, which can be realized in an efficient manner only by using network calculation software. A computer-aided protection environment can assist the engineer by automating the setting rules. Some examples of commercial software can be: DISTAL, CUSS, CAPE Relay Setting Module, CMC, ELEKTRA PROTECT and ASPEN relay database.

- DISTAL (Distance Protection Grading) [173] calculates the setting values of the impedance for the three steps and for the overreach zones (automatic reclosing and signal comparison) of distance protection equipment in any kind of meshed network.
- CUSS (Computer-aided Protective Grading) [174] indicates grading paths and grading diagrams, checks the interaction of the current-time characteristics with regard to selectivity and generates setting tables for the protection equipment.
- CAPE Relay Setting Module [175] provides a means for automatic computation of relay settings following the user's own setting philosophies and techniques. This module computes "first-pass" relay settings for a given relay, group of relays or zone of protection. It also allows calculation of the relay settings for new installations.
- CMC [176, 177]. The test modules are designed to automate tests and provide automatic assessments based on user-defined parameters. Standard report settings can quickly and easily be generated, saved, and loaded to customer reports.
- The PC-program ELEKTRA includes a PROTECT module developed to determine the settings of protection devices. Specially designed for distance and overcurrent relays, some of the solutions proposed by this software are the following: representation of the setting values as graphic or in tables; graphical and numerical adaptation of the settings; automatic calculation and representation of the shortest electrical periphery; representation of all peripheries of the short circuit nodal point selected to monitor selectivity; impedance curve representation on the base of exact short circuit calculation

to check the settings calculated by length dependent procedure with consideration of the starting security; translation of the valid settings into Excel or into special protection data forms; calculation of maximal and minimal short circuit currents; representation of tripping characteristics in dependence on special type data of the overcurrent protection (definite time, inverse time, fuses); etc.

- Aspen One Liner (TM) [178] is a Windows based program that allows interactive simulation of unbalanced short circuits (using a phasor based model of the power system) and the performance of relays sensing the simulated fault currents and voltages. The relay models are detailed phasor based models of distance relays, and time and instantaneous directional overcurrent relays. Although deliberate time delays of the distance relays are modeled, the inherent time performance and effect of memory polarizing is not modeled. In terms of using phasor based models with no time domain modeling (except intentional current independent or dependent time delays) the Aspen One Liner relay models are similar to those included in numerous commercial programs that help protection engineers select appropriate settings for protective relays based on phasor simulation of balanced and unbalanced short circuits on power systems.

## **5.6. Conclusions**

This chapter has presented a wide range of information sources, which can be useful for the development of protection relay software models. They range from general publications, technical papers and manufacturer's documentation to software products incorporating various modules for building protection relays and schemes.

When building a model of a specific relay design the information obtained directly from the manufacturer is of primary importance. It should be noted that accuracy of the models could be significantly improved if more specific information were available from manufacturers. However, when exact information on a block of a relay is not available, it is often possible to make some approximations. One technique, which could be suggested to overcome the problem, is to utilise Artificial Neural Networks (ANN) for modeling of the behaviour of the block with insufficient amount of data.

The computer programs and systems are necessary tools for development of the relay models. They facilitate proper interface with primary power system simulation and provide a flexible environment where the relay model can be tested and modified.

## 6.0 Modeling Methodology

Development of relay models for use in electromagnetic transient program includes steps illustrated in Figure 6.1. The process is iterative. The first step is to identify the components of the relay to be modeled depending on the studies to be done. Issues and procedures involved in modeling of various components are discussed in the following sections. Once a model has been developed, it should be validated to confirm that it could represent the behaviour of the modeled relay under conditions to be studied. Various methods for validating a relay model are discussed in Chapter 7 of this report. If the developed model meets the requirements, the modeling process is complete. However, if it does not, the components that need to be remodeled or any additional components that need to be added should be identified and a revised model should be developed. This revised model should again be validated. This process is continued till a suitable model is achieved.

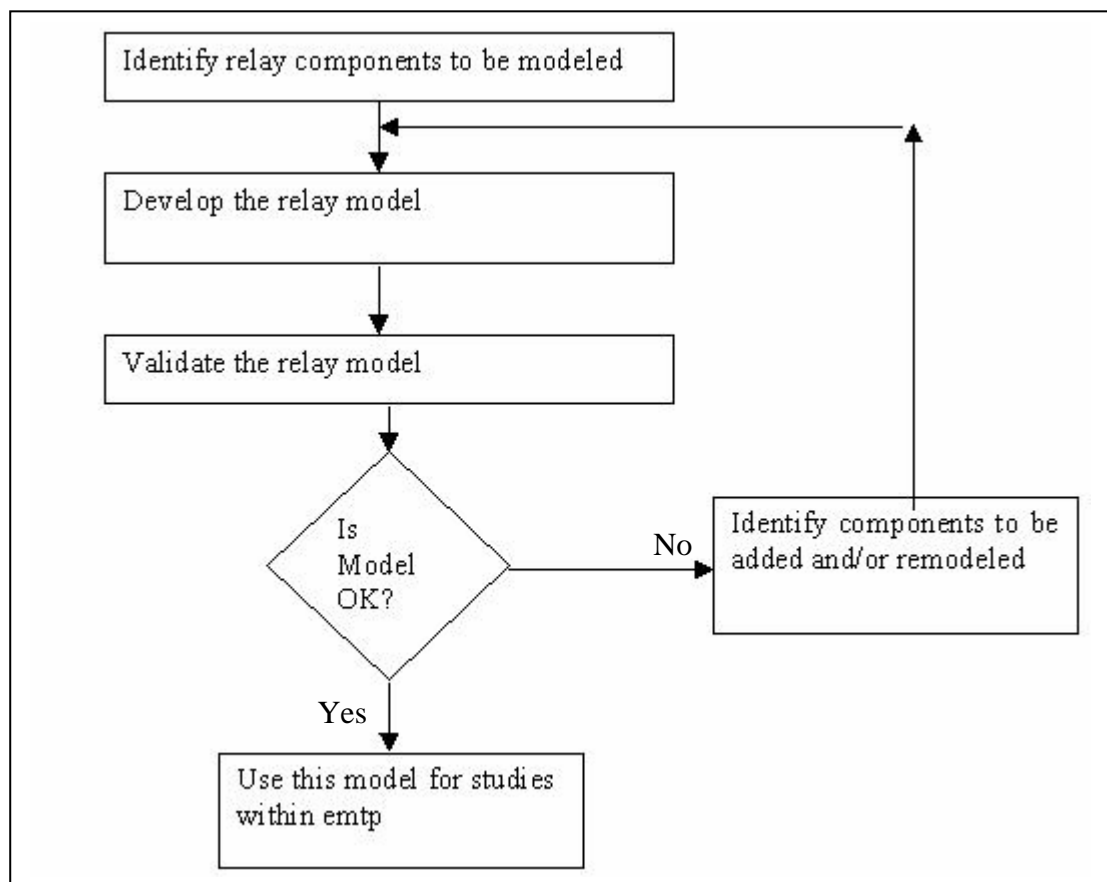


Figure 6.1: Process of developing a relay model

Two types of relay models programs are presently available for electromagnetic transient programs. The models of the first category are programmed in TACS or MODELS language and work from within the analysis programs. The models of the second type are programmed in FORTRAN, MATLAB, APL, C++ (and others). These models can be attached to the electromagnetic transient programs.

It is well known that modeling of electromechanical relays is hard, less accurate and is generally valid in a limited range. However, a number of models for these types of relays have been suggested. On the other hand, microprocessor relays being numerical in nature are inherently suitable for development of their accurate numerical models. The modeling of numerical relays

has been discussed in some detail in an IEEE tutorial [179]. As the use of microprocessor-based relays is expanding, this section predominantly focuses on modeling of microprocessor relays. Models of protection systems, for use in conjunction with emtp, consist of major components that are displayed in Figure 6.2

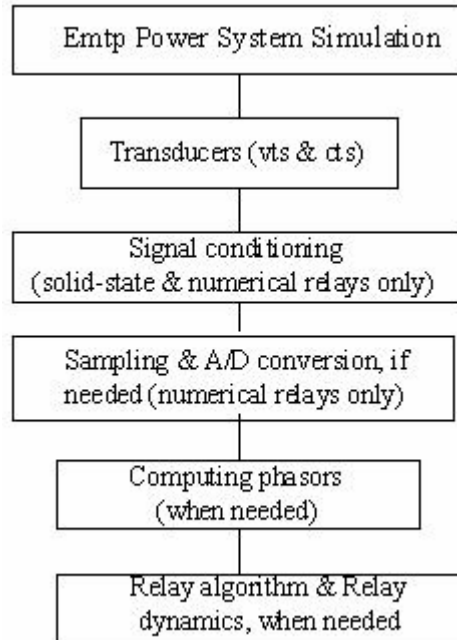


Figure 6.2: Functional blocks of a relaying system to be modeled

Power system components, including transducers, are usually available in the transient analysis programs. Signal-level reduction and signal conditioning are necessary for solid-state and microprocessor based relays. Instantaneous values of analog signals must be converted to numerical form for microprocessor relays.

If needed, phasors must be computed for use in relay models. For example, phasors of currents must be computed for modeling inverse time overcurrent electromechanical relays. Relay dynamics must also be modeled for some relays, such as time overcurrent relays, and second and third zone distance relays. The aspects of modeling, identified in Figure 6.2, are presented in this section.

## 6.1. Instrument and Auxiliary Transformer Models

Because high voltage and high current signals cannot be applied to relays directly, voltage and current levels are reduced by using transducers. In North America, voltage levels are reduced to 110 V (nominal) and current levels are reduced to 5 A (nominal) [180]. Models of these transducers are usually available within the transient analysis programs and therefore, do not form a part of the relay models. Therefore, models of CTs and VTs are not presented in this section.

Solid-state and microprocessor based relays cannot process 110V nominal (during normal operation) and 150 A (or so) relay level currents during faults. The voltages are usually reduced to a level of 5 to 10 V range so that the electronic components are not damaged. The voltage reduction is achieved by using either auxiliary VTs or resistance dividers. Since these devices operate in their linear range, proportionality factors are used in the relay models.

Auxiliary CTs are used to reduce the levels of currents applied to the relay. The outputs of the auxiliary CTs are passed through precision resistors. Voltage drops across the resistors are used to represent currents. If no saturation is expected, modeling the CT and its burden is a straightforward process. As a prudent practice, it is important that provision for modeling saturation of auxiliary CTs, including saturation due to low frequency signals be made in the relay models.

## 6.2. Signal Conditioning Filters

Currents and voltages applied to solid-state and microprocessor relays during faults contain components of high frequencies. While designing the circuitry of solid-state relays it is assumed that the applied signals are of the fundamental frequency. Most algorithms of microprocessor-based relays are adversely affected by components of high frequencies. Some high frequency components are also likely to seem to be of the fundamental frequency because of aliasing. Therefore, low pass filters are used in solid-state and numerical relays. These filters are analog devices [181].

The numerical data obtained from transient analysis studies are applied to the relay models. The procedure described in this section can be used to model low pass filters for signal conditioning of the data.

Consider that the relay being modeled uses a fourth order low pass filter. The performance of the filter used to process the transient analysis data should be compatible with the performance of the analog filter used in the relay. Let the transfer function of the analog filter be:

$$H(s) = \left[ \frac{k}{s+k} \right]^4 \quad (6.1)$$

The output of this filter at the cutoff frequency should be at –3 dB level. Therefore, the following equation must be satisfied:

$$\left| \frac{k}{j\omega_c + k} \right|^4 = \frac{1}{\sqrt{2}} \quad (6.2)$$

If the cutoff frequency is  $600\pi$  r/s (300 Hz),  $k$  works out to be 4333. The cutoff frequency of a digital filter is somewhat different from the cutoff frequency of the analog filter because of the warping effect.

The cutoff frequency of the analog filter for a selected cutoff frequency of the digital filter is given by:

$$\omega_c = \frac{2}{\Delta T} \tan \left[ \frac{\Omega_c \Delta T}{2} \right] \quad (6.3)$$

In this equation  $\Delta T$  is the time between two consecutive samples. If the transient program is calculating data 11,520 times per second and the cutoff frequency of the digital filter is to be  $600\pi$  r/s (300 Hz),  $\omega_c$  should be 1889.2 r/s. The transfer function of the fourth order analog filter of this cutoff frequency is:

$$H(s) = \left[ \frac{4343}{s + 4343} \right]^4 \quad (6.4)$$

Bilinear transformation can be applied to obtain the transfer function in the  $z$  domain. The procedure consists of replacing:

$$s \text{ with } \frac{2}{\Delta T} \left[ \frac{1 - z^{-1}}{1 + z^{-1}} \right]$$

Making this substitution in Equation 6.4 and using the selected value of  $\Delta T$ , the following equation is obtained:

$$H(z) = \left[ \frac{0.15859 (1 + z^{-1})}{1 - 0.6828 z^{-1}} \right]^4 \quad (6.5)$$

Replacing  $H(z)$  with  $\frac{Y(z)}{X(z)}$ , expanding the right-hand side of Equation 6.5 and rearranging provides the following equation:

$$\begin{aligned} Y(z)(1 - 2.731z^{-1} + 2.797z^{-2} - 1.273z^{-3} + 0.2173z^{-4}) = \\ X(z)[6.326 * 10^{-4} (1 + 4z^{-1} + 6z^{-2} + 4z^{-3} + z^{-4})] \end{aligned} \quad (6.6)$$

Replacing the  $z$  operators with time delays, provides the following equation:

$$\begin{aligned} y(n\Delta T) = 6.326 * 10^{-4} \left\{ \begin{aligned} &x(n\Delta T) + 4x(n-1)\Delta T + 6x(n-2)\Delta T \\ &+ 4x(n-3)\Delta T + x(n-4)\Delta T \end{aligned} \right\} \\ + 2.731y(n-1)\Delta T - 2.797y(n-2)\Delta T \\ + 1.273y(n-3)\Delta T - 0.2173y(n-4)\Delta T \end{aligned} \quad (6.7)$$

Notice that this is a recursive digital filter.

### 6.3. Sampler and Analog to Digital Converters

While electromechanical and solid-state relays process signals in the analog form, microprocessor relays convert the analog information to numerical form using sampler and analog to digital (A/D) converters. A/D conversion process can be considered as a two-stage process consisting of a sampler and a quantizer as shown in Figure 6.3.

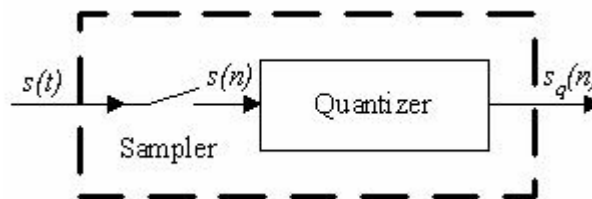


Figure 6.3: Block diagram of analog to digital conversion process

The first stage sampler creates the sequence  $s(n)$  by sampling the analog signal  $s(t)$  at regular intervals of  $\Delta T$  seconds. This part of the process is usually considered accurate and without any addition of errors.

The second stage expresses each sample of the sequence  $s(n)$  by a finite number of bits giving the sequence  $s_q(n)$ . The difference between the elements of the sequence  $s_q(n)$  and  $s(n)$ ,  $E_{\Delta T} = s_q(n) - s(n)$ , is the quantizing noise (it is also called A/D conversion noise). The quantizing process either could truncate the signal as it converts the analog information to numerical form or could round it.

The quantizer stage of a relay model may be skipped for some cases. Depending on the accuracy requirements of the relay model, the values obtained from the sampler may be directly used for phasor calculations and for modeling relay algorithm and relay dynamics.

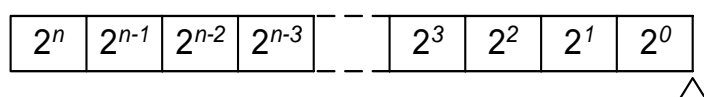
### 6.3.1. Numerical interpretation of a quantizer

When numbers are handled by words of finite length, one of the following three representations of negative numbers is used.

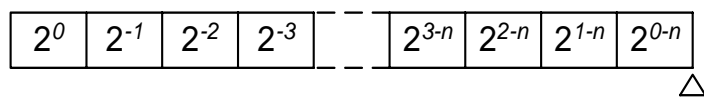
- sign and magnitude representation,
- one's complement representation or
- two's complement representation.

The two's complement representation is most commonly used and will be considered in this section. While integers are considered in this discussion, the discussion can be extended to floating point arithmetic.

Consider a word of  $n+1$  bits as shown in Figure 6.4(a). The least significant digit (LSB) represents a numerical value of  $2^0$  and the most significant digit (MSB) represents a value of  $2^n$ . The normalized values of these representations, using  $2^n$  as the base are  $2^{-n}$  and 1 respectively as shown in Figure 6.4(b).



(a) Representation of bits of a word



(b) Normalized Representation of bits of a word

Figure 6.4: Numerical values of bits of a word

Because rounding of numbers is used, the error lies between  $-\frac{1}{2} 2^{-n}$  and  $+\frac{1}{2} 2^{-n}$  i.e.  $\pm \frac{1}{2}$  LSB. The characteristic of the quantizer is shown in Figure 6.5.

Notice that if truncation was used, the errors would have been in the range of  $-2^{-n}$  to 0 for positive numbers and in the range of 0 to  $+2^{-n}$  for negative numbers.

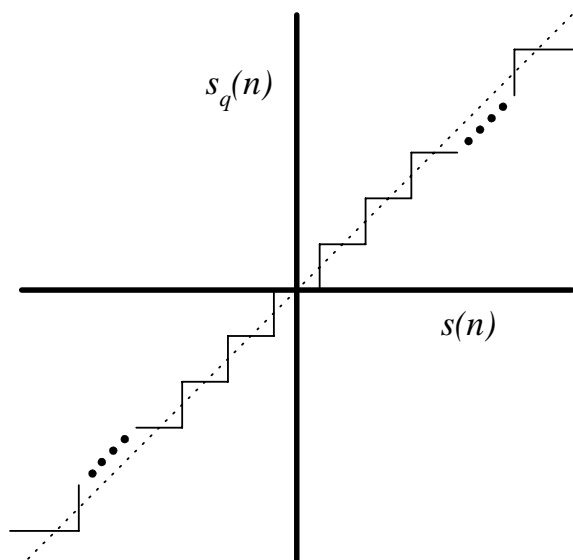


Figure 6.5: The quantizer characteristic when rounding is used

### 6.3.2. A/D converter model [121, 182, 183]

Consider that an A/D converter can handle inputs in the range from  $-V_{AD}$  to  $+V_{AD}$  volts and an input (output of the low pass filter) of  $v$  volts is applied. The quantized value  $Q_{AD}$  when  $v$  is positive is given by:

$$Q_{AD} = Ron \left[ \frac{v(2^n - 1)}{V_{AD}} \right] \quad (6.8)$$

In this equation,  $Ron$  represents rounding of the computed value. If the input voltage is negative, the quantized value is calculated using the following equation:

$$Q_{AD} = Ron \left[ \frac{(2V_{AD} - |v|)2^n}{V_{AD}} \right] \quad (6.9)$$

The saturation of the A/D converter is modeled by selecting  $+V_{AD}$  for positive inputs and by selecting  $-V_{AD}$  for negative inputs.

## 6.4. Microprocessor Modeling

Microprocessor modeling may be necessary to study the timing aspects and the effects of limited word resolution on the computed quantities [10]. The numbers provided by analogue-to-digital acquisition systems are integers. Digital processing inside the relay could however be either in integer or floating-point form. The main source of error however is the quantizing of numbers due to the limited resolution of the acquisition system. The processing of numbers in the integer form could introduce substantial errors if the bit-size of the word is small. However, processing in the floating-point format has a limited impact on the overall accuracy and modern relays generally employ floating-point microprocessors.

Modeling of timing aspects may be necessary at the design level. This will generally include facilities to benchmark a program and determine its execution times. This facility may not have much use for application studies.

It is possible to use commercially available microprocessor emulators as microprocessor models within a protection system model.

## 6.5. Computing Phasors

Several studies use modules of the electromagnetic transient analysis programs that produce steady-state values. The modules provide voltage and current phasors and, therefore, it is not necessary to perform any computations for obtaining information in the phasor form.

On the other hand, electromagnetic transient analysis programs also calculate voltage and current waveforms as functions of time. In those situations, it may be necessary to convert the sequences of the values of voltages and currents to their equivalent phasors as functions of time. For example, modeling of solid-state relays would use, in most cases, the time-sequences for making relaying decisions. If a transmission line model were used by a numerical relay for detecting line faults, it would not be necessary to convert the sequences to phasors. On the other hand, numerical distance relays that compute apparent impedance have to compute phasors. This is done by using one of the several signal-processing techniques. The technique used by the relay being modeled should be used in the relay-model. Two commonly used techniques are described in this section.

### 6.5.1. Discrete Fourier transform algorithm

This algorithm correlates one cycle of data with sine and cosine waveforms of the frequency of the component that is to be extracted [101]. Consider that the signal can be expressed by:

$$v = V_p \cos(\omega_0 t + \theta) \quad (6.10)$$

The real and imaginary components of the phasor of  $v$  can be obtained by correlating the signal with sine and cosine waveforms and integrating over one cycle of  $\omega_0$ .

The procedure consists of the following equations:

$$V_p \cos(\theta) = \frac{1}{\pi} \int_{\omega_0 t=0}^{2\pi} v \cos(\omega_0 t) d\omega_0 t \quad (6.11)$$

$$V_p \sin(\theta) = -\frac{1}{\pi} \int_{\omega_0 t=0}^{2\pi} v \sin(\omega_0 t) d\omega_0 t \quad (6.12)$$

These equations can be modified as follows for use with discrete data:

$$V_{Rk} = \frac{2}{m} \sum_{n=0}^m v_{k+n-m} \cos\left(\frac{2\pi n}{m}\right) \quad (6.13)$$

$$V_{Ik} = -\frac{2}{m} \sum_{n=0}^m v_{k+n-m} \sin\left(\frac{2\pi n}{m}\right) \quad (6.14)$$

In these equations,  $m$  represents the number of samples taken in one cycle of the fundamental frequency and  $k$  represents the most recent sample of the voltage.

The peak value and angle of the phasor are calculated using the following equations:

$$V_k = \sqrt{V_{Rk}^2 + V_{Ik}^2} \quad (6.15)$$

$$\theta = \arctan\left(\frac{V_{Ik}}{V_{Rk}}\right) \quad (6.16)$$

### 6.5.2. Least Squares algorithm

Development of a least squares algorithm consists of the following steps [184]:

1. Select a model that appropriately represents the signals to be processed.
2. Linearize the model.
3. Select a sampling rate.
4. Select a data window size.
5. Express the process in the matrix form.
6. Calculate the left pseudo-inverse of the coefficient matrix.
7. Chose the appropriate rows of the left pseudo-inverse to compute phasors.

Consider that a current can be expressed by Equation 6.17 that includes a decaying DC term, a term of the fundamental frequency and several harmonics:

$$i(t) = K_0 e^{-t/\tau} + \sum_{m=1}^N K_m \sin(m\omega_0 t + \theta_m) \quad (6.17)$$

The following two steps are performed to linearize this equation:

1. Replace the exponential by its Taylor series expansion and keep the first two terms of the series.
2. Expand the sinusoids by using the rules of trigonometry.

These substitutions lead to a linear equation of current  $i$  at time  $t_1$  as follows:

$$i(t_1) = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 + \dots \quad (6.18)$$

where;

$$\begin{array}{ll} x_1 = & K_0 & a_{11} = & 1 \\ x_2 = & -K_0 / \tau & a_{12} = & t_1 \\ x_3 = & K_1 \cos(\theta_1) & a_{13} = & \sin(\omega_0 t_1) \\ x_4 = & K_1 \sin(\theta_1) & a_{14} = & \cos(\omega_0 t_1) \end{array}$$

Since time is arbitrary,  $t_1$  is known; all  $a$ 's are, therefore known. All  $x$ 's are the unknowns.

The next sample of current is taken at time  $t_2 = t_1 + \Delta T$ ; this sample can be expressed as an equation of the following form:

$$i(t_2) = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + a_{24}x_4 + \dots \quad (6.19)$$

If the number of unknowns is  $n$  and  $m (> n)$  samples are taken, the equations can be written in the matrix form as follows:

$$\begin{matrix} [A] & [X] & = & [I] \\ m \times n & n \times 1 & & m \times 1 \end{matrix} \quad (6.20)$$

The vector of unknowns can be calculated using the following equation:

$$\begin{matrix} [X] & = & [A]^+ & [I] \\ n \times 1 & & n \times m & m \times 1 \end{matrix} \quad (6.21)$$

The matrix  $[A]^+$  is the left pseudo-inverse of  $[A]$  and can be calculated using the following equation.

$$[A]^+ = [[A]^T [A]]^{-1} [A]^T \quad (6.22)$$

All the elements of  $[A]$  are known from the design of the algorithm and, therefore, the left pseudo-inverse  $[A]^+$  can be computed in advance and its elements can be stored for use in the real-time application.

The elements of the rows are the weighting factors that are used to compute the phasors.

## 6.6. Modeling Relay Dynamics [185-187]

In many situations, the modeling of relay dynamics is a straightforward procedure. For example, a trip command is to be issued when the apparent line impedance is less than the first zone setting of the relay. The modeling, in this case, consists of:

- comparing the calculated impedance with the set value and
- issuing the command if the calculated impedance is less than the setting.

In other situations, an appropriate time delay is to be incorporated. If the time delay is fixed, the modeling remains a straightforward process. The procedure would consist of the following steps:

1. Start a timer when a trip command is indicated.
2. Check the trip criteria after the next iteration is performed by the analysis program.
3. Increment the timer if the trip criterion is satisfied.
4. If the trip criteria are not satisfied, either decrement the timer or reset it. The decision should be based on what the relay being modeled is designed to do.
5. Check if the desired time delay has elapsed or not.
6. If it has, model the tripping of the appropriate circuit breakers. Otherwise, revert to step 2.

Another situation consists of modeling inverse-time delays, such as in inverse-time overcurrent relays. The modeling of these electromechanical, numerical and distance relays is described in the next section.

### 6.6.1. Modeling electromechanical inverse-time overcurrent relays

The electromechanical inverse-time overcurrent relays do not make trip decisions during the existence of the transient components of the faults. Therefore, it is adequate to model these relays using phasors. If such a relay is present in a transient electromagnetic study, the transient

data representing the waveforms should be first converted to the phasor form using one of the signal-processing algorithms.

Inverse-time overcurrent relays of different characteristics are used in power systems. Figure 6.6 shows the characteristics of a CO-7 electromechanical relay marketed by ABB.

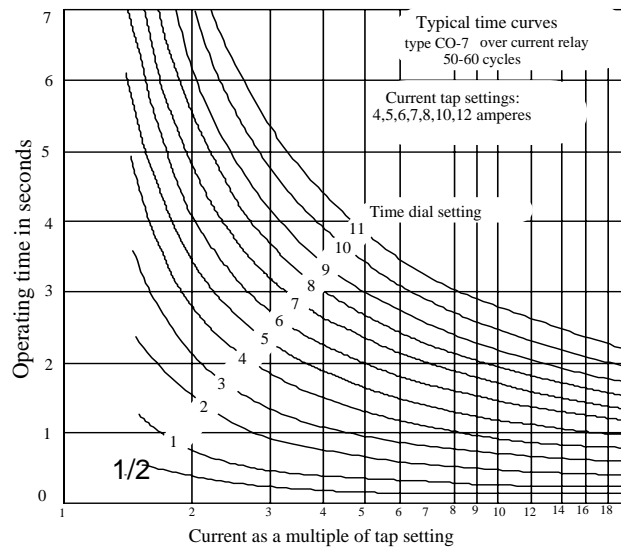


Figure 6.6: Operating characteristic of a CO-7 inverse time overcurrent relay

The operating characteristic shown in this figure is for currents exceeding the set value (one multiple of tap setting). When a relay of this type operates, it energizes the trip coil of the circuit breaker controlling an electric element. The circuit breaker interrupts the flow of current to the element. Now there is no current in the relay because there is no current in the circuit. The relay starts to reset. The resetting characteristic is not shown in Figure 6.6

The operating and resetting characteristic of inverse-time overcurrent relays can be expressed by the following mathematical equations:

$$t(I) = \left( T_0 + \frac{K}{M^P - 1} \right) \quad (6.23)$$

$$t(I) = \left( \frac{t_r}{M^2 - 1} \right) \quad (6.24)$$

In these equations,  $t(I)$  is the trip time in Equation 6.23 and reset time in Equation 6.24,  $t_r$  is the reset time for  $M = 0$ ,  $M$  is the relay current in multiples of tap setting and  $K, T_0$  and  $P$  are constants that describe the operating characteristic of the relay that is being modeled.

The current phasor is calculated from the data provided by the transient analysis program. The nominal current and tap setting of the relay are known. Now, the trip time  $t(I)$  can be calculated. One way of arriving at the trip decision is to implement the following equation:

$$\int_{\tau=0}^T \frac{1}{t(I)} d\tau = 1 \quad (6.25)$$

The integration is evaluated after completing each iteration of the analysis. A trip command is generated as soon as the integration becomes equal to or greater than one.

### 6.6.2. Modeling numerical inverse-time overcurrent relays

Numerical inverse-time overcurrent relays are designed for use in power systems that have their electromechanical counterparts in service. The operating characteristics of numerical overcurrent relays, therefore, are similar to those of their electromechanical counterparts.

Because the current in the circuit could change while a fault is being experienced, Equation 6.23 must be implemented by an integration procedure. One possible approach is to redefine the process of Equations 6.23 and 6.25. Equation 6.23 can be rewritten as:

$$(M^P - 1) \geq \frac{K}{t(I) - T_0} \quad (6.26)$$

Integrating both sides of this equation provides

$$\int_{\tau=0}^T (M^P - 1) d\tau \geq \frac{1}{t(I) - T_0} \int_{\tau=0}^T K d\tau \quad (6.27)$$

The left-hand side of Equation 6.27 can be evaluated using the trapezoidal rule. The right-hand side is an integration of constants. The integral equation can be written in the form of summation for the left-hand side and calculated threshold for the right-hand side as follows:

$$\begin{aligned} & \frac{1}{2} [M^P(\tau = 0) - 1] + \left\{ \sum_{n=1}^{N-1} [M^P(\tau = n\Delta T) - 1] \right\} \\ & + \frac{1}{2} [M^P(\tau = N\Delta T) - 1] \geq \frac{N\Delta T}{N\Delta T - T_0} \left( \frac{K}{\Delta T} \right) \end{aligned} \quad (6.28)$$

The left-hand side should be evaluated starting with the inception of a fault. The right-hand side should be evaluated after the minimum time,  $T_0$ , has elapsed. The inequality should be checked at the end of each iteration to determine if the required time has elapsed or not.

Another approach for modeling numerical inverse-time overcurrent relays is to implement the inequality:

$$\int y(\tau) d\tau \geq K' \quad (6.29)$$

In this equation:

$$\begin{aligned} y(\tau) &= 0 && \text{when the current is less than or} \\ & && \text{equal to the pickup value and} \\ y(\tau) &= \frac{K'}{t(I)} && \text{when the current is greater than the} \\ & && \text{pickup value.} \end{aligned}$$

This equation can be written in the numerical integration form as follows:

$$\sum_{n=1}^N X_n \geq K' \quad (6.30)$$

$$X_n = 0 \quad \text{when the current is less than or equal to the pickup value and}$$

$$X_n = \frac{K'\Delta T}{t(I)_n} \quad \text{when the current is greater than the pickup value.}$$

The values of  $\frac{K'\Delta T}{t(I)_n}$  can be calculated for the selected characteristic over the operating range of the relay and can be stored in a lookup table. Using the lookup table has the advantage of providing the flexibility of modeling characteristics of irregular shapes.

The value of  $X_n$  is computed at each iteration and the inequality defined by Equation 6.30 is checked to confirm if the relay operation should be implemented. This implementation procedure is similar to the procedure recommended in References 181 and 186.

### 6.6.3. Modeling distance relays

Distance relays are used for protecting transmission lines. While several generic characteristics are used, modeling of only admittance, and quadrilateral relays is presented in this section.

#### 6.6.3.1. Electromechanical admittance relays

Electromechanical admittance relays are implemented in the form of amplitude and phase comparators that can be defined by the following mathematical equations:

$$\left| I_L \frac{Z_R}{2} \right| > \left| V_L - I_L \frac{Z_R}{2} \right| + k \quad (6.31)$$

$$\left| I_L Z_R - V_L \right| \cos(\varphi) > k \quad (6.32)$$

In this equation:

- $V_L$  is the phasor of the relay voltage,
- $I_L$  is the phasor of the relay current,
- $Z_R$  is the impedance setting,
- $k$  is the torque due the restraining spring,
- $I_L \frac{Z_R}{2}$  is the operating signal,
- $V_L - I_L \frac{Z_R}{2}$  is the restraining signal,
- $I_L Z_R - V_L$  is the operating signal,
- $V_L$  is the polarizing signal and
- $\varphi$  is the phase angle of the operating signal less the phase angle of the polarizing signal.

Another alternative to the modeling of phase comparators by Equation 6.32 is to compute the phasors of the polarizing and operating signals and, perform the following check.

$$-90^\circ < \varphi < +90^\circ \quad (6.33)$$

Line to line voltages and differences of line currents are applied to phase-distance relays. The voltages and currents used in Equations 6.31-6.33 are as listed in Table 6.1.

Fault between phases	Applied Signals	
	Voltage	Current
A-B	$V_A - V_B$	$I_A - I_B$
B-C	$V_B - V_C$	$I_B - I_C$
C-A	$V_C - V_A$	$I_C - I_A$

Table 6.1: Voltages and currents used for detecting two-phase and two-phase-ground faults

One of the problems with admittance relays is that, for a close-in fault the voltage collapses and the relays do not operate even when the fault is on the line side. Either memory action is built in or leading phase polarization is used and can be included in the modeling equations.

### 6.6.3.2. Solid-state admittance relays

Solid state relays do not work with phasors of voltages and currents. They make decisions from the relationships of voltage and current waveforms. For example, the waveforms of the polarizing and operating signals of Equation 6.32 could be as shown in Figure 6.7 The relay operates if the coincidence is more than  $90^\circ$ .

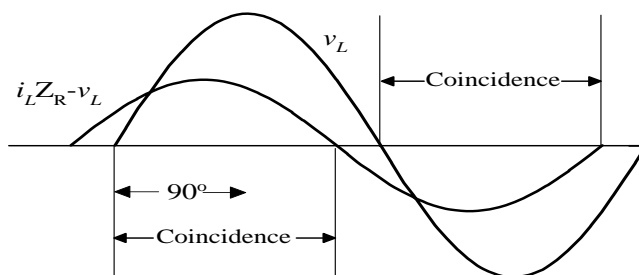


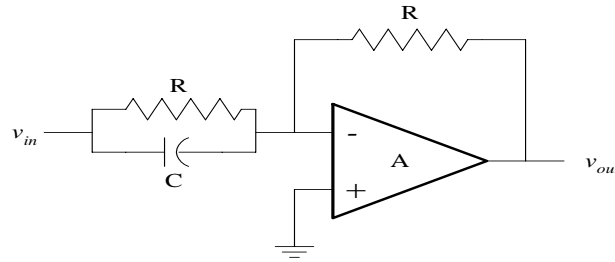
Figure 6.7: Waveforms of operating and polarizing signals

This relay can be modeled by performing the following steps:

1. Take the data generated by the electromagnetic transient program.
2. Filter the data using a cutoff frequency of about one-third the computing frequency used by the analysis program.
3. Model the relay impedance and start generating the sequence representing  $i_L Z_R$  and  $i_L Z_R - v_L$ , as discussed later in this section.
4. Compare the sign of the sequence produced in Step 3 and the sequence of  $v_L$ .
5. Monitor the duration of coincidence and simulate tripping if the duration exceeds one quarter of the nominal frequency and the first zone relay is being modeled. In case the second zone is being modeled, monitor the operation and trip after the specified time delay.

#### Modeling relay impedance

One approach for generating  $i_L Z_R$  is to use the circuit shown in Figure 6.8:


 Figure 6.8: A phase-shifting circuit for generating  $i_L Z_R$ .

The transfer function of this circuit is given by the following equation:

$$H(s) = -\frac{s + \omega_c}{\omega_c} \quad (6.34)$$

In this equation, the term  $\omega_c = \frac{1}{RC}$ . The gain and phase of this transfer function at a selected frequency are given by the following equations:

$$|H(j\omega)| = \sqrt{1 + \left(\frac{\omega}{\omega_c}\right)^2} \quad (6.35)$$

$$\angle H(j\omega) = \arctan\left(\frac{\omega}{\omega_c}\right) \quad (6.36)$$

The voltage applied to the circuit is proportional to the current  $i_L$ . The term  $\omega_c$  is chosen such that the phase angle of the transfer function is equal to  $-\angle Z_R$ . Both, the amplitude and phase angle are adjusted by using an inverting amplifier of an appropriate gain in series with the circuit of Figure 6.8. The combination provides an output proportional to the term  $i_L Z_R$ .

Applying bilinear transformation to Equation 6.34 provides:

$$H(z) = -\left[ \frac{2}{\omega_c \Delta T} \left( \frac{1 - z^{-1}}{1 + z^{-1}} \right) + 1 \right] \quad (6.37)$$

The input-output equation works out to:

$$Y(z) = -\left[ \frac{2}{\omega_c \Delta T} + 1 - \left( \frac{2}{\omega_c \Delta T} - 1 \right) z^{-1} \right] X(z) - z^{-1} Y(z) \quad (6.38)$$

If the phase angle of the relay impedance is  $75^\circ$  and the analysis program is computing voltages and currents 11,520 times per second, Equation 38 provides the following for calculating the output of the circuit of Figure 6.8.

$$v_{out}(n\Delta T) = 229.1v_{in}(n\Delta T) - 227.1v_{in}((n-1)\Delta T) - v_{out}((n-1)\Delta T) \quad (6.39)$$

The consequence of having large coefficients in this equation is that noise will be amplified. This is likely to result in serious errors in the implementation of this model. An alternative solution to

this problem is to decimate the data sequences generated by the electromagnetic transient program. For example, if the data is decimated to 720 Hz, the equation reduces to:

$$v_{out}(n\Delta T) = 15.255v_{in}(n\Delta T) - 13.255v_{in}((n-1)\Delta T) - v_{out}((n-1)\Delta T) \quad (6.40)$$

While this represents a substantial improvement, care must be taken when implementing the required phase shift. It is interesting to note that if the phase angle of the relay impedance is reduced to  $60^\circ$ , the first two coefficients of Equations 6.39 and 6.40 would reduce to less than 50% of their present values.

### 6.6.3.3. Numerical distance relays

Numerical distance relays may be divided into three categories. The first category is of generic relays that emulate their electromechanical or solid-state counterparts. These relays implement the amplitude or phase comparator equations after computing the voltage and current phasors.

The second category is of relays that:

- compute voltage and current phasors from the sampled and quantized data,
- calculate the impedance from the voltage and current phasors and then
- use appropriate logic to arrive at a trip decision.

The issues of sampling and quantizing data and techniques for computing phasors have already been discussed in earlier sections. The impedances as seen from the relay terminal are calculated from appropriate phasors. (The voltages and currents used for identifying phase-phase and phase-phase-ground faults have been listed in Table 6.1.)

The third category of relays use voltage and current samples to estimate the seen impedance by fitting the parameters of the fault loop in the form of first-order differential equation. A number of numerical techniques can be used to replace the continuous-time differential equations at various instants into algebraic equations. A set of these equations is then solved to estimate the seen impedance. These relays also use appropriate logic, as relays of second category, to make a trip decision.

The relays in second and third category generally use mho or quadrilateral type characteristics. The logic for implementing admittance and quadrilateral characteristics is presented here.

A typical admittance characteristic is shown in Figure 6.9. In this figure,  $Z$  is the impedance calculated by a numerical relay when a fault is in its operating zone and  $Z_C$  is the impedance where the center of the relay characteristic is located.

The magnitude of the vector from the center of the relay characteristic to the impedance seen by the relay is given by:

$$|Z_{CF}|^2 = (R - R_C)^2 + (X - X_C)^2 \quad (6.41)$$

The tripping logic could be implemented by comparing the square of the vector, calculated by using Equation 6.41, with the square of the radius of the circle, which is equal to  $\left|\frac{Z_R}{2}\right|^2$ .



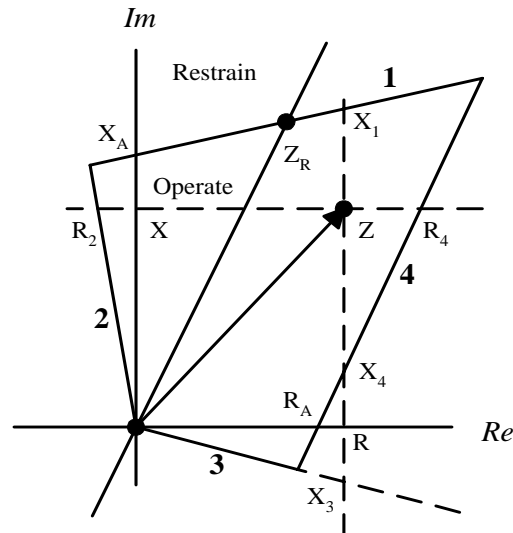


Figure 6.10: A typical characteristic of a quadrilateral relay

The other option is to use the value of  $R$  (resistance) measured by the numerical relay in Equations 6.42-6.45 and obtain the corresponding values of  $x_{L1}$ ,  $x_{L2}$ ,  $x_{L3}$  and  $x_{L4}$ .

These are the intercepts of the vertical line through  $Z$  and the sides of the quadrilateral. The impedance seen by the relay is in the operating zone if the following criteria are satisfied.

$$\begin{aligned}
 &X < x_{L1}, \\
 &X > x_{L2}, \\
 &X > x_{L3}, \text{ and} \\
 &X > x_{L4}
 \end{aligned}
 \tag{6.47}$$

#### 6.6.4. Other relays

Several other relays that are used in power systems that are not discussed in this section include directional relays, offset impedance relays, reactance relays and blinders. The modeling of these relays is based on procedures that are similar to those outlined in this document. Modeling of relay schemes should include models of communication interface, logic and channel including uncertainty of delay, channel noise, jitter, fading and loss of channel. The extent and inclusion of these effects in a relay scheme model depends on the type of study to be conducted.

## **7.0 Validation of Relay Models**

In order to ensure adequate accuracy of the produced results, a very important stage of the model development process is a detailed validation and verification procedure.

### **7.1. The Principle and Different Methods of Validation**

The general principle of validation is based on comparison of the results produced by the model and those of the actual device under various genuine and simulated power system fault conditions. The actual relay data can be obtained either by testing a relay device in the laboratory, from the manufacturer's type testing documentation or from other public domain publications (e.g. generic operational characteristics).

#### **7.1.1. Modular validation**

Validation procedures may concern individual components of the relay as well as the whole relay. It is always easier to validate simple components rather than complicated structures. However, the design of the device does not always facilitate such an approach. Validation of the individual components is feasible when the relay has a modular architecture and each module (component) can be monitored separately i.e. there is access to the internal signals within the relay device or the relay provides internal signal recording facility. The range of input/output signals should be sufficient to capture the required operational characteristics of the modeled component. Validated model components may then be utilized to build models of larger structures and/or entire relays.

The validation of the components, however, does not eliminate the need for validation of the whole relay. The procedures may be less extensive if the component validation was performed but, nevertheless, it is still necessary to validate the relay in order to determine the performance of the protection and eliminate possible modeling mistakes, which are very likely to occur in complicated structures.

#### **7.1.2. Validation with the use of secondary injection**

Nowadays, the relays can be tested by means of specialized injection equipment which reproduces secondary current and voltage waveforms from digital fault recorder data. An actual fault record from a network event can be used as an input signal or the record obtained by means of simulation, however, it has to be considered that recorded events in general are filtered before recording.

In the utilities' practice, a common method of testing relays in the field is to inject only the fundamental frequency components of waveforms and to instantaneously switch from the pre-fault state to the faulted state without consideration of the low or high frequency components that exist in a real power system during the transition. This type of test has been called "Pseudo Transient" testing [188] or "Dynamic State Simulation" [189]. It is based on the assumption that the relay measures only fundamental frequency components, and it is not necessary to consider the other frequency components of the measured signal during testing.

Injection of the real relay and the model with the same signal is a very effective method of validation since both the relay and the model are always subjected to the same input signals and therefore the same response is expected. However, when using the phasor based test method or the Pseudo Transient testing, differences between the model and the real relay may be observed due to the non-realistic nature of this type of test.

An example validation approach based on injection equipment is represented in Figure 7.1.

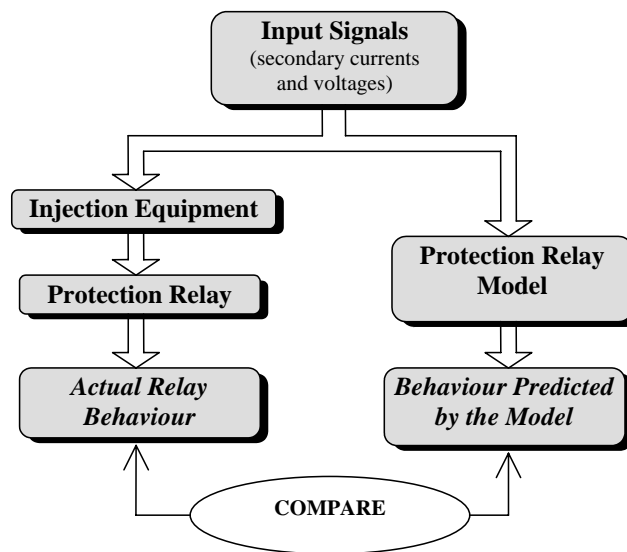


Figure 7.1: Injection Equipment Based Method of Model Validation [17]

### 7.1.3. Validation using published test results and relay technical specification

It is also possible to validate the performance of a relay model using public domain data or the data from the manufacturer’s type testing procedures. However, often such model created on the basis of manufactures description of operation does not fully correspond to the actual dynamic behaviour of the relay. Therefore, this approach is particularly practical in the case of phasor-based models, which do not require detailed dynamic behaviour to be taken into account. In such cases theoretical characteristics may be sufficient to validate the required scope of operation of the model.

If, for some reason, accurate dynamic behaviour is necessary, it is important to perform an extensive validation procedure in order to assess the accuracy of the simulation results under varying power system fault conditions, and if possible, perform some additional amendments to the relay model.

### 7.1.4. Selection of the validation method

It is important to bear in mind that the type and method of validation depends on few factors such as:

- type of relay;
 

In the case of electromechanical relays, validation primarily involves the calibration of model parameters such as resistances and magnetic properties of the relay’s mechanism. Because of the strong interdependence of all the parts it is usually not possible to apply the modular approach. Especially, accurate modeling of the time response and saturation effects requires large expenses. On the other hand, electronic and numerical devices are usually suited to a structural approach to validation due to their internal modular architecture.
- extent of modeling;
 

Static vector-based relay models do not require a very detailed dynamic verification procedure. In such cases, validation can be constrained to the comparison of the relay theoretical (or measured) static tripping characteristics with the model simulation results. The time factor is not taken into account since the relay model does not have enough detail in order to respond dynamically to the input signals. However, a constant time delay can still be incorporated, especially for the evaluation of the time response of higher zones. On the other

hand, dynamic models of protection require more extensive measurement and validation procedures. Not only must the static tripping characteristic be consistent, but also tripping times under various system conditions have to be considered and tested. Therefore, accurate and detailed test programs need to be designed and performed.

- availability of data from the relay;  
Different designs of relays provide different levels of information, which is an important factor in the determination of the validation method. For example internal recording facilities are very useful for the purposes of individual module validation. In addition, some relays have internal measuring points connected to a special socket, which is accessible from the front panel of the relay. In other designs where the number of accessible signals is limited due to the relay design, confidentiality or other reasons, the testing program needs to be more extensive.

## **7.2. Relay Testing Procedures**

The scope of the testing procedures may vary depending on the type of model and on the type of relay design. A general guiding principle is that, as much as possible, the test program should include the range of realistic conditions under which the device is expected to operate. This includes the faults under which the relay trips as well as those when the relay remains stable. Due to the limited number and range of recorded genuine network faults, only a restricted test set could be formed by getting fault records. The most effective way of creating a suitably extensive test set is by means of network simulation. Programs such as EMTP, PSCAD/EMTDC and others can simulate various system configurations and fault events. The tests to be conducted for model validation should contain, depending on the type of relay and the type of model, some or all of the following test categories:

- operational tests (static conditions);  
The tests of this type are performed in order to ensure the proper steady state operation of the relay. Simulations include the marginal conditions for relay operation such as, for instance the faults on the verge of a zone in the case of distance relays or high resistance faults and external worst case scenario faults for unit protection relays. Operational tests are considered sufficient for the vector-based static relay models; in this case the input signals are presented in the form of vectors rather than sampled voltage and current waveforms.
- timing tests (dynamic conditions);  
Timing tests are designed to verify the dynamic response of the relay. Under various fault configurations a number of simulations are performed and the tripping times are recorded. The variable fault parameters could include: (1) the type of protected circuit (overhead line, cable, transformer, etc.), (2) the length of protected circuit, (3) the position of the fault along the protected circuit, (4) power system fault level, (5) fault connection and resistance, (6) type of earthing in the grid. This category of tests is necessary for transient relay models. Input signals are sampled current and voltage traces.
- comparison of transient traces inside the relay (dynamic conditions);  
If possible it is recommended to utilise the recording of transient signals from inside the relay. In the case of transient models of complex relays this helps to verify individual sections of the device model through comparing model and relay transient responses. This is the most reliable method of validation of the dynamic protection models.

Such diversity of the simulation scenarios may lead to a rather large quantity of tests. Therefore, the marginal values of the variables have to be identified carefully and in accordance with the expected conditions under which the relay might operate.

### **7.3. Assessment of the Accuracy**

The proper assessment of the accuracy of the results produced by the model is essential for further interpretation of relay simulation results and diagnoses. A suitable method for accuracy evaluation needs to be adopted according to the design and the scope of the relay model operation. It is natural that the scope of the testing procedures determines the area of further application of the model. It is often difficult to predict or assess the accuracy outside the scope of testing. The maximum as well as average error should be calculated since this better indicates the sensitivity of the model to changing fault conditions. A maximum error, which is much larger than the average value, indicates high sensitivity of the model to certain types of faults. Additional information indicating under which specific conditions the relay model accuracy deteriorates most is useful in indicating the confidence of the results of the protection system studies. The maximum possible deviation between relay and its model is of special interest with investigations of the protection behaviour during system disturbances.

There are various ways of expressing an error depending on the type of model and extent of validation:

1. In the case of static (vector based) models, the error can only be measured in terms of operational characteristics of the relay. The time response has to be neglected since the model by its nature does not define its response to transient fault conditions. These models may be used in steady-state power system protection studies. Suggested accuracy indices for distance and unit type protection can be as follows:
  - For the operation of distance zones the error can be expressed as a percentage of the length of the protected circuit;
  - For unit protection marginal conditions, under the faults with high resistance, the error may be expressed as a percentage of the marginal fault resistance for which the relay trips;
2. In the case of detailed dynamic models, apart from the consistency of the static operational characteristics, time response needs to be assessed as well. The models of this type are suited to simulation studies involving transient and/or non-linear system conditions. In terms of time response two general categories of operation can be distinguished:
  - For fast operating relays (instantaneous tripping within one or two cycles) the tripping time error can be characterized in terms of an absolute time difference between the model and the relay (in ms);
  - For slower operating schemes (IDMT or time delayed zone 2 or zone 3 tripping – operation from a few hundred milliseconds to seconds) the error can be expressed as the percentage of the recorded actual tripping time.

### **7.4. Validation Examples**

Two validation examples are presented in the following sections. The first case presents results of the validation exercise performed on a custom-built relay model of the distance relay X. The relay model was based on available public domain documentation.

The second example presents the validation test results for a model of the distance relay Y. In this case, the relay model was provided directly by the manufacturer.

The names of the relays have been purposefully concealed in order to avoid any possible confidentiality issues.

### 7.4.1. Validation of the relay model X

#### 7.4.1.1. Description of the relay and the model

Type X distance relay is a modern numerical distance protection relay containing individual measuring elements for different types of faults in different impedance zones. A model of the relay has been developed, including five impedance zones (Z1, Z1X, Z2, Z3 and Z4) with selectable shape (MHO or Quadrilateral) and polarization method (self or memory polarized), directional line and load blinder lines. A model of the high set instantaneous overcurrent protection contained within the relay was also included. The model was entirely based on available public domain documentation, and although, is not an exact replica of the relay algorithm, it does adequately reflect the relay's behaviour. The model algorithm was implemented using C++ language, which was selected because of its computational efficiency but also because of the object oriented structure, which allowed the description the relay internal architecture in a more natural manner. The overall modular structure of the single relay is presented in Figure 7.2.

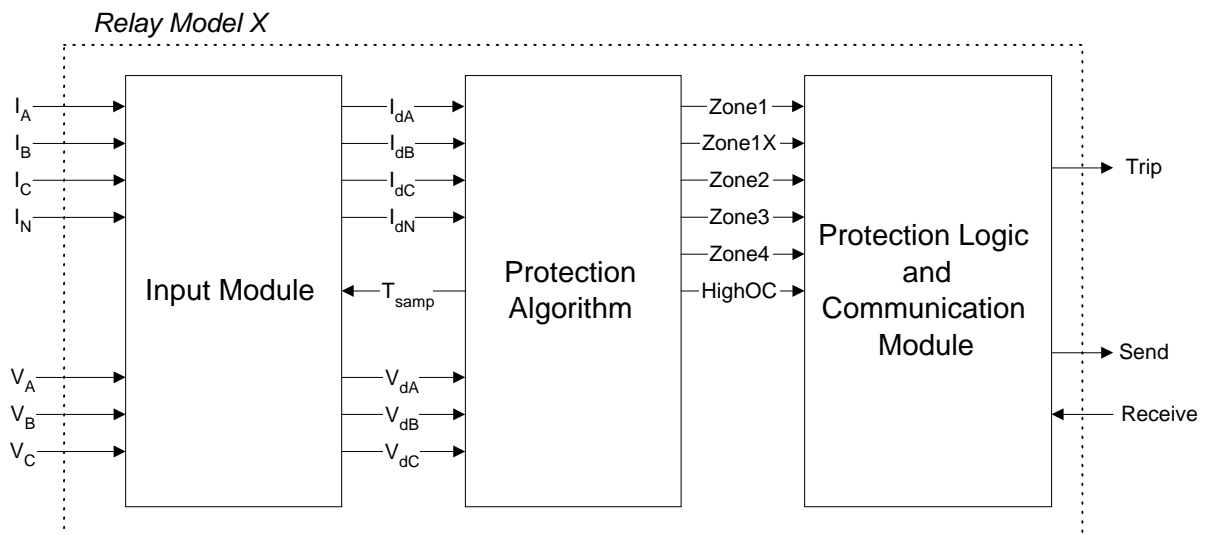


Figure 7.2: Structure of the relay model X

The transient display of the model shown in Figure 7.3. presents the locus of the impedance vector for 6 different types of fault connections (AE, BE, CE, AB, BC, CA). Together with the impedance locus, the individual zone boundaries ( $z_1, z_2, z_3$  and  $z_4$ ) are plotted on the transient display. Operation of a particular comparator of the selected zone is illustrated by means of the small circle (e.g. in Figure 7.3, zone 2 was selected for visualization and an operation of the phase A to phase B zone  $z_2$  comparator can be observed).

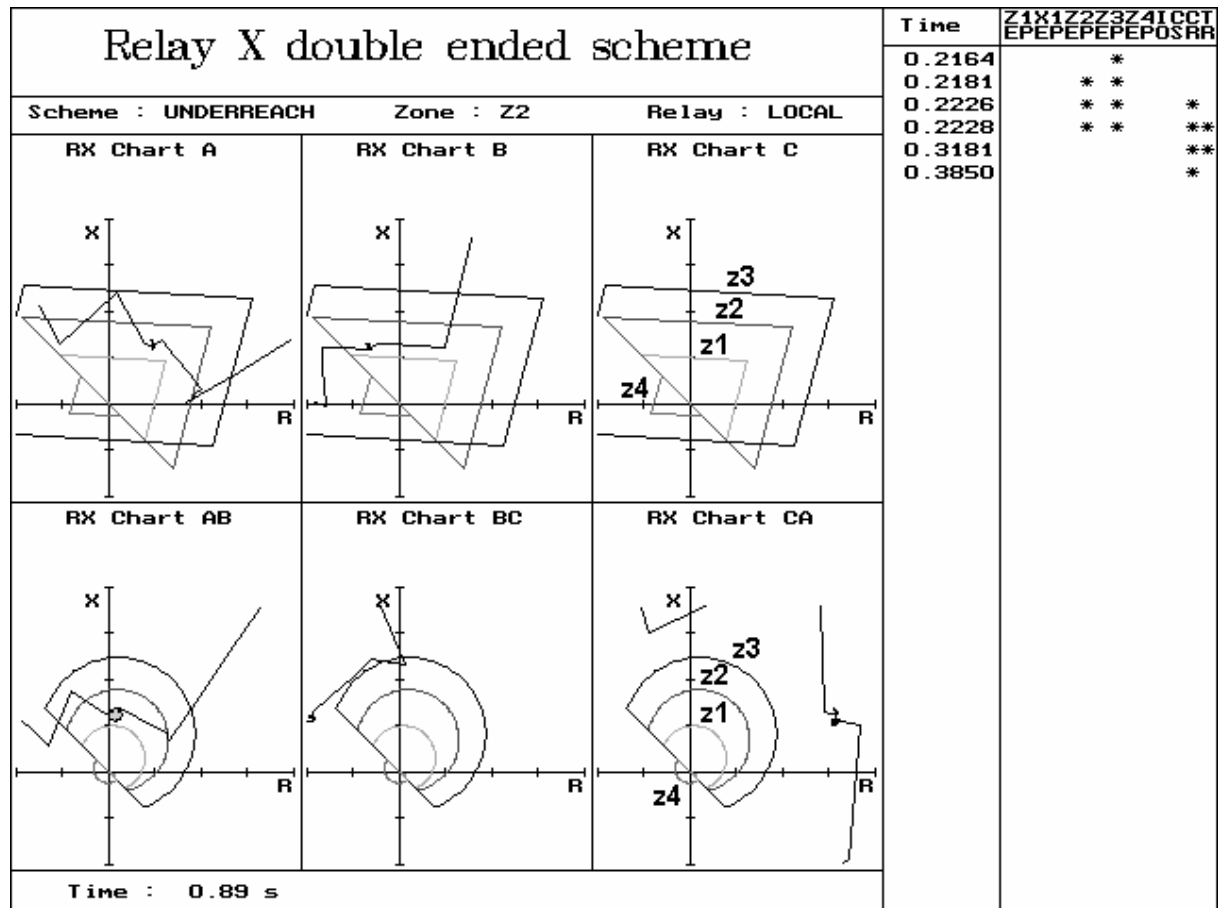


Figure 7.3: Graphical display of the distance relay model X

The event box on the right hand side contains the record of the following signals:

- Z1E - output of the Zone 1 phase to earth comparators;
- Z1P - output of the Zone 1 phase to phase comparators;
- Z1XE - output of the Zone 1X phase to earth comparators;
- Z1XP - output of the Zone 1X phase to phase comparators;
- Z2E - output of the Zone 2 phase to earth comparators;
- Z2P - output of the Zone 2 phase to phase comparators;
- Z3E - output of the Zone 3 forward looking phase to earth comparators;
- Z3P - output of the Zone 3 forward looking phase to phase comparators;
- Z4E - output of the Zone 4 forward looking phase to earth comparators;
- Z4P - output of the Zone 4 forward looking phase to phase comparators;
- IO - output of the high set instantaneous overcurrent module;
- CS - carrier send (blocking or acceleration);
- CR - carrier receive (blocking or acceleration);
- TR - relay trip output.

#### 7.4.1.2. Test program

The test program was based on the simulation results obtained by means of the ATP simulation of the 400 kV power network presented in Figure 7.4. The system currents and voltages recorded in the simulation were applied to an example relay using a secondary injection toolkit.

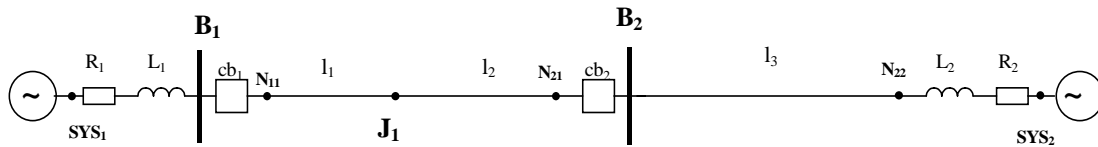


Figure 7.4: Test network for the relay model X

The parameters of the system components and fault configurations are summarized in the tables below. The relay Zone 1 setting was 80% of line length, Zone 2 setting 150% of line length, Zone 3 setting 200% of line length.

• **Operational Tests**

VARIABLES	PARAMETERS	
Line Length ( $l_1+l_2$ ):	50 km	200 km
Fault Connection:	A – E	A - B
Infeeds B <sub>1</sub> - N <sub>22</sub> :	5 - 20 GVA	20 - 5 GVA
Fault Resistance:	0	10 Ohms      20 Ohms

The goal of the operational tests is to find the fault position ( $J_1$ ) at margins of operation. A series of simulations were performed for each case by moving the fault position by 1% of the line length at a time. The margins of operation were recorded for zone 1 and zone 3. The above specification results in  $2*2*2*3=24$  different tests for each zone of operation.

• **Timing Tests**

Tests for zone 1 only

VARIABLES	PARAMETERS	
Line Length ( $l_1+l_2$ ):	50 km	200 km
Fault Position ( $J_1$ ):	0%	50%
Point-on-wave:	0°	45°      90°
Fault Connection:	A – E	A - B
Infeeds B <sub>1</sub> - N <sub>22</sub>	5 - 20 GVA	20 - 5 GVA

The above timing test specification results in  $2*2*3*2*2=48$  different tests. The tripping times of the relay were recorded by means of the digital inputs provided with the injection toolkit.

**7.4.1.3. Test results**

All of the test results are presented in the tables and graphically illustrated on the accompanying charts in “Appendix 7A. Test Results of the Relay X”.

Table 7A-1 and Figure 7A-1 present the results of the timing tests. Each test was performed 10 times on the actual relay in order to assess repeatability of the results. The minimum and maximum tripping times of the relay together with the model tripping time were recorded and these results are contained in Table 7A-1. The time error has been defined in the following way:

$$TimeError = \begin{cases} T_{Mod} - T_{RelMax} & \text{for } T_{Mod} > T_{RelMax} \\ 0 & \text{for } T_{RelMax} \geq T_{Mod} \geq T_{RelMin} \\ T_{RelMin} - T_{Mod} & \text{for } T_{RelMin} > T_{Mod} \end{cases} \quad (1)$$

Where:

$T_{Mod}$  - model tripping time;  
 $T_{RelMin}$  - relay minimum tripping time;  
 $T_{RelMax}$  - relay maximum tripping time.

The maximum error resulting from the tests is 1.3 ms (test No 37), the average error for all the tests being only 0.19 ms. This indicates high accuracy in the simulation results. With the exception of the worst test (No 37) the tripping times produced by the model all produce an error below 1 ms, half of the tests being within the range of times obtained during injection tests on the actual relay.

The operational test results are presented in Table 7A-2 (for zone 1) and Table 7A-3 (for zone 3) respectively. Again, each test was repeated 10 times. Some results include two numbers in the 'relay reach' column. These are the cases when the relay operation was not entirely secure and when repeated 10 times the relay tripped on some occasions and remained stable on others. The lower limit shows the test in which all of the 10 injections resulted in a relay trip and the upper limit indicates the test in which at least one of the 10 injections caused the relay to trip. A further increase in the fault position distance resulted in no-trip. The average value of the two is graphed in Figure 7A-2 (for zone 1) and Figure 7A-3 (for zone 3). The error (expressed as a percentage of the line length) is defined as the absolute difference between the relay device's medium reach and the model's reach. From the tripping tests it can be concluded that the general performance of the model is not worse than 1% (average error 0.25%) of the line length for zone 1 and 3% (average error 0.875%) for zone 3.

However, the hardware test results could be slightly biased by the inaccuracy of the injection toolkit (zone 3 results in particular since the current levels are much lower and are generated with much less relative accuracy). The injection equipment amplifiers utilized for the purposes of this validation exercise introduce an error of about 1-2% and therefore a higher level of the modeling accuracy was not possible. Additionally, it has been discovered during the tests that the current analogue amplifiers produced a high frequency noise (>10kHz), which distorted produced current waveforms significantly. Although, in most cases due to the filtering circuits installed in the relays the influence of this noise can be considered marginal it can have an effect on some relay designs and has to be somehow limited.

## 7.4.2. Validation of the relay Y

### 7.4.2.1. Description of the relay and the model

The distance relay Y is a combined control and protection device, which can be used for operation in medium and high voltage grids. All six loops (phase to phase and phase to earth) are watched permanently.

It has two basically different starting functions:

- Under voltage controlled overcurrent starting function;
- Under impedance starting function.

For the selected tests the first one was used. The angle between voltage and current of the short circuit loop can be used to get a higher sensitivity especially for fault locations behind long transmission lines (as presented in Figure 7.5.).

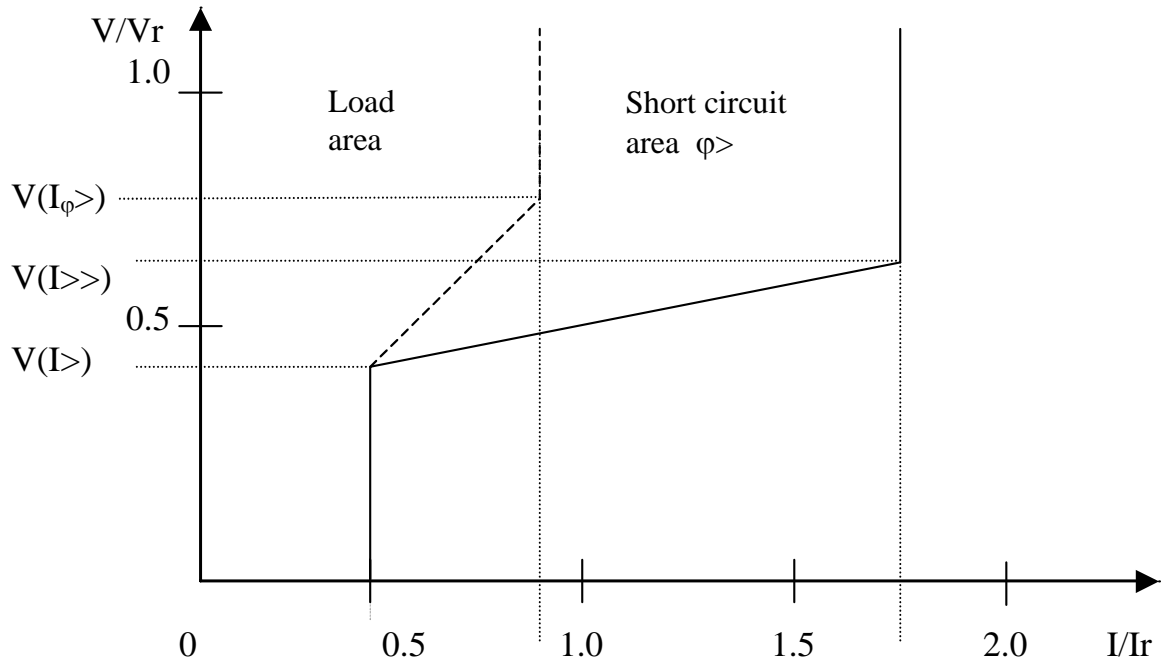


Figure 7.5: Under voltage controlled over current starting function of the relay Y

If the overcurrent starting function is not used the under impedance starting function is realized by each tripping zone itself.

It is possible to define a so-called load section in which the distance function is blocked. The tripping characteristics are presented in Figure 7.6.

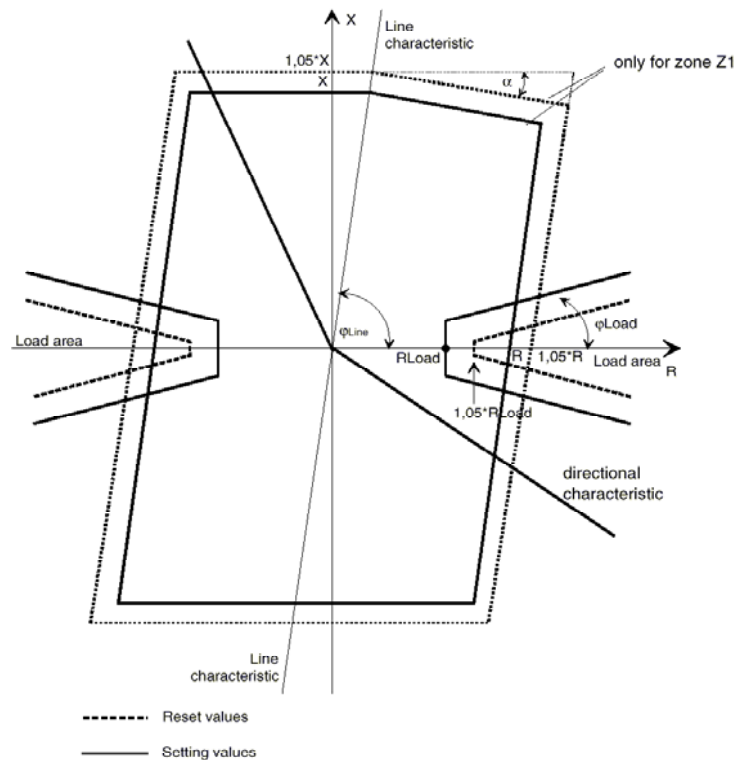


Figure 7.6: Tripping characteristics of the relay Y

The digital model was provided by the manufacturer. The model consists of several parts:

- The man-machine-interface with the surface of the relay, the signaling, the leds;
- The parameterisation tool;
- The interface to the process (e.g. relay input transformers, binary inputs, etc.);
- The protection software module;
- Debug module.

The protection software module is the same as used in the real relay. So it is possible to analyze the protection behaviour very carefully by help of the debug function. Later on it is planned to support the technical staff with this protection model to investigate the behaviour of the relays during network disturbances. The front end of the model is shown in Figure 7.7. It is identical to the outfit of the real relay.

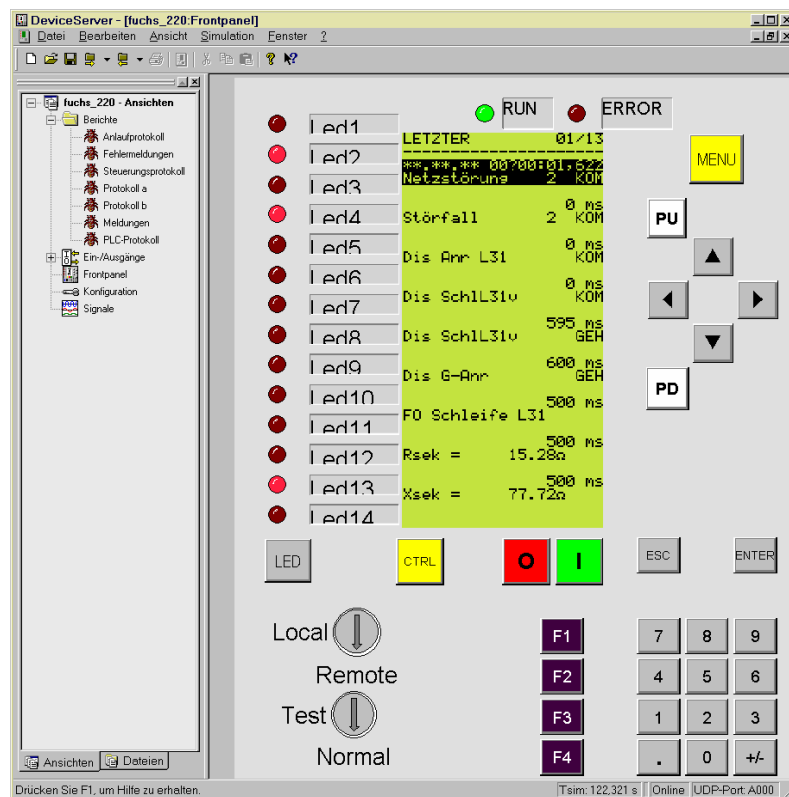


Figure 7.7: Front end of the relay model Y

#### 7.4.2.2. Realisation of the comparison tests

The voltage and current transients were calculated by EMTP/ATP with data of a 220-kV double system of overhead lines of a regional supplier. The whole network is shown in Figure 7.8. The tests with the real relay were realized in the protection test laboratory of KEMA-IEV in Dresden/Germany. With the same transients, saved as COMTRADE-Files, the digital model of this distance protection was also tested.

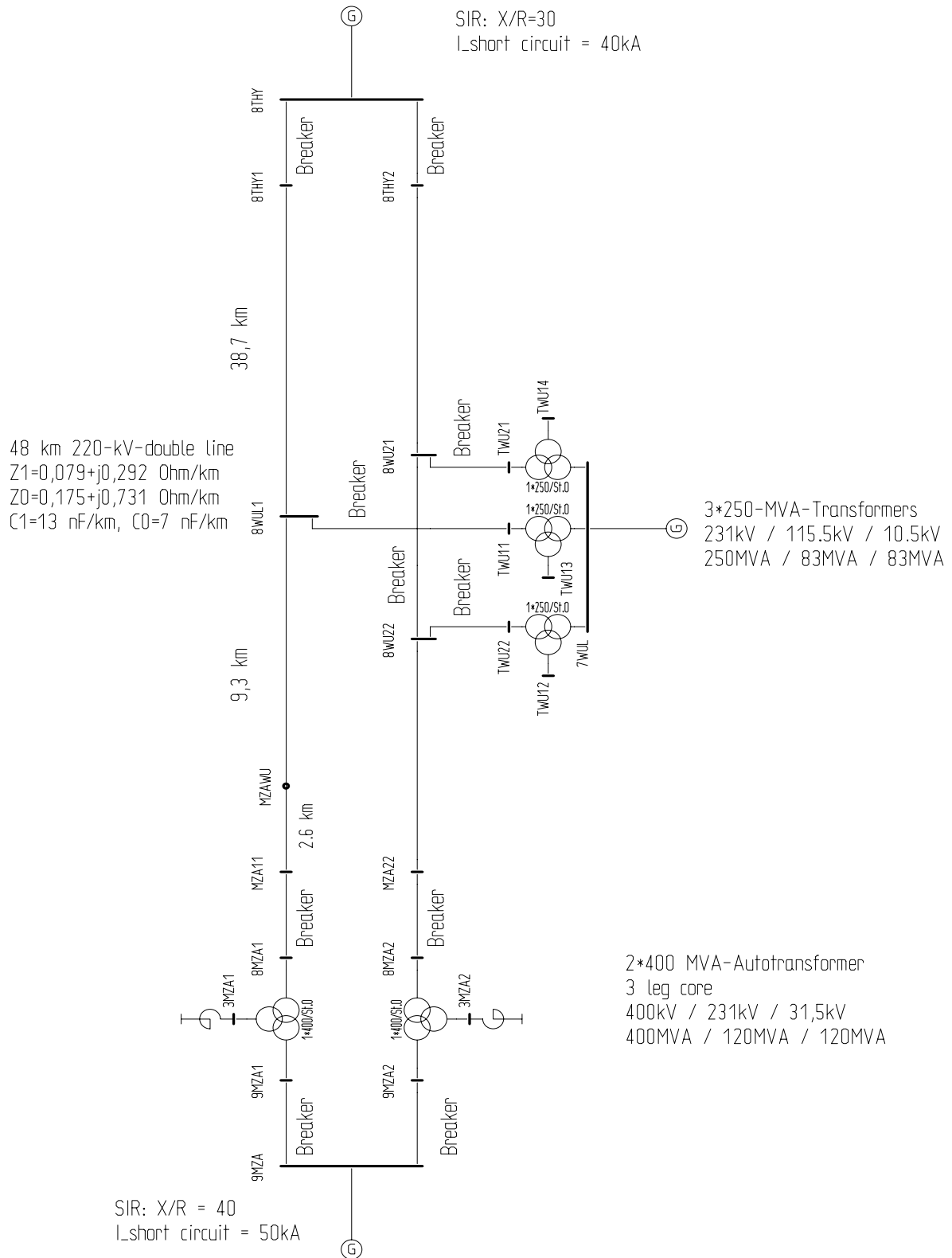


Figure 7.8: Digital model of 220-kV-double overhead line of a regional supplier

Some steady state condition tests were realized first:

Type of short circuit	Setpoint value for starting	Digital relay		Digital Relay model	
		pick up value	resetting value	Pick up value	resetting value
Ph1-Earth	0.20 A	0.20 A	0.18 A	0.20 A	0.19 A
Ph2-Earth	0.63 A	0.65 A	0.54 A	0.63 A	0.55 A
Ph3-Ph1	0.35 A	0.36 A	0.30 A	0.35 A	0.30 A
Ph2-Ph3	1.50 A	1.50 A	1.41 A	1.49 A	1.42 A

Table 7.1: Pick up and resetting values with stationary currents and voltages

It can be stated that in general the accuracy of both the digital relay and the digital relay model is very high and deviations between relay and relay model are relatively low especially with vertical parts of the pick up characteristic (see Figure 7.5. and line 1 and 4 of Table 7.1.). The accuracy of segments of the pick up characteristic between the values of  $I >$  and  $I >>$  is a little bit different between the real relay and the model (line 2 and 3 of Table 7.1.). The deviation of the real relay reaches up to 3.2% (line 2 of Table 7.1.).

The detailed results of the model validation exercise are included in “Appendix 7B. Test results of the Relay Y”. The transients and the reactions of the model of the relay referring to line 2 are presented in Figure 7B-1.

A short description of selected transient files used for dynamic tests is given in Table 7.2:

File of transients	Location of protection	Description
22008	8MZA1→MZA11	Three phase short circuit at 9MZA1, switch off of 9MZA→9MZA1 after 85 ms
22009	8MZA1→MZA11	Ph1-Ph2 short circuit at 9MZA1, switch off of 9MZA→9MZA1 after 85 ms
22021	8MZA1→MZA11	Evolving fault at MZAWU: Ph1-E → Ph1-Ph2-E 8ms later, $R_{F\text{ Ph1-Ph2}} = 0\Omega$ , $R_{F\text{ -E}} = 0.1\Omega$
22022	8MZA1→MZA11	Evolving fault at MZAWU: Ph3-E → Ph3-Ph1-E 8ms later, $R_{F\text{ Ph3-Ph1}} = 0\Omega$ , $R_{F\text{ -E}} = 0.1\Omega$
22024	8THY→8THY1	Evolving fault at MZAWU: Ph3-E → Ph3-Ph1-E 8ms later, $R_{F\text{ Ph3-Ph1}} = 0\Omega$ , $R_{F\text{ -E}} = 2.0\Omega$
22026	8THY→8THY1	Evolving fault at MZAWU: Ph3-E → Ph3-Ph1-E 8ms later, $R_{F\text{ Ph3-Ph1}} = 0\Omega$ , $R_{F\text{ -E}} = 15.0\Omega$
22031	8THY→8THY1	Evolving fault at 8WUL1: Ph1-E → Ph1-Ph2-E (11ms later) → Ph1-Ph2-E+Ph3-E (7ms later) → Ph1-Ph2-Ph3 (7ms later)
22M30	8MZA1→MZA11	Evolving fault at 8WUL1: Ph1-E → Ph1-Ph2-E (32ms later) → Ph1-Ph2-E+Ph3-E (37ms later) → Ph1-Ph2-Ph3 (16ms later)
22T30	8THY→8THY1	Evolving fault at 8WUL1: Ph1-E → Ph1-Ph2-E (32ms later) → Ph1-Ph2-E+Ph3-E (37ms later) → Ph1-Ph2-Ph3 (16ms later)

Table 7.2: Description of test files used

The following table gives an overview of the results of the realised dynamic tests with short circuits calculated with the model of the 220 kV overhead line presented in Figure 7.8.

File	Starting time in ms		Tripping time in ms		Remarks
	Model	Relay	Model	Relay	
22008	21	32	410	420	correct operation, short circuit backward
22009	10 (Ph) 119 (E)	20 (Ph) 160 (E)	-	-	incorrect operation caused by inrush currents, short circuit backward, Figure 7B-2
22021	19	25	19	26	correct operation, short-line fault without DC-component
22022	33	42	33	43	correct operation, short-line fault with DC-component
22024	28	37	217	234	correct operation, short circuit in 2 <sup>nd</sup> zone with fault resistance to earth, Figure 7B-3
22026	35	47	47	58	overfunction, short circuit in 2 <sup>nd</sup> zone with higher fault resistance to earth
22031	16	34	222	233	correct operation, evolving fault in 2 <sup>nd</sup> zone
22M30	27	43	27	45	short-line evolving fault, correct but slow reaction of the relay
22T30	15	20	212	60	evolving fault in 2 <sup>nd</sup> zone, correct operation of the model, but overfunction (3%) of the relay, Figure 7B-4

Table 7.3: Results of realised dynamic tests

Evaluating Table 7.3 can be stated the following:

- The table contains results of tests with transients difficult to handle for the protection;
- In most cases the reactions of the relay and its model are the same;
- The relay needs from about 5 to almost 20 ms more time than the model;
- The model reacts correct with the last transient, the overfunction of the relay lies within the tolerance of about 5%.

#### 7.4.2.3. Model validation conclusions for the relay Y

The test results both of the stationary and the dynamic tests show the following:

- The accuracy of both the model and the relay is within the tolerances given;
- The model reacts a bit faster (5 ... 20 ms) than the real relay;
- The reactions of both the model and the relay are the same ones in most cases.

So the digital model of the relay can be used to investigate if:

- the parameterization of the relay or the whole relay itself is suited to solve the protection task;
- the behaviour of the relay was correct during the network disturbance;
- a better parameterization of the relay referring the protection task is possible

Such a model can also be a basis for discussions about protection problems with customers, e.g. representatives of energy supply companies.

## **7.5. Conclusions**

The validation procedure is a very important part of the model development process. Although it cannot guarantee a high level of accuracy under all possible fault conditions, it can indicate the constraints and the scope of application of the model. However, when the tests of marginal conditions are carefully chosen, the majority of actual network incidents will remain within the scope of the testing procedures.

With a properly selected scope of testing procedures, the validation exercise can also be used to establish the model application limits. This task may require an iterative approach to testing, where the modification of test conditions and re-application of tests is required after the completion of the initial test program. Another limiting factor in the relay validation cycle is the accuracy of the hardware used for testing. To achieve higher modeling accuracy more sophisticated and accurate injection system is required which can increase the cost of validation procedures significantly. Therefore, the hardware cost often forms a natural economic barrier, which may prevent from achieving high accuracy results. For more in depth observations on the limits of the relay modeling and the relay model application refer to chapter “Challenges of Relay Models”.

In the majority of cases, the models that are based on public domain information (e.g. manufacturers’ manuals) require more extensive testing procedures (relay model X in section 7.4.1.), than models supplied by manufacturers. These are usually more reliable and require only specific dynamic tests to be performed (relay model Y in section 7.4.2.). The ultimate validation exercise will be, however, to observe the performance of a model over time in practical diagnostic applications.

### Appendix 7A. Test Results of the Relay X

Test	Line Length [km]	Fault Position [%]	Point on Wave [°]	Fault Connection	Infeeds [GVA]	Relay Time [ms]		Model Time [ms]	Abs Error [ms]
						Min	Max		
1	50	0	0	P-E	5-20	17.2	18.5	18.1	0.0
2	50	50	0	P-E	5-20	18	19.4	19.7	0.3
3	50	50	0	P-P	5-20	17.5	19	19.7	0.7
4	50	0	0	P-P	5-20	16.7	18.7	18.0	0.0
5	50	0	45	P-E	5-20	15.9	17.7	17.2	0.0
6	50	50	45	P-E	5-20	16.1	17.3	17.2	0.0
7	50	50	45	P-P	5-20	16	18	18.8	0.8
8	50	0	45	P-P	5-20	15.6	17.1	17.2	0.1
9	50	0	90	P-E	5-20	18.1	19.8	18.1	0.0
10	50	50	90	P-E	5-20	18.5	19.6	18.1	0.4
11	50	50	90	P-P	5-20	18.6	20.5	19.7	0.0
12	50	0	90	P-P	5-20	18	20	19.7	0.0
13	200	0	0	P-E	5-20	16.6	17.9	16.4	0.2
14	200	50	0	P-E	5-20	17.2	18.6	18.1	0.0
15	200	50	0	P-P	5-20	17	18.8	18.0	0.0
16	200	0	0	P-P	5-20	16.5	17.7	16.3	0.2
17	200	0	45	P-E	5-20	15.7	17	15.6	0.1
18	200	50	45	P-E	5-20	15.5	16.7	15.6	0.0
19	200	50	45	P-P	5-20	16.1	18.6	18.8	0.2
20	200	0	45	P-P	5-20	14.9	17	17.2	0.2
21	200	0	90	P-E	5-20	18.2	19.5	18.1	0.1
22	200	50	90	P-E	5-20	18	20.1	18.1	0.0
23	200	50	90	P-P	5-20	18.5	19.6	19.7	0.1
24	200	0	90	P-P	5-20	17.8	19.6	18.0	0.0
25	50	0	0	P-E	20-5	16.5	17.6	16.4	0.1
26	50	50	0	P-E	20-5	17.1	18.8	18.1	0.0
27	50	50	0	P-P	20-5	16.8	18.4	18.0	0.0
28	50	0	0	P-P	20-5	16	17.8	16.3	0.0
29	50	0	45	P-E	20-5	15	16.9	15.6	0.0
30	50	50	45	P-E	20-5	15.5	17.4	17.2	0.0
31	50	50	45	P-P	20-5	15.5	17.1	17.2	0.1
32	50	0	45	P-P	20-5	14.9	16.9	17.2	0.3
33	50	0	90	P-E	20-5	17.6	19.4	18.1	0.0
34	50	50	90	P-E	20-5	18.6	20	18.1	0.5
35	50	50	90	P-P	20-5	18.1	19.6	18.0	0.1
36	50	0	90	P-P	20-5	17	19.1	18.0	0.0
37	200	0	0	P-E	20-5	16	17.5	14.7	<b>1.3</b>
38	200	50	0	P-E	20-5	17	18.5	18.1	0.0
39	200	50	0	P-P	20-5	16.8	18.2	18.0	0.0
40	200	0	0	P-P	20-5	15.6	17.2	14.7	0.9
41	200	0	45	P-E	20-5	14.7	16.3	13.9	0.8
42	200	50	45	P-E	20-5	15.4	17.1	15.6	0.0
43	200	50	45	P-P	20-5	15.6	17	17.2	0.2
44	200	0	45	P-P	20-5	14.7	16.1	13.8	0.9
45	200	0	90	P-E	20-5	17.6	18.9	18.1	0.0
46	200	50	90	P-E	20-5	18.2	19.9	18.1	0.1
47	200	50	90	P-P	20-5	18.1	19.7	18.0	0.1
48	200	0	90	P-P	20-5	17.2	18.7	18.0	0.0
								Max. Error	1.3
								Avg. Error	0.18

Table 7A-1: Results of timing tests

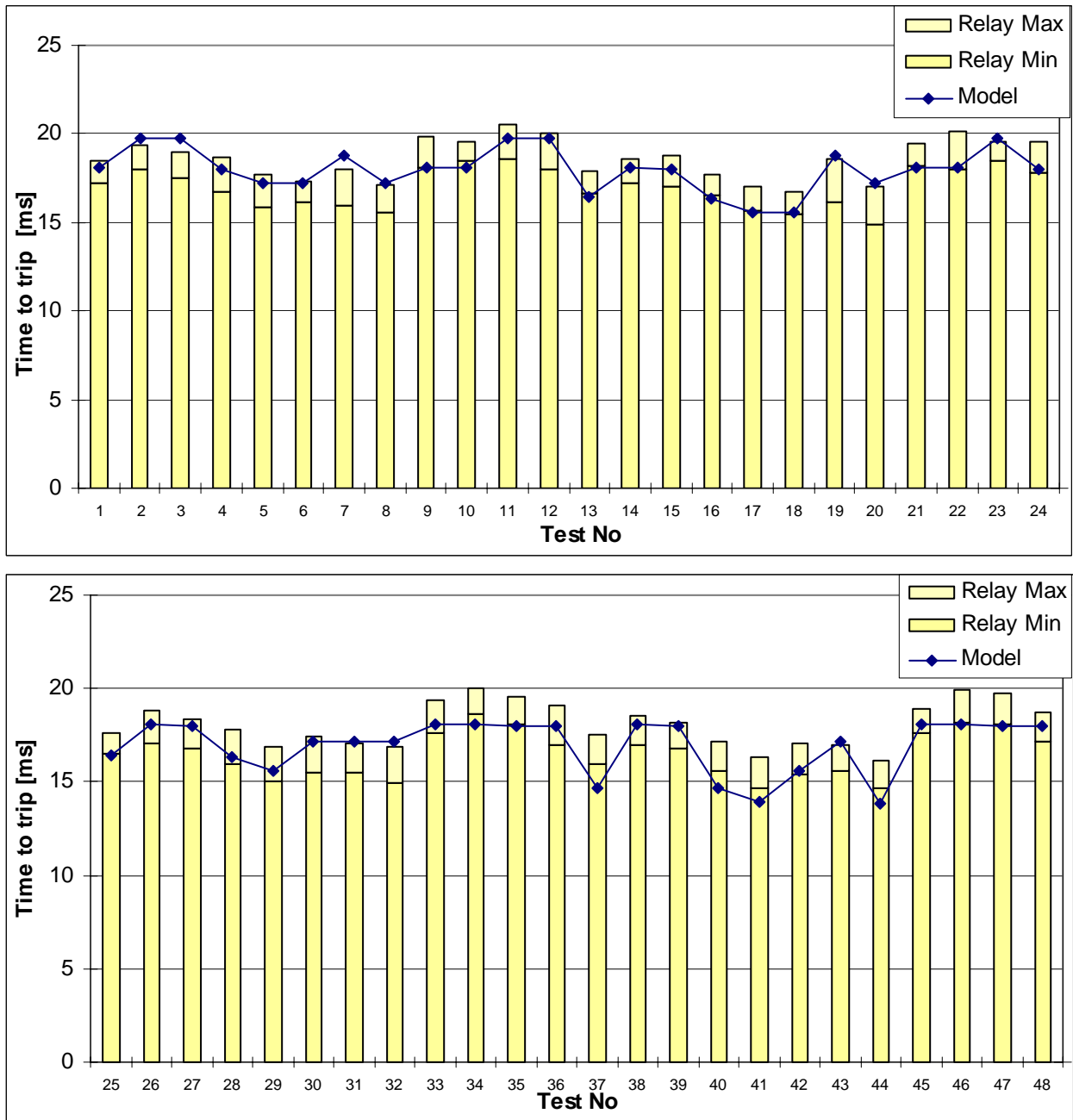


Figure 7A-1: Zone 1 timing tests comparison

Test No	Line Length [km]	Infeeds [GVA]	Fault Connection	Fault Resistance [ $\Omega$ ]	Relay Reach [%]	Model Reach [%]	Error [%]
1	50	5-20	P-E	0	80 – 81	80	0.5
2	50	5-20	P-E	10	49 – 50	50	0.5
3	50	5-20	P-E	20	0	0	0
4	50	5-20	P-P	0	81	82	1
5	50	5-20	P-P	10	65	65	0
6	50	5-20	P-P	20	36	36	0
7	200	5-20	P-E	0	80	80	0
8	200	5-20	P-E	10	78	78	0
9	200	5-20	P-E	20	77	77	0
10	200	5-20	P-P	0	82	82	0
11	200	5-20	P-P	10	82	82	0
12	200	5-20	P-P	20	76	76	0
13	50	20-5	P-E	0	81	80	1
14	50	20-5	P-E	10	76	76	0
15	50	20-5	P-E	20	0	0	0
16	50	20-5	P-P	0	81	82	1
17	50	20-5	P-P	10	72	72	0
18	50	20-5	P-P	20	44	44	0
19	200	20-5	P-E	0	80	80	0
20	200	20-5	P-E	10	78	79	1
21	200	20-5	P-E	20	78	77	1
22	200	20-5	P-P	0	81	81	0
23	200	20-5	P-P	10	80	80	0
24	200	20-5	P-P	20	77	77	0
Max. Error							1
Av. Error							0.25

Table 7A-2: Results of the Zone 1 operation tests

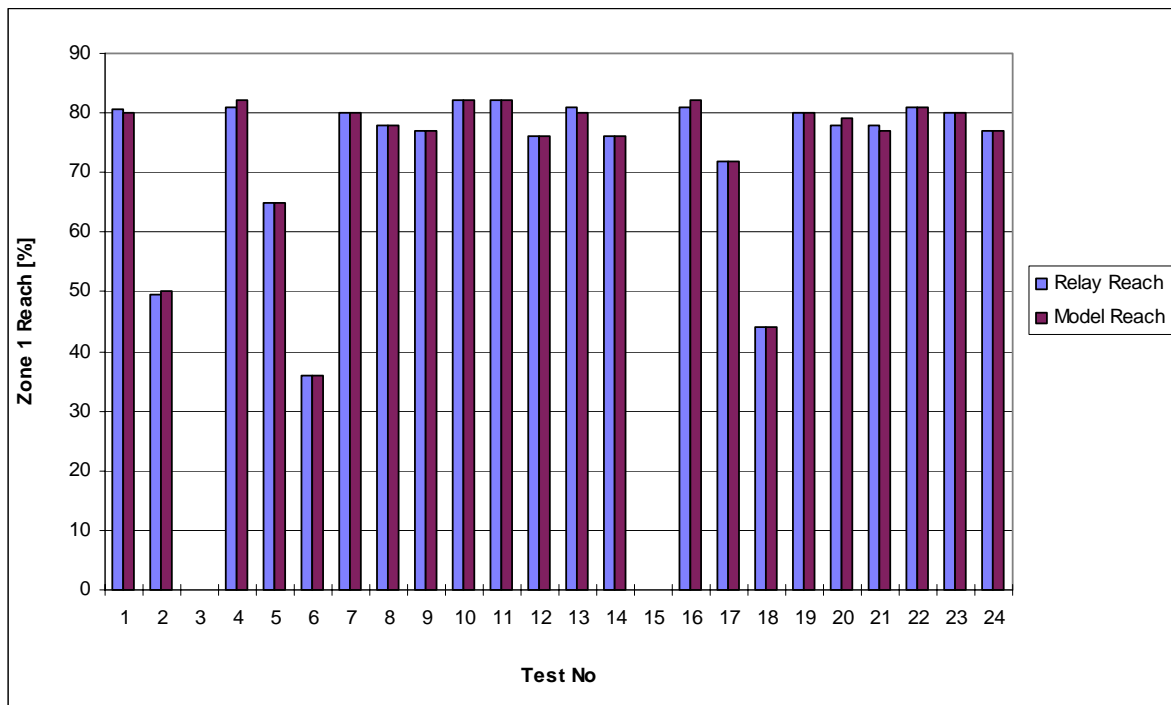


Figure 7A-2: Zone 1 operation test comparison

Test No	Line Length [km]	Infeeds [GVA]	Fault Connection	Fault Resistance [ $\Omega$ ]	Relay Reach [%]	Model Reach [%]	Error [%]	
1	50	5-20	P-E	0	204	201	3	
2	50	5-20	P-E	10	157	157	0	
3	50	5-20	P-E	20	95 – 96	94	1.5	
4	50	5-20	P-P	0	204	204	0	
5	50	5-20	P-P	10	150 – 151	150	0.5	
6	50	5-20	P-P	20	105	105	0	
7	200	5-20	P-E	0	193	190	3	
8	200	5-20	P-E	10	184	184	0	
9	200	5-20	P-E	20	178	177	1	
10	200	5-20	P-P	0	193	193	0	
11	200	5-20	P-P	10	181	181	0	
12	200	5-20	P-P	20	170	170	0	
13	50	20-5	P-E	0	204	201	3	
14	50	20-5	P-E	10	196	195	1	
15	50	20-5	P-E	20	174	175	1	
16	50	20-5	P-P	0	205	204	1	
17	50	20-5	P-P	10	191	190	1	
18	50	20-5	P-P	20	161	161	0	
19	200	20-5	P-E	0	193	191	2	
20	200	20-5	P-E	10	189	188	1	
21	200	20-5	P-E	20	186	185	1	
22	200	20-5	P-P	0	194	193	1	
23	200	20-5	P-P	10	188	189	1	
24	200	20-5	P-P	20	182	182	0	
							Max. Error	3
							Avg. Error	0.875

Table 7A-3: Results of the Zone 3 operation tests

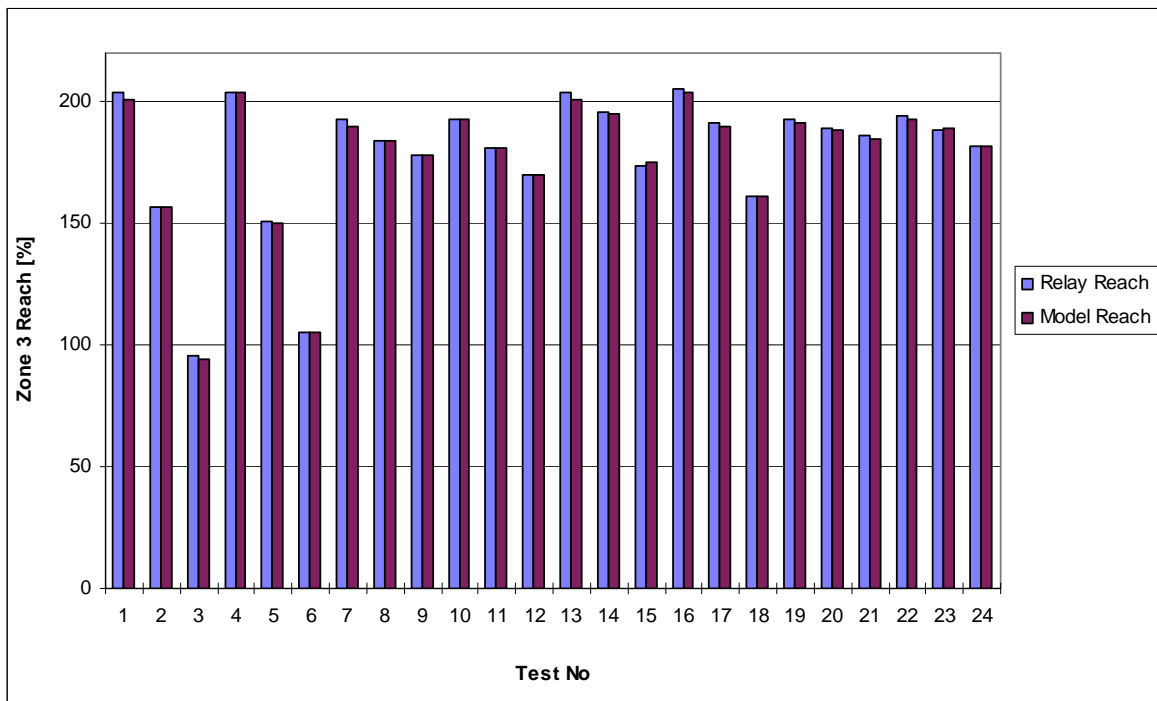
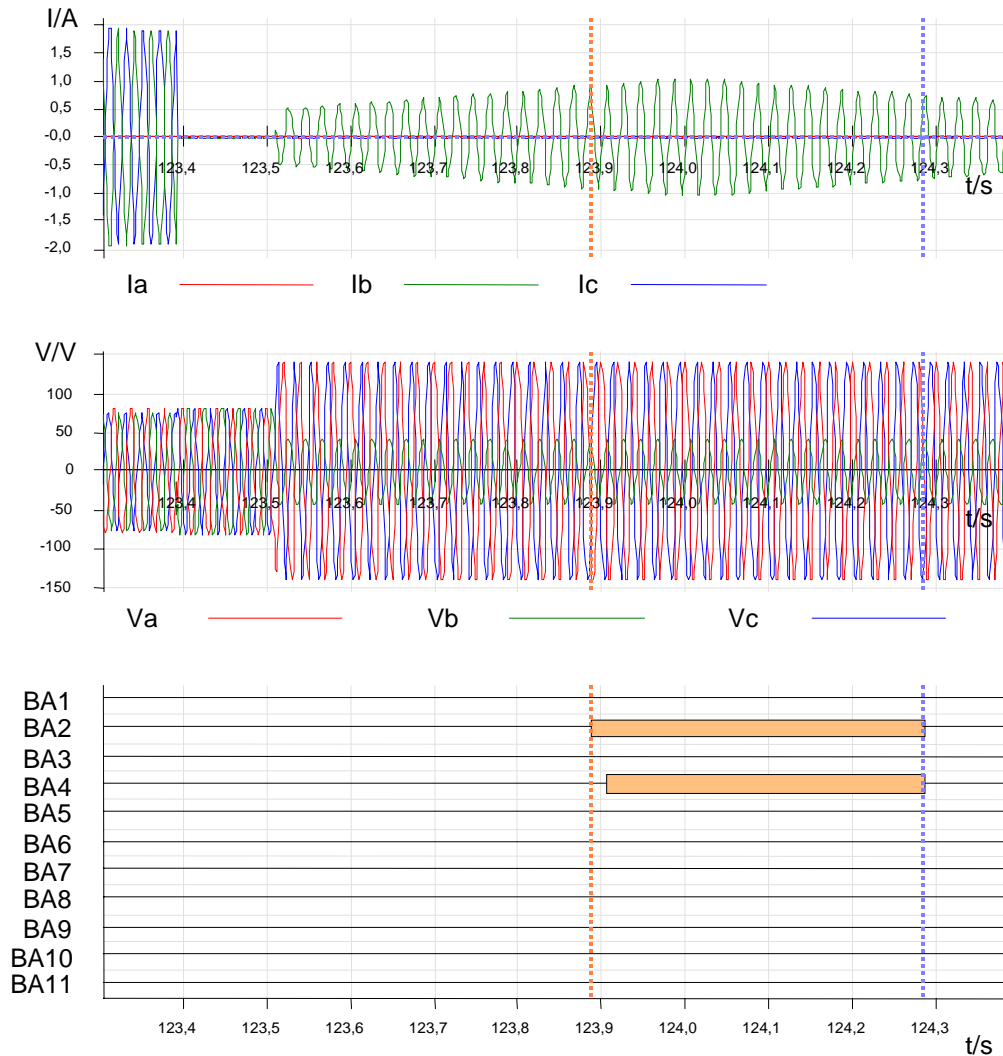


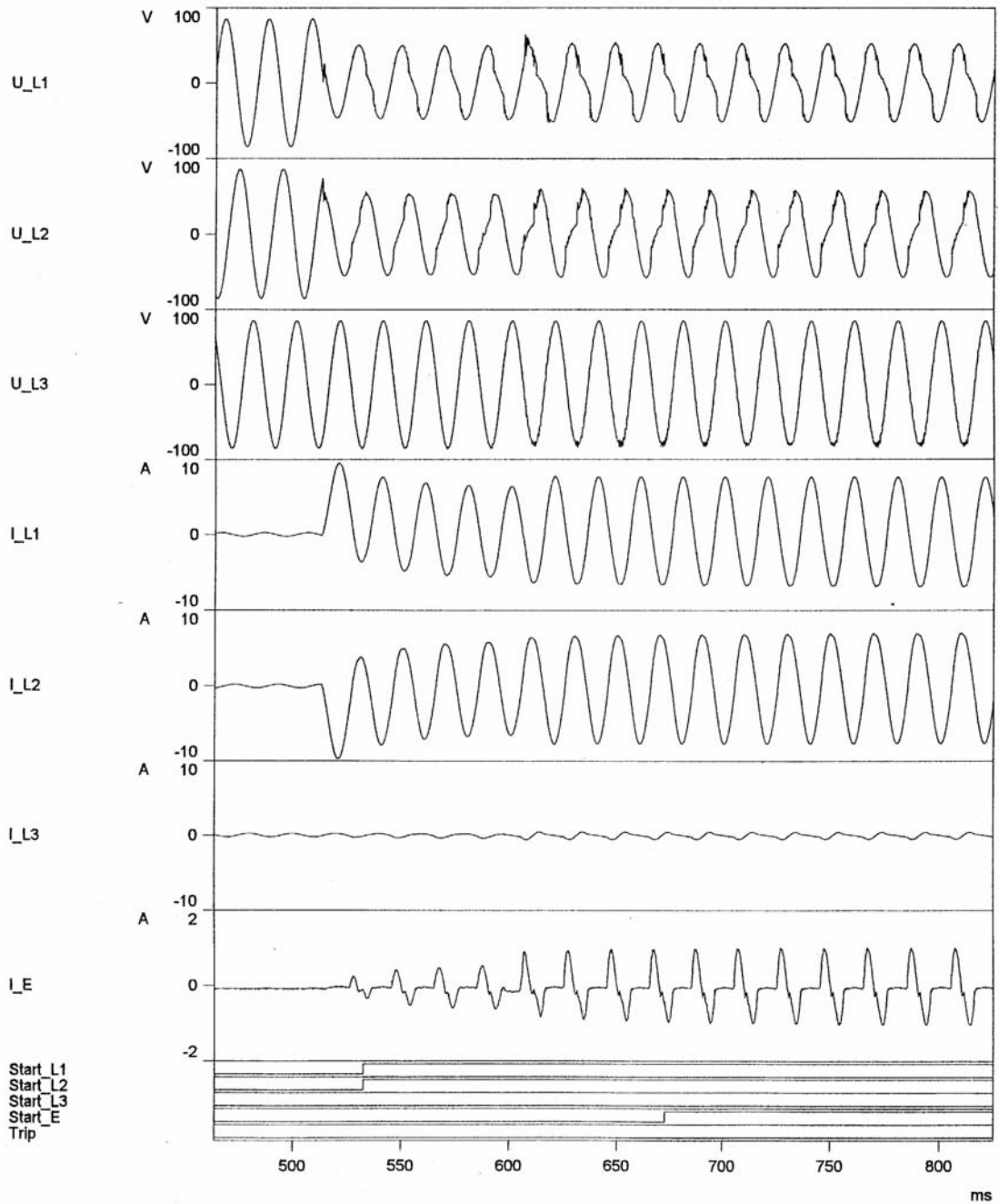
Figure 7A-3: Zone 3 operation test comparison

## Appendix 7B. Test Results of the Relay Y



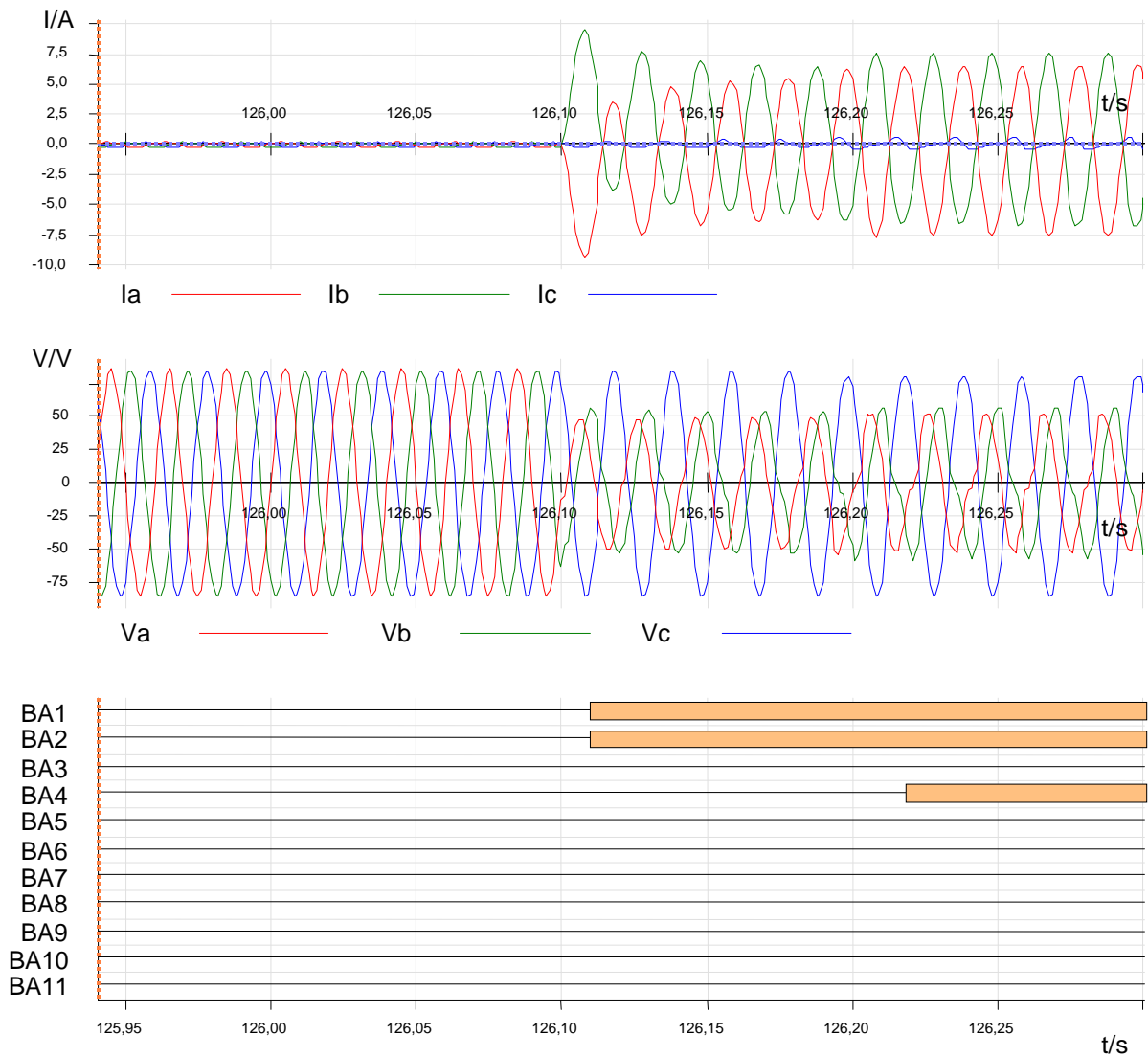
- 123.889 : Network disturbance starts
- 123.889 : general device starting signal appears
- 123.889 : starting signal Phase B of distance function appears (BA2)
- 123.904 : starting signal Earth of distance function appears (BA4)
- 123.904 : starting signal Phase B - Earth of distance function appears
- 124.284 : general device starting signal disappears
- 124.284 : starting signal Phase B of distance function disappears
- 124.284 : starting signal Earth of distance function disappears
- 124.284 : starting signal Phase B - Earth of distance function disappears
- 124.321 : Network disturbance ends

Figure 7B-1: Performance of the digital relay model with current ramp function short circuit Phase B – Earth



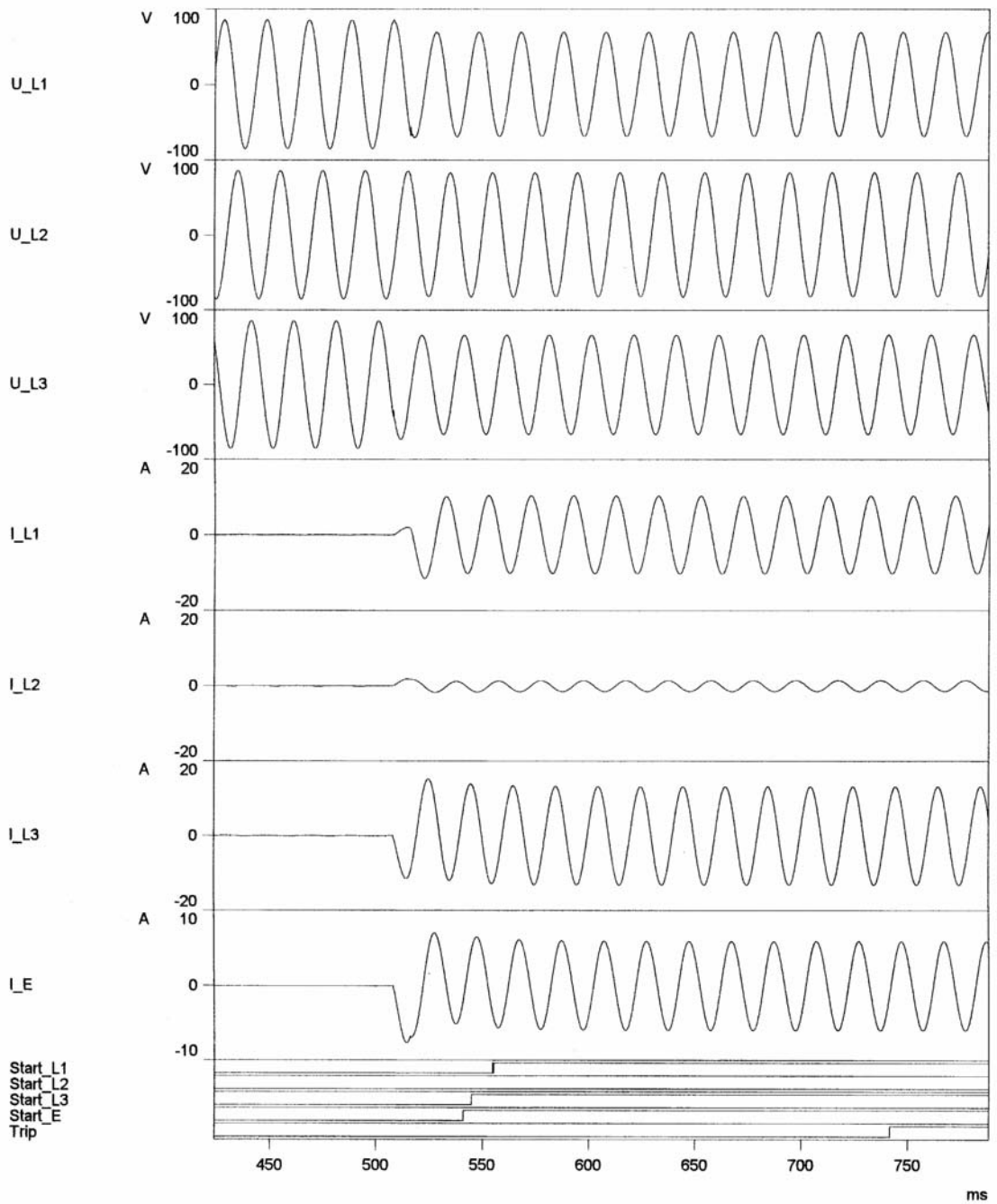
01.11.00 16:05:14 KEMA Dresden, Network Protection Laboratory

Figure 7B-2A: Performance of the digital relay with test file 22009



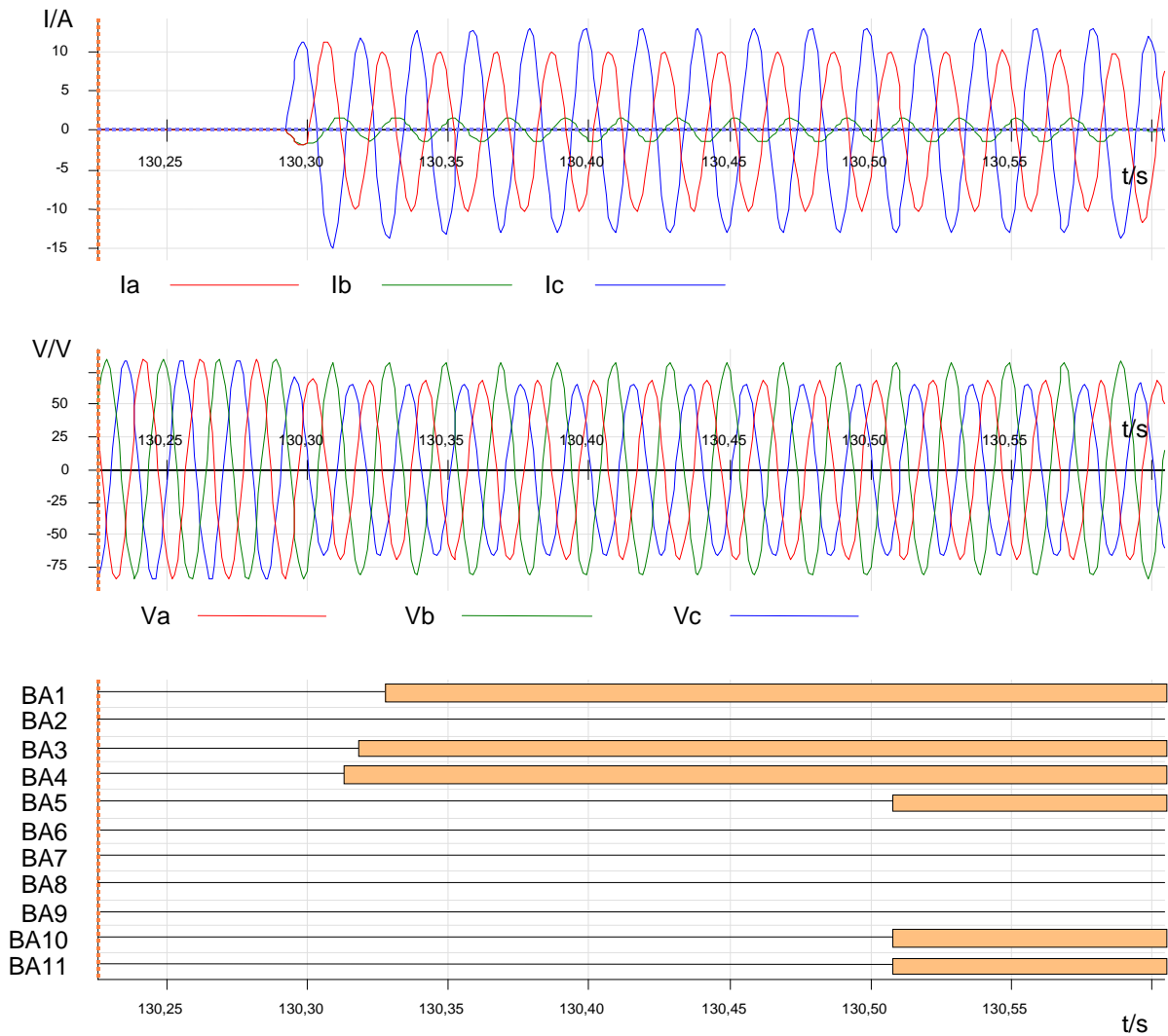
- 126.110 : Network disturbance starts
- 126.110 : general device starting signal appears
- 126.110 : starting signal phase A of distance function appears (BA1)
- 126.110 : starting signal phase B of distance function appears (BA2)
- 126.110 : starting signal loop phase A-B backward of distance function appears
- 126.219 : starting signal Earth of distance function appears (BA4)
- 126.219 : starting signal loop phase A-B backward of distance function disappears

Figure 7B-2B: Performance of the digital relay model with test file 22009



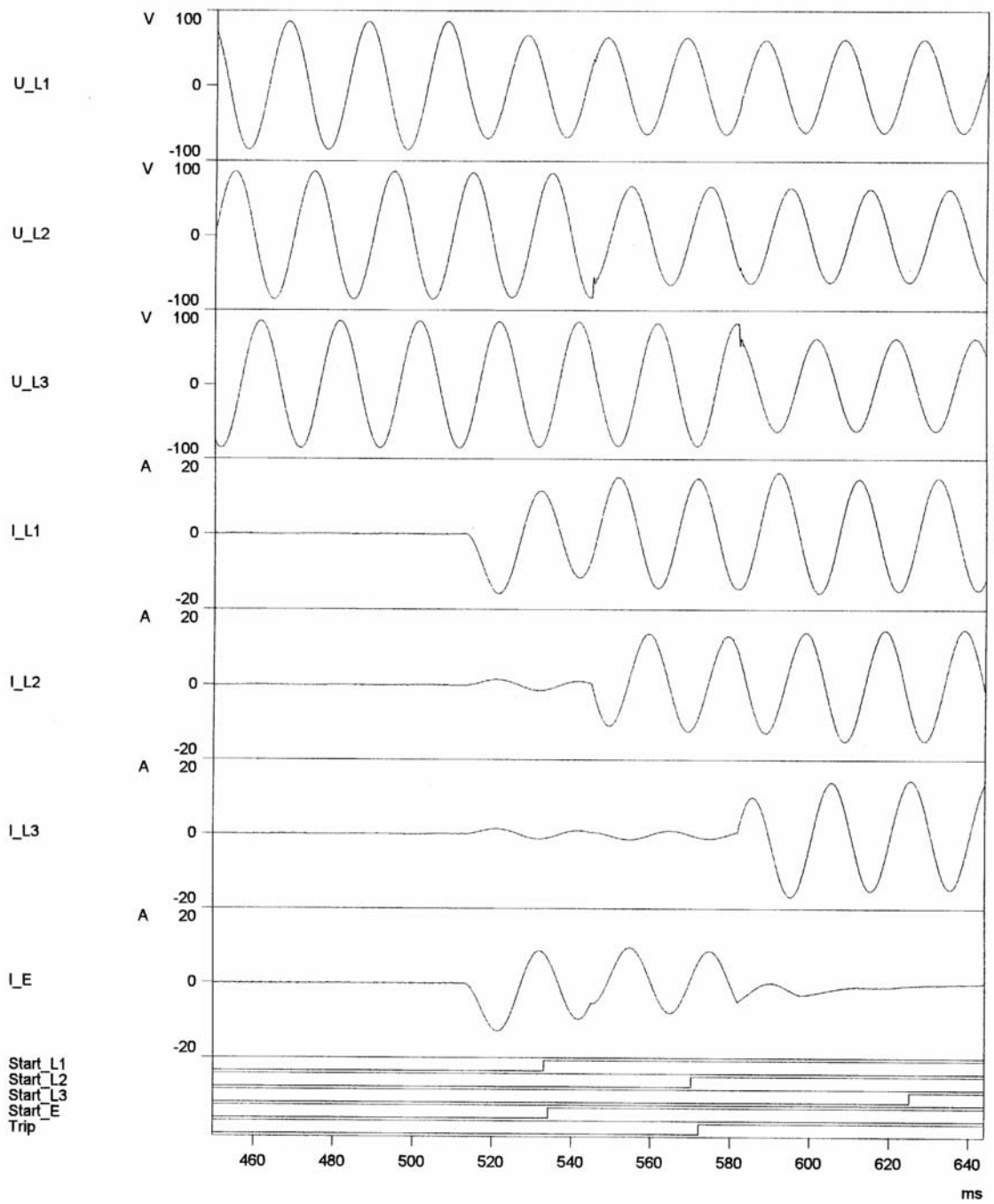
02.11.00 10:33:36 KEMA Dresden, Network Protection Laboratory

Figure 7B-3A: Performance of the digital relay with test file 22024



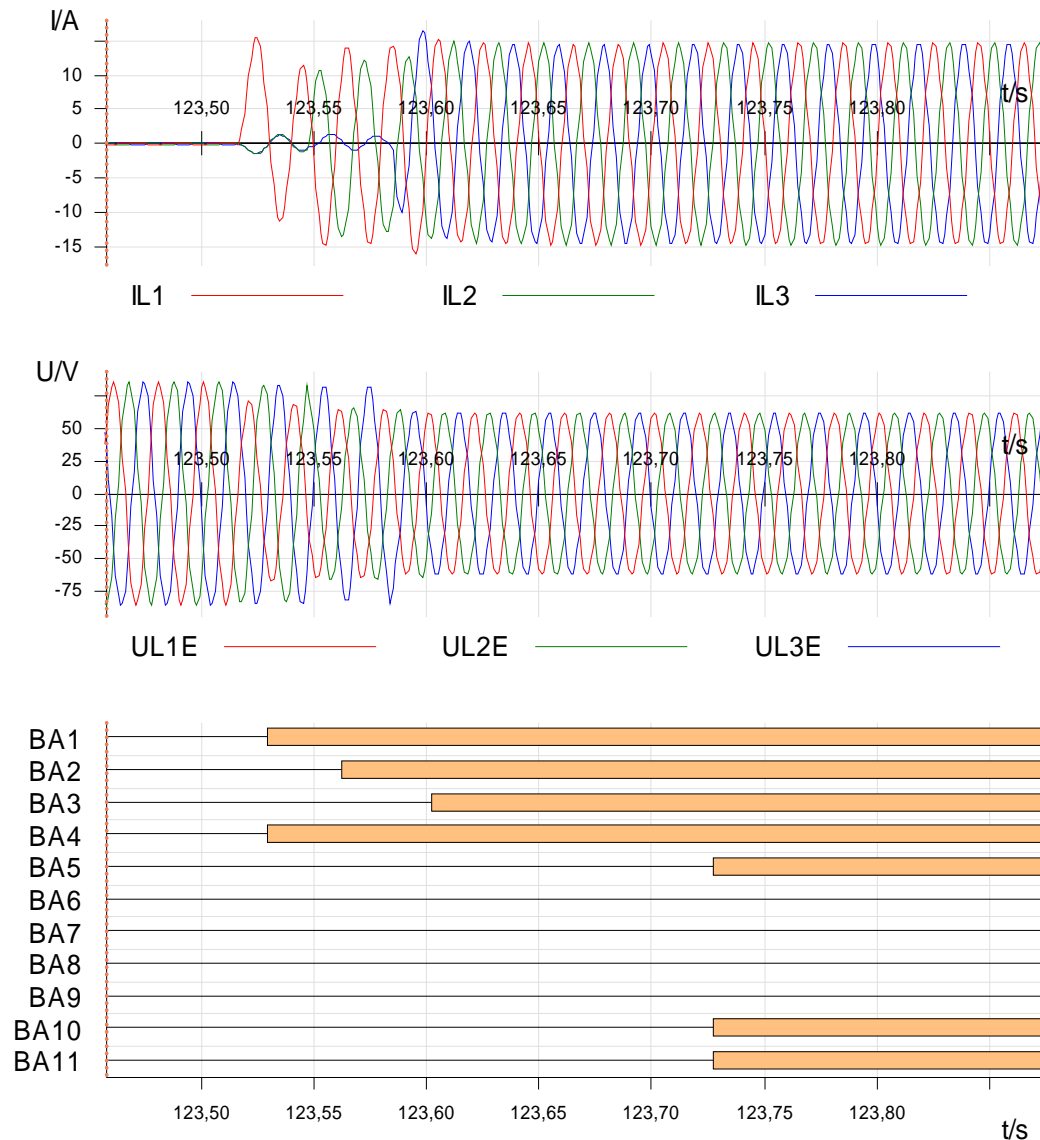
- 130.313 : Network disturbance starts
- 130.313 : general device starting signal appears
- 130.313 : starting signal Earth of distance function appears (BA4)
- 130.318 : starting signal Phase C of distance function appears (BA3)
- 130.318 : starting signal loop Phase C - Earth of distance function appears
- 130.328 : starting signal Phase A of distance function appears (BA1)
- 130.328 : starting signal loop Phase A - Phase C - Earth of distance function appears
- 130.328 : starting signal loop Phase C - Earth of distance function disappears
- 130.333 : starting signal loop Phase A - Earth of distance function appears
- 130.343 : starting signal loop Phase A - Phase C of distance function appears
- 130.508 : tripping command of distance function (BA5)

Figure 7B-3B: Performance of the digital relay model with test file 22024



02.11.00 16:30:34 KEMA Dresden, Network Protection Laboratory

Figure 7B-4A: Performance of the digital relay with test file 22T30



- 123.529 : Network disturbance starts
- 123.529 : general device starting signal appears
- 123.529 : starting signal phase A of distance function appears (BA1)
- 123.529 : starting signal Earth of distance function appears (BA4)
- 123.529 : starting signal loop phase A – Earth forward appears
- 123.529 : starting signal zone 2 appears
- 123.562 : starting signal phase B of distance function appears (BA2)
- 123.562 : starting signal loop phase A – phase B - Earth appears
- 123.562 : starting signal loop phase A – Earth disappears
- 123.572 : starting signal loop phase B – Earth nondirectional appears
- 123.577 : starting signal loop phase A – phase B forward appears
- 123.582 : starting signal loop phase B – Earth forward appears
- 123.602 : starting signal phase C of distance function appears (BA3)
- 123.602 : starting signal phase ABCE of distance function appears
- 123.727 : tripping command of distance function

Figure 7B-4B: Performance of the digital relay model with test file 22T30

## **8.0 Interfacing Relay Models**

### **8.1. Introduction**

The ability to test a software model of a relay, using as inputs the signals that closely resemble actual events, allows one to check whether a given relay is suitable for the specific power system application at hand. This approach has advantages over the approach where the decision is based solely on the data provided in the relay manuals. The use of software models improves the knowledge of the personnel about the relay behavior. In addition, the flexibility of using relay models is unsurpassed if a complex relaying scheme or system solution involving multiple events and relays is to be evaluated. A typical example of such a case is a relay performance evaluation during cascade events as discussed in a recent IEEE survey paper on the subject [190].

Another important issue is how the power system behavior can be represented most accurately for the purpose of evaluating the relay performance. Two major options have been used extensively in the past: a) accurate simulation programs for generating the fault waveforms; b) records of fault waveforms captured at the relay inputs. In either case, the fault waveforms are interfaced to the relay models for further performance evaluation. The dynamic interactions between the relays and power system are the key to the evaluation; hence an important issue that needs to be addressed is how the implementation of the interaction using the available modeling and simulation means may be achieved.

This section first gives a generic discussion of interfacing requirements and possible implementation options and then a summary of the earlier attempts with a discussion of the specific approaches taken. Providing practical interfacing examples for relay models is important for design issues and some specific requirements related to the interfacing are illustrated. It also discusses on emtp and interfacing relays to recorded simulator data. The most important points about the interfacing are summarized in the Conclusions.

### **8.2. Interfacing Requirements**

#### **8.2.1. Power System Interfacing**

The interface between relays and power systems is via instrument transformers. Most of the power system simulation packages will generate analog waveforms that relate to the primary (network) level of voltage and current signals. The relays receive these signals after they are passed through instrument transformer models. To make sure the relay inputs are properly specified during a given event, the representation of instrument transformers is very important. The issues and related requirements when using software models to represent instrument transformer behaviour are discussed at length in a recent IEEE survey paper [191]. One of the particularly important issues is the influence of the relay burden on the transformer response.

An equally important part of the interface is the effect of relay operation on contact changes associated with operation of circuit breakers and communication channels during fault clearing sequences. The operation of circuit breaker contacts may need detailed investigation to determine how the switching taking place during the fault clearing affects power system behavior. Regarding the communication channels, if they are implemented using power line carrier, possible impacts of the faults on the channel behavior need to be accurately represented.

### 8.2.2. Representing Dynamic Interactions

The most important part of the relay evaluation is to properly reflect dynamic interactions between the power system and relays during fault events as well as during normal operations that cause disturbances that may be misinterpreted as faults. A summary of the most relevant dynamic interactions that the interfacing has to capture is given in Table 8.1. It is critical that the dynamic interactions are evaluated through some well-established benchmark means so that the complex interactions are properly represented.

Depending on the means of implementing the scenarios for relay evaluation, some interfaces will have inherent constraints regarding the representation. A good example is the real-time interaction during an autoreclosing action, which cannot be readily represented in the open- loop modes of simulation.

Event	Dynamic Interaction
Autoreclosing	Automatic change of power system model
Power swing	Power oscillations between the equivalent sources
Switching transients	Circuit breaker switching sequences
Line energizing to a "Hot" bus	Synchronizing and synchro-check

Table 8.1: Summary of Dynamic Interaction Requirements

### 8.2.3. Interfacing Relay Models

This section summarizes some of the options related to power network modeling, modeling of protective relays and interfacing between the power network models and relay models.

Interfacing options reported in recent papers are summarized in Table 8.2. Software packages used to model the networks are listed under “Network Programs”. The implementation languages for relay models are categorized as “Relay Programs”. References describing a particular interfacing approach are indicated in the cell that is at a cross point between the row indicating the network program used and a column indicating the language utilized for the model implementation. Additional references describe the network and relay modeling programs themselves.

Particularly powerful are the approaches, discussed below, that use MATLAB for relay modeling. This general purpose signal processing package with its extensions Power Blockset and Simulink [199, 200], provides a very flexible set-up for modeling relays and interfacing the models of the power network and relay. Numerous transient electromagnetic softwares such as EMTP/ATP and PSCAD/EMTDC allow MATLAB and other high level language relay models to run interactively inside the power system solution. [14, 22, 66, 201, 202]

Some papers present the relay models unrelated to any particular software used for network modeling. Sidhu [10] describes the possibility of a generalized modeling technique for generating a software model for any microprocessor-based relay implemented using the general-purpose hardware. A modeling package based on MATLAB has been developed for generating

models of relays. Further links with FORTRAN and C languages are possible. Saengsuwan [62] describes how to model the dynamic behavior of a quadrilateral or polarized MHO distance relay using MATLAB. As an example, it is demonstrated how the simulated distance relay can be tested using data generated by EMTP/ATP. Any transient power system simulator could also be used.

		RELAY SIMULATION PLATFORM					
		TACS [192]	MODELS [193]	FORTRAN	C++	MATLAB SIMULINK [200]	EMTDC RTDS
NETWORK PROGRAMS	EMTP	[13,24,25,196, 197]		[25,196]	[12,17]	[66,62]	
	ATP	[55,28]	[57,58,197,198]			[22]	
	EMTDC						[16,61]
	MATLAB/ PSB					[10,201]	

Table 8.2: Interfacing Options

### 8.3. Present Implementations Using General Purpose Commercial Software

Description of an interface between MATLAB software package on one hand, and ATP and Power System Blockset (PSB) programs [66, 199, 200] on the other is presented below [203].

A power network is modeled either in ATP or PSB and interfaced with the relay model and scenarios implemented in MATLAB. This setup can be used to initiate either open- or closed-loop relay simulation for defined scenarios. All selected fault or no-fault cases, specified by the user, are simulated automatically without any user intervention.

#### 8.3.1. Power Network Model Interfacing

Even though both PSB and ATP simulation programs can be employed for solving power network transients, their usefulness depends on the case studied. For the case with simple power network (few buses) more convenient is modeling in PSB. PSB is fully integrated into MATLAB software package as its Toolbox. This integration enables easy control of all SIMULINK and consequently PSB simulations, by using MATLAB's commands. Relay models are realized either as SIMULINK blocks or MATLAB "m" files, and easily interact with power network model in PSB using SIMULINK built-in features. Using this approach closed loop simulations may be readily achieved.

For bigger power networks (i.e. more than 5 busses), the simulation speed becomes a very important issue. PSB runs unacceptably slow and a more useful simulation program is ATP. Also, ATP can be the preferred tool if the network model contains specific network components not available in PSB. In this case the interface between ATP and MATLAB becomes more involved. A specially developed MATLAB program is needed for this purpose. The MATLAB program automatically controls ATP simulations for each of the desired scenarios and gets interactive simulation results for the relays and related recordings (Fig. 8.1).

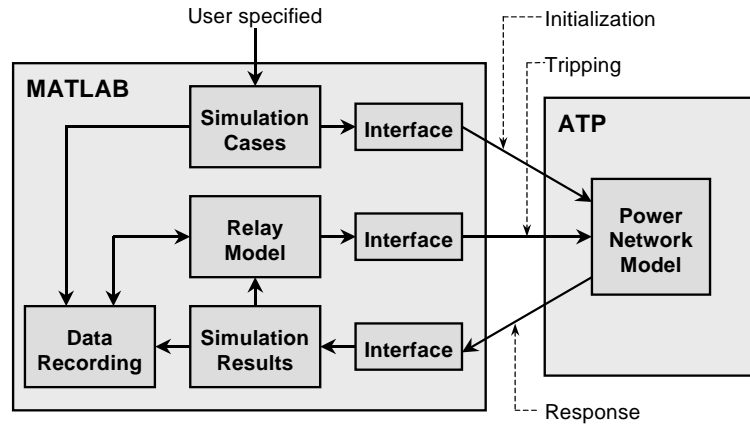


Figure 8.1: Integrated simulation tools for protective relaying by using MATLAB and ATP

### 8.3.2. Generating Simulation Cases

The user can specify, through a MATLAB file or otherwise, all the changes in the network topologies and parameters, as well as desired combinations of these changes for each simulation case. This includes variation of fault parameters (type, location, impedance and inception time), variation of source/load voltages, sequence of line switching, and many others. For most of scenarios this can be done in a systematic way where the user may specify few hundreds or thousands of scenarios through several simple steps. For each specified simulation case, the program automatically updates the data (related to changed components) in the network model or file, and initiates simulation for each of those cases. This means that each specified change in the network is updated between consecutive simulations. After each simulation the results obtained are in a complex form and the program converts them into a data format understandable by MATLAB or the program being used, and memorizes them for further processing.

As an example, Table 8.3 gives a listing of the fault and simulation parameters (that need to be specified for executing a large number of test cases) as well as functions of corresponding MATLAB subroutines.

User specification	Subroutine function
Fault type	Adjust opening and closing times for the switches used for fault realization
Fault inception time	
Fault location	Adjust line section lengths from the remote busses to the faulted point
Fault impedance	Adjust fault impedance
Integration step time	Adjust ATP settings
Simulation end time	

Table 8.3: Available fault and simulation parameters and corresponding subroutines for updating the network model

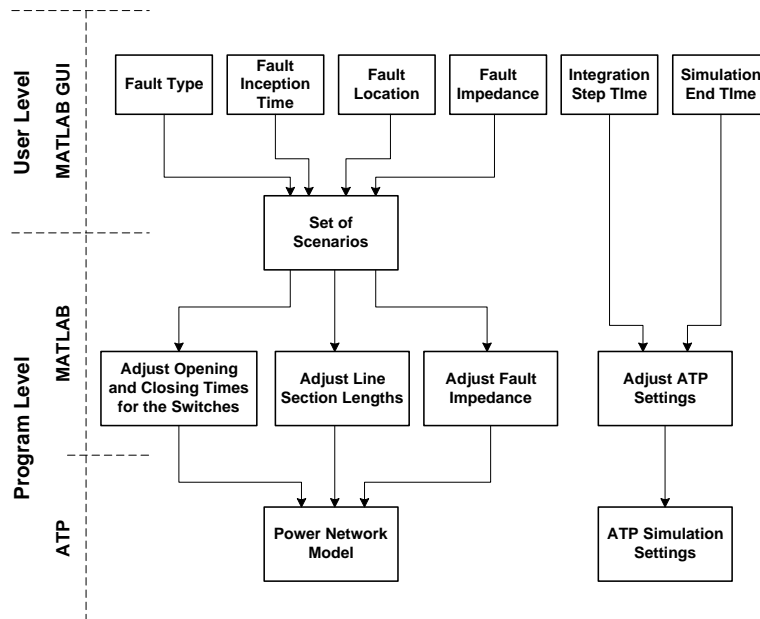


Figure 8.2: The hierarchy between user and program levels

Fig 8.2 shows the hierarchy between the user and program levels, where the MATLAB GUI provides user access to create the scenarios and control the simulation settings, while MATLAB initiates network model updating and simulation.

#### 8.4. Present Implementations Using Custom Developed Software

The examples presented in this section illustrate three different ways of interfacing relay models with power system simulation software using custom software: (a) open loop interfacing, (b) semi-closed loop interfacing and (c) closed loop interfacing [204]. Each method has its advantages and disadvantages and has to be selected depending on the type and the purpose of study.

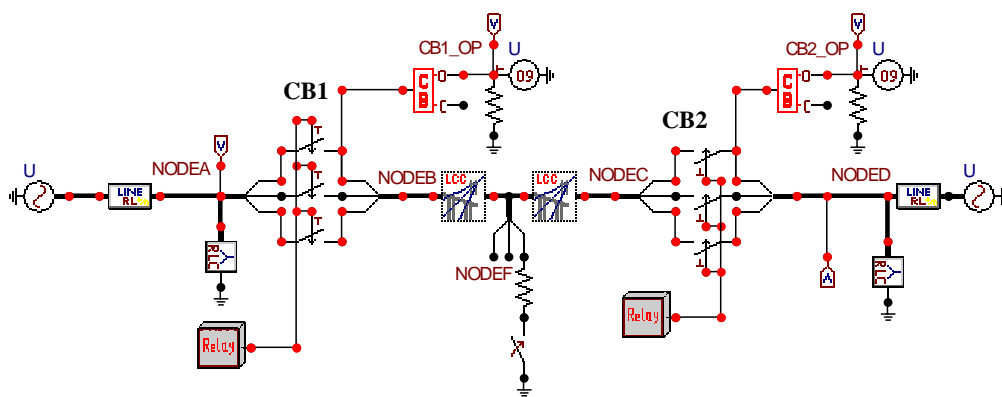


Figure.8.3: ATP Draw diagram of a double ended circuit protected by a unit protection scheme

In all three cases the simulation of a single phase to earth intermittent fault in the middle of the doubly fed transmission line will be used (as shown in Fig 8.3.). The assumed duration of the fault is approximately 360ms. A unit protection scheme with autoreclose relay is applied to

protect the circuit. The protection is designed to disconnect the circuit immediately after the fault occurrence and attempt to reconnect it after a pre-set time delay of 200ms.

The following examples explain the principles and illustrate the features of different ways of relay software interfacing.

#### 8.4.1. Interfacing Protection Relay Models in an open loop regime

This is the most basic and easy to implement way of interfacing relay models with a power system modeling package. The principle is illustrated in Fig 8.4. Using a power system simulation package (e.g. EMTP) primary current and voltage waveform are simulated and saved in a disk file. Subsequently, CT and CVT models using the simulated waveforms calculate the secondary values according to the user selectable ratio. The secondary voltages and currents, therefore, include any possible distortion introduced by the transducers. Finally, the protection scheme model processes the secondary values and produces protection system response.

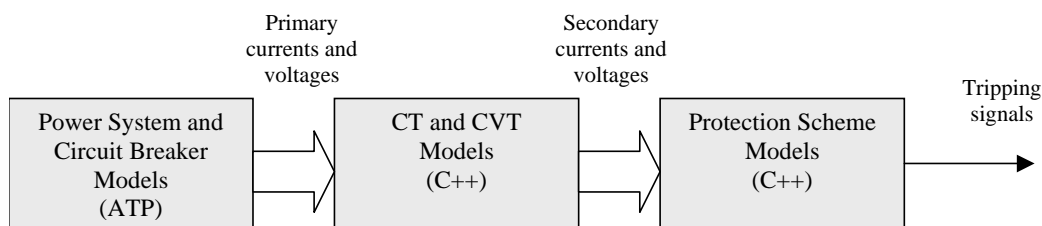


Figure 8.4: Interaction between primary power system and protection scheme

The positive aspect of this approach is its relative ease of implementation even in cases when the power system, transducers and protection are modeled using different software packages or programming languages. No closed loop integration is required. In many cases the immediate tripping response of the relay gives a sufficient answer of the simulated event, but in more complex scenarios it is impossible to obtain the correct answer.

In response to the phase to earth fault described earlier it can be seen from Fig. 8.5, that the initial response of the relay produces a tripping activity at 0.0705s but since the interaction with primary power system is not provided the fault current continues for the whole duration of the intermittent fault (~360ms).

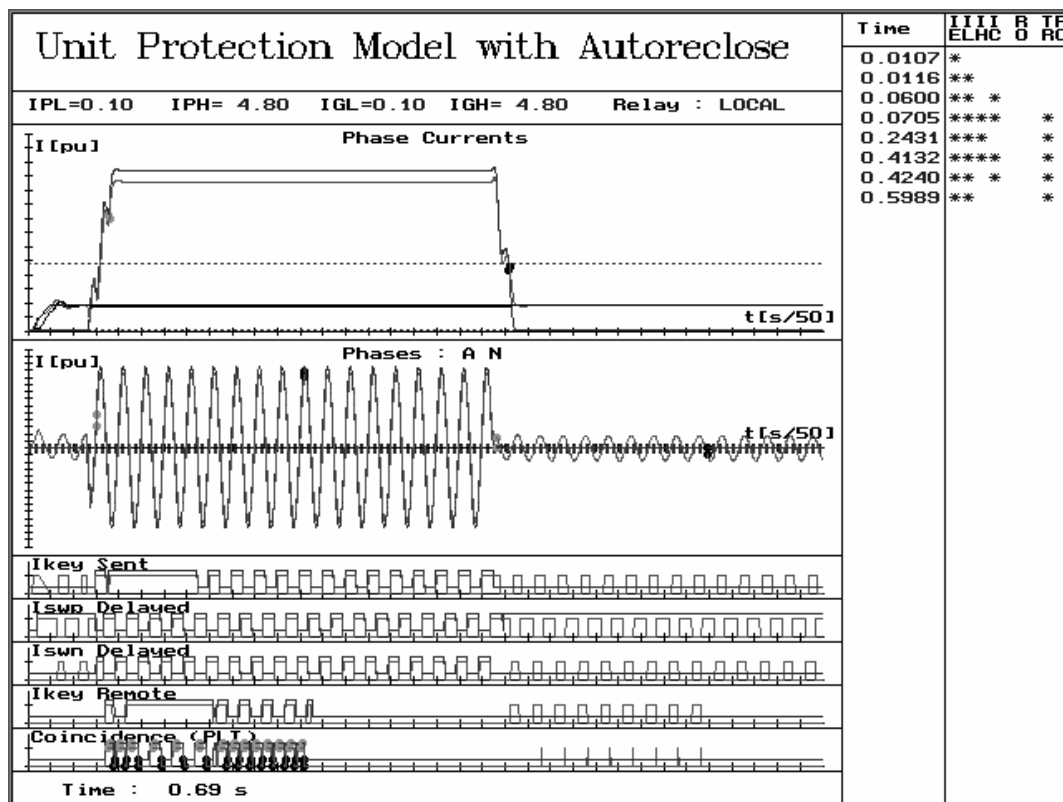


Figure 8.5: Response of the unit protection scheme to a single phase to earth fault in an open loop simulation

### 8.4.2. Interfacing Protection Relay Models in a semi-closed loop regime

The second way of interfacing the relay models with primary power system simulation takes advantage of the fact that the feedback from the protection scheme in most cases is limited to a few tripping/reclosing activities during the simulation of a disturbance. Therefore, it is possible to temporarily break the loop and run the whole simulation in a sequence: Primary Power System, CT&VT and then Protection Scheme (ref. to Fig. 8.6.).

At this point, knowing the response of the protection scheme to the simulated disturbance, the correct tripping times can be applied to the circuit breakers. This involves another loop of simulation, which takes into account the initial response of the protection scheme and produces an amended protection system response. Should the new response differ in any way from the previous one, the simulation loop is repeated. This iteration continues until the same result is obtained from two consecutive protection system responses.

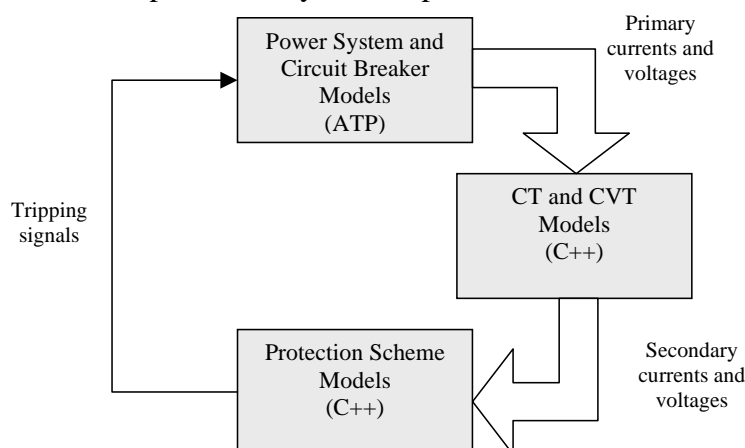


Figure 8.6: Interaction between primary power system and protection scheme

In the example of the phase to earth fault the sequence “Power System, Transducers, Protection” needs to be repeated three times in order to arrive to the final conclusion. After the first iteration the result is the same as in case of the open loop simulation (ref. to Fig 8.7.). Now the tripping activity induces a second simulation loop, which takes care of the initial tripping times for the circuit breakers CB1 and CB2. The result of the second simulation loop is presented in Fig 8.7. As can be observed the fault current is interrupted after a few cycles as a result of protection scheme operation and an autoreclose activity appears at the time instant 0.524s following a successful opening of CB1 and CB2 but the circuit still stays disconnected till the end of the simulation.

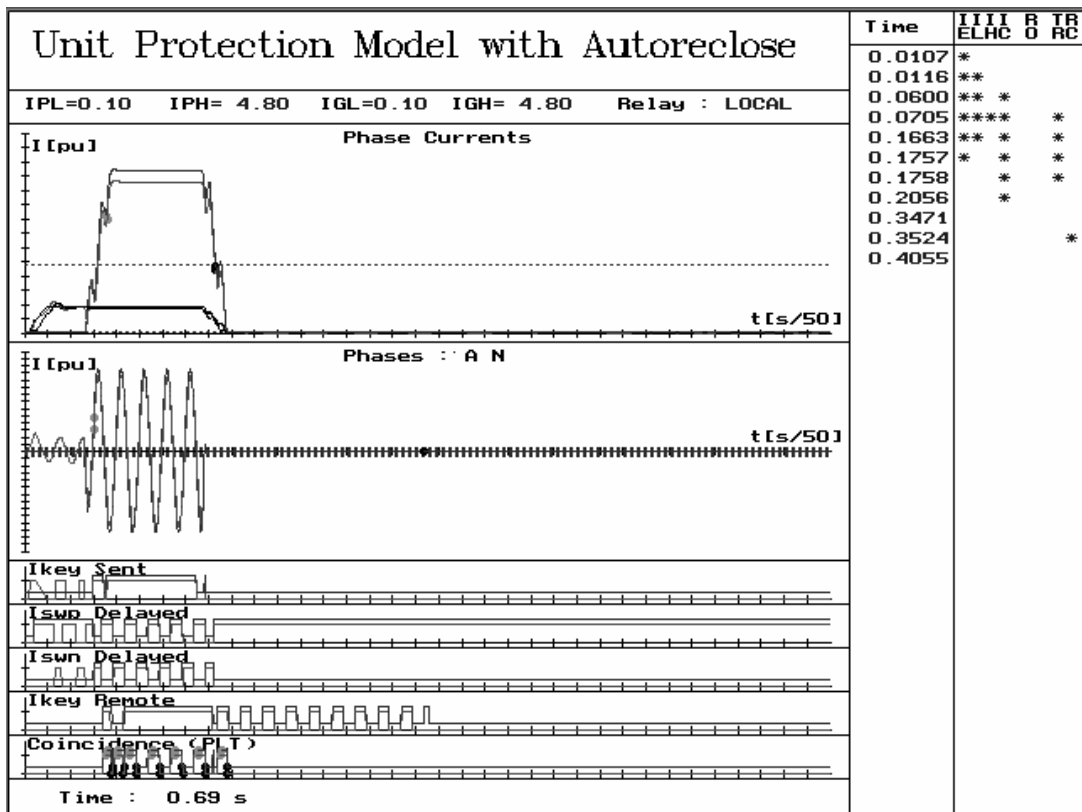


Figure 8.7: Response of the unit protection scheme to a single phase to earth fault (second run)

Subsequently, the third simulation loop is needed in order to take into account the reclosing command. The final result of the three iterations is presented in Fig. 8.8, where the load current appearing after the reconnection of the circuit can be observed.

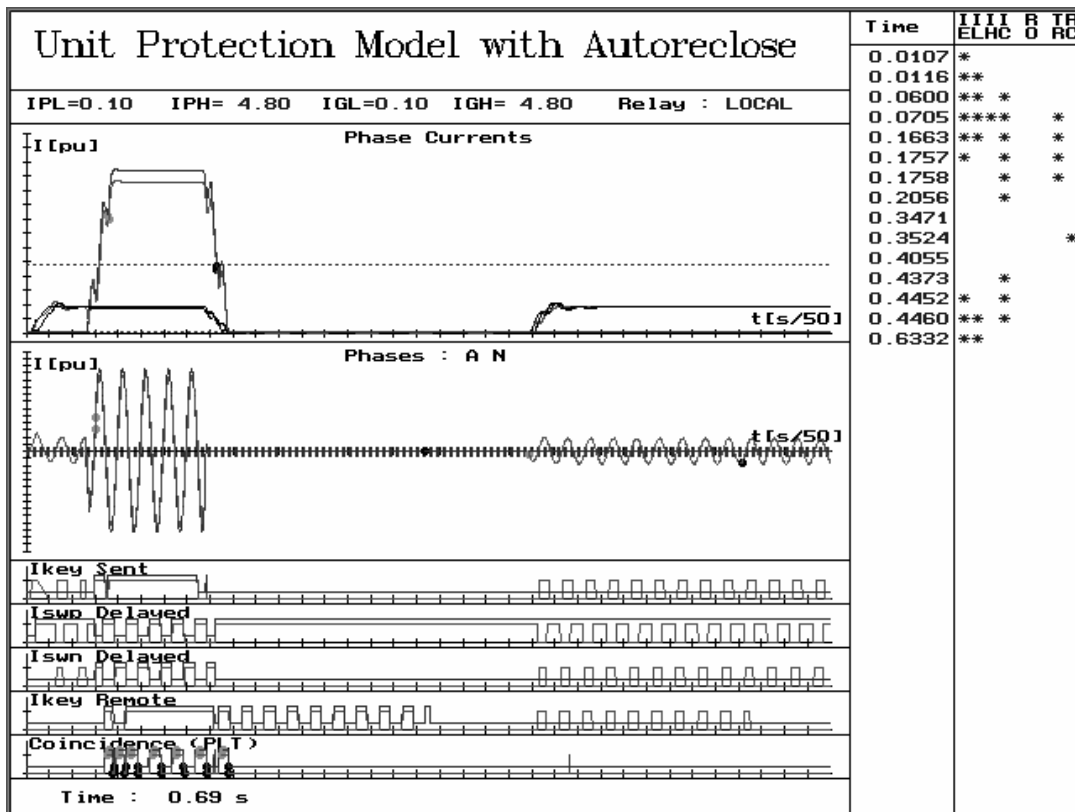


Figure 8.8: Response of the unit protection scheme to a single phase to earth fault (third run)

This way of software interaction between the primary power system and protection system can potentially lead to lengthy simulations, especially in more complex fault scenarios or in systems containing more than one protection scheme. On the other hand in such designed simulation systems there is an added value of flexibility which allows the use of protection relay models not necessarily only within the primary power system context but also for other purposes such as automated model based assessment and diagnosis of protection system [190].

### 8.4.3. Interfacing Protection Relay Models in a closed loop regime

The closed loop method of interfacing is most advanced and is particularly suitable for complex protection schemes involving a lot of tripping activity. At the same time it is the most challenging interfacing task since it requires that the interaction between the power system and protection model is performed on a step-by-step basis. Data exchange through disk files is usually not suitable and other much faster methods using RAM memory is required. The major advantage is that in all cases the simulation needs to be performed only once.

In the example of the phase to earth fault the result (shown in Fig .8.8) is obtained after one simulation execution instead of three as it was in the case of semi-closed loop explained earlier.

H. Li gives an example of an interactive study on a double circuit case using Matlab models for the four relays involved, plus the communication link, running interactively inside PSCAD/EMTDC. MATLAB was also used to track the dynamic characteristic of the adaptive relay at each time step. This study revealed that for a certain range of communication delay, maloperation of relays on the healthy line could occur following the trip of the breakers on the faulted line.[205]

## **8.5. Interfacing Relay Models to Recorded Data**

### **8.5.1. Sources of Recorded Data**

Relay models can be verified besides by means of numerical simulation of fault transients using recorded voltages and currents from the real power system or laboratory tests.

The sources of recorded data that are used as input signals for relays and relay models are:

- Analog/digital fault recorders installed in utility and industrial power networks
- Field and laboratory tests performed to validate and test certain relay functions
- Fault records available from modern numerical relays that are in service.

The main advantage of the recorded data is the effects of the current and voltage transformers, time-varying fault resistance and non-linearities of the power system components are already included in the recorded fault data. In this way, the performance of relay models can be further verified in a more realistic environment than pure computer simulation. In addition, the recorded data may be used to improve the system model to reproduce more realistic power system transients.

Prior to availability of digital fault recorders (DFR) and transient recorders the field and laboratory tests were recorded using analog tape recorders [211]. The analog tapes are in most cases multi-track recordings with a certain bandwidth and high sampling rate that is comparable to DFR (generally up to 10 kHz).

DFRs are used to monitor power system voltages, currents and events. These devices record analog signals by periodically sampling them and converting the measured signals to digital values. Typical recorders monitor 16-64 analog/digital input channels and a comparable number of events. Samples of voltage and current waveforms are recorded with a high sampling rate up to 10 kHz. However, a lower sampling rate is usually required by numerical protection relays and relay models. Most of the DFRs support as output file COMTRADE format [212]. Recorded fault data can be also used in adaptive neural network-based relay systems to train the neural network [209].

Field and laboratory tests under realistic conditions provide valuable test data to verify relay models and certain relay functions [206, 207]. In such tests usually digital transient recorders of high resolution and of high sampling rate are used. For example, in [208] about fault arc tests is reported that were performed in a high-power test laboratory. The tests were carried out on original arrangements of insulators for overhead lines with arcing fittings of 20-kV, 110-kV and 220-kV lines. In these tests the input signals relevant to the distance protection, the line voltage and the line current (both single-phase) and in addition the arc voltage was measured and they were digitized by a transient recorder of 12-bit resolution and 6- $\mu$ s sampling period.

Records of staged fault tests performed on transmission systems before placing new components in service are essential to further verify and improve relay models in a more realistic environment [209]

Numerical relays that are in service and are equipped with data recording facility can record faults and events that represent a deviation from normal operation. While a fault condition persists in the power system, the relevant signals and measured fault data tagged with date and time at signal start and signal end, are stored in a non-volatile ring memory. The time resolution

of fault data acquisition is rather low and lies in the range of 20 to 50 sampled values per system period (50/60 Hz). The recorded numerical data consists of, in general pre-fault (2-3 periods) interval and fault duration until 2-3 periods beyond the time point when tripping signal is issued. The fault recording may cover up to 15 seconds in total depending on the available memory. They can be useful to test and improve relay algorithms particularly in case of misoperation of the relay in service. In the case of general starting of the relay without subsequent tripping the event may be recorded by the digital relay, too. These records can be used later as input for relay models for testing purposes. The advantage of using relay-recorded signals is that there is no need for the scaling of the recorded quantities. Resampling may be needed as explained in section 8.5.3. Some numerical relays can generate COMTRADE files [212] of recorded fault data as output.

### **8.5.2. Types of Recorded Data for Relay Model Testing**

Different recording methods are applied depending on the intended usage of recorded data. In general, voltage and current waveforms measured at a certain location (usually at relay location) in the power system are digitized and recorded. Besides, Phasor Measurement Units (PMU) generate synchronized phasors of measured three-phase voltages and currents marked with time using timing signal from GPS (Global Positioning System) receiver. PMU based protection scheme is used for example to determine fault location on lines with synchronized measurements at both line ends [213].

The recorded data may belong to a disturbance at normal conditions in a power system or to a fault condition. It can be important to test the relay model with signals recorded at normal operation. Such system transients might be misinterpreted by the relays as faults.

Some protection schemes like differential protection of transformers and cables require measured data from two or three terminals. Numerical data recorded by such relays of numerical type are automatically synchronized or contain small synchronization time error in the range of 100  $\mu$ s. Those recorded data can be used to test such relay models that require multi-terminal measured data.

The foreign recorded data available off-line can be used only for open-loop testing of relay models without feedback from the system.

### **8.5.3. Conversion of Recorded Data for Relay Model Interfacing**

Samples of voltage and current waveforms, e.g. by DFR are usually captured at a high sampling rate in a certain bandwidth. Protective relays and relay models however have lower sampling rate. Sampling rate of relay models is selected by the user, while the sampling rate is fixed for real DFRs or other transient recorders. Therefore resampling is required before feeding recorded data to numerical relay models [214]. In general, the operation of reducing the sampling rate by an integer factor including any pre-filtering is called down-sampling. Down-sampling can be performed without aliasing if the bandwidth of the signal is reduced before sampling rate reduction. The sampling rate can be reduced by an integer factor  $M$  without appearance of aliasing effect, if the original sampling rate is at least  $2M$  times greater than the *Nyquist* frequency. The principal method of down-sampling which is also called decimation includes a low-pass anti-aliasing filter and a compressor as shown in Fig. 8.9 The cut-off frequency of the filter is calculated from the selected relay sampling rate. Finite Impulse Response (FIR) filters are suitable for anti-aliasing.

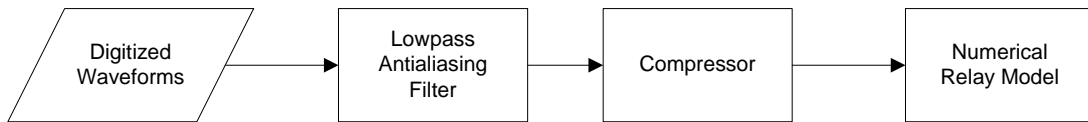


Figure 8.9: Method of down-sampling to feed relay models with recorded numerical data

There may be situations that re-sampling of time-discrete signals by a non-integer factor is necessary. This operation is performed by applying sequentially sampling rate expander and decimator. Sampling rate expansion is called also interpolation [214]. Fig. 8.10 shows the principal procedure of the sampling rate adjustment by a non-integer factor  $L/M$  where  $L$  is the integer factor for up-sampling and  $M$  is the integer factor for down-sampling. Low-pass anti-aliasing filters needed for up- and down-sampling can be unified in one filter as shown in Fig. 8.10.

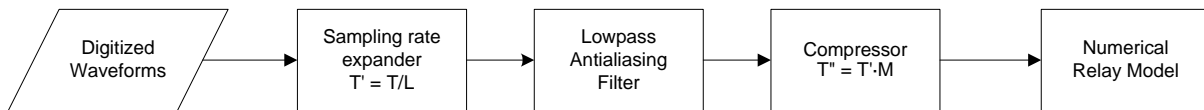


Figure 8.10: Procedure of sampling rate adjustment by a non-integer factor

Mathematical software *MATLAB* [166] (see Section 5.4.3) and *MathCad* [170, 171] (see Section 5.4.6) provide add-on packages that contain built-in functions for resampling and filtering. Consequently, feeding recorded data into relay models that are developed using these programs can be established in a relatively easy way.

In the case TACS or MODELS of ATP/EMTP [159, 160] are used to develop the relay models (see Section 8.2.3), testing and verification of the relay model by means of foreign recorded fault data are possible using POSTPROCESS PLOT FILE option of ATP/EMTP [210]. Recorded data have to be converted first to an ATP/EMTP plot file in text format that can be read in by TACS/MODELS using special request POSTPROCESS PLOT FILE. The "widexx" plot file that consists of columns of data of certain width can be created using any text editor [215]. The resampling and filtering can be easily done using partly built-in functions of MODELS like LAPLACE or ZFUN.

## 8.6. Conclusion

This section has given a survey of interfacing techniques that may be used for evaluating protective relays using software models. Two examples of an advanced solution to interfacing are also discussed. The following are major conclusions that may be drawn related to the interfacing problem:

- In all mentioned cases, the power system network can be modeled very accurately using a software package for simulating electromagnetic transients.
- Behavior of instrument transformers is very important for relay evaluation and detailed models of instrument transformers need to be used.
- Relay models can also be evaluated using waveforms recorded in the field at the low side of the instrument transformer. It should be understood that those waveforms already reflect the impact of the instrument transformer response.
- Relay models may be implemented using a variety of options. The final decision may be driven by the convenience of interfacing with the simulation programs or recorded data files. Interfacing the relay models to the network models can be readily achieved but the degree of flexibility in representing the dynamic interaction depends on the interfacing option.

## 9.0 Limits of relay models

Relay models cannot replace relays in evaluating the performance of protection systems because of several limitations. These limitations include :

- Purpose of using relay models
- Valid operating range and modeling critical components
- Modeling communication channels
- Studies that cannot be conducted with models

### 9.1. Purpose of using relay models

Studies conducted with relay models can be used to identify critical cases for which relay systems should be tested. The relays could then be tested for the identified scenarios. The use of relay models in protection system studies cannot replace relay testing.

### 9.2. Valid operating range and modeling critical components

Electromechanical, solid-state and numerical relays can be used for studies in which the range of system operation is limited. This limitation is caused by the fact that all components of these relays are not modeled. Specific examples of the practice are discussed in this section.

#### 9.2.1. Electromechanical and Electromagnetic relays

Models of Electromechanical and Electromagnetic relays are usually valid for a limited range because, in most cases, the models of the magnetic circuits do not include the impact of saturation when the exciting currents and voltages exceed the limits used in the designs of the magnetic circuits.

The dynamics of the electromagnetic and electromechanical relays are complex issues and are, therefore, not generally included in the models. Because of these factors, performance of relay models could be substantially different from those of the relays.

#### 9.2.2. Solid-state relays

The models of solid-state relays do not include appropriate models of auxiliary current and voltage transformers. The relay models are, therefore, valid when the system voltages and currents used to verify the performance are not high enough to saturate the auxiliary transformers.

The properties of most electronic components change with time. This factor is not included in the models. The models, therefore, should be used with care when they are used to evaluate the performance of relays and relay systems.

#### 9.2.3. Numerical relays

Many factors affect the performance of numerical relays. Some of these factors cannot be or are not modeled in sufficient details. An awareness of these factors and their impact is essential so that the users may not draw incorrect conclusions from the studies conducted with relays models. The specific issues in these cases include:

- Modeling of auxiliary transformers,
- Modeling of A/D converters,
- Algorithm design,
- Deviation of frequency,
- Accumulation of errors in recursive computations and

- Integrity of components

These issues are discussed briefly in this section.

#### ***Modeling auxiliary transformers***

Several components of numerical relays are not usually included in the models. For example, the models of numerical relays usually do not include the magnetic characteristics of the cores of auxiliary transformers. If these transducers saturate, the signals are distorted and the computed phasors and logic are adversely affected.

#### ***Modeling A/D converters***

Another important component, which is sometimes not included in the relay model, is the A/D converter. The saturation of A/D converters in numerical relays impacts the performance in a manner that is somewhat similar to the saturation of CTs and VTs. The nature of the impact of A/D saturation is demonstrated by the example that follows immediately.

Consider a voltage, representing a current, applied to an A/D converter can be defined by the following equation:

$$v = 3\sqrt{2} \sin(120\pi t) \text{ V} \quad (9.1)$$

Now, consider that a 12-bit A/D converter is used to convert the values of the samples of the voltage to equivalent integers. The range of the numbers in this 12-bit converter would be from -2048 to 2047. Also, consider that 1.0-volt applied to the A/D converter generates the number 600. The signal represented by Equation 9.1, sampled at 960 Hz and the quantized output of the converter would be as shown in Figure 9.1. The true positive peak value in this case is 2546 whereas the largest positive value of the truncated signal is 2047. Three samples in each positive half cycle have this value. A similar phenomenon is experienced during the negative half cycles. The true negative peak value is -2456 whereas the smallest value during the negative half cycle is -2048. Different algorithms are affected differently by the truncation. For example, if the three sample least squares algorithm (assuming that the signal is of the fundamental frequency) were used for calculating the peak values from the full as well as truncated signals, the results obtained would be different; these results are shown in Figure 9.2.

This figure shows that the values calculated from the full signal are stationary at 2545 as expected but the peak values computed from the truncated samples are less than the true value in the regions in which the truncated samples are used to calculate the peak values.

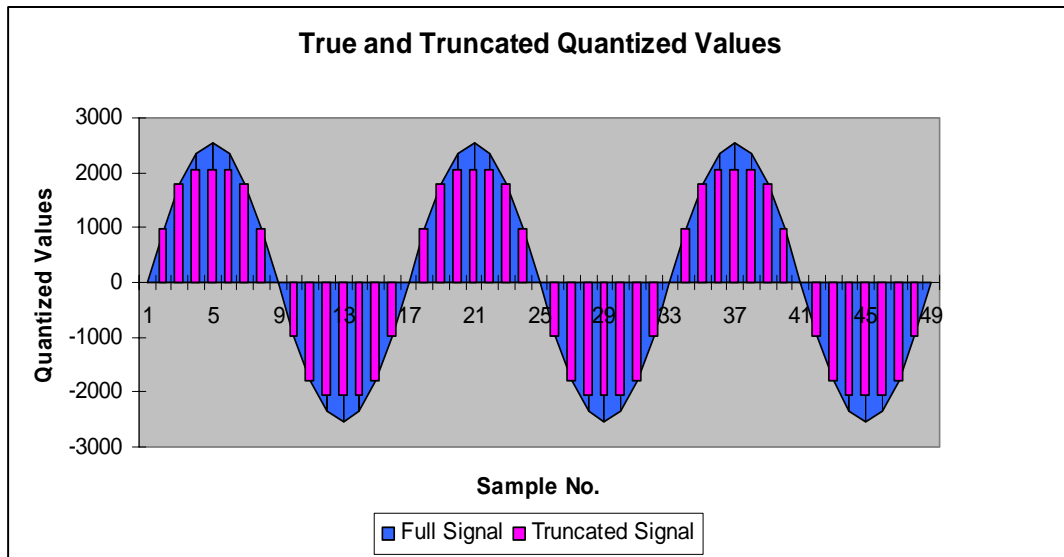


Figure 9.1: A signal, its sampled value without and with truncation

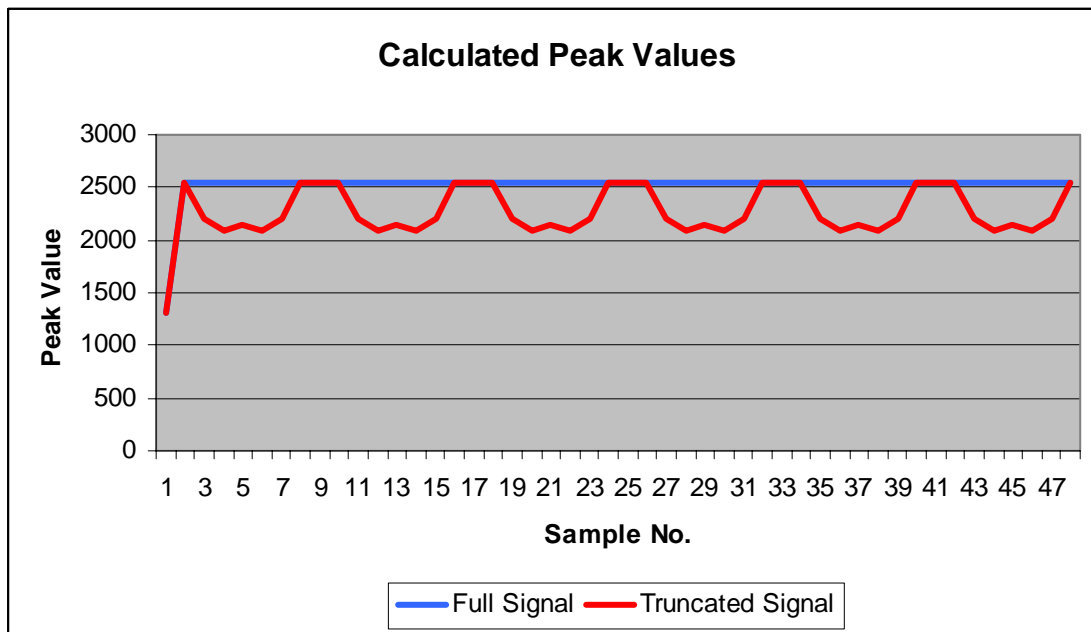


Figure 9.2: Peak values computed from truncated and not-truncated samples

### Algorithm design

Different devices calculate impedances seen from a relay location by using different philosophies. For example, a model may calculate the impedance from voltage and current phasors calculated by a fault analysis or a transient stability study. These programs calculate the fundamental frequency components of the system voltages and currents from a power-system model in which most components are represented by their linear models. Many non-linearities of components and controllers are not modeled in these studies. In an actual power system, voltages and currents contain, in addition to the fundamental frequency voltages and currents, components of other frequencies, such as harmonics, high frequencies due to traveling waves and decaying dc components. The models based on phasors do not provide correct results if the modeled relays are high-speed relays, such as zone-1 distance relays and directional relays.

The phasor-based models also do not take in to account the fact that, in numerical relays, data windows are made up of a finite number of samples. As a fault progresses, the pre-fault data is gradually replaced by the fault data. The impedance calculated by a relay, therefore, changes from the pre-fault value to the impedance during the fault in discrete steps. A sample trajectory of this phenomenon is shown in Figure 9.3. This trajectory is seen by a mho relay; the trajectory shows the impedances seen by the relay before the inception of a three-phase fault in the protected-zone and the changes of the impedance computed by the algorithm after the inception of the fault. The Discrete Fourier Transform is used to convert the sampled data, which consists of 24 samples per cycle of the fundamental frequency, to phasors and the calculated phasors are used to calculate the impedances seen by the relay. The voltages and currents contain the fundamental frequency components and 100 percent decaying dc offset in the current and corresponding decaying dc offset (in the voltage). The high frequency components that decay in a few milliseconds were not simulated in this case.

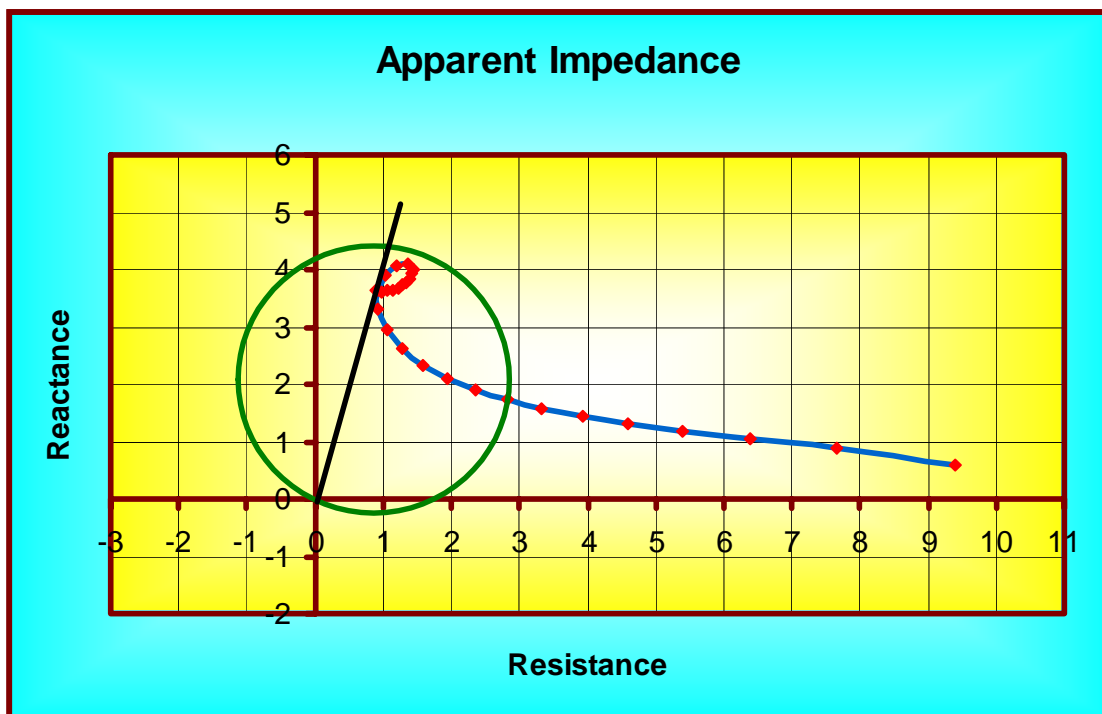


Figure 9.3: A typical impedance trajectory seen by a mho relay

### ***Deviation of frequency***

The system frequency deviation impacts the ability of phasor-calculation techniques. A decrease in system frequency reduces the calculated peak values from true values whereas an increase of system frequency increases the estimated peak values of the phasors. The phase angle estimates are also affected by the change of system frequency.

Figure 9.4 shows the errors in the calculated peak values of a current of 58 Hz frequency by the DFT technique that assumes that the signal is of the 60 Hz frequency. This figure shows that the errors are in the  $\pm 2\%$  range. The mean value of the phasor magnitude is reduced by 0.2 % and a component of about 118 Hz of peak value of slightly less than 2% is superimposed over the average value.

These errors could accumulate with the errors due to other factors, such as CT and VT errors and equipment parameter errors. If the phasors are to be used for revenue metering, these errors are not acceptable. To remedy the problem, the frequency should be measured and corrections

should be applied to the phasor calculating technique as the frequency changes. If a relay model does not take in to account the frequency of the voltages and currents, the results obtained from the models could have unacceptable errors.

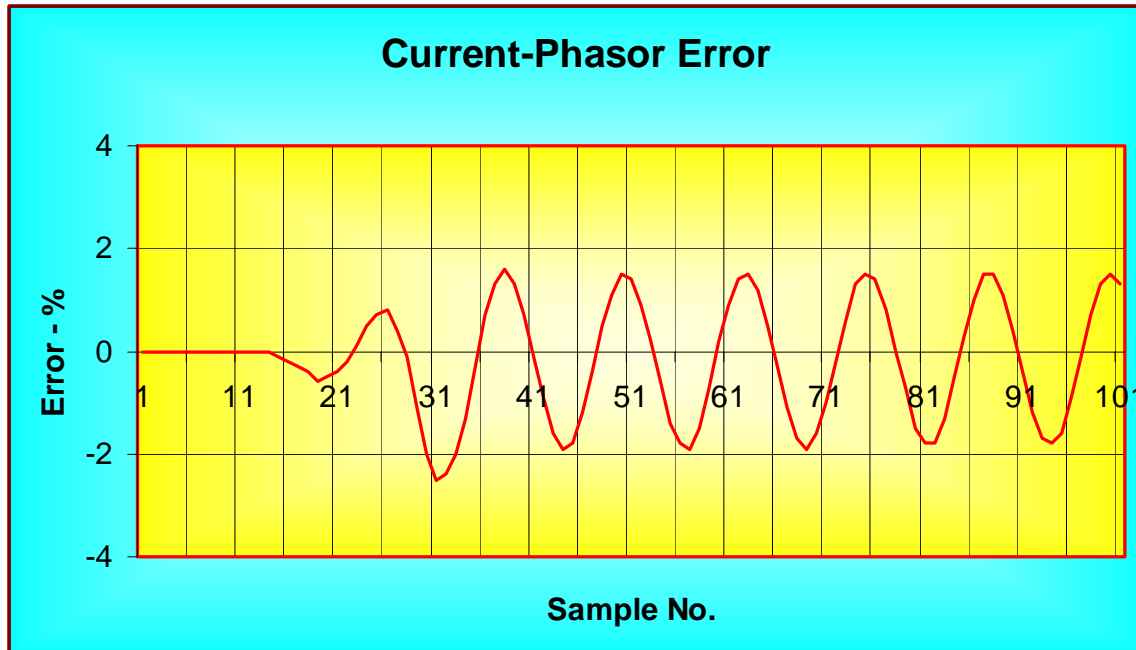


Figure 9.4: Percentage error in calculating the peak value of a phasor

#### ***Accumulation of errors***

A relay could use a recursive process for computing phasors. If this were done, errors from one computation would add to the next computation. The errors, therefore, accumulate over the time of the simulation. These errors in a relay model will most probably will not be identical to those experienced in the relay.

#### ***Integrity of hardware components***

The models are based on the assumption that the relays are functioning normally and none of its components is defective. If a study were intended to determine the impact of a component failure, a special model would be needed.

The accuracy of a model depends on the factors listed in this section as well as some other factors. The users must, therefore, have an appreciation whether the results provided by a model are close the expected results or are substantially different.

### **9.3. Modeling communication channels**

The performances of relay systems are affected by the performance of communication channels used for inter-trip or blocking. In some cases, the communication channels and their delays can be included in a relay modeled but, in other cases, it is almost an impossible task. For example, if a utility uses lines of a telephone company for sending messages from one end of the line to the other but no dedicated telephone line is assigned for this purpose, the messages would follow a different route each time they are sent. The delay in the transmission of messages will be different at each occasion and, therefore, impossible to correctly model in a protection system..

### **9.4. Studies that cannot be conducted with models**

Several types of studies cannot be performed using models. For example, models cannot be used to study the impact of power supply deviations and the impacts of high frequency surges on the

power supply. Impacts of RF radiation on relays, seismic disturbances, contact bouncing and environmental factors are not usually included in relay models.

Some limitations of relay models have been discussed in this section. This list, like most lists, is not complete; the users will find other limitations of models and should be vigilant when power system protection studies are conducted using software analysis packages and relay models.

## 10.0 Future Developments

The validity of any simulation is dependent on the accuracy of the models used. As simulation studies become a more important part of the planning process it is to be expected that manufacturers will come under increasing pressure to supply accurate models in some form or other. Provided a manufacturer has a detailed software model of the relay it may soon be possible to link an off-line power system simulation running in a computer in a customer's premises to a relay model running on a computer in the manufacturer's premises [216, 217]. This is illustrated in Figure 10.1. The link would be over the internet with the customer's computer transmitting the system variables and logic signals needed by the relay model and the relay model transmitting back any trip, pilot or timing signal needed for the customer's simulation. The internet link, timing and data protocols will be controlled from a master computer, probably the customer's computer. The speed of the simulation will depend on the slowest model linked to the system and any delays encountered in communicating over the internet. The relay model can be in any language used by the manufacturer and the system model can be in a different language. Only the data format and timing protocols need to be common to all computers participating in the simulation. The system simulation might be supplying information to numerous relays connected at different busbars in the system. Several different manufacturers might be involved in the simulation each running their own model on a local computer. This allows the manufacturer to use a detailed model of their relay without having to divulge details to a customer or a competitor. This process can apply to any piece of apparatus involved in the simulation where a manufacturer wishes to participate with a detailed model of say a power system stabilizer or a fault current limiter which they do not wish to release to the customer. Each computer can have a graphical interface, which dynamically shows the local variables of interest. The manufacturer may choose to make these available to the customer in due course but they can retain any information of a proprietary nature.

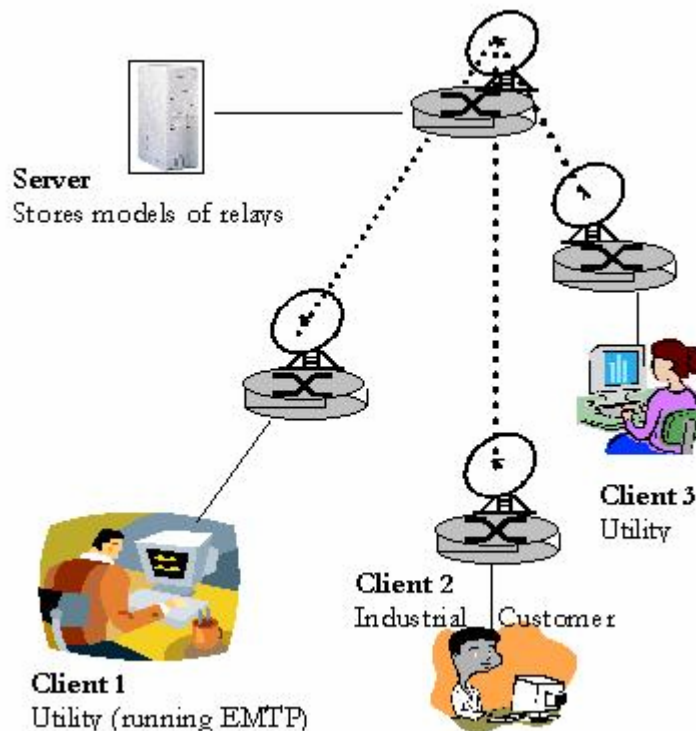


Figure 10.1: Client-server paradigm for relay studies

A variation on this theme would be if a manufacturer provided a DSP or FPGA board running a model of their apparatus, which could be plugged into a user's computer. This is not as secure as the remote participation but is less transparent than providing a detailed software model. It is also likely to allow the simulation to run more quickly.

As well as testing individual relays it is becoming necessary to test groups of relays in a bay or substation including the substation control computer. Wide area back-up protection may require simultaneous testing of relays in several different substations. In situations where the relays and controller are available, say prior to going on line in a new substation, this can be carried out using a real time simulator. At the planning stage the relays are not likely to be available and it is then necessary to use software models for both the relays and the controller running in an off-line simulation. If the controller is available without the relays then the controller can be interfaced to a real time simulator, which is running both the system simulation and the relay simulations.

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